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Kosmonavta Komarova avenue 1
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Phone: +38044 408 24 29
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Volodymyr Kharchenko[1]
Yuriy Chynchenko[2]

MODELS OF AIR TRAFFIC CONTROLLERS ERRORS PREVENTION IN TERMINAL CONTROL AREAS UNDER UNCERTAINTY CONDITIONS

National Aviation University
Kosmonavta Komarova avenue 1, 03680, Kyiv, Ukraine
E-mails: [1]kharch@nau.edu.ua; [2]chynchenko@gmail.com

Abstract

Purpose: *the aim of this study is to research applied models of air traffic controllers' errors prevention in terminal control areas (TMA) under uncertainty conditions. In this work the theoretical framework descripting safety events and errors of air traffic controllers connected with the operations in TMA is proposed.* ***Methods:*** *optimisation of terminal control area formal description based on the Threat and Error management model and the TMA network model of air traffic flows.* ***Results:*** *the human factors variables associated with safety events in work of air traffic controllers under uncertainty conditions were obtained. The Threat and Error management model application principles to air traffic controller operations and the TMA network model of air traffic flows were proposed.* ***Discussion:*** *Information processing context for preventing air traffic controller errors, examples of threats in work of air traffic controllers, which are relevant for TMA operations under uncertainty conditions.*

Keywords: air traffic controller; air traffic services; error management; proficiency skills; safety of flights; terminal control area; uncertainty factors.

1. Introduction

Air traffic control (ATC) service in terminal control areas (TMA) is a highly complex human activity that requires controllers to utilise specific skills/abilities in response to a number of varying unfavourable operational situations/conditions in order to ensure the safe flight of aircraft. Controlled TMA airspaces in most of industrial countries are becoming increasingly crowded with the growth in the number of incidents/accidents caused by the wrong actions/inactions of involved human operators (pilots, air traffic controllers, flight data operators, etc.).

It has been estimated that 60-90 percent of major incidents in complex systems such as aviation are caused by human errors/violations [1]. Human errors are generically defined as "all those occasions in which a planned sequence of mental or physical activities fail to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency" [2].

The research is focused exclusively on air traffic controller errors and investigates primary impacting variables such as information processing, situation awareness, memory, attention, etc. Identifying the underlying causes of commonly occurring incidents/accidents will help future studies in designing preventive measures that may help eliminate these errors.

A number of factors are explored, with the aim to establish links between the core variables and the safety occurrences in terminal control areas as well as to establish links between the core variables and the uncertainty factors in operation of air traffic controllers [3-5].

2. Analysis of the latest research and publications

Rapid advancements in technology have resulted in complex work systems in which operators must adapt their performance to suit dynamic environments, concurrent task demands, time pressure and tactical constraints. In research [1] the 'mental workload', which describes the capacity of the operator to meet task demands and physical co-ordination (task demands) is considered.

A number of vulnerabilities inherent in human information processing have been found in ATC [1]. Information processing assumes that human beings receive information from the environment, act cognitively on that information in a number of ways and emit some response back to the environment, as it discussed in [6].

Mental models are the "mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states and predictions about future system states". The mental picture represents the mental picture of the traffic situation and the necessary actions a controller has taken and should take. Mental imagery plays a significant role in air traffic control and has been equated to concepts of situational awareness and mental models, represented in [7].

Memory is a critical factor in establishing effective mental pictures and situation awareness in controllers [8]. Memory is a cognitive function that is fundamental to most of a controller's tasks and is a common thread in most variables. Shorrock [8] found that 38% of memory errors in ATC involved a failure to complete an intended action and states that controllers rely primarily on working memory and long-term memory. Working memory is a "temporary store for recently activated items of information that are currently occupying consciousness and can be manipulated and moved in and out of short-term memory" [9].

Decision making can be defined as a task in which (a) an individual must select one choice from a number of choices, (b) there is information available with respect to the decisions, (c) the time frame is longer than a second and (d) the choice is associated with uncertainty, proposed in [10].

Attention is broadly defined as "sustained concentration on a specific stimulus, sensation, idea, thought or activity enabling one to use information processing systems with limited capacity to handle vast amounts of information available from the sense organs and memory stores" [11]. Attention can be subdivided into four primary groups; selective, focused, sustained and divided. Sustained attention refers to the ability to sustain attention over long periods of time [12].

Situation awareness (SA) is an understanding of the state of the environment (including relevant parameters of the system). SA constitutes the primary basis for subsequent decision making and by extension, performance in the operation of complex, dynamic systems [13]. Situation awareness was stated as the primary cognitive task reported by controllers and included maintaining understanding current and projected positions of aircraft in the controller's sector in order to determine events that require or may require controller activity [14].

Air Traffic Management (ATM) is a complex system that requires computer systems designed purely for the tasks of aircraft management. This study investigated the sociotechnical systems specific to ATM, noting any delays or errors in systems as well as errors in the use of the system, capturing the reciprocal nature of human-machine interface (HMI). The various models (such as the decision making and SA models) stress the importance of perception and analysis of the environment. The conceptual environmental approach builds on this by recognising the crucial role that environment scanning and perception have on the reciprocal nature of the HMI [15].

3. Safety events and errors of air traffic controllers connected with the operations in TMA

There are two principal safety events that can occur through erroneous Air Traffic Controlling, namely, which are connected with activities in TMA:

– loss of separation (LoS);

– runway incursions (RI).

A ***runway incursion*** is defined as "any occurrence at an aerodrome involving the incorrect presences of an aircraft, vehicle or person on the protected area of a surface designated for the aircraft landing and take-off". Aerodrome controllers are required to maintain a constant visual watch over the area the aerodrome is responsible for in order to ensure that it remains free of obstructions, vehicles and other obstructions when needed for aircraft movements.

A ***loss of separations*** (LoS) involves an infringement of both horizontal and vertical separation minima in controlled airspace. There are a number of procedures that are considered compulsory for controllers. These procedures include the practice of read-back, issuing traffic information and using radio telephony (R/T) phraseology.

Read-back is defined as a procedure whereby the receiving station repeats a received message or an appropriate part thereof back to the transmitting station so as to obtain confirmation of correct reception.

Traffic information is issued in a strict format that must be followed and forwarded to aircraft in the airspace and R/T phraseology sets out the phrasing of communications to be used when controlling.

There are three distinct types of errors (Fig. 1): slips, lapses and mistakes. Slips and lapses are "errors which result from some failure in the execution and or storage of an action sequence, regardless of whether or not the plan which guided them was adequate to achieve its objective".

Mistakes are "failures in judgemental and/or inferential processes involved in the selection of an objective or in the specification of the means to achieve it, irrespective of whether or not the actions directed by this decision scheme run according to plan".

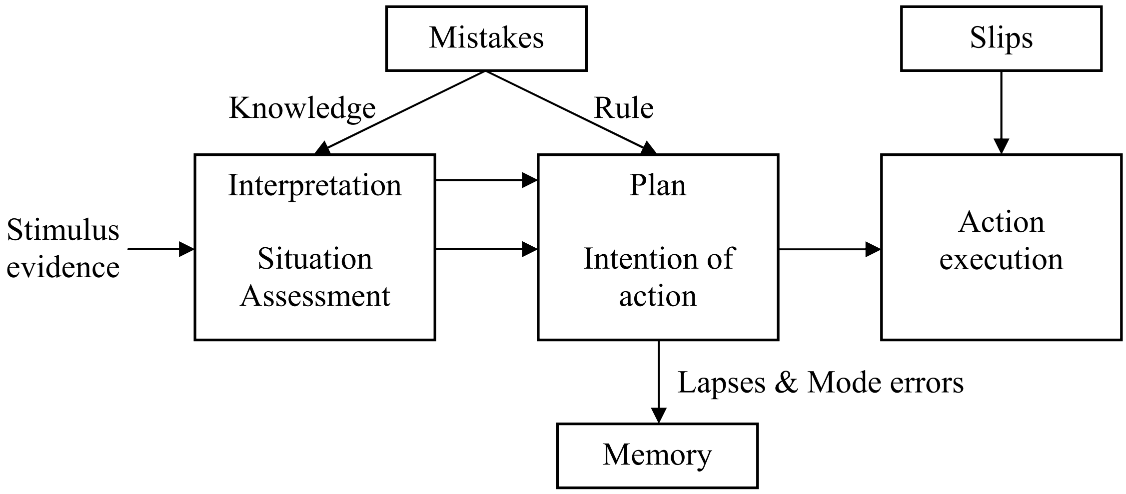

Fig. 1. Information Processing Context for preventing air traffic controller errors

Following the working definitions, human operating errors can occur in two ways; through an action that goes according to plan when the plan was inadequate or when the action is deficient despite a satisfactory plan [6]. In summary, Reason [6] argues for three primary classification types of errors; skill-based slips, rule-based mistakes and knowledge-based mistakes. Execution failures correspond to skill based levels of performance and planning failures with rule and knowledge-based levels [6]. Planning failures are classified as mistakes and execution failures as slips or lapses.

The human factors variables, which are associated with safety events in work of air traffic controllers under uncertainty conditions, are divided in such clusters as follows:

1. Information Processing:
– Monitoring failure;
– Information Overload;
– Ambiguous instructions issued;
– Similar call signs;
– Misjudged Aircraft projection.
2. Situation Awareness:
– Erroneous hear-back;
– Misjudged aircraft projection;
– Erroneous Perception;
– Failure to recognize risk;
– Instruction issued to wrong aircraft.
3. Memory:
– Forgot planned action;
– Inaccurate recall of temporary memory;
– Working memory failure;
– Rarely used information.
4. Attention:
– Divided;
– Selective;
– Focused.
5. Human Machine Interface:
– System delay;
– Poor label management;
– Insufficient use of tools.
6. Workload:
– High/Low complexity;
– High/Low volume;
– Underload/Overload;
– Subjective traffic complexity rating;
– Subjective workload rating.

It was found that time since start of shift is a significant predictor of safety events. Furthermore, time frames 0-30 minutes and 91 – 151 minutes were the most frequently occurring time of the safety events. In terms of safety events, it was found that information processing (human factors), workplace design (external factors), poor adherence to communication standards and lack of memory cues (risk factors) are significant predictors of safety events.

With respect to human error, lapses were found to predict two components of information processing; detection and auditory errors. Poor workplace design was found to be a significant predictor of lapses.

4. The Threat and Error management model application to air traffic controller operations

The Threat and Error Management (TEM) model is a conceptual framework that assists in understanding, from an operational perspective, the inter-relationship between safety and human performance in dynamic and challenging operational contexts.

The TEM model focuses simultaneously on the operational context and the people discharging operational duties in such context. The model is descriptive and diagnostic of both human and system performance.

It is descriptive because it captures human and system performance in the normal operational context, resulting in realistic descriptions. It is diagnostic because it allows quantifying complexities of the operational context in relation to the description of human performance in that context, and vice-versa.

There are three basic components in the TEM model, from the perspective of flight crews: threats, errors and undesired aircraft states. The model proposes that threats and errors are part of everyday aviation operations that must be managed by flight crews, since both threats and errors carry the potential to generate undesired aircraft states.

Flight crews must also manage undesired aircraft states, since they carry the potential for unsafe outcomes. Undesired state management is an essential component of the TEM model, as important as threat and error management. Undesired aircraft state management largely represents the last opportunity to avoid an unsafe outcome and thus maintain safety margins in flight operations.

Table 1 presents examples of threats, grouped under two basic categories derived from the TEM model. Environmental threats occur due to the environment in which flight operations take place. Some environmental threats can be planned for and some will arise spontaneously, but they all have to be managed by flight crews in real time.

Organizational threats, on the other hand, can be controlled or, at least, minimised, at source by aviation organizations.

Table 1

Examples of threats

Environmental Threats	Organizational Threats
Weather: thunderstorms, turbulence, icing, wind shear, cross/tailwind, very low/high temperatures. **ATC:** traffic congestion, TCAS RA/TA, ATC command, ATC error, ATC language difficulty, ATC non-standard phraseology, ATC runway change, ATIS communication, units of measurement (QFE/meters). **Airport:** contaminated/short runway; contaminated taxiway, lack of/confusing/faded signage/markings, birds, aids U/S, complex surface navigation procedures, airport constructions. **Terrain:** High ground, slope, lack of references, “black hole”. **Other:** similar call-signs.	**Operational pressure:** delays, late arrivals, equipment changes. **Aircraft:** aircraft malfunction, automation event/anomaly, MEL/CDL. **Cabin:** flight attendant error, cabin event distraction, interruption, cabin door security. **Maintenance:** maintenance event/error. **Ground:** ground handling event, de-icing, ground crew error. **Dispatch:** dispatch paperwork event/error. **Documentation**: manual error, chart error. **Other:** crew scheduling event

5. The TMA network model of air traffic flows

We divide the airspace into line elements on which we model the density of aircraft. These line elements are called paths and in practice often coincide with jetways. We represent a link on a path as a segment $[0,L]$ and we denote by $u(x,t)$ the number of aircraft between distances 0 and x at time t. In particular, $u(0,t)=0$ and $u(L,t)$ is the total number of aircraft in the path modelled by $[0,L]$ at time t. We make the additional assumption of a steady velocity profile $v(x)>0$ which depicts the mean velocity of aircraft flow at position x and time t. Applying the conservation of mass to a control volume comprised between positions x and $x+h$, and letting h tend to 0, one easily finds the following relation between the spatial and temporal derivatives of $u(x,t)$ [16]:

$$\begin{cases} \dfrac{\partial u(x,t)}{\partial t}+v(x)\dfrac{\partial u(x,t)}{\partial x}=q(t) \\ u(x,0)=u_0(x) \\ u(0,t)=0 \end{cases} \quad (1)$$

where $q(t)$ represents the inflow at the entrance of the link $(x=0)$ or in terms of the density $q(t)=\rho(0,t)v(0)$.

We can define the density of aircraft as the weak derivative of $u(x,t)$ with respect to x: $\rho(x,t)=\dfrac{\partial u(x,t)}{\partial x}$.

The aircraft density is a solution of the partial differential equation:

$$\begin{cases} \dfrac{\partial \rho(x,t)}{\partial t}+v(x)\dfrac{\partial \rho(x,t)}{\partial x}+v'(x)\rho(x,t)=0 \\ \rho(x,0)=\rho_0(x) \\ \rho(0,t)=\dfrac{q(t)}{v(0)} \end{cases} \quad (2)$$

This is a linear advection equation with positive velocity $v(x)$ and a source term: $v'(x)\rho(x,t)$. Clearly, these two partial differential equations are equivalent and model the same physical phenomenon.

We now consider a junction with m incoming links numbered from 1 to m and n outgoing links numbered from $m+1$ to $m+n$; each link k is represented by an interval $[0,L_k]$. One can see that any network is composed of a number of such junctions. We define an allocation matrix $M=(m_{ij}(t))$ for $1\le i\le m, m+1\le j\le m+n$ where $0\le m_{ij}(t)\le 1$ denotes the proportion of aircrafts from incoming link i going to the outgoing link j; we should also have $\sum_{j=m+1}^{m+n} m_{ij}(t)=1$ for $1\le i\le m$. The system of partial differential equations on the network can be written as [16]:

$$\begin{cases} \dfrac{\partial \rho_k(x,t)}{\partial t}+v_k(x)\dfrac{\partial \rho_k(x,t)}{\partial x}+v'_k(x)\rho_k(x,t)=0 \\ \rho_k(x,0)=\rho_{0,k}(x) \\ \rho_i(0,t)=\dfrac{q_i(t)}{v_i(0)} \\ \rho_j(0,t)=\dfrac{\sum_{i=1}^{m} m_{ij}(t)\rho_i(L_i,t)v_i(L_i)}{v_i(0,t)} \end{cases} \quad (3)$$

We will now show that on such a network, the preceding system of partial differential equations admits a unique solution hence that the problem is well-posed.

6. Conclusions

In this research we considered the human factors variables, which are associated with safety events in work of air traffic controllers under uncertainty conditions. The threat and error management model was analysed and proposed its application in air traffic controller operations. Also we provided examples of threats in work of air traffic controllers, which are relevant for TMA operations under uncertainty conditions.

Utilisation of the TMA network model of air traffic flow in link with above mentioned models will decrease number incidents/accidents caused by air traffic controllers (and associated personnel) and improve safety of flights.

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В.П. Харченко[1], Ю.В. Чинченко[2]

Моделі попередження помилок авіадиспетчерів в термінальних диспетчерських районах у умовах невизначеності

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680
E-mails: [1]kharch@nau.edu.ua; [2]chynchenko@gmail.com

Мета: метою цієї статті є дослідження прикладних моделей попередження помилок авіадиспетчерів у термінальних диспетчерських районах в умовах невизначеності. У роботі запропоновано теоретичні основи формального опису подій з безпеки польотів та помилок авіадиспетчерів, пов’язаних із виконанням технологічних операцій в ТМА. **Методи дослідження:** оптимізація формального опису термінального диспетчерського району, що ґрунтується на моделі управління загрозами та помилками та мережевій моделі потоків повітряного руху в ТМА. **Результати:** отримано показники, пов’язані з подіями з безпеки польотів у роботі авіадиспетчерів в умовах невизначеності. Запропоновано принципи застосування моделі управління загрозами та помилками та мережевої моделі потоків повітряного руху в ТМА. **Обговорення:** середовище обробки інформації для попередження помилок авіадиспетчерів, приклади загроз в роботі авіадиспетчерів, які характерні для виконання технологічних операцій в ТМА в умовах невизначеності.

Ключові слова: авіадиспетчер; безпека польотів; обслуговування повітряного руху; професійно-важливі якості; термінальний диспетчерський район; управління помилками; фактори невизначеності.

В.П. Харченко[1], Ю.В. Чинченко[2]

Модели предотвращения ошибок авиадиспетчеров в терминальных диспетчерских районах в условиях неопределенности

Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03680
E-mails: [1]kharch@nau.edu.ua; [2]chynchenko@gmail.com

Цель: целью данной статьи является исследование прикладных моделей предупреждения ошибок авиадиспетчеров в терминальных диспетчерских районах в условиях неопределенности. В данной работе предложены теоретические основы формального описания событий по безопасности полетов и ошибок авиадиспетчеров, связанных с выполнением технологических операций в ТМА. **Методы исследования:** оптимизация формального описания терминального диспетчерского района, основанная на модели управления угрозами и ошибками и сетевой модели потоков воздушного движения в ТМА. **Результаты:** получены показатели, связанные с событиями по безопасности полетов в работе авиадиспетчеров в условиях неопределенности. Предложены принципы применения модели управления угрозами и ошибками и сетевой модели потоков воздушного движения в ТМА. **Обсуждение:** среда обработки информации для предупреждения ошибок авиадиспетчеров, примеры угроз в работе авиадиспетчеров, характерные для выполнения технологических операций в ТМА в условиях неопределенности.

Ключевые слова: авиадиспетчер; безопасность полетов; обслуживание воздушного движения; управление ошибками; профессионально-важные качества; терминальный диспетчерский район; факторы неопределенности.

Kharchenko Volodymyr. Doctor of Engineering. Professor.
Vice-Rector on Scientific Work of the National Aviation University, Kyiv, Ukraine.
Editor-in-Chief of the scientific journal Proceedings of the National Aviation University.
Winner of the State Prize of Ukraine in Science and Technology, Honoured Worker of Science and Technology of Ukraine.
Education: Kyiv Institute of Civil Aviation Engineers, Kyiv, Ukraine.
Research area: management of complex socio-technical systems, air navigation systems and automatic decision-making systems aimed at avoidance conflict situations, space information technology design, air navigation services in Ukraine provided by CNS/ATM systems.
Publications: 520.
E-mail: knarch@nau.edu.ua

Chynchenko Yuriy (1976). Candidate of Engineering. Associate Professor.
Department of Air Navigation Systems, National Aviation University, Kyiv, Ukraine.
Education: Faculty of Air Traffic Services, State Flight Academy of Ukraine, Kirovograd, Ukraine (1998).
Research area: improvement and automation of a professional selection system and development of professional-major skills of civil air traffic controllers.
Publications: 142.
E-mail: chynchenko@gmail.com

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Volodymyr Kharchenko[1]
Denys Matiychyk[2]

JUSTIFICATION OF CONTROL SYSTEM TYPES OF UNMANNED AERIAL VEHICLE FOR CIVIL AVIATION

National Aviation University
1 Kosmonavta Komarova Avenue, 03058, Kyiv, Ukraine
E-mails: [1]kharch@nau.edu.ua; [2]dennis_j@mail.ru

Abstract

Objective: *The problem of unmanned aerial vehicle control systems is a complicated issue which requires consideration of the tasks and applications of unmanned aerial vehicles. The typology of control systems combination for civil unmanned aerial vehicle is suggested and justified.* ***Methods:*** *The methodology of the research was based on application of the varieties of the experts method for rationale of the variants of control system combinations for a specific type of unmanned aerial vehicle and the morphological analysis was used to generate the variants of control system combinations.* ***Results:*** *The causes that lead to discrepancies in types of control systems for civil unmanned aerial vehicle are revealed. Compliance between remote radio control application and type of feedback signal are considered. Based on morphological analysis method, 25 variants of combined unmanned aerial vehicle control systems are suggested.* ***Discussion:*** *Regulatory, substantive and technical components of basic unmanned aerial vehicle control systems are considered. The practical experience of the development by Scientific Production Center of Unmanned Aviation "Virazh" is used to demonstrate the applicability of findings.*

Keywords: automatic control system; civil unmanned aerial vehicle; morphological analysis; remote radio control.

1. Introduction

It is well known that the basis of flight route compliance by the Civil Unmanned Aerial Vehicle (CUAV) is the flight carried out according to the flight plan developed in advance. The flight plan on uses the straight line segments connected through the points, which are called Route Turning Points (RTP). This ensures congruence of task performance for patrolling, surveillance or other aerial works (are entitled to route type) with the objects and the actual position of the UAV in the airspace over the object. [1].

Modern technical means of radio control, radio programming, automation, satellite air navigation support of flight revealed a whole layer of various Control Systems (CS) that allow the UAV perform very complicated tasks in the air.

In general, CS can be categorized into two basic groups of systems. The first group is called Remote Radio Control System (RRCS). The second large group includes Automatic Control Systems (ACS). There are formed the relationships between the group elements which eventually generate a particular type of UAV CS. For example «Ikarus» CS for small UAVs is a combination of RRCS with telemetry and video support [2].

Today there is no unity in the definition of UAV CS type, taking into account the known basic systems. The reason for this, in our opinion, is the contradiction which emerged as a result of rapid development of microelectronics and programming and the natural need for appropriate, new synthesis of UAV CS.

2. Analysis of the latest research and publications

The Air Code of Ukraine identifies CUAV as "the aircraft intended for the flight without a pilot on board, where the flight management and control is performed by a special control station located outside the aircraft" [3].

Circular № 328 ICAO expressly states that "in order to ensure the integration of the UAV application in the general airspace on common airfields, the pilot that is responsible for the flight of UAV is required. Pilot can use the appropriate equipment, such as autopilot, which helps to perform the pilot's duties, but under no circumstances, in the foreseeable future the responsibility of the pilot will be transferred to the technology" [4].

In fact, these regulatory documents emphasize that the UAV CS must provide its remote control in the first place. ACS is rather a desirable option, but not the main one. However, the practice of modern UAV flight proves that its manual piloting for a long time (5-10 hours) is associated with a significant overload for the external pilot (herein the authors introduce the name "*operator*" instead of the conventional name "*pilot*") and, similar to the piloted aviation there exists the need of automation of the piloting process.

3. Aim of the research

The main aim is justification of Civil Unmanned Aerial Vehicle CS types.

The specified task can be completed through the availability of UAV control system devices that can provide remote, automatic and combined UAV control.

It is known that modern Remote Radio Control (RRC) is industrially implemented in the form of the merged and dispersed systems. The merged RRC is the most common system which looks like a handheld transmitter (a remote control with two short handles – manipulators) produced by "Hi-Tec", "Futaba", etc. [5]. Accordingly, its receiving part is on board of the UAV. The dispersed system is less widespread. This system combines the output spools of the standard transmitter connected to the remote amplifier and a remote antenna to increase the range of communication. Sometimes the manipulators and the transmitter itself are structurally separated. Often, instead of handles-manipulators used a standard three-axis joystick.

4. Research results

Analysis of modern UAV RRC revealed the significant difference in their functions. For example, in UAV "Tango" uses the "pure" radio control link "Futaba", whereas the control system of UAV "Orbiter" provides feedback in the form of telemetry link from on-board sensors [6]. Obviously, such a difference in the functions of RRC is motivated by the tasks/applications that are set for the RRC. Eventually, the only restriction for this issue is the question of flight within the optical sight or beyond it.

Flight beyond the optical sight via radio control system is possible only if there is a certain type of feedback. Today among the technically implemented systems telemetry, terrain video image and virtual model of the area are able to provide feedback.

Given this, remote control of UAV could be typed as follows (Table 1).

Table 1

Compliance between RRC application and type of feedback signal

RRC type	Application	Type of feedback signal
D1	within the optical sight	none
D2	beyond the optical sight	telemetry
D3	beyond the optical sight	telemetry + real video image
D4	beyond the optical sight	telemetry + virtual video image
D5	beyond the optical sight	telemetry + real video image + virtual video image

The result of the analysis also revealed a great variety in the functions of automatic control [7]. The simplest variant of automation is the automation of the flight at the level of such basic function as auto maintenance of speed, flight altitude and position in space between the RTP's, which are assigned "manually" ("simple" autopilot). However, today there are UAV control systems, which allow perform the flight task from the start to finish with the certain freedom of choice for the whole trajectory or its segment [8]. It is obvious that there are some intermediate types of AC in between of the first simplest and the last most difficult examples of automation.

If the first system of AC is taken as basic variant of ACS, then while adding some options to the basic variant in order to expand the range of its functions, the above mentioned types of UAV ACS can be represented in the following form of Table 2.

As shown in Tables 1 and 2, the generalized variants of remote radio control and automatic control systems of UAV can be formalized according to the identified types of CS. Each these variants can be considered as an independent type of CS. But usually when real UAV CS is analyzed, it can be noted that in the "pure" form, CS are used only in UAVs limited by the specific requirements. Thus, the systems of D1 type are used for sports and for scientific purposes. Systems of D2-D5 type are limited by time of continuous piloting by an external pilot [8]. The more widely spread variants in military application are A2 and A3 types of AC, only in the class of short range UAV (5-15 km range) and small UAV (5 - 20 kg takeoff weight [9].

For CUAVs within the class of above 20 kg, the more suitable variant are the combined CS with prioritization of RC and automation, while support of the accuracy compliance of planned the route is carried out through the usage of automation. Such a practical variation implies the idea of certain amount of correspondence between the RRC and CS types suggested in Tables 1 and 2.

Table 2

Compliance of type and functions of different ACSs

Type of AC	Functions of ACS
A1	Automatic control of speed, altitude and position in space between RTPs defined "manually" («simple» autopilot)
A2	Route automatic control («simple» autopilot + flight program)
A3	Route automatic control, automatic take-off and landing («complex» autopilot + flight program)
A4	Route automatic control («complex» autopilot + flight program + subprograms archive of «behavior» on the route)
A5	Route automatic control with independent choice of movement "scenarios" on its segments («complex» autopilot + flight program + subprograms archive of «behavior» on the route + elements of artificial «intelligence»)

To obtain variants of CS combinations, presented in Tables 1 and 2, morphological analysis method was used [10].

The morphological matrix, in this case, is a symbolic entry of remote and automatic control systems variants represented as:

D1	D2	D3	D4	D5
A1	A2	A3	A4	A5

In order to generate a certain number of variants of combined CS it is necessary to multiply the amount of RC systems variants by the amount of AC systems variants, i.e.:

$$Y_k = D_{ns}A_{ns}$$

$$D_{ns}A_{ns} = \begin{cases} 1 if n = 1, \dots, 5;\ s = 1, \dots, 5;\ s \in Z \\ 0\ otherwise \end{cases}$$

$$\sum Y_k = 25$$

We respectively obtain 25 variants of combined UAV CSs. Every combination should contain the element "D" and the element "A", for example, D2A3, D5A4, etc. Through detailed analysis of every variant, which is carried out using one of the experts method, for example, the method of synectics or "brainstorming", the accuracy of selecting a CS combination for a particular UAV type can be confirmed or denied. Let us consider the variant D2A3, used in "Bird Eye 400", while «Predator RQ -1» uses a D5A4 combination of systems.

It should be added that the basic variants of CS taken from Tables 1 and 2 are self-sufficient and appropriate to control UAVs in the specified part, so these variants can be used independently.

Table 3 shows the complete list of variants for the combination of systems «D» and «A».

Table 3

Variants for the combination of systems «D» and «A» and their designation

№ var	Designation	№ var	Designation
1	D_1A_1	13	D_3A_3
2	D_1A_2	14	D_3A_4
3	D_1A_3	15	D_3A_5
4	D_1A_4	16	D_4A_1
5	D_1A_5	17	D_4A_2
6	D_2A_1	18	D_4A_3
7	D_2A_2	19	D_4A_4
8	D_2A_3	20	D_4A_5
9	D_2A_4	21	D_5A_1
10	D_2A_5	22	D_5A_2
11	D_3A_1	23	D_5A_3
12	D_3A_2	24	D_5A_4
		25	D_5A_5

Based on the obtained variants for the combination of systems «D» and «A» some variants for individual UAVs and Unmanned Aviation Systems (UASs) can be defined. These variants were developed and are in operation at Scientific Production Center of Unmanned Aviation (SPCUA) «Virazh» (*Reference needed*). The following UAVs and UASs are considered:

1. *M-7V5 "Sky Patrol"* (Fig. 1) [11]. This UAV uses D5A3 system combination, since the flights performed it performs are not limited by optical sight. Telemetry, real time video images transmitted from onboard cameras is utilized. The software ensures formation of the virtual video image in accord to the UAV position on the route. Application of the ACS on the route, automatic launch and landing are planned.

Fig. 1 UAV M-7V5 «Sky Patrol»

2. *M-6-3 «Zhayvir»* (Fig. 2) [12] and *M-10 «Oko 2»* (Fig. 3) [13]. Unmanned Aviation Complexes (UACs) uses D3A3 system combination, since the flights not limited by optical sight.

Fig. 2 UAC M-6-3 «Zhayvir»

Telemetry, real time video images transmitted from onboard cameras is utilized.

Fig. 3 UAC M-10 «Oko 2»

Application of the ACS on the route, automatic launch and landing are planned.

5. Conclusions

1. The main reason that leads to ambiguity in typology of CUAV CSs is the contradiction between the need to ensure operation of CUAVs of different weight classes in common airspace and the absence of structures and composition of CSs, respective to these weight classes.

2. Due to significant overload of the external pilot of CUAV when "manually" piloting the UAV for a long period of time (5-10 hours) there is a need to automate the process.

3. ICAO regulations and the Air Code of Ukraine states that CUAV is, in the first place, a "remotely piloted aircraft", so the automatic control is rather a desirable option, but not the main one.

4. Basic UAV CSs are entitled to two groups; the first group is remote radio control systems and the second group is the automatic control systems. Some relationships are formed between the elements of the groups that eventually produce a particular type of UAV CS.

5. To obtain specific combinations of the basic UAV CS variants the method of morphological analysis was used.

6. In the future, for a detailed analysis of the specific variant of UAV CS the experts methods, for example, synectics or "brainstorming" can be employed.

7. Selected analysis of the RRC and AC for some UAV and UAC was conducted. The UAVs and UACs were developed and are in operation by SPCUA «Virazh». UAV M-7V5 «Sky Patrol» uses the variant of system combination D5A3. D3A3 variant of system combination is applicable for UAC M-6-3 «Zhayvir» and UAC M-10 «Oko 2».

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В.П. Харченко[1], Д.М. Матійчик[2]

Обґрунтування типів систем керування безпілотними повітряними суднами цивільної авіації

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03058
E-mails: [1]kharch@nau.edu.ua; [2]dennis_j@mail.ru;

Мета: Проблема систем керування безпілотних повітряних суден є складним питанням, яке потребує розгляду завдань і застосування безпілотних повітряних суден. Запропоновано і обґрунтовано типологію комбінації систем керування безпілотними повітряними суднами цивільної авіації. **Методи:** Методологія дослідження ґрунтується на застосуванні різновидів методу експертних оцінок для обґрунтування варіантів комбінацій системи керування для конкретного типу безпілотного повітряного судна, застосований морфологічний аналіз для генерування варіантів комбінацій систем управління. **Результати:** Розкрито причини що приводять до різночитання у типізації систем керування безпілотними повітряними суднами цивільної авіації. Розглянуто відповідність між застосуванням дистанційного радіокомандного керування та типом зворотного зв’язку. На базі методу морфологічного аналізу запропоновано 25 варіантів комбінованих систем керування безпілотними повітряними суднами. **Обговорення:** Розглянуто нормативну, змістовну та технічну складові базових систем керування безпілотних повітряних суден. Для демонстрації застосовності результатів використано практичний досвід розробки Науково-виробничого центру безпілотної авіації «Віраж».

Ключові слова: безпілотне повітряне судно цивільної авіації; дистанційне радіокомандне керування; морфологічний аналіз; система автоматичного керування.

В.П. Харченко1[1], Д.М. Матийчик[2]

Обоснование типов систем управления беспилотными воздушными судами гражданской авиации

Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03058
E-mails: [1]kharch@nau.edu.ua; [2]dennis_j@mail.ru;

Цель: Проблема систем управления беспилотных воздушных судов является сложным вопросом, который требует рассмотрения задач и применения беспилотных воздушных судов. Предлагается и обоснована типология комбинации систем управления для беспилотных воздушных судов гражданской авиации. **Методы:** Методология исследования основана на применении разновидностей метода экспертных оценок для обоснования вариантов комбинаций системы управления для конкретного типа беспилотного воздушного судна и применен морфологический анализ для генерирования вариантов комбинаций системы управления. **Результаты:** Раскрыты причины, приводящие к разночтению в типизации систем управления беспилотными воздушными судами гражданской авиации. Рассмотрено соответствие между применением дистанционного радиокомандного управления и типу обратной связи. На базе метода морфологического анализа предложено 25 вариантов комбинированных систем управления беспилотными воздушными судами. **Обсуждение:** Рассмотрены нормативная, содержательная и техническая составляющие базовых систем управления беспилотных воздушных судов. Для демонстрации применимости результатов использован практический опыт разработки Научно-производственного центра беспилотной авиации «Вираж».

Ключевые слова: беспилотное воздушное судно гражданской авиации; дистанционное радиокомандное управление; морфологический анализ; система автоматического управления.

Volodymyr Kharchenko. Doctor of Engineering. Professor.
Vice-Rector on Scientific Work of the National Aviation University, Kyiv, Ukraine.
Editor-in-Chief of the scientific journal Proceedings of the National Aviation University.
Winner of the State Prize of Ukraine in Science and Technology, Honored Worker of Science and Technology of Ukraine.
Education: Kyiv Institute of Civil Aviation Engineers, Kyiv, Ukraine.
Research area: management of complex socio-technical systems, air navigation systems and automatic decision-making systems aimed at avoidance conflict situations, space information technology design, air navigation services in Ukraine provided by CNS/ATM systems.
Publications: 520.
E-mail: knarch@nau.edu.ua

Denys Matiychyk (1991). Postgraduate student.
Department of Air Navigation Systems, National Aviation University, Kyiv, Ukraine.
Education: National Aviation University, Kyiv, Ukraine (2012).
Research area: Unmanned Aerial Systems.
Publications: 5.
E-mail: dennis_j@mail.ru

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Volodymyr Kharchenko[1]
Tatyana Shmelova[2]
Yevgeniya Znakovska[3]
Dmitriy Bondarev[4]
Andriy Stratiy[5]

MODELLING OF DECISION MAKING OF UNMANNED AERIAL VEHICLE'S OPERATOR IN EMERGENCY SITUATIONS

[1, 2, 3, 4,5]National Aviation University
Kosmonavta Komarova prospect, 1, 03680, Kyiv, Ukraine
E-mails: [1]kharch@nau.edu.ua; [2]shmelova@ukr.net; [3]zea@nau.edu.ua; [4]dmytriy.bondarev@gmail.com; [5]stratij@gmail.com

Abstract

Purpose: *lack of recommendation action algorithm of UAV operator in emergency situations; decomposition of the process of decision making (DM) by UAV's Operator in emergency situations; development of the structure of distributed decision support system (DDSS) for remotely piloted aircraft; development of a database of local decision support system (DSS) operators Remotely Piloted Aircraft Systems (RPAS); working-out of models DM by UAV's Operator.* ***Methods:*** *Algoritm of actions of UAV operator by Wald criterion, Laplace criterion, Hurwitz criterion.* ***Results:*** *The program "UAV_AS" that gives to UAV operator recommendations on how to act in case of emergency.* ***Discussion:*** *The article deals with the problem of Unmanned Aerial Vehicles (UAV) flights for decision of different tasks in emergency situation. Based on statistical data it was analyzing the types of emergencies for unmanned aircraft. Defined sequence of actions UAV operator and in case of emergencies.*

Keywords: algorithm, decision making process, emergency situation, unmanned aircraft system.

1. Introduction

Unmanned aircraft has several advantages, namely low operating cost, good concealment and flexibility, simplicity and availability of technology compared to manned aircraft and Unmanned Aerial Vehicles (UAV) can be used in cases where the usage of manned aircraft is impractical, expensive or risky [1; 2]. The main advantage of using UAVs is tasks that involve risk to humans and efficiency in solving economic problems.

Obviously, UAVs are effective in monitoring forest fires, search and rescue operations in the processing of agricultural crops, relay communications and the movement of goods. In this sense, the usage of UAVs is more appropriate: to relay communications in those places - where the antenna coverage cannot be set because of difficult terrain, agriculture, with aerial photography, moving cargo. In addition, UAVs were used for military purposes since 1961 [1].

The disadvantages of unmanned aircraft include the limited capacity due to the small size of UAV that can be satisfied for the group flight usage [2].

Emergency situations may occur when flying both in manual, and in the autonomous management. For operations carried out "manually", plays an important role the human factor and a significant part of emergency arises due to wrong actions of the operator. Using a constant two-way radio comes to continuous Manual control device parameters, which leads to certain restrictions and inconveniences - the operator can't be distracted from the management and takes full responsibility for the state-controlled UAVs, for his safety and for the safety of the environment and people.

Let we have some UAV that performed different tasks purposes. Air traffic controller using technological procedures "ASSIST" (Acknowledge, Separate, Silence, Inform, Support, Time) decides in emergency situations of flight. At a certain stage of flight is probable extraordinary or emergency situations (for example: loss of control, engine failure, etc.), where it is some risk to lost UAVs. Taking into account the high cost of UAVs it is proposed to build an algorithm of UAV's operator actions using module «ASSSIST» (Acknowledge, Separate, Synergetic ((Coordinated, Cooperation, Consolidation)) Silence, Inform, Support, Time) for each type of UAV. Module «ASSSIST» includes in Distributed Decision support system (DDSS) and has models of the Decision Making (DM) by H-O under Certainty, Risk and Uncertainty [3].

The purposes of the article are: lack of recommendation action algorithm of UAV operator in emergency situations; decomposition of the process of DM by UAV's Operator in Emergency Situations; development of the structure of DDSS for remotely piloted aircraft; development of a database of local DSS operators Remotely Piloted Aircraft Systems (RPAS); working-out of models DM by UAV's Operator (DM under Certainty, DM under Risk and DM under Uncertainty).

2. Distributed control system for remotely piloted aircraft

Advantages of UAV's are to perform the tasks associated with the risk for man and effectiveness in solving economic problems. In this sense, the use of UAVs is more appropriate: to relay communications in those places - where the antenna coverage cannot be set because of difficult terrain, agriculture (group of spraying fields), with photo/video monitoring (group survey of large areas, monitoring of forest fires, patrol areas, etc.), moving cargo [2]. Obviously is the usage of UAVs for military purposes.

Noted additional useful properties: faster coverage of area fragment and consequently more effective at photo/video monitoring, relay communications, agricultural operations - owned group compared UAV using one UAV [4 - 8]. But despite a number of advantages there are some drawbacks, namely the main problem associated with the use of airspace allocation of the frequency range for UAVs management and transmission of information from the board to the ground; lack of recommendation action algorithm of UAV operator in case of emergency situations [5; 6].

In [2; 7; 8] investigated an emergency engine stop, electrical problems, in excess of the maximum and minimum the display height of the flight of the parachute release is done automatically, with transferring the coordinates of the forced landing site to the operator's monitor. The use of a parachute landing system will not only provide reliable survival craft in an emergency situation, but also to simplify its operation.

When a loss of communication with the UAV made an immediate report to the ATM unit. The report states the time and place of loss of communication, the height of the UAV flight, the estimated remaining time of flight and follow the course of landing area (falling) UAV [2]. When hovering UAV in the crown of the trees must be up to the crown, fix the UAV tether and if necessary, to cut the branches and holding, drop to the ground [2].

Remotely piloted aircraft controlled with remote piloting station (RPS) with the management and control line (C2). Together with other components such as the starter equipment and equipment for the return, if it is used, remotely piloted aircraft (RPA), remote piloting station RPS and the line C2 constitute RPAS [9].

3. Aims of the work

1. Lack of recommendation action algorithm of UAV operator in emergency situations.
2. Decomposition of the process of DM by UAV's Operator in Emergency Situations;.
3. Development of the structure of DDSS for remotely piloted aircraft; development of a database of local DSS operators Remotely Piloted Aircraft Systems (RPAS).
4. Working-out of models DM by UAV's Operator (DM under Certainty, DM under Risk and DM under Uncertainty).

4. Estimation of situation's complexity in case of PCS with the help of fuzzy sets method

There are following classification of UAV's that is shown on Table 1 [6]. The type of UAV designs are divided into sets, which are made of airplane (fixed - wing) and helicopter (rotary - wing) schemes and devices with flapping wings.

The type of take-off UAVs are divided into sets of take-off from the runway and a vertical take-off (usually used depending of the purpose).

Unmanned aerial vehicles are classified by way of take-off and landing, airfield and non-airfield, also taking off from the runway or with a catapult; landing to the runway or by parachute or by using snares [8].

Table 1

UAV types

№	Class	Classification	Subclass	Code name
1	A	UAV classification by purposes	Surveillance UAVs	A_1
			Agricultural UAVs	A_2
			Relays communications UAVs	A_3
			…	A_n
2	B	UAV classification by duration of the flight	UAV of a short flight (1 hour)	B_1
			Medium-flight UAV's(from 1 to 6 hours),	B_2
			Early flight UAV's (6 hours).	B_3
			…	B_n
3	C	UAV classification by weight.	Micro UAVs (to 1kg).	C_1
			Small 1 - 100 kg.	C_2
			Lightweight 100 - 500 kg.	C_3
			Medium 500 - 5000kg.	C_4
			Heavy 5000 - 15000 kg.	C_5
			Superheavy 15,000 kg or more	C_6
			…	C_n
4	D	UAV classification by the type of aircraft	UAVs airplane (fixed-wing)	D_1
			UAVs helicopters (rotary-wing)	D_2
			UAVs with flapping wings.	D_3
			…	D_n
5	E	UAV classification by way of take-off	Airfield take off UAV	E_1
			Non-airfield UAV taking off from a catapult;	E_2
			Non-airfield UAV taking off from hands	E_3
			…	E_n
7	F	UAV classification by landing way	Airfield landing UAV	F_1
			Non-airfield UAV landing with the help of parachute;	F_2
			Non-airfield UAV landing with the help of snares;	F_3
			…	F_n
8	G	UAVs by the number of applications	UAV of single usage	G_1
			UAV of repeated usage	G_2
			…	G_n

By the purpose, the UAV classified as agricultural, surveillance, search and rescue, cargo and relays communications. As the number of applications classified as single and multiple applications. Typically, these UAVs are used in monitoring forest fires and search and rescue operations where there is a high probability of loss of the aircraft. For the duration of the flight of the UAV are classified on the aircraft a short flight (1 hour), medium-flight (from 1 to 6 hours), and early flight (6 hours). Given the rather large variety of UAVs also classified by weight. Micro to 1kg., Small 1 - 100 kg., Lightweight 100 - 500 kg., Medium 500 - 5000kg., Heavy 5000 - 15000 kg., Extra heavy 15,000 kg or more. All the above types of UAVs by weight are classified depending on flight distance and maximum take-off weight [7]. So, according to ASSIST there are such types of emergency situations which can be on a board of UAV: bird strike, brake problems, communication failure, electrical problems, emergency descent, engine failure, fire on a board, fuel problems, gear problems, problems with the hydraulic system, icing, fuel dumping, emergency landing, take off abort, low oil pressure. And actions of UAV's operator almost the same like actions of a pilot of a civil aircraft [3; 6; 9].

For example, let us consider the pre-flight preparing of UAV Birdeye 500 (Fig. 1). There are 7 main steps of preparing (Table 2, 3):

1. Make sure that the system is deployed, all cables are connected and the power is turned on remote controll and UAVs.
2. As data channel, set the channel maintenance.
3. Ensure you have a strong signal reception of UAV.
4. Put terrestrial channel to mode «Чисто».
5. Check for a strong signal transmission.
6. Set the working channel.
7. Set the operating mode Secure (if necessary), and set the number sequence.

The middle index of t_n is shown in Table 3, for example time of 1st step

$$t_1 = \{t_{11}, t_{12}, \ldots, t_{1n}\} = 5$$

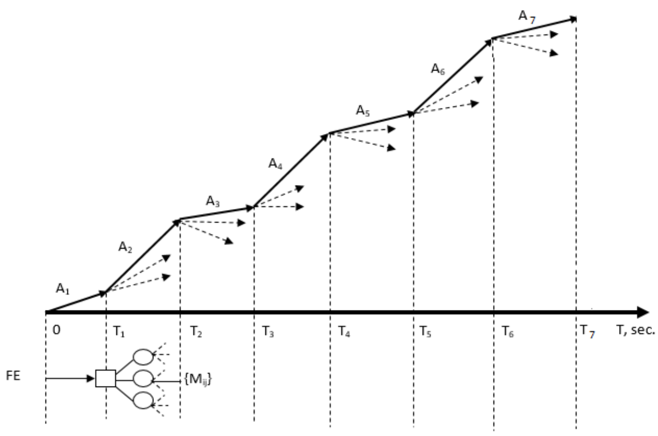

Fig 1. Determination grapf of preparing process

So, according to ASSIST there are such types of emergency situations which can be on a board of UAV: birdstrike, bomb warning, brake problems, communication failure, electrical problems, emergency descent, engine failure, fire on a board, fuel problems, gear problems, problems with the hydraulic system, icing, fuel dumping, emergency landing, takeoff abort, low oil pressure. And actions of UAV's operator almost the same like actions of a pilot of a civil aircraft (Fig.2).

For planning and flight control UAV developed a distributed Adoption Support System Solutions (ASSS), which represents a complex system with complex interactions geographically distributed local ASSS operators of UAS.

Table 2

Generalized structural-hourly table of the technology of the air traffic controller work in FE

№	Contents of the work	Designation of the work	Set of the operations	Support on the work	Time of the performing the work
	Setting of primary connection				
1.	Make sure that the system is deployed, all cables are connected and the power is turned on remote controll and UAVs.	A_1	$\{a_{11}, a_{12}, \ldots, a_{1n}\}$	–	$\{t_{11}, t_{12}, \ldots, t_{1n}\}$
2.	As data channel, set the channel maintenance.	A_2	$\{a_{21}, a_{22}, \ldots, a_{1n}\}$	A_1	$\{t_{21}, t_{22}, \ldots, t_{2n}\}$
3.	Ensure you have a strong signal reception of UAV	A_3	$\{a_{31}, a_{32}, \ldots, a_{3n}\}$	$A_1 \cap A_2$	$\{t_{31}, t_{32}, \ldots, t_{3n}\}$
4.	Put terrestrial channel mode ***Чисто***.	A_4	$\{a_{41}, a_{42}, \ldots, a_{4n}\}$	A_1 U A_2 U A_3	$\{t_{41}, t_{42}, \ldots, t_{4n}\}$
5.	Check for a strong signal transmission.	A_5	$\{a_{51}, a_{52}, \ldots, a_{5n}\}$	$A_1 \cap A_2 \cap A_3 \cap A_4$	$\{t_{51}, t_{52}, \ldots, t_{5n}\}$
6.	Set the working channel.	A_6	$\{a_{61}, a_{62}, \ldots, a_{6n}\}$	$A_1 \cap A_2 \cap A_3 \cap A_4 \cap A_5$	$\{t_{61}, t_{62}, \ldots, t_{6n}\}$
7.	Set the operating mode ***Secure*** (if necessary), and set the number sequence.	A_7	$\{a_{61}, a_{62}, \ldots, a_{7n}\}$	$A_1 \cap A_2 \cap A_3 \cap A_4 \cap A_5 \cap A_6$	$\{t_{11}, t_{12}, \ldots, t_{1n}\}$

Table 3

Main steps of preparing

Setting of primary connection	Make sure that the system is deployed, all cables are connected and the power is turned on remote controll and UAVs.	5 minutes
	As data channel, set the channel maintenance.	15 seconds
	Ensure you have a strong signal reception of UAV	5 seconds
	Put terrestrial channel modeЧисто.	5 seconds
	Check for a strong signal transmission.	5 seconds
	Set the working channel.	30 seconds
	Set the operating mode Secure (if necessary), and set the number sequence.	30 seconds

During the flight UAVs may be controled by remote piloting station (RPS). At any given time t_i k-UAV must piloted by only one j-th RPS, if necessary, at time t_{i+1} to be transmitted to the control (j + 1) th RPS (Fig. 3). This transfer flight control of the j-th RPS to (j + 1) -th RPS to be safe and effective, which is provided through the local DSS operators UAV.

At any given time t_i k-RPA can be controlled from only one *j-th* RPS, if necessary, at time t_{i+1} to be transmitted to the control *(j + 1)th* RPS for using DDSS (Figure 1). This transfer flight control of the j-th RPS to *(j + 1) -th* RPS to be safe and effective, which is provided through the local DSS operators RPAS (Figure 2). According to the recommendations of the ICAO guidelines [9] task system can perform one or more nodes (local DSS operators RPAS). With the formation of the database addresses issues related to the inclusion of RPA the existing regulatory framework of civil air navigation system; description and classification of UAVs and related components; rules of flight, such as instrument flight rules (IFR) and Visual Flight Rules (VFR) flights in the visual line of sight (VLOS) and beyond line of sight (BVLOS) [9].

To coordinate interaction and exchange of information between remoted pilots developed database of local RPS NoSQL [10]. During developing a database of local RPS, UAV users, it was made UAS components analysis, UAV, RPS, C2, and so on.

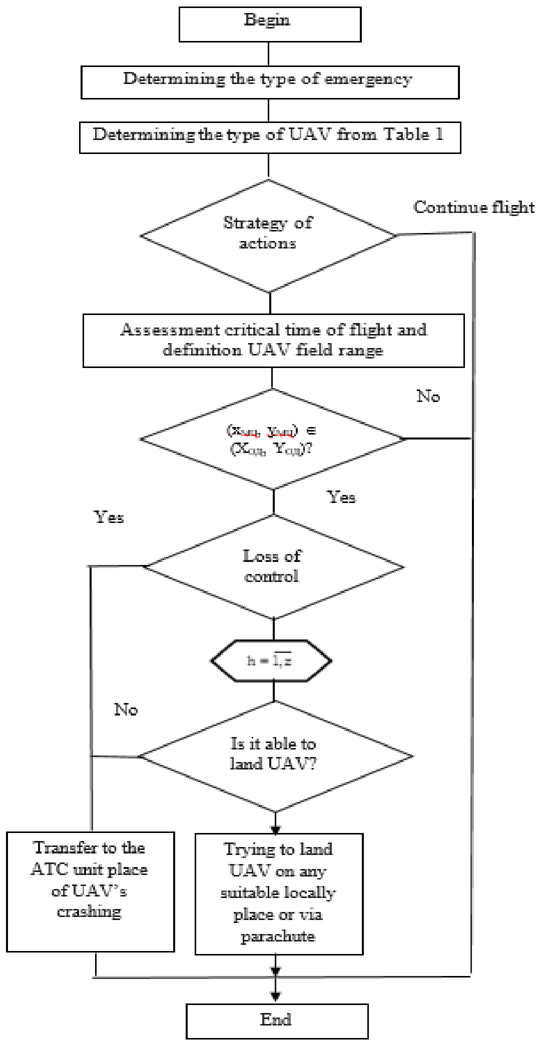

Fig. 2. Algoritm of actions of UAV operator

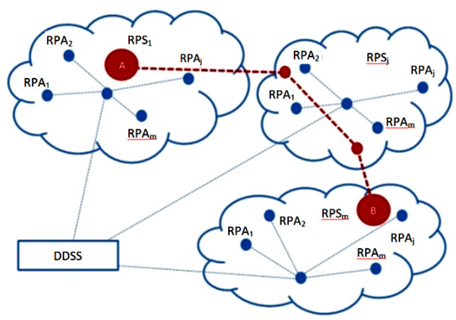

Fig 3. The structure of distributed RPS Mission Control UAVs

For optimization the solution of problems are developed models of determination the optimal landing site in case of an extraordinary situation, search for optimal flight routes UAS with the module «ASSSIST». The investigation into the processes of modelling the DM by UAV's operator in the normal and unusual situations enabled to build the following models: DM under Certainty, DM under Risk and DM under Uncertainty [3-6]. For example, for determine of the optimal landing aerodrome in flight emergencies (FE) we using model of DM under Uncertainty [3;11;12].

Pre-flight planning should include consideration to alternate aerodromes / recovery sites, as appropriate, in the event of the emergency or meteorological-related contingency. Before selecting an alternate recovery / landing, location the remote pilot should consider the adequacy fuel / energy, reserves, reliability of C2 links with the RPA, ATC communication capability as necessary and meteorological conditions at the alternate. For using known criteria of decision making under uncertainty are finding optimal landing aerodrome in FE [9].

To coordinate interaction and exchange of information between remoted pilots developed database of local RPS NoSQL [8]. During developing a database of local RPS, UAV users, it was made UAS components analysis, UAV, RPS, C2, and so on. Taking into account the UAVs operating procedure that includes the purpose of the flight, flight rules, flight areas, functional level C2 lines and other standards (Fig. 4).

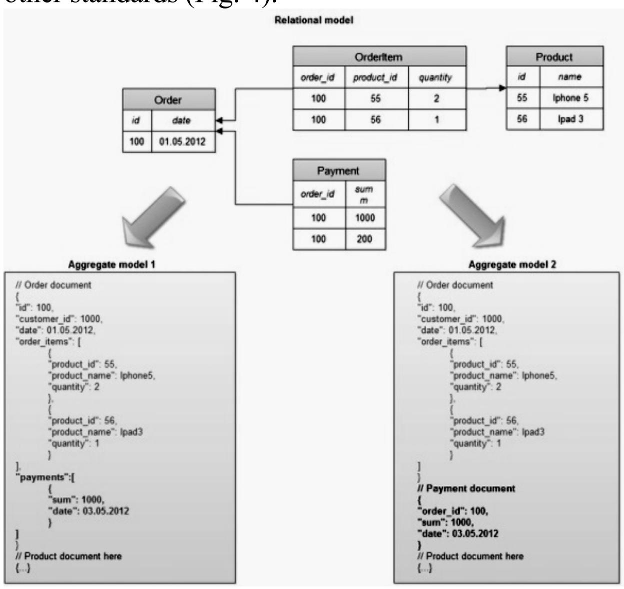

Fig. 4. Fragment of NoSQL database of local RPS UAVs users

Algorithm of determination of the optimal landing aerodrome in flight emergencies:

1. Formation of the set of alternative decisions {A}:

$$\{A\} = \{A_{dest} \cup A_{dep} \cup \{A_{alt}\}\} = \{A_1, A_2, \ldots A_i, \ldots, A_n\},$$

where

A_{dest} – is an alternative decision to land at the destination aerodrome; A_{dep} – is an alternative decision to return to the aerodrome of departure; A_{alt} – is a set of the alternative decision to alternate aerodromes / recovery sites.

2. Formation of the set of factors {λ}, influencing the choice of alternate aerodromes / recovery sites:

$$\{\lambda\} = \lambda_1, \lambda_2, ..., \lambda_j, ..., \lambda_m,$$

where

$\lambda_1, \lambda_2, ..., \lambda_j$ – is set of factors (fuel level, remoteness of the aerodromes, technical characteristics of runways of destination aerodromes, meteorological conditions, reliability of C2 links with the RPA, etc.).

3. Formation of the set of possible results of decision making under the influence of specified factors in FE, that were determined by the method of expert estimates by rating scales according to the regulations:

$\{U\} = U_{11}, U_{12}, …, U_{ij}, …, U_{nm}$.

4. Formation of the decision matrix $M = \|M_i\|$ (Table 1). It was created computer program [11] for optimal solutions using criteria decision making under uncertainty (Fig. 5).

The program "UAV_AS" gives to UAV operator recommendations on how to act in case of emergency. To start you must select the file UAV_AS.exe and run it. After starting the main file software opens the main window (Fig. 6).

Choosing of the optimal aerodrome, in case of forced landing is carried out by the methods of decision making under uncertainty [10]. Selection of criterion of DM under uncertainty (Wald, Laplace, Hurwitz, Savage) is conducted according to the type of flight.

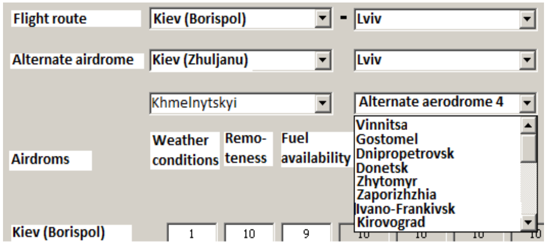

Fig. 5. The program „UAV_AS": choosing of alternate airdrome

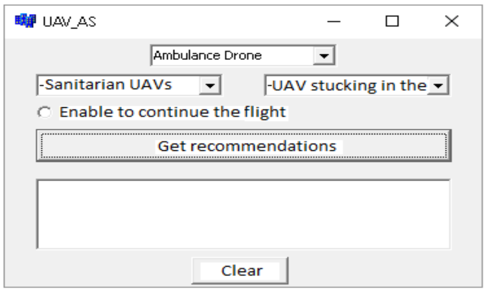

Fig. 6. The program „UAV_AS": the main window

Wald criterion (min/max) is based on the principle of "conservative attitude", and is applied if it is necessary to find a guaranteed solution in case of primary flight:

$$A^* = \max_{A_i}\left\{\min_{\lambda_j} u_{ij}(A_i, \lambda_j)\right\}.$$

Laplace criterion is based on the principle of "insufficient reason" and applied is in case of regular flight:

$$A^* = \max_{A_i}\left\{\frac{1}{m}\sum_{j=1}^{n} u_{ij}(A_i, \lambda_j)\right\}.$$

Hurwitz criterion uses coefficient of a pessimism-optimism α ($0 \le \alpha \le 1$) and is applied in case of flight once in 2 weeks:

$$A^* = \max_{A_i}\left\{\begin{aligned}&\alpha \max_{\lambda_j} u_{ij}(A_i, \lambda_j) + \\ &+ (1-\alpha)\min_{\lambda_j} u_{ij}(A_i, \lambda_j)\end{aligned}\right\}$$

Table 4

Matrix of possible results of decisions in the task of choosing of the optimal landing aerodrome / recovery site

Alternative decisions		Factors influencing the decision making					
		adequacy fuel /energy on RPA	remoteness of the aerodromes / recovery sites	technical characteristics of runways of aerodromes / recovery sites	meteorological conditions at aerodromes / recovery sites	reliability of C2 links with the RPA	ATC communication capability
A_1	A_{dest}	u_{11}	u_{12}	…	u_{1j}	…	u_{1n}
A_2	A_{dep}	u_{21}	u_{22}	…	u_{2j}	…	u_{2n}
A_1	A_{alt}	u_{11}	u_{12}	…	u_{1j}	…	u_{1n}
A_n	A_{alt}	u_{m1}	u_{m2}	…	u_{mj}	…	u_{mn}

The optimal solution for the Savage criterion can be found using matrix of "regret". In case of win the elements of the "regret" matrix $r_{ij}(A_i, \lambda_j)$ are defined as the difference between the maximum value u_{ij} in the row and other values in the row. Then, with the help of the "regret" matrix according to the min/max principle the minimum deviations are determined:

$$r_{ij}(A_i,\lambda_j) = \underset{A_i}{\Delta} = \max_{\lambda_k} u_{ij}(A_i,\lambda_j) - u_{ij}(A_i,\lambda_j) \cdot$$

$$A^* = \min_{\lambda_j} \max_{A_i} r_{ij}(A_i,\lambda_j) \cdot$$

Thus the person, who makes a decision, expresses with the help of matrix $\|r_{ij}\|$ his "regret" if he can't make a best decision in the condition λ_j. Making this decision the person, who makes a decision, has a guarantee that in the worst conditions the obtained income would be not lower than the found income. If flight of UAV is a scheduled one, Laplace and Hurwitz ($0 \le \alpha \le 0.5$) criteria are used for decision making. If the flight of UAV is performed for the first time, Vald, Savage and Hurwitz ($0,5 \le \alpha \le 1$) criterions are used for decision making.

5. Conclusions

Further research should be directed to the solution of practical problems of actions UAV's operator in case of emergencies, software creation. Models of FE development and of DM by UAV's in FE will allow to predict the H-O's actions with the aid of the informational-analytic and diagnostics complex for research H-O behavior in extreme situation.

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Харченко В.П.[1], Шмельова Т.Ф.[2], Знаковська Є.А.[3] , Бондарєв Д.І.[4], Стратій А.В.[5]

Моделювання прийняття рішень оператором дистанційно пілотованого літального апарату в аварійних ситуаціях

Просп. Космонавта Комарова 1, 03680, Київ, Україна
E-mails: [1]kharch@nau.edu.ua; [2]shmelova@ukr.net; [3]zea@nau.edu.ua; [4]dmytriy.bondarev@gmail.com; [5]stratij@gmail.com

Мета: Відсутність алгоритму рекомендацій дій оператора БПЛА в надзвичайних ситуаціях, розкладання процесу прийняття рішень оператором БПЛА в надзвичайних ситуаціях, розробка структури системи підтримки прийняття рішень для оператора БПЛА, розробка моделей прийняття рішень оператором БПЛА. **Методи:** Створення алгоритму прийняття рішень за допомогою критеріїв Вальда, Гурвіца, Ла Пласа. **Результати:** програма "UAV_AS", що дає рекомендації оператору БПЛА про те, як діяти в разі виникнення надзвичайної ситуації. Авторами розроблено алгоритм дій рекомендації оператора БПЛА в надзвичайних ситуаціях. Представлений процес прийняття рішень оператором БПЛА в надзвичайних ситуаціях у вигляді детермінованої моделі із застосуванням методів мережевого моделювання. Побудовано мережевий граф, за яким визначено критичний час на парирування надзвичайної ситуації у разі польоту БПЛА. Розроблено структуру розподіленої СППР для колективного управління пілотованих та безпілотних літальних апаратів оператором. Авторами розроблено бази даних для локальних СППР операторів управління БПЛА, Розроблено моделі прийняття рішень оператором БПЛА в умовах ризику та в умовах невизначеності у разі аварійної посадки БПЛА. **Обговорення:** У статті розглядаються проблеми польотів безпілотних літальних апаратів для вирішення різних завдань в надзвичайній ситуації, засноване на статистичних даних від аналізу типів надзвичайних ситуацій для безпілотних літальних апаратів. Визначається послідовність дій оператора БПЛА в разі виникнення надзвичайних ситуацій.

Ключові слова: алгоритм; безпілотні авіаційні системи; надзвичайна ситуація; процес прийняття рішень.

Харченко В.П.[1], Шмелева Т.Ф.[2], Знаковська Е.А.[3], Бондарев Д.И.[4], Стратий А.В.[5]

Моделирование принятия решений оператором дистанционно пилотируемых летательных аппаратов в аварийных ситуациях

Просп. Космонавта Комарова 1, 03680, Киев, Украина
E-mails: [1]kharch@nau.edu.ua; [2]shmelova@ukr.net; [3]zea@nau.edu.ua; [4]dmytriy.bondarev@gmail.com; [5]stratij@gmail.com

Цель: Отсутствие алгоритма рекомендаций действий оператора БПЛА в чрезвычайных ситуациях, разложение процесса принятия решений оператором БПЛА в чрезвычайных ситуациях, разработка структуры системы поддержки принятия решений для оператора БПЛА, разработка моделей принятия решений оператором БПЛА. **Методы исследования**: Создание алгоритма принятия решений с помощью критериев Вальда, Гурвица, Ла Пласа. **Результаты:** программа "UAV_AS", что дает рекомендации оператору БПЛА о том, как действовать в случае возникновения чрезвычайной ситуации. Авторами разработан алгоритм действий рекомендации оператора БПЛА в чрезвычайных ситуациях. Представлен процесс принятия решений оператором БПЛА в чрезвычайных ситуациях в виде детерминированной модели с применением методов сетевого моделирования. Построено сетевой граф, по которому определено критическое время на парирование чрезвычайной ситуации в случае полета БПЛА. Разработана структура распределенной СППР для коллективного управления пилотируемых и беспилотных летательных аппаратов оператором. Авторами разработаны базы данных для локальных СППР операторов управления БПЛА, Разработаны модели принятия решений оператором БПЛА в условиях риска и в условиях неопределенности в случае аварийной посадки БПЛА. **Обсуждение:** В статье рассматриваются проблемы полетов беспилотных летательных аппаратов для решения различных задач в чрезвычайной ситуации, основанное на статистических данных от анализа типов чрезвычайных ситуаций для беспилотных летательных аппаратов. Определяется последовательность действий оператора БПЛА в случае возникновения чрезвычайных ситуаций.

Ключевые слова: алгоритм; беспилотные авиационные системы; аварийные ситуации; процесс принятия решений.

Kharchenko Volodymyr. Doctor of Engineering. Professor.
Vice-Rector on Scientific Work of the National Aviation University, Kyiv, Ukraine.
Editor-in-Chief of the scientific journal Proceedings of the National Aviation University.
Winner of the State Prize of Ukraine in Science and Technology, Honoured Worker of Science and Technology of Ukraine.
Education: Kyiv Institute of Civil Aviation Engineers, Kyiv, Ukraine.

Research area: management of complex socio-technical systems, air navigation systems and automatic decision-making systems aimed at avoidance conflict situations, space information technology design, air navigation services in Ukraine provided by CNS/ATM systems.
Publications: 520.
E-mail: knarch@nau.edu.ua

Shmelova Tetyana. Doctor of Engineering. Professor.
Air Navigation Systems Department of the National Aviation University, Kyiv, Ukraine.
Education: Kirovograd National Technical Univercity, Kropivnitskiy, Ukraine.
Research area: Modelling of decision making process of human operator and air navigation system in special cases of flight, Decision Support Systems in Air Navigation System, investigation of the operators and groups of operators in the Air Navigation System, Aviation Socionics
Publications: 238.
E-mail: Shmelova@ukr.net

Znakovs'ka Evgeniya. PhD (Engineering) , Associate Professor.
ANS Department of the National Aviation University, Kyiv, Ukraine.
Education: National Aviation Univercity, Kyiv, Ukraine.
Research area: The integrity of air navigation facilities, unmanned aerial vehicles, satellite systems, operating systems, programming C ++, Java
Publications: 38.
E-mail: znakovskaya@bk.ru

Bondarev Dmitriy. Postgraduate student.
ANS Department of the National Aviation University, Kyiv, Ukraine.
Education: National Aviation Univercity, Kyiv, Ukraine.
Research area: unmanned aerial vehicles, Decision Support Systems in Air Navigation System.
Publications: 5.
E-mail: dmytriy.bondarev@gmail.com

Stratij Andriy. Postgraduate student.
Postgraduate student of ANS Department of the National Aviation University, Kyiv, Ukraine.
Education: National Aviation Univercity, Kyiv, Ukraine.
Research area: unmanned aerial vehicles, Decision Support Systems in Air Navigation System.
Publications: 4.
E-mail: stratij@gmail.com

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Svitlana Pavlova[1],
Olexander Volkov[2]

SYSTEM OF GUARANTEED RESOLUTION OF DYNAMIC CONFLICTS OF AIRCRAFTS IN REAL TIME

National Aviation University
Kosmonavta Komarova Avenue 1, 03680, Kyiv, Ukraine
E-mails: [1]psv@nau.edu.ua; [2]alexvolk@ukr.net

Abstract

Purpose: *The present work is devoted to improving of flight safety in civil aviation by creating and implementing a new system of resolution of dynamic conflict of aircrafts. The developed system is aimed at ensuring a guaranteed level of safety when resolution of rarefied conflict situations of aircraft in real-time.* ***Methods:*** *The proposed system is based on a new method of conflict resolution of aircraft on the basis of the theory of invariance.* ***Results:*** *The development of the system of conflict resolution of aircraft in real time and the implementation of the respective algorithms such control will ensure effective prevention of dangerous approaches.* ***Discussion:*** *The system is implemented as single unified equipment using satellite and radar navigation systems that will ensure the positioning of aircraft in real time. Provided that the system should be installed on all aircraft and integrated on board to properly ensure its functionality and interact with navigation systems.*

Keyword: aircraft; air traffic; civil aviation; conflict situation; threat of collision.

1. Introduction

Flight safety is largely connected with the task of collisions avoidance of aircrafts in the air. At present this task is entrusted to the air traffic controls of air traffic control systems, aircraft crew and airborne collision avoidance systems. However, with the growth of air traffic the air traffic controls (ATC) and aircraft crews face increasing difficulties of preventing dangerous approaches of aircraft in the air.

Technical means and collision avoidance systems installed on board the aircraft no longer meet the modern requirements and do not provide the required level of safety [1].

2. Relevance

Visual methods used in the piloting, do not provide the necessary safety, as even in very good visibility the pilots in some cases find a counter aircraft when the time for the execution of the avoidance maneuver is still not enough. In addition, visual methods are associated with subjective errors in determining the distance to the aircraft, its speed and in assessing the degree of risk of collision [2].

The existing ATC system, due to overloads of air traffic controllers in the control process and some limitations of technical means also does not fully ensure the control of maintaining the prescribed navigation parameters with each aircraft flying on instruments. In addition, the ATC system does not allow for the control of flights in all airspace, especially at low altitudes and in difficult to monitor areas (the mountains, tundra, the poles, the oceans etc.).

A very effective means of improving the reliability and operability of ground-based ATC is the automation of supervision and mission control, the introduction of more advanced system of radar, computer systems, and information display systems.

We can say that the ATC automation is the Foundation of dispatching control supervisory control over flying aircraft and the introduction of automated systems now greatly improves the efficiency and safety of air traffic, reduces strain on dispatchers and pilots.

We can say that the ATC automation is the basis for the development of means of ground control of flight control of the aircraft and that the introduction of automated systems has already significantly improves the efficiency and safety of air traffic, reduces the workload of controllers and pilots. However, the automation of processes to ensure safety and improve radar equipment cannot adequately provide the avoidance of dangerous approaches on the routes with heavy traffic in hard-to-reach areas and when intercontinental flights [3].

3. Analysis of recent research

There are two concepts when considering the problems of avoidance collisions of aircrafts in the air: dangerous approach of aircraft and aircraft collision. The dangerous approach of aircrafts is the situation in which the aircrafts closer to the minimum distance, even when it is possible to prevent a collision by executing evasive maneuvers. The collision is the situation in which the aircraft approached at a distance equal or less than the safe distance parting.

There are several modern aircraft collision avoidance systems [4].

The system of prevention of dangerous approaches of aircraft in the air (TCAS – Traffic Collision Avoidance System) is used today to reduce the risk of collisions of aircrafts. There are various options of this system. ICAO (International Civil Aviation Organization) recommends the use of TCAS II system, as it is now fully complies with the ACAS (Airborne Collision Avoidance System) and installed on most commercial aircraft. TCAS II system can detect aircrafts at distances up to 40 miles, provides information about air situation and direct advice on how to resolve the conflict. The system can simultaneously track up to 30 aircraft and to issue commands to resolve conflict simultaneously for three aircraft.

While the advantage of using the TCAS is undeniable, this system has a number of significant restrictions:

- ATC does not receive instructions issued by the TCAS aircraft, so air traffic controllers may not have enough information, and also give conflicting guidance that is the reason for the uncertainty in the actions of the crews;
- it is necessary for the efficient operation of the TCAS, all aircraft were equipped with this system, as the aircraft detect each other at the transponders;
- the system fails to detect aircraft not equipped with transponders. If for some reason the sensor of the conflicting aircraft does not give data on its altitude, the system may not identify it on the display;
- to correct a conflict, the system generates commands for maneuvering only in the vertical plane, maneuvers in the horizontal plane remain for it impossible.

Within the framework of the project "iFly" [5] Eurocontrol has attempted to develop a new system for safe separation ASAS (Airborne Separation Assurance (Assistance) System). ASAS is an on-board system that allows the crew to maintain safe separation of aircraft and provides the necessary information on air traffic. One of the basic functions of ASAS is to improve crew situational awareness, which is to provide him with all necessary information about the air traffic around its own aircraft to make the right and timely decisions to ensure separation with other aircraft.

The project provides that the distance between aircrafts is reduced, and this, in turn, requires the development of a system to prevent aircraft "Wake." Algorithms of ASAS in general are not yet standardized. This is due to the complexity of the transition to the new principles for the allocation of responsibility between an air traffic controller and a pilot to support safe aircraft separation. The above can be attributed to the main shortcomings of the system.

Consider also new technology automatic dependent surveillance ADS-B (Automatic Dependent Surveillance-Broadcast), which is an advanced method of ADS (Automatic Dependent Surveillance). ADS-B technology, now being implemented on the territory of the United States and in other countries, allows pilots in the cockpit and air traffic controllers on the ground to "see" traffic of aircraft with more precision than was available previously, and to obtain aeronautical information [6-7].

ADS-B also transmits real-time weather information to pilots. This information greatly enhances the pilot's awareness of the situation and increases safety. In addition, access to ADS-B information is free. Any user that is in the air or on the ground within range of the broadcast transmission may process and use this information for their own purposes. This information may be used by ATC and ACAS.

Disadvantages of ADS-B [8-10]:

- the absence of any means of protection during data transfer;
- ability to send broadcast fake data or replace information in these data packets;
- party accepting these packages cannot be confident of the validity of the package and identify the sender.

4. Highlighting the unresolved part of the problem

Based on the above described can be concluded.

Developed and implemented modern systems and technologies of conflict resolution of aircrafts have significant drawbacks that do not provide a guaranteed level of safety. The system of conflict resolution of aircrafts must synthesize recommendations in the presence of a detected conflict, which should provide in general the spatial avoidance maneuver to prevent a possible dangerous approach of aircrafts, and after the conflict resolution to ensure the aircraft return to the planned trajectory and it's further maintaining. In the process of issuing recommendations for execution of maneuver the optimality criteria (fuel consumption, time and space cost of performing the maneuver, the comfort of passengers, etc.) should be taken into account.

5. Statement of research problems

In this regard, at present, to solve the problem of collision avoidance is considered technically and economically feasible to supplement the ATC system special onboard collision avoidance system of aircraft capable of autonomous, independent from the ATC system, in real time, to provide a safe separate of aircraft when there is a threat of collision.

The purpose of this work is the creation of a new system and technology resolution of dynamic conflict situations of aircraft with maintenance of the guaranteed level of flight safety.

To avoidance collisions with aircraft through ATC technical means must be made:

- measurement location coordinates and parameters of aircraft motions;
- prediction by simulation with the specified steps possible positions of aircraft after a certain time to detect the threat of collision;
- information exchange with aircrafts for warning and coordinate their maneuvers to avoid collisions;
- ensure the implementation of an automated process resolution of conflict situation.

It is precisely such functional tasks are put for the creation of the new system of dynamic conflicts resolution of aircraft for the organization of decentralized control of air traffic in the modern conditions of safety.

6. System of guaranteed resolution of dynamic conflicts of aircrafts in real time

We propose a solution system of dynamic conflicts aircraft (with necessary and sufficient time) in real time to enhance the security of aviation and aeronautical engineering efficiency.

The paper proposes a system of guaranteed resolution of dynamic rarefied (with necessary and sufficient lead time) conflicts of aircraft in real time to improve safety in aviation and aeronautical engineering efficiency.

The system is implemented as single unified equipment that works using satellite and radar navigation systems that will ensure the positioning of aircraft in real time. Provided that the system should be installed on all aircraft and is integrated into onboard systems to adequately ensure its functionality and interact with navigation systems.

The block diagram of the system is presented in Fig.1. As shown, the system of resolution of dynamic conflict of aircrafts (1) operating in real time consists of two modules that contain blocks, and some individual blocks that perform additional functional tasks.

The system contains the following modules:

- the module for determining the threat of collision (4);
- the module of calculation of maneuvering parameters (9).

In turn, the module for determining the threat of collisions include: the block determining the aircraft coordinates (5), the block of calculation of projected motion paths (6), the block of data analysis and definition of the threat of collision (7) and the accounting block "zones of uncertainty" (8).

The module of calculation of maneuvering parameters includes: the block computation and comparison of "controllability areas" (10), the block prioritizing and selecting the type of maneuver (11), the block determining the trajectory maneuver (12), the block determine the trajectory of the return to the initial trajectory (13), the global optimum (14) (temporal and spatial assessment of losses in performing the maneuver to resolve conflict situations).

In addition, the system contains several separate blocks, namely:

- the data reception block (2);
- the data processing block (3);
- the issuing control commands, alarms and indication (15).

Consider the principle of operation of the system. The system to ensure its work obtains information from: on-board computer (A), radar systems (B), air data system (C) and flight navigation systems (D), inertial systems (E) and control system of engine and control surfaces (F). Information from these subsystems comes first on the data reception block and contains information about all aircraft within a specified limited part of space, their motion parameters, altitude, speed, acceleration, heading, information about the priority and additional parameters of their mathematical model. In addition, information about the aircraft, its flight parameters and characteristics is also supplied to the system.

The data processing block provides digital data processing, check and, if necessary, a certain accumulation of information. Then the information goes to the input of the module for determining the threat of collisions.

This module, using the block determining the aircraft coordinates, the block of calculation of projected motion paths, the block of data analysis and definition of the threat of collision and the accounting block "zones of uncertainty" provides the coordinates of all aircraft to the space-time grid. Possible "zones of uncertainty" of the locations of the aircrafts is added to the obtained coordinate values of the aircrafts in the airspace. Further, aggregate information from all the received data on the aircraft is used to calculate and simulate the predicted trajectory of each of them. The data obtained is analyzed and the determination of risk of collision of the aircraft is modeled. In the absence of such a threat the system cyclically resumes. In case there is a threat of collision information is passed to the module of calculation of maneuvering parameters.

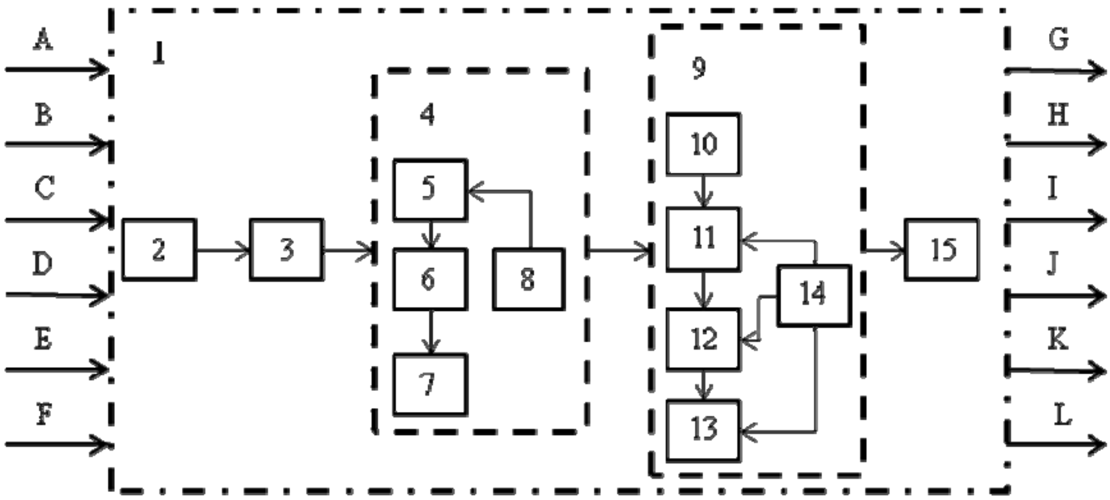

Fig.1. Block diagram of the system

Module calculation of maneuvering parameters uses the information to determine the necessary changes of the aircraft motion and ensure relevant economic indicators, namely route optimization maneuver by distance and time, fuel economy, facilities for the carriage of passengers and luggage. These indicators and criteria in the future are taken into account when calculating and determining trajectories maneuver. These indicators and criteria in the future are included in the calculation and determination of trajectories of avoidance. In addition, the block computation and comparison of “controllability areas” calculates controllability areas ("controllability areas" based on the models of kinematics and dynamics of motion of the aircraft describe the capabilities of the aircraft to modify the motion at any point in time and allow to consider the nonlinearity behavior of the aircraft) for each of the aircraft involved in a conflict at any time. Based on these results the analytical selection of the aircraft or set of aircraft, which will perform the avoidance maneuver is performed (is determined on the basis of an analysis of ("controllability areas" of the aircraft involved in the conflict to prioritize and the type of maneuver is determined (the height, speed, heading or a combination of these). Further information is given on the block determining the trajectory maneuver, where the calculation and determination of the trajectory of the avoidance maneuver of a particular aircraft occurs. This module also provides the calculation and determination of the trajectory of the return to the initial trajectory.

To generate control commands the information is supplied to the onboard computer, the display system and alarm systems in the crew cabin (G), the control stations on earth (H), radar systems (I), autopilot (J), flight control and navigation complexes (K) and systems of communication and data transmission of the aircraft (L). In addition, the control commands in the form of supplementary information through feedback transmitted to the data processing block to ensure the cyclic operation of the system.

7. Conclusions

Creating the system of guaranteed resolution of dynamic conflicts of aircrafts in real time and implement such control relevant algorithms will ensure effective avoidance of dangerous approaches.

The developed system of dangerous approaches to authorization will provide difference aircraft relative to each other at a distance corresponding to the norms of separation, in the context of complex multiple conflicts, including a large number of aircraft (up to 50) and with extremely complex geometry (intersection of two dense traffic, intersection at one point and at the same time, a conflict with a combination of intersections and overtaking several aircraft at one point, etc.). The developed system of detection and resolution of dangerous approaches will provide a separation of the aircrafts relative to each other at a distance corresponding rules of aircraft separation, in a complex of multiple conflicts involving large (up to 50) number of aircraft and extremely complex geometry of the conflict (the intersection of two dense streams of aircraft converge at the same point and at the same time aircraft flying in different directions, a conflict with a combination of intersections and overtaking several aircraft at one point, etc.).

Control commands are generated automatically, simultaneously with other participants in air traffic.

There is the principal possibility to implement effective control as in the present structure and intensity of traffic flows, and when switching to perspective the principles of "FreeFlight".

Developed and implemented communication, navigation and surveillance systems in the coming years will provide the technical possibility to organize decentralized control of air traffic. Determined flight parameters on board each aircraft by volume, frequency of updates and precision are sufficient for effective use for system of conflict resolution of aircrafts.

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С.В. Павлова[1], О.Є. Волков[2]

Система гарантованого вирішення динамічних конфліктів повітряних кораблів в масштабі реального часу

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680
E-mails: [1]psv@nau.edu.ua; [2]alexvolk@ukr.net

Мета: Робота присвячена питанням підвищення безпеки польотів у цивільній авіації шляхом створення йі впровадження нової системи розв’язання динамічних конфліктних ситуацій між літаками. Розроблена система спрямована на забезпечення гарантованого рівня безпеки при розв’язанні розріджених конфліктних ситуацій між літаками в масштабі реального часу. **Методи дослідження:** Пропонується система розв’язання динамічних конфліктів повітряних кораблів з метою підвищення рівня безпеки польотів, заснована на новому методі розв’язання конфліктів повітряних кораблів, з використанням теорії інваріантності. **Результати:** Створення системи розв’язання динамічних конфліктних ситуацій повітряних кораблів в масштабі реального часу і реалізація потрібного управління відповідними алгоритмами для забезпечення ефективного запобігання небезпечних зближень. **Обговорення:** Система реалізується у вигляді окремого уніфікованого обладнання, що працює з використанням супутникових та радіолокаційних систем навігації, що дозволить забезпечити визначення координат повітряних кораблів в масштабі реального часу. Передбачено, що система повинна бути встановлена на всі повітряні кораблі і інтегрована в бортове середовище для належного забезпечення її функціональності і взаємодії з бортовими навігаційними системами.

Ключові слова: загроза зіткнення; конфліктна ситуація; повітряний рух; повітряне судно; цивільна авіація.

С.В. Павлова[1], А.Е. Волков[2]

Система гарантированного разрешения динамических конфликтов воздушных судов в масштабе реального времени

Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03680
E-mails: [1]psv@nau.edu.ua; [2]alexvolk@ukr.net

Цель: Настоящая работа посвящена вопросам повышения безопасности полетов в гражданской авиации путем создания и внедрения новой системы разрешения динамических конфликтных ситуаций между самолетами. Разработанная система направлена на обеспечение гарантированного уровня безопасности при разрешении разреженных конфликтных ситуаций между самолетами в реальном масштабе времени. **Методы исследования:** Предлагается система разрешения динамических конфликтов воздушных суден с целью повышения уровня безопасности полетов, основанная на новом методе разрешения конфликтов воздушных судов с использованием теории инвариантности. **Результаты:** Создание системы разрешения динамических конфликтных ситуаций воздушных судов в масштабе реального времени и реализация необходимого управления соответствующими алгоритмами для обеспечения эффективного предотвращения опасных сближений. **Обсуждение:** Система реализуется в виде отдельного унифицированного оборудования, работающего с использованием спутниковых и радиолокационных систем навигации, что позволит обеспечить определение координат воздушных судов в масштабе реального времени. Предусмотрено, что система должна быть установлена на все воздушные судна и интегрирована в бортовую среду для

надлежащего обеспечения её функциональности и взаимодействия с бортовыми навигационными системами.

Ключевые слова: воздушное движение; воздушное судно; гражданская авиация; конфликтная ситуация; угроза столкновения.

Pavlova Svitlana (1966). Doctor of Engineering. Professor.
Department of air navigation systems, National Aviation University.
Education: Kyiv Civil Engineering Institute, Kyiv, Ukraine (1988).
Research area: analysis and synthesis of nonlinear ergatic systems, critical technology, nonlinear dynamics.
Publications: 150.
E-mail: psv@nau.edu.ua

Olexander Volkov (1990). Post-graduate Student.
Senior Engineer, Department of air navigation systems, National Aviation University.
Education: National Aviation University, Kyiv, Ukraine (2013).
Research area: flight dynamics, intelligent control of dynamic objects.
Publications: 70.
E-mail: alexvolk@ukr.net

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Denys Vasyliev

METHOD FOR OPTIMAL RESOLUTION OF MULTI-AIRCRAFT CONFLICTS IN THREE-DIMENSIONAL SPACE

Ukrainian State Air Traffic Services Enterprise (UkSATSE)
Airport, 08301, Boryspil, Kyiv region, Ukraine
National Aviation University
1, Kosmonavta Komarova Avenue, 03058, Kyiv, Ukraine
E-mail: dvasyliev@ukr.net

Abstract

Purpose: *The risk of critical proximities of several aircraft and appearance of multi-aircraft conflicts increases under current conditions of high dynamics and density of air traffic. The actual problem is a development of methods for optimal multi-aircraft conflicts resolution that should provide the synthesis of conflict-free trajectories in three-dimensional space.* ***Methods:*** *The method for optimal resolution of multi-aircraft conflicts using heading, speed and altitude change maneuvers has been developed. Optimality criteria are flight regularity, flight economy and the complexity of maneuvering. Method provides the sequential synthesis of the Pareto-optimal set of combinations of conflict-free flight trajectories using multi-objective dynamic programming and selection of optimal combination using the convolution of optimality criteria. Within described method the following are defined: the procedure for determination of combinations of aircraft conflict-free states that define the combinations of Pareto-optimal trajectories; the limitations on discretization of conflict resolution process for ensuring the absence of unobservable separation violations.* ***Results:*** *The analysis of the proposed method is performed using computer simulation which results show that synthesized combination of conflict-free trajectories ensures the multi-aircraft conflict avoidance and complies with defined optimality criteria.* ***Discussion:*** *Proposed method can be used for development of new automated air traffic control systems, airborne collision avoidance systems, intelligent air traffic control simulators and for research activities.*

Keywords: aircraft; air traffic control; conflict resolution; dynamic programming; flight safety; multi-aircraft conflict; multi-objective optimization.

1. Introduction

The evolution of air traffic management (ATM) system is primarily aimed at increasing of its capacity in conditions of a constant growth of the flights intensity. For this a new air traffic control (ATC) procedures are introduced, separation minima are reduced and special airspace areas within aircraft are allowed to choose their own routes (Free Route Airspace) are allocated. However, high dynamics and density of current air traffic cause the increasing of separation minima infringements between several aircraft at the same time, i.e. multi-aircraft conflict situations in which prescribed separation minima were not maintained simultaneously between three or more aircraft.

The main requirements for ATM system are ensuring of flight safety and efficiency (regularity, economy). Potential conflict avoidance or actual conflict resolution is a complex cyclical process which consists of the sequence of interrelated actions: monitoring, estimation and prediction of aircraft trajectories; detection of potential conflicts; determination the potential conflict characteristics; finding of possible solutions for conflict resolution; decision-making and control of the selected solution realization. Therefore, the problem of conflict resolution should be considered as the multi-objective optimization problem with limitations and uncertainties in relative importance of optimality criteria and priorities.

2. Analysis of researches and publications

The results of analysis show that most of known methods for multi-aircraft conflicts resolution have a number of significant limitations.

The class of force fields methods contains various methods that use different properties of electric fields, vortex force fields and artificial gravitational fields [1-6]. Common disadvantages of these methods are that they use only heading change maneuvers for conflict resolution and the synthesized conflict-free trajectories are complex for civil aircraft. Application of force fields methods is more promising for avoidance of conflicts between unmanned aerial vehicles, which generally have a lower inertia of motion.

Another class consists of optimization methods that use optimality criteria to find the solution.

The method of multi-aircraft conflict resolution under Free Flight [7-9] is based on the cascade procedure of conflict-free trajectory planning. This method provides the resolution of horizontal plane conflicts using heading change maneuvers.

A well-known is the method of optimal cooperative conflict resolution between multiple aircraft that perform horizontal flight [10]. For conflict-free trajectories determination this method uses a single optimality criterion which defined as total time of aircraft maneuverings.

The method proposed in [11] provides the resolution of multi-aircraft conflicts in horizontal plane using heading changes with minimization of deviations from the planned trajectories. The main disadvantage is that the defined maneuvers are used only for conflict avoidance without returning to the planned flight trajectories.

In articles [12, 13] the method for two- and multi-aircraft conflicts resolution in three-dimensional space is proposed. This method provides a synthesis of heading or altitude change maneuvers considering the instantaneous kinetic energy of aircraft as optimality criterion.

The method described in [14] uses only speed change maneuvers for conflict avoidance.

The summarized disadvantages of discussed optimization methods are disusing of simultaneous combinations of heading, speed and altitude change maneuvers to avoid a conflict and using of single optimality criterion that do not allow to find the most effective solution.

Therefore it is necessary to develop new optimal methods for multi-aircraft conflict resolution in three-dimensional space that should provide the synthesis of conflict-free trajectories using heading, speed and altitude change maneuvers simultaneously according to different flight efficiency criteria.

The method developed in this article is the evolution of method proposed in articles [15, 16] taking into account an approach described in [17].

3. Problem statement

The conflict situation between $n \geq 3$ aircraft is considered. Conflict resolution is a controlled process and aircraft are the dynamic system $\mathbf{S}$. All aircraft change heading, airspeed and vertical speed to avoid the conflict.

The process of maneuvers synthesis is observed in the time interval $[t_0, t_k]$ where t_0 is the moment of a potential conflict detection, t_k is the planned time when all aircraft exit from an ATC area.

Controlled motion of each aircraft is described using the vector differential equation:

$$\dot{\mathbf{X}}(t) = f(\mathbf{X}(t), \mathbf{U}(t), t), \ \mathbf{X}(t_0) = \mathbf{X}_0,$$

where $\mathbf{X} = [x \quad y \quad h \quad V \quad V_h \quad \varphi]^{\mathrm{T}}$ – state vector; x, y – horizontal coordinates; h – altitude; V – true airspeed; V_h – vertical speed; φ – heading; $\mathbf{U} = [\gamma_a \quad V_a \quad V_{ha}]^{\mathrm{T}}$ – vector of controls; γ_a – assigned bank angle; V_a – assigned true airspeed; V_{ha} – assigned vertical speed.

An absolute constraint is the flight safety ensured by separation minima maintenance. The state $\mathbf{X}^m(t)$ of aircraft $m = \overline{1, n}$ belongs to the set of conflict-free states $\mathbf{D}_{\mathbf{X}}^m(t)$ if the separation minima with other aircraft are not violated:

$$\mathbf{X}^m(t) \in \mathbf{D}_{\mathbf{X}}^m(t) \big| \mathbf{X}^m(t) \notin \Omega^m(t),$$

where the space of a conflict $\Omega^m(t)$ is a space of states where the separation minima with other aircraft are violated:

$$\Omega^m(t) =$$
$$= \left\{ \mathbf{X}^m(t) \middle| \left(d\left(\mathbf{X}^m(t), \mathbf{X}^{ref}(t)\right) < d_S \right) \wedge \left(\Delta h\left(\mathbf{X}^m(t), \mathbf{X}^{ref}(t)\right) < h_S \right) \right\},$$
$$ref = \overline{1, n}, m \neq ref,$$

where $d\left(\mathbf{X}^m(t), \mathbf{X}^{ref}(t)\right)$ – horizontal distance between aircraft; $\mathbf{X}^{ref}(t)$ – state of aircraft ref; $\Delta h\left(\mathbf{X}^m(t), \mathbf{X}^{ref}(t)\right)$ – vertical distance between aircraft; d_S – lateral (horizontal) separation minimum; h_S – vertical separation minimum. The initial states of all aircraft are conflict-free $\mathbf{X}^m(t_0) \notin \Omega^m(t_0)$.

Controls are limited according to the aircraft performances. Let $\mathbf{D}_\mathrm{U}^m(\mathbf{X}^m(t),t)$ be a set of possible controls $\mathbf{U}^m(t)$ in a state $\mathbf{X}^m(t)$.

Optimality criteria characterizing the efficiency of conflict resolution are flight regularity c_1, flight economy c_2 and the complexity of maneuvering c_3.

The numerical estimations of trajectories for each aircraft according to defined optimality criteria are: J_1^m – deviation from planned flight time; J_2^m – deviation from planned altitude; J_3^m – fuel consumption; J_4^m – number of flight profile changes.

Estimations constitute the vector $\mathbf{J}^m = \{J_i^m\},\ i = \overline{1,4}$.

The numerical estimations of trajectories at time interval $[t_0, t_k]$ are defined as follows [15]:

$$J_1^m = \Lambda_1^m(\mathbf{X}^m(t_k), t_k),$$

$$J_2^m = \Lambda_2^m(\mathbf{X}^m(t_k), t_k),$$

$$J_3^m = \int_{t_0}^{t_k} \lambda_3^m(\mathbf{X}^m(t), \mathbf{U}^m(t), t)dt + \Lambda_3^m(\mathbf{X}^m(t_k), t_k),$$

$$J_4^m = \int_{t_0}^{t_k} \lambda_4^m(\mathbf{X}^m(t), \mathbf{U}^m(t), t)dt + \Lambda_4^m(\mathbf{X}^m(t_k), t_k),$$

where Λ_1^m– estimation of deviation from planned flight time; Λ_2^m,– estimation of deviation from planned altitude; λ_3^m – instantaneous fuel consumption; λ_4^m – speed of flight profile changes; Λ_3^m – estimation of fuel consumption for real exit from an ATC area relatively to actual position at the time moment t_k; Λ_4^m – estimation of flight profile changes for real exit from an ATC area relatively to actual position at the time moment t_k.

As a result the problem of optimal multi-aircraft conflict resolution is determined as follows:

$$\begin{cases} \min\limits_{\mathbf{U}^1(t)\in\mathbf{D}_\mathrm{U}^1(\mathbf{X}^1(t),t)} \mathbf{J}^1(\mathbf{X}^1(t), \mathbf{U}^1(t), t),\ \mathbf{X}^1(t)\in \mathbf{D}_\mathbf{X}^1(t), \\ \min\limits_{\mathbf{U}^2(t)\in\mathbf{D}_\mathrm{U}^2(\mathbf{X}^2(t),t)} \mathbf{J}^2(\mathbf{X}^2(t), \mathbf{U}^2(t), t),\ \mathbf{X}^2(t)\in \mathbf{D}_\mathbf{X}^2(t), \\ \dots \\ \min\limits_{\mathbf{U}^n(t)\in\mathbf{D}_\mathrm{U}^n(\mathbf{X}^n(t),t)} \mathbf{J}^n(\mathbf{X}^n(t), \mathbf{U}^n(t), t),\ \mathbf{X}^n(t)\in \mathbf{D}_\mathbf{X}^n(t), \end{cases} \quad (1)$$

$$t \in [t_0, t_k]$$

The **aim** of this article is to develop the method for optimal resolution of multi-aircraft conflicts in three-dimensional space based on multi-objective dynamic programming.

4. Synthesis of conflict-free trajectories using multi-objective dynamic programming

The problem (1) is solved by synthesizing the set of Pareto-optimal combinations of the conflict-free trajectories of all aircraft and choosing of the optimal combination.

Let $\mathbf{E}(\mathbf{X}^m(t),t)$ be a set of Pareto-optimal estimations of conflict-free trajectories for a state $\mathbf{X}^m(t)\in \mathbf{D}_\mathbf{X}^m(t)$:

$$\mathbf{E}(\mathbf{X}^m(t),t) = \{\mathbf{J}^m(\mathbf{X}^m(t), \mathbf{U}_e^m(t), t) | \neg\exists \mathbf{U}^m(t) \in \mathbf{D}_\mathrm{U}^m(\mathbf{X}^m(t),t):$$
$$\mathbf{J}^m(\mathbf{X}^m(t), \mathbf{U}^m(t), t) \le \mathbf{J}(\mathbf{X}^m(t), \mathbf{U}_e^m(t), t), \mathbf{U}_e^m(t) \ne \mathbf{U}^m(t)\},$$

$$\mathbf{J}^m(\mathbf{X}^m(t), \mathbf{U}^m(t), t) = \left\{\Lambda_1^m, \Lambda_2^m, \int_t^{t_k} \lambda_3^m dt + \Lambda_3^m, \int_t^{t_k} \lambda_4^m dt + \Lambda_4^m\right\}.$$

Based on Bellman's principle of optimality [18] the system of multi-objective dynamic programming equations for determination of the set $\mathbf{E}_\mathbf{Z}(t)$ of Pareto-optimal estimations of combinations of conflict-free trajectories is written as follows:

$$\begin{cases} \mathbf{E}(\mathbf{X}^1(t),t) = \mathrm{eff}\,\Im^1, \mathbf{X}^1(t)\in \mathbf{D}_\mathbf{X}^1(t),\ \mathbf{X}^1(t+\tau)\in \mathbf{D}_\mathbf{X}^1(t+\tau), \\ \mathbf{E}(\mathbf{X}^2(t),t) = \mathrm{eff}\,\Im^2, \mathbf{X}^2(t)\in \mathbf{D}_\mathbf{X}^2(t),\ \mathbf{X}^2(t+\tau)\in \mathbf{D}_\mathbf{X}^2(t+\tau), \\ \dots \\ \mathbf{E}(\mathbf{X}^n(t),t) = \mathrm{eff}\,\Im^n, \mathbf{X}^n(t)\in \mathbf{D}_\mathbf{X}^n(t),\ \mathbf{X}^n(t+\tau)\in \mathbf{D}_\mathbf{X}^n(t+\tau), \end{cases}$$

$$\Im^m = \bigcup_{\mathbf{U}^m(t)\in\mathbf{D}_\mathrm{U}^m(\mathbf{X}^m(t),t)} \left(\left\{0, 0, \int_t^{t+\tau} \lambda_3^m dt, \int_t^{t+\tau} \lambda_4^m dt\right\} \oplus \mathbf{E}(\mathbf{X}^m(t+\tau), t+\tau)\right),$$

$$m = \overline{1,n},$$

with boundary condition

$$\mathbf{E}(\mathbf{X}^m(t_k), t_k) = \{\Lambda_1^m, \Lambda_2^m, \Lambda_3^m, \Lambda_4^m\},$$

where eff – the operator of determination of Pareto-optimal estimations; τ – a small value; $\oplus$ – direct sum.

The set $\mathbf{P}_\mathbf{Z}$ of Pareto-optimal combinations of conflict-free flight trajectories is determined by the set of estimations $\mathbf{E}_\mathbf{Z}(t_0)$ at the moment of conflict detection t_0.

Finding all possible solutions of the equations system is difficult computational problem. It is proposed to limit the number of combinations of conflict-free trajectories and apply the following method of their synthesis using discrete multi-objective dynamic programming.

The dynamic system $\mathbf{S}$ is discretized in time (the conflict resolution process is decomposed into k stages) and in state space. It is assumed that all aircraft maneuver for conflict avoidance during stages $j=\overline{1,k-1}$ and return to the planned flight trajectories during last stage k. Time interval $[t_{j-1},t_j],\, t_j=t_{j-1}+\Delta t$ corresponds to each stage j, except for the last one. The time interval of the last stage $j=k$ is different because of the different time that each aircraft needs to reach the fixed final state when transiting from the states at the previous stage.

The flight of each aircraft is considered separately, taking into account the overall limitation on maintaining the separation minima.

In general, it is considered that each aircraft m can transit into the state $\mathbf{X}^m(j)$ from several states $\mathbf{X}^m(j-1)$ at the previous stage:

$$\mathbf{X}^m(j)=f\left(\mathbf{X}^m(j-1),\mathbf{U}^m(j-1)\right).$$

States $\mathbf{X}^m(j)$ form the set $\mathbf{D}^m(j)$ of possible states .The final state $\mathbf{X}^m_k=\mathbf{X}^m(k)$ is specified only by the horizontal coordinates of the point at which an aircraft exits an ATC area at planned time. It is expected that aircraft may transit into the final state from all the states of the previous stage.

To increase the computational efficiency of the method, it is proposed to monitor the separation minima violations in defined states at each stage.

The set of conditionally conflict-free states $\widehat{\mathbf{D}}^m_{\mathbf{X}}(j)$ of aircraft m includes the states $\mathbf{X}^m(j)\in\mathbf{D}^m(j)$ in which the violations of separation minima with other aircraft may be present for some of their states $\mathbf{X}^{ref}(j)$, or the violations of separation minima are absent:

$$\begin{gathered}\mathbf{X}^m(j)\in\widehat{\mathbf{D}}^m_{\mathbf{X}}(j):\exists\mathbf{X}^{ref}(j),\left((d\ge d_s)\wedge(\Delta h\ge h_s)\right)\vee\\ \vee\left((d\ge d_s)\wedge(\Delta h< h_s)\right)\vee\left((d< d_s)\wedge(\Delta h\ge h_s)\right),\\ \mathbf{X}^{ref}(j)\in\mathbf{D}^{ref}(j),\, ref=\overline{1,n},\, m\ne ref,\end{gathered}$$

where d, Δh – horizontal distance and vertical interval between aircraft in states $\mathbf{X}^m(j)$ and $\mathbf{X}^{ref}(j)$ respectively.

It is necessary to check the maintaining of separation minima in limited time periods in which unobservable violations of separation cannot occur.

The procedures for each stage $j=\overline{1,k}$ are:

– determination of sets of possible controls $\mathbf{D}^m_{\mathbf{U}}\left(\mathbf{X}^m(j-1)\right)$;

– simulation of aircraft flight trajectories and determination of sets of conditionally conflict-free states $\widehat{\mathbf{D}}^m_{\mathbf{X}}(j)$;

– determination of efficiency estimations $\Delta J^m_i\left(\mathbf{X}^m(j-1),\mathbf{U}^m(j-1)\right)$ when transiting from states $\mathbf{X}^m(j-1)$ under the action of controls $\mathbf{U}^m(j-1)$.

The trajectories simulation is performed using the kinematics-energy model of the controlled aircraft motion proposed in article [19], which takes into account the dynamic properties of motion, aircraft performance characteristics stored in the EUROCONTROL Base of Aircraft Data (BADA), and allows to calculate the fuel consumption.

The efficiency estimations ΔJ^m_i for aircraft m are defied using expressions [15]:

$$\Delta J^m_1\left(\mathbf{X}^m(j-1),\mathbf{U}^m(j-1)\right)=\begin{cases}0,\ j\ne k,\\ \left|t_k-t^m_f\right|,\ j=k,\end{cases}\qquad(2)$$

$$\Delta J^m_2\left(\mathbf{X}^m(j-1),\mathbf{U}^m(j-1)\right)=\begin{cases}0,\ j\ne k,\\ \left|h^m_k-h^m_f\right|,\ j=k,\end{cases}\qquad(3)$$

$$\Delta J^m_3\left(\mathbf{X}^m(j-1),\mathbf{U}^m(j-1)\right)=Q^m\left(\mathbf{X}^m(j-1),\mathbf{U}^m(j-1)\right),\qquad(4)$$

$$\begin{gathered}\Delta J^m_4\left(\mathbf{X}^m(j-1),\mathbf{U}^m(j-1)\right)=\lambda^m_{41}\left(\mathbf{X}^m(j-1),\mathbf{U}^m(j-1)\right)+\\ +\lambda^m_{42}\left(\mathbf{X}^m(j-1),\mathbf{U}^m(j-1)\right)+\lambda^m_{43}\left(\mathbf{X}^m(j-1),\mathbf{U}^m(j-1)\right),\end{gathered}\qquad(5)$$

$$\lambda^m_{41}=\begin{cases}1,\ \left|\varphi^m(j)-\varphi^m(j-1)\right|>\Delta\varphi,\\ 0,\end{cases}$$

$$\lambda^m_{42}=\begin{cases}1,\ V^m_a(j-1)\ne V^m(j-1),\\ 0,\end{cases}$$

$$\lambda^m_{43}=\begin{cases}1,\ V^m_{ha}(j-1)\ne V^m_{h0},\\ 0,\end{cases}$$

where t^m_f – actual time of reaching the final state $\mathbf{X}^m_k$; h^m_k, h^m_f – planned and actual altitude of the control point overflight; Q^m – fuel consumption;

$\Delta\varphi$ – parameter that takes into account the small heading changes; V_{h0}^{m} – planned vertical speed.

To determine a set $\mathbf{E}(\mathbf{X}^m(j))$ of Pareto-optimal estimations of conflict-free trajectories when transiting into the state $\mathbf{X}^m(j)\in\widehat{\mathbf{D}}_{\mathbf{X}}^m(j)$ from states $\mathbf{X}^m(j-1)\in\widehat{\mathbf{D}}_{\mathbf{X}}^m(j-1)$ the following equation of multi-objective dynamic programming is used [15, 16]:

$$\mathbf{E}(\mathbf{X}^m(j))=\bigcup_{\mathbf{X}^m(j-1)\in\Pi(\mathbf{X}^m(j))}\left(\mathbf{E}(\mathbf{X}^m(j-1))\oplus\Delta\mathbf{J}^m\right),$$
$$\Delta\mathbf{J}^m=\{\Delta J_i^m(\mathbf{X}^m(j-1),\mathbf{U}'^m(j-1))\}, \qquad (6)$$
$$\mathbf{X}^m(j)\in\widehat{\mathbf{D}}_{\mathbf{X}}^m(j),\ \mathbf{X}^m(j-1)\in\widehat{\mathbf{D}}_{\mathbf{X}}^m(j-1),$$

where $\Pi(\mathbf{X}^m(j))$ – a set of states of aircraft m at the stage $(j-1)$ due to which the transition into the state $\mathbf{X}^m(j)$ is possible; $\mathbf{U}'^m(j-1)$ – are controls which allow an aircraft m to transit from the state $\mathbf{X}^m(j-1)\in\Pi(\mathbf{X}^m(j))$ into the state $\mathbf{X}^m(j)$.

At each stage, except the last one, sets of Pareto-optimal estimations of conflict-free trajectories $\mathbf{E}(\mathbf{X}^m(j))$ are determined using equation (6), corresponding sets $\mathbf{D}_{\mathbf{U}}^{\mathbf{E}}(\mathbf{X}^m(j))$ of Pareto-optimal controls and sets $\Pi_{\mathbf{E}}(\mathbf{X}^m(j))\in\Pi(\mathbf{X}^m(j))$ of Pareto-optimal states are determined.

Then the conflict-free combinations $\mathbf{I}(j)$ of states are determined. All conflict-free combinations at the stage j create the set $\mathbf{D}_{\mathbf{I}}(j)$. Let denote a conflict-free combination as follows:

$$\mathbf{I}(j)=\{\mathbf{X}^1(j),\mathbf{X}^2(j),\ldots,\mathbf{X}^n(j)\}=\{\mathbf{X}^m(j)\},$$
$$\mathbf{X}^m(j)\in\widehat{\mathbf{D}}_{\mathbf{X}}^m(j).$$

Each combination contains the states which meet following conditions [17].

Condition 1. The violations of separation minima between all aircraft are absent in the states of combination $\mathbf{I}(j)$:

$$\forall a,b:((A\ge d_S)\wedge(B\ge h_S))\vee((A\ge d_S)\wedge(B<h_S))\vee$$
$$\vee((A<d_S)\wedge(B\ge h_S)),$$
$$A=d(\mathbf{X}^a(j),\mathbf{X}^b(j)),$$
$$B=\Delta h(\mathbf{X}^a(j),\mathbf{X}^b(j)),\mathbf{X}(j)\in\mathbf{I}(j),$$
$$a=\overline{1,n},\ b=\overline{1,n},\ a\ne b.$$

Condition 2. All aircraft have transited into states $\mathbf{X}^m(j)\in\mathbf{I}(j)$ under the action of Pareto-optimal controls $\mathbf{U}^m(j-1)\in\mathbf{D}_{\mathbf{U}}^{\mathbf{E}}(\mathbf{X}^m(j))$ from the states $\mathbf{X}^m(j-1)\in\Pi_{\mathbf{E}}(\mathbf{X}^m(j))$, which combinations where conflict-free at the previous stage:

$$\{\mathbf{X}^m(j-1)\}\in\mathbf{D}_{\mathbf{I}}(j-1),$$
$$\mathbf{X}^m(j-1)\in\Pi_{\mathbf{E}}(\mathbf{X}^m(j)),\mathbf{X}(j)\in\mathbf{I}(j).$$

Condition 3. Depending on the actual separation between two aircraft in states $\mathbf{X}^a(j)$ and $\mathbf{X}^b(j)$ the one of following conditions must be met:

– if $(A\ge d_S)\wedge(B\ge h_S)$ aircraft have transited into the states $\mathbf{X}^a(j)$, $\mathbf{X}^b(j)$ from any states, which meet the condition 2;

– if $(A\ge d_S)\wedge(B<h_S)$ aircraft have transited into the states $\mathbf{X}^a(j)$, $\mathbf{X}^b(j)$ from states, which meet the condition 2 and in which the horizontal and vertical separation or only horizontal separation between this aircraft is ensured;

– if $(A\ge d_S)\wedge(B<h_S)$ aircraft have transited into the states $\mathbf{X}^a(j)$, $\mathbf{X}^b(j)$ from states, which meet the condition 2 and in which the horizontal and vertical separation or only vertical separation between this aircraft is ensured.

Each combination $\mathbf{I}(j)$ determines the combinations of Pareto-optimal trajectories, which transfer the aircraft to the states of this combination. In general, each combination $\mathbf{I}(j)$ corresponds to several combinations of Pareto-optimal trajectories.

At the last stage k for each aircraft m the set $\mathbf{z}^m$ of full trajectories $\mathbf{T}^m=\{\mathbf{X}_0^m,\mathbf{X}^m(1),\ldots\mathbf{X}_k^m\}$, which transfer the aircraft to the final state $\mathbf{X}_k^m$ from the states $\mathbf{X}^m(k-1)\in\widehat{\mathbf{D}}_{\mathbf{X}}^m(k-1)$, is determined. For this the special backward procedure is applied [15].

The combinations $\mathbf{Z}$ of full conflict-free trajectories of all aircraft are determined. Combination $\mathbf{Z}$ is a combination of trajectories, which transfer the all aircraft from states of combination $\mathbf{I}(k-1)$ to the final states $\mathbf{X}_k^m$:

$$\mathbf{Z}=\{\mathbf{T}^1,\mathbf{T}^2,\ldots,\mathbf{T}^n\}=\{\mathbf{T}^m\},$$
$$\mathbf{T}^m\in\mathbf{z}^m:\mathbf{X}^m(k-1)\in\mathbf{T}^m,\mathbf{X}^m(k-1)\in\mathbf{I}(k-1).$$

Each possible combination $\mathbf{Z}$ of trajectories $\mathbf{T}^m$ is characterized by extended vector optimality criterion $\mathbf{J}_\Sigma(\mathbf{Z})$:

$$\mathbf{J}_\Sigma(\mathbf{Z}) = \{\mathbf{J}^m(\mathbf{T}^m)\},\ \mathbf{J}^m(\mathbf{T}^m) \in \mathbf{E}(\mathbf{X}_k^m),\ m = \overline{1,n}.$$

Then the set $\mathbf{P_Z}$ of Pareto-optimal combinations of conflict-free trajectories is determined:

$$\mathbf{P_Z} = \{\mathbf{Z}_p \mid \neg\exists\ \mathbf{Z} : \mathbf{J}_\Sigma(\mathbf{Z}) \le \mathbf{J}_\Sigma(\mathbf{Z}_p), \mathbf{Z}_p \ne \mathbf{Z}\}.$$

Selection of optimal $\mathbf{Z}^*$ combination of conflict-free trajectories from the set of Pareto-optimal $\mathbf{P_Z}$ is performed with use of linear convolutions of optimality criteria by solving the optimization problem [20]:

$$\mathbf{Z}^* = \arg \min_{\mathbf{Z}\in\mathbf{P_Z}} \max_{\mathbf{W}\in\mathbf{D}_w} \sum_{i=1}^{3} w_i \bar{c}_i(\mathbf{Z}),\ \mathbf{Z}\in\mathbf{P_Z}, \qquad (7)$$

where $\bar{c}_1$, $\bar{c}_2$, $\bar{c}_3$ – normalized estimations of combinations $\mathbf{Z}$ efficiency by flight regularity c_1, flight economy c_2 and the complexity of maneuvering c_3 criteria respectively with the domain of allowable values $\mathbf{D}_{\bar{c}} = \{\bar{c} \mid \bar{c} \in [0,1]\}$; w_i – the weighting coefficients reflecting the relative importance of criteria and forming a vector $\mathbf{W} = \{w_i\}, i = \overline{1,3}$ with the domain of allowable values $\mathbf{D}_w$ and minimal value w_0:

$$\mathbf{D}_w = \left\{ \mathbf{W} \middle| \sum_{i=1}^{3} w_i = 1;\ w_i \ge w_{i+1},\ i = \overline{1,2};\ w_3 \ge w_0 > 0 \right\}.$$

The estimation $\bar{c}_1$ is the normalized linear convolution of the normalized total deviation from the planned flight time and the normalized total deviation from planned altitude of all aircraft:

$$\bar{c}_1(\mathbf{Z}) = \frac{c_\Sigma(\mathbf{Z}) - \min_{\mathbf{Z}\in\mathbf{P_Z}} c_\Sigma(\mathbf{Z})}{\max_{\mathbf{Z}\in\mathbf{P_Z}} c_\Sigma(\mathbf{Z}) - \min_{\mathbf{Z}\in\mathbf{P_Z}} c_\Sigma(\mathbf{Z})},$$

$$c_\Sigma(\mathbf{Z}) = 0{,}5\frac{\sum_{m=1}^{n} J_1^m(\mathbf{T}^m) - \min_{\mathbf{Z}\in\mathbf{P_Z}} \sum_{m=1}^{n} J_1^m(\mathbf{T}^m)}{\max_{\mathbf{Z}\in\mathbf{P_Z}} \sum_{m=1}^{n} J_1^m(\mathbf{T}^m) - \min_{\mathbf{Z}\in\mathbf{P_Z}} \sum_{m=1}^{n} J_1^m(\mathbf{T}^m)} + ,$$

$$+ 0{,}5\frac{\sum_{m=1}^{n} J_2^m(\mathbf{T}^m) - \min_{\mathbf{Z}\in\mathbf{P_Z}} \sum_{m=1}^{n} J_2^m(\mathbf{T}^m)}{\max_{\mathbf{Z}\in\mathbf{P_Z}} \sum_{m=1}^{n} J_2^m(\mathbf{T}^m) - \min_{\mathbf{Z}\in\mathbf{P_Z}} \sum_{m=1}^{n} J_2^m(\mathbf{T}^m)},\ \mathbf{T}^m \in \mathbf{Z}.$$

The normalized estimations $\bar{c}_2$ and $\bar{c}_3$ are defined as follows:

$$c_i(\mathbf{Z}) = \frac{\sum_{m=1}^{n} J_{i+1}^m(\mathbf{T}^m) - \min_{\mathbf{Z}\in\mathbf{P_Z}} \sum_{m=1}^{n} J_{i+1}^m(\mathbf{T}^m)}{\max_{\mathbf{Z}\in\mathbf{P_Z}} \sum_{m=1}^{n} J_{i+1}^m(\mathbf{T}^m) - \min_{\mathbf{Z}\in\mathbf{P_Z}} \sum_{m=1}^{n} J_{i+1}^m(\mathbf{T}^m)},$$

$$\mathbf{T}^m \in \mathbf{Z},\ i = \overline{2,3}.$$

5. Discretization aspects

The conflict resolution process is decomposed into k stages. Discretization step Δt is defined taking into account values of possible controls. The first requirement is the stabilization of assigned airspeed during time interval Δt.

To ensure separation minima between aircraft while they transiting between states it is necessary to check the violations at fixed time moments in limited time periods during which an unobservable violations of separation cannot occur.

When the changes of heading, airspeed speed and vertical speed are used to avoid a conflict with crossing angle of initial tracks $\le 90^\circ$ the discretization step Δt is determined according to inequalities system:

$$\begin{cases} \Delta t < d_s / V_{\max}, \\ \Delta t < \Delta h_s / V_{h\max}, \end{cases}$$

where V_{max} – maximum ground speed of all aircraft; $V_{h\max}$ – maximum vertical speed of all aircraft.

The number of stages is defined using following expression:

$$k = \left[\frac{\sum_{m=1}^{n}(t_m - t_0)}{2\Delta t \cdot n} + \frac{\sum_{p=1}^{q}(t_{conf}^p - t_0)}{2\Delta t \cdot q} \right],$$

where t_m – planned time of exit from ATC area for aircraft m; t_{conf}^p – center of the time interval when the conflict between a pair of aircraft $p = \overline{1,q}$ is existed; q – number of aircraft pairs; $[\cdot]$ – rounding operator.

The discretization of states and controls is performed using following procedure based on approach that was described in [14].

Generally, it is assumed that each aircraft can make a left/right turn with bank angle γ or to do not change the heading; to increase/decrease the airspeed on ΔV or to do not change it; to increase/decrease the vertical speed on ΔV_h or to do not change it. Let $\mathbf{D}_{U0}(\mathbf{X}(j-1))$ be the basic set that contains all possible 27 combinations of controls. When applying controls $\mathbf{U}(j-1)\in \mathbf{D}_{U0}(\mathbf{X}(j-1))$, an aircraft transits into different states $\mathbf{X}'(j)$ with efficiency estimations $\Delta J_i'(\mathbf{X}(j-1),\mathbf{U}(j-1))$ that are defined using expressions (2)-(5). The rule for formation of new states $\mathbf{X}(j)$ which combine states $\mathbf{X}'(j)$ is defined.

At the stage $j=1$ all states $\mathbf{X}'(1)$ are new $\mathbf{X}(1)=\mathbf{X}'(1)$ and efficiency estimations of transition to new states $\mathbf{X}(1)$ are equal to $\Delta J_i'(\mathbf{X}_0,\mathbf{U}(0))$.

At the stages $j=\overline{2,k-1}$ the new states $\mathbf{X}(j)$ are formed as a combination of states $\mathbf{X}'(j)$ in which aircraft altitudes are equal, horizontal coordinates and headings have proximate values (proximity criteria are adjustable). It means that an aircraft can transit into the state $\mathbf{X}(j)$ under the action of several controls $\mathbf{U}'(j-1)$. As a result the set $\Pi(\mathbf{X}(j))$ of states at the stage $(j-1)$ from which an aircraft can transit into the state $\mathbf{X}(j)$ is defined.

Coordinates and heading of an aircraft in new state $\mathbf{X}(j)$ are determined as arithmetic mean of these parameters for the states $\mathbf{X}'(j)$ which are combined in this new state $\mathbf{X}(j)$.

Estimations $\Delta J_i(\mathbf{X}(j-1),\mathbf{U}'(j-1))$ when transiting into new states $\mathbf{X}(j)$ from the states of the set $\Pi(\mathbf{X}(j))$ is determined using nearest-neighbor interpolation of values $\Delta J_i'(\mathbf{X}(j-1),\mathbf{U}(j-1))$ for states $\mathbf{X}'(j)$ which are combined:

$$\Delta J_i(\mathbf{X}(j-1),\mathbf{U}'(j-1))=\Delta J_i'(\mathbf{X}(j-1),\mathbf{U}(j-1)),$$
$$\mathbf{X}(j-1)\in \Pi(\mathbf{X}(j)),\ \mathbf{U}'(j-1)=\mathbf{U}(j-1).$$

6. Computer simulation

The conflict situation between three aircraft Boeing 737-800 was simulated. The lateral separation minimum is equal to $d_s=18{,}5$ km (10 nautical miles) and the vertical separation minimum is equal to $\Delta h_S=300$ m (1000 feet). The initial parameters of aircraft flight are represented in Table 1. The characteristics of predicted multi-aircraft conflict are represented in Table 2.

It was assumed that to avoid the conflict all aircraft should make manoeuvres. The process was discretized in time on $k=5$ stages. The discretization step for the first 4 stages is equal to $\Delta t=59$ s.

It was assumed that aircraft №1 and №2 can change heading and airspeed; aircraft №3 can change heading and vertical speed. The bank angle during turns is equal to 20°, turning time is limited to 15 s. During transition between stages the absolute value of airspeed change is equal to 5 m/s and the absolute value of vertical speed change is equal to 4 m/s.

The minimal value of weighting coefficients in the optimization problem (7) is equal to $w_0=0{,}1$.

The optimal combination of conflict-free trajectories is shown in Fig. 1. The dependences of horizontal and vertical distance between aircraft from time are shown in Fig. 2 and Fig. 3. The assigned airspeeds and vertical speed for conflict resolution are represented in Table 3. The efficiency parameters of optimal combination of trajectories are represented in Table 4.

Table 1

The initial parameters of aircraft flight

Parameter	Aircraft		
	№1	№2	№3
Heading, degrees	0	80	220
Airspeed, m/s	225	200	220
Vertical speed, m/s	0	0	-6
Initial coordinates $(x_0;y_0)$, km	(40; 0)	(0; 30)	(55,7; 60,6)
Initial altitude, m	10050	10050	11350
Assigned altitude, m	10050	10050	9150
Distance to the control point, km	80	75	80
Planned time of control point overflight, s	356	375	364

Table 2

The characteristics of predicted multi-aircraft conflict

Parameter	Pair of aircraft		
	№1, №2	№1, №3	№2, №3
Time interval of separation violation, s	[118, 245]	[167, 191]	[167, 207]
Predicted minimum horizontal distance between aircraft, m	6215	9395	3397
Predicted minimum vertical distance between aircraft, m	0	154	58

Table 3

The assigned airspeeds and vertical speed for conflict resolution

Stage	1	2	3	4	5
Airspeed of aircraft №1, m/s	225	225	225	230	230
Airspeed of aircraft №2, m/s	200	200	205	210	210
Airspeed of aircraft №3, m/s	220	220	220	220	220
Vertical speed of aircraft №3, m/s	-2	-2	-10	-10	-10

Table 4

The efficiency parameters of optimal combination of conflict-free flight trajectories

Parameter	Aircraft		
	№1	№2	№3
Deviation from the planned flight time, s	4,5	9	19,4
Deviation from the assigned altitude at control point, m	–	–	20
Additional fuel consumption, %	-2,15	5,6	10,3
Number of flight profile changes	4	7	5

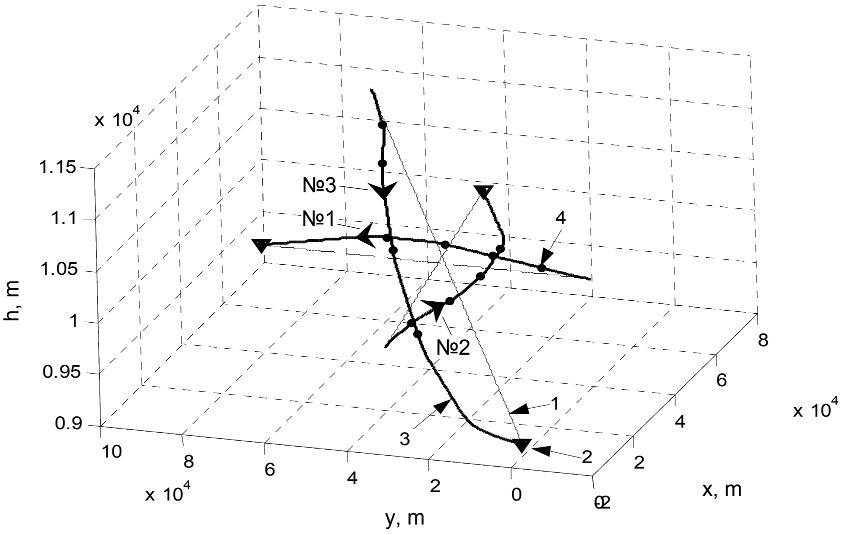

Fig. 1. The aircraft trajectories in three-dimensional space:
1 – planed trajectories; 2 – control points on the routes; 3 – optimal conflict-free trajectories; 4 – states at the stages.

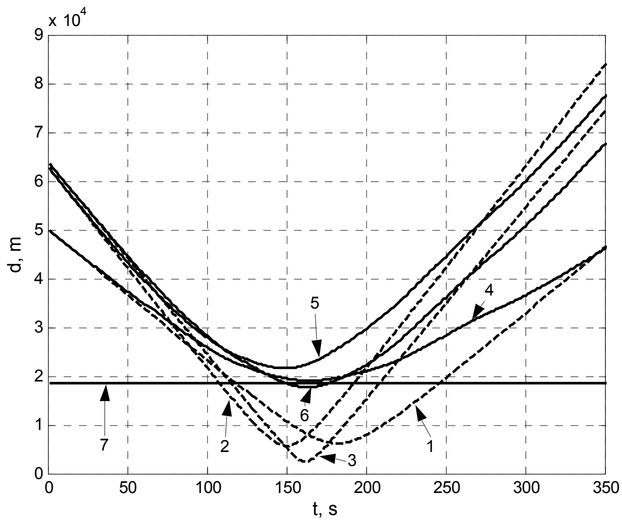

Fig. 2. The dependence of horizontal distances between aircraft from time:
1, 2, 3 – between aircraft №1 and №2, №1 and №3, №2 and №3 respectively during flight by planed trajectories; 4, 5, 6 – between aircraft №1 and №2, №1 and №3, №2 and №3 respectively during conflict resolution; 7 – separation minimum.

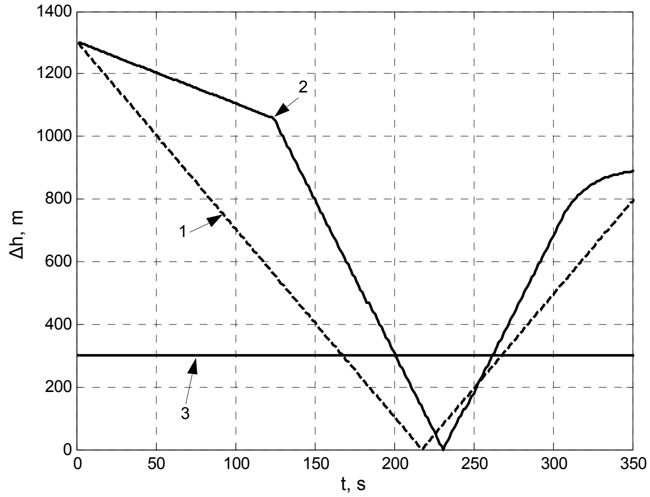

Fig. 3. The dependence of vertical distances between aircraft №1 and №2, №2 and №3 from time: 1 – during flight by planed trajectories; 2 – during conflict resolution; 3 – separation minimum.

7. Conclusions

The method for optimal resolution of multi-aircraft conflicts in three-dimensional space has been developed. Method provides the synthesis of optimal combination of conflict-free flight trajectories of aircraft that use heading, airspeed and vertical speed change maneuvers according to flight regularity, economy and the complexity of maneuvering criteria. The synthesis of Pareto-optimal combinations of conflict-free trajectories is carried out using the multi-objective dynamic programming and special procedure for determination of combinations of aircraft conflict-free states. The selection of optimal combination of conflict-free trajectories from the set of Pareto-optimal is carried out using the convolution of optimality criteria.

The correctness, adequacy and efficiency of proposed method were proved by computer simulation.

Developed method can be used for development of new automated ATC systems, airborne collision avoidance systems (ACAS), intelligent ATC simulators and for research activities.

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Д.В. Васильєв

Метод оптимального розв'язання групових конфліктних ситуацій між повітряними суднами у тривимірному просторі

Державне підприємство обслуговування повітряного руху України (Украерорух), Аеропорт, м. Бориспіль, Київська обл., Україна, 08301

Національний авіаційний університет, просп. Космонавта Комарова, 1, м. Київ, Україна, 03058

E-mail: dvasyliev@ukr.net

Мета: В сучасних умовах високої динамічності і щільності повітряного руху значно зростає небезпека критичного зближення відразу декількох повітряних суден і виникнення групових конфліктних ситуацій. Актуальною проблемою є розробка методів оптимального розв'язання групових конфліктних ситуацій, які повинні забезпечувати синтез безконфліктних траєкторій у тривимірному просторі. **Методи:** Розроблено метод оптимального розв'язання групових конфліктних ситуацій із застосуванням маневрування зміною курсу, швидкості та висоти польоту. Критеріями оптимальності визначені регулярність, економічність польотів і складність маневрування. Метод полягає у послідовному синтезі множини Парето-оптимальних комбінацій безконфліктних траєкторій сукупності повітряних суден з використанням дискретного багатокритеріального динамічного програмування та визначенні оптимальної комбінації із застосуванням із застосуванням згортки критеріїв оптимальності. В рамках методу визначено: процедуру формування безконфліктних комбінацій станів сукупності повітряних суден, які визначають комбінації Парето-оптимальних траєкторій; обмеження, які накладаються при дискретизації процесу розв'язання конфлікту для забезпечення відсутності неспостережуваних порушень ешелонування. **Результати:** Дослідження запропонованого методу виконано шляхом комп'ютерного моделювання, результати якого показали, що синтезована комбінація безконфліктних траєкторія забезпечує усунення групової конфліктної ситуації та відповідає встановленим критеріям оптимальності. **Обговорення:** Запропонований метод може бути використаний при розробці нових автоматизованих систем управління повітряним рухом, бортових систем попередження зіткнень, інтелектуальних тренажерів керування повітряним рухом та для проведення наукових досліджень.

Ключові слова: багатокритеріальна оптимізація; безпека польотів; групова конфліктна ситуація між повітряними суднами; динамічне програмування; повітряне судно; розв'язання конфліктної ситуації; управління повітряним рухом

Д.В. Васильев. Метод оптимального разрешения групповых конфликтных ситуаций между воздушными судами в трехмерном пространстве

Государственное предприятие обслуживания воздушного движения Украины (Украэрорух), Аэропорт, г. Борисполь, Киевская обл., Украина, 08301
Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03058
E-mail: dvasyliev@ukr.net

Цель: В современных условиях высокой динамичности и плотности воздушного движения значительно возрастает опасность критического сближения сразу нескольких воздушных судов и возникновения групповых конфликтных ситуаций. Актуальной проблемой является разработка методов оптимального разрешения групповых конфликтных ситуаций, которые должны обеспечивать синтез бесконфликтных траекторий в трехмерном пространстве. **Методы:** Разработан метод оптимального разрешения групповых конфликтных ситуаций с применением маневрирования по изменению курса, скорости и высоты полета. Критериями оптимальности определены регулярность, экономичность полетов и сложность маневрирования. Метод заключается в последовательном синтезе множества Парето-оптимальных комбинаций бесконфликтных траекторий совокупности воздушных судов с использованием дискретного многокритериального динамического программирования и определении оптимальной комбинации с использованием свертки критериев оптимальности. В рамках метода определены: процедура формирования бесконфликтных комбинаций состояний совокупности воздушных судов, определяющих комбинации Парето-оптимальных траекторий; ограничения, которые накладываются при дискретизации процесса разрешения конфликта для обеспечения отсутствия ненаблюдаемых нарушений эшелонирования. **Результаты:** Исследование предложенного метода выполнено путем компьютерного моделирования, результаты которого показали, что синтезированная комбинация бесконфликтная траектория обеспечивает устранение групповой конфликтной ситуации и соответствует установленным критериям оптимальности. **Обсуждение:** Предложенный метод может быть использован при разработке новых автоматизированных систем управления воздушным движением, бортовых систем предупреждения столкновений, интеллектуальных тренажеров управления воздушным движением и для проведения научных исследований.

Ключевые слова: безопасность полетов; воздушное судно; групповая конфликтная ситуация между воздушными судами; динамическое программирование; многокритериальная оптимизация; разрешение конфликтной ситуации; управление воздушным движением

Denys Vasyliev (1987). PhD in Engineering.
Instructor of Training and Certification Centre of Ukrainian State Air Traffic Services Enterprise (UkSATSE), Boryspil, Ukraine
Associate Professor of Air Navigation Systems Department of National Aviation University, Kyiv, Ukraine.
PhD in Engineering on specialty “Navigation and Traffic Control” (2014)
Education: National Aviation University, Kyiv, Ukraine (2010).
Research area: situation analysis and decision-making in air traffic management.
Publications: 41
E-mail: dvasyliev@ukr.net

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Viacheslav Gusynin[1],
Andrii Gusynin[2],
Helen Tachinina[3]

ESTIMATE OF ACCURACY OF APPROXIMATE SOLUTIONS OF NON-LINEAR BOUNDARY VALUE PROBLEMS BY THE MULTI-STEP DIFFERENTIAL TRANSFORM METHOD

[1] Binational company «Alcântara Cyclone Space»
Av. L3 Norte – Ed. Finatec – Bloco H, Brasilia-DF – Brasil
[2] National Technical University of Ukraine «Igor Sikorsky KPI»
37, Peremohy ave., Kyiv, 03056, Ukraine
[3] National Aviation University
1, Kosmonavta Komarova ave., Kyiv, 03680, Ukraine
E-mails: [1]viacheslav.gusynin@gmail.com; [2]gusynin@gmail.com; [3]tachinina@mail.ru

Abstract

Purpose: *The present paper is aimed at estimating of accuracy and justification the application effectiveness of the multi-step differential transform method for solving non-linear boundary value problems.* ***Methods:*** *This article reviews the multi-step differential transform method for solving non-linear boundary value problem.* ***Results:*** *The upper bound of estimate of accuracy of approximate solutions of non-linear boundary value problems by the multi-step differential transform method for the case of accounting of restricted quantity of discretes of differential spectra is offered. We present results of numerical solution of a non-linear boundary value problem and shown the efficiency of application of the multi-step differential transform method compared with traditional differential transform method.* ***Discussion:*** *It is shown, that upper bound of error estimate of the multi-step differential transform method compared with traditional differential transform method is decreased in p^s time, where s is the quantity of accounted discretes, p is the quantity of intervals, over which the given time interval is divided. The multi-step differential transform method gives the principal possibility to get more exact value of random analytic function $x(t)$ on the end of interval at restricted quantity of discretes of differential spectrum compared with the differential transform method application.*

Keywords: approximate solution; differential transform method; estimate of accuracy; multi-step differential transform method; simulation; upper and lower bounds of error estimate.

1. Introduction

Non-linear boundary value problems occur frequently in modeling of different problems in various areas of science and engineering, including optimal control, flight dynamics, nuclear physics, quantum mechanics and others. In general, boundary value problems are described by non-linear differential equations, don't have analytical solutions and are solved by various numerical and numerical-analytical methods. However, application of majority of these methods is associated with overcoming of the variety of mathematical and computational difficulties.

One way to overcome given shortcoming is the application of operation method of differential-taylor transformations (differential transform method, DTM), whose basic definition and the fundamental theorems are given in [1-5]. It can be applied directly to solve non-linear differential equations without preliminary linearization, eliminates dependence of variables from time argument, admits the possibility to obtain solution in analytic form and considerably reduces the computing volume [6,7]. But along with the evident advantages, the DTM has some drawbacks. Restoring the differential equation solution as a formal Taylor series, generally can be impossible through the small radius of convergence, which could be essentially less than transient time.

For extending the search region solution of non-linear boundary value problems, different modifications of DTM methods have been proposed including the multi-step differential transform method (MsDTM) [8-13]. The sense of last method consists in dividing of entire interval into sub-intervals, searching over each subinterval the solution by the DTM based method and obtaining the general solution of equation as sum of solutions over sub-intervals. In [14] was proposed the modification of the MsDTM by using of approximation of non-linear terms of differential equations by Adomian polynomials permitting to obtain the solution of non-linear differential equations in more wide range with acceptable accuracy.

The solution accuracy of non-linear boundary value problems, obtained using different methods of DTM, essentially dependent from the quantity of accounted discretes used for restoring Taylor series solution. The bigger quantity of discretes would be accounted, the more exact the approximate solution would be obtained. In practice at dynamic process simulation the maximum quantity of accounted discretes always are restricted through the great volume of needed calculation that complicates the obtaining of task solution in the real and speeding up time. This results to increase the simulation error of dynamical processes in the field of originals and necessity of estimate of accuracy of solution obtained.

2. Research tasks

The present paper is aimed at estimating of accuracy and justification the application effectiveness of the MsDTM for solving non-linear boundary value problems.

3. Estimate of error of approximate solution

Consider the following non-linear boundary value problem

$$\frac{\mathrm{dx}}{\mathrm{dt}} = f\left(t, \mathrm{x}, \mathrm{x}', ..., \mathrm{x}^{(\mathrm{m})}\right) = 0, \qquad (1)$$

subject to the initial conditions

$$x^{(r)}(t_0) = c_r, \ r = 0,1,...,m-1 .$$

The problem solution (1) will consider over the interval $t_0 \le t \le T$, where the length of interval $L = T - t_0$ is selected inside the radius R of convergence of Taylor series, i.e. $0 \le L \prec R$. Assume that analytic function x(t) is continuously differentiated in any point $t \in [t_0, T]$, has derivatives of m^{th} - order, which are limited in total for any whole $m \ge 1$ so that,

$$\left|x^{(m)}(t)\right| \le C < +\infty, \ t \in [t_0, T]. \qquad (2)$$

Let us apply the basic features of DTM to the function x(t)

$$X(k) = \frac{H^k}{k!}\left[\frac{d^k x(t)}{dt^k}\right]_{t=t_0} \Leftrightarrow \mathrm{x(t)} = \sum_{\mathrm{k}=0}^{\infty}\left(\frac{\mathrm{t}}{\mathrm{H}}\right)^k X(k)$$

. (3)

where $x(t)$ is the original function, which represents the continuous and bounded together with all its derivatives the function of real argument t; $X(k)$ is the discrete function of integer argument $k = 0,1,2,...$, which is termed as the differential image of original $x(t)$ (the differential spectrum); H is the scale stationary value having dimensionality of argument t and often equals the time interval L, over which we want to find the function $x(t)$; $\Leftrightarrow$ is the correspondence symbol between the original $x(t)$ and its differential image $X(k)$.

The expression to the left of symbol $\Leftrightarrow$ in (3) defines the differential direct transform, permitting by the original $x(t)$ to find the image $X(k)$, and on the right - the differential inverse transform, which recovers the original $x(t)$ by the images $X(k)$.

Following the ideology of the MsDTM, the entire time interval $[\mathrm{t}_0, T]$ is divided into p given sub-intervals, $T_q = t_q - t_{q-1}$, $q = \overline{1,\mathrm{p}}$, $\sum_{q=1}^{\mathrm{p}} T_q = T - t_0 = L$, of equal step-size $h = L/p$. Restrict the quantity of discretes of differential spectrum $X(k)$ some given number $s \succ 0$ so, that integer argument $k = 0,1,2,...$ is changed within bounds $k = 0,1,2,...,s$. Applying the DTM over the first sub-interval $[\mathrm{t}_0, t_1]$, we will obtain the approximate solution of equation (1) with taking into account the finite quantity of discretes s in the form:

$$x_1(t_0) \approx \sum_{k=0}^{s} X_1(k)(t - \mathrm{t}_0)^k, \ t \in [t_0, t_1].$$

Taking into account the initial condition $x_1^{(r)}(t_0) = c_r$ and the expression (3) we will find for the first sub-interval all values of differential spectrum $\mathrm{X}_1(k)$, $k = 0,1,2,...,s$. For $q \ge 2$ and at each following sub-interval $[t_{q-1}, t_q]$ we will use the initial condition $x_q^{(r)}(t_{q-1}) = x_{q-1}^{(r)}(t_{q-1})$. Then the expression (1) for the q^{th} sub-interval will be following:

$$X_q(k) = \frac{H^k}{k!}\left[\frac{d^k x_{q-1}(t)}{dt^k}\right]_{t=t_{q-1}}, k \geq 0.$$

By applying given approach to each sub-interval will obtain the sequence of approximate solutions $x_q(t),\ q = 0,1,...,p$ for the solutions $x(t)$ of equation (1):

$$x_q(t) \approx \sum_{k=0}^{s} X_q(k)(t - t_{q-1})^k = y_q(t),\ t \in [t_{q-1}, t_q]. \quad (4)$$

Finally, the MsDTM assumes the following solution of equation (1):

$$x(t) = \begin{cases} x_1(t) \approx y_1(t),\ t \in [t_0, t_1], \\ x_2(t) \approx y_2(t),\ t \in [t_1, t_2], \\ \ldots.. \\ x_p(t) \approx y_p(t), t \in [t_{p-1}, t_p] \end{cases} \quad (5)$$

It is easily observed that if $p = 1$, then the MsDTM reduces to the classical DTM.

The quantity of accounted discretes s for restoring of the solution (5) as Taylor series is one of the most essential factors that effect on the solution accuracy obtained. Restriction of given quantity of discretes leads to error of result obtained. The upper bound of error estimate $|\varepsilon_0| = |x(t) - y(t)|$ of the DTM (3) is given by the expression [15,16]:

$$|\varepsilon_0| \leq \frac{L^{s+1}}{(s+1)!} \sup_{0<t_l<L} \left|x^{(s+1)}(t_l)\right|. \quad (6)$$

Taking into account the constraint (2), the expression (6) can be written as:

$$|\varepsilon_0| \leq C\frac{L^{s+1}}{(s+1)!} = |\hat{\varepsilon}_0|. \quad (7)$$

In [17] as a criterion of preliminary estimation of upper error bound of obtained solution $G(n, m)$ at the restriction of quantity of discretes used for restoring solution as a power series is considered the expression that links solutions, obtained for n and $n + m$ discretes:

$$G(n, m) = \sqrt{\frac{1}{s}\sum_{i=0}^{N}\left|1 - \frac{x(t_i, n)}{x(t_i, n+m)}\right|^2},\ t_i \in [0, L]. \quad (8)$$

Use the given criterion is enough awkward, because besides the dual solution calculation it demands the additional m discretes $X(n+1), X(n+2),..., X(n+m)$ calculation too. For non-linear differential equations with complex nonlinearities, the expression (8) in some particular cases can give the wrong solution, when discretes $X(n)$ and $X(n+m)$ have the same sign. In these cases, are necessary to choose $m > 0$, so that $X(n)$ and $X(n+m)$ have the different signs.

For the MsDTM, the expression (6) for the upper bound of error estimate $|\varepsilon_q| = |x_q(t) - y_q(t)|$ over q^{th} sub-interval with taking into account s discretes can be written as:

$$|\varepsilon_q| \leq \frac{(L/p)^{s+1}}{(s+1)!} \sup_{\xi \in [t_q, t_{q-1}]} \left|x_q^{(s+1)}(\xi)\right|,\ q = 1,...p. \quad (9)$$

On the ground of the constraint (2) can make the conclusion, that over q^{th} sub-interval

$$C_q = \sup_{\xi \in [t_q, t_{q-1}]} \left|x_q^{(s+1)}(\xi)\right| \leq C < +\infty. \quad (10)$$

Really, if the $(s+1)^{th}$ derivative of function $x_q(t)$ achieves the maximum value over the interval $[t_0, t_q]$ then $C_q = C$, otherwise $C_q < C$.

The error estimate (9) with taking into account the constraint (10) can be written as

$$|\varepsilon_q| \leq C\frac{(L/p)^{s+1}}{(s+1)!}. \quad (11)$$

From the expression (11) follows that obtained error at dividing the entire interval into equal p sub-intervals, is the same over sub-intervals and depends only from the quantity of accounted discretes s. Convert the given estimate to the relative error estimate. Let us select as a comparison base the error (7) for the DTM. Then for the relative error on q^{th} sub-interval obtain:

$$\left|\frac{\varepsilon_q}{\hat{\varepsilon}_0}\right| \leq \frac{(L/p)^{s+1}}{L^{s+1}},\quad q = 1, ..., p. \quad (12)$$

Consider the full relative error of the MsDTM $\varepsilon_s = \varepsilon_1 + \varepsilon_2 + ... + \varepsilon_p$ over the entire interval in relation to the error ε_0 of the DTM:

$$\left|\frac{\varepsilon_s}{\hat{\varepsilon}_0}\right| = \left|\frac{\varepsilon_1}{\hat{\varepsilon}_0}\right| + \left|\frac{\varepsilon_2}{\hat{\varepsilon}_0}\right| + ... + \left|\frac{\varepsilon_p}{\hat{\varepsilon}_0}\right|. \quad (13)$$

From expression (12) follows, that components of relative errors are changed in the bounds:

$$0 \le \left| \frac{\varepsilon_{s_i}}{\hat{\varepsilon}_0} \right| \le 1, \quad i = 1,2,\ldots, p . \qquad (14)$$

Bigger deviation of approximate solution from exact solution, usually, falls on the end of time interval. At that, it will be maximum in the case of the same signs ε_{s_i}. Then, taking into account (12), the expression (13) will be following:

$$\left| \frac{\varepsilon_s}{\hat{\varepsilon}_0} \right| \le \left| \frac{1}{p^{s+1}} \right| + \left| \frac{1}{p^{s+1}} \right| + \ldots + \left| \frac{1}{p^{s+1}} \right| = \frac{1}{p^s} = p^{-s} . \qquad (15)$$

This means that the upper bound of error estimate of the MsDTM in p^s time less than the upper bound of error estimate of the DTM at dividing of given interval into p sub-intervals of equal step-size, i.e.:

$$|\varepsilon_s| \le p^{-s} |\hat{\varepsilon}_0| , \qquad (16)$$

where s is the quantity of accounted discretes of differential spectrum $X(k)$ above the zeroth discrete $X(0)$, i.e. the quantity s is equal the number of the last accounted discretes of differential spectrum $X(k)$. The analysis of obtained expression shown, that with increasing of quantity of accounted discretes s, the upper bound of summary error is reduced on the exponential rule and at $s \to \infty$ reduced to the zeroth lower bound. Therefore, the range of changing of summary error at dynamical processes simulation using MsDTM is defined by constraints:

$$0 \le |\varepsilon_s| \le p^{-s} \cdot |\hat{\varepsilon}_0| , \qquad (17)$$

where $|\hat{\varepsilon}_0|$ is defined by expression (7).

From the expression (17) can make the conclusion, that the MsDTM at the restricted quantity of discretes s of differential spectrum $X(k)$ gives the possibility to get more exact solution of boundary value problem (1) in the point $t = T$ at condition execution (2), than the DTM.

The DTM (3) gives the exact value of analytical function $x(t)$ in the point $t = T$ only in particular case, when solution $x(t)$ is approximated by polynomial of $n \le s$ order. In other cases, the error of the DTM (3) is equal $|\varepsilon_0| > 0$ for restricted quantity of discretes $s < +\infty$ of differential spectrum $X(k)$. The error $|\varepsilon_0| > 0$ couldn't be reduced to zero by dividing the interval $[t_0, T]$ over any finite sub-interval quantity $p < +\infty$, as the zeroth error value of the DTM (3) gives in the general case over the random non-null time interval only at taking into account infinite amount of Taylor series terms or discretes of differential spectrum $X(k)$ [16].

The constraint (17) shows, that with increasing of the quantity of accounted discretes s of differential spectrum, the application effectiveness of the MsDTM compared with the DTM is increasing on the law of exponential function. Therefore, for the high-accuracy calculation is appropriate to apply the MsDTM instead of the DTM.

Enhance the solution accuracy of non-linear boundary value problems and also to expand the admissible solution interval, the restriction on which is defined by the radius of convergence of Taylor series is possible on the basis of application of shifted differential transformations. In contrast to traditional, shifted transformations are obtained by transferring of the center of expansion of original to a Taylor series from the initial point $t = 0$ to the shifted point $t = t_q$. The best from the standpoint of reducing the solution error is the arrangement of the center of expansion of the original in a Taylor series in the middle of the given interval [16]. In fact, it means that given interval is divided into two sub-intervals of same length and obtaining the solution over each sub-interval using two models in the area of shifted transformations: the direct model (from shifted point to the end of interval) and the inverse model (from shifted point to the start of interval). At that has been obtained that compared with traditional DTM the upper bound of error estimate of shifted differential transformations is decreasing in 2^s time, where s is the quantity of accounted discretes of differential spectrum. This is agreed with above result obtained for the MsDTM, the use of which allows to decrease the error in p^s time, where p is the quantity of sub-intervals into which given interval is divided.

4. The effectiveness of multi-step differential transform method

The effectiveness of the MsDTM can be illustrated by following example.

Let us consider the following boundary value problem, which is described by non-linear ordinary differential equation with the quadratic source term [14]:

$$\frac{dx(t)}{dt} = 2x(t) - x^2(t) + 1, \; x(0) = 0, \quad t \in [0;1.2]. \qquad (18)$$

The exact solution is given by:

$$x(t) = 1 + \sqrt{2}\tanh\left(\sqrt{2}t + \frac{1}{2}\log\left(\frac{\sqrt{2}-1}{\sqrt{2}+1}\right)\right). \quad (19)$$

Let us divide the given interval $[0;1,2]$ into 10 sub-intervals of the equal step-size $h = 1,2/10$.

By applying the DTM, we write the equation (18) in the spectral form for each sub-interval:

$$\begin{aligned} &(k+1)X_q(k+1) = 2X_q(k) - \widetilde{A}_{kq} + \sigma(k), \\ &X_1(0) = x_1(0) = x(0) = 0,\ t_0 = 0,\ q = 1, \\ &x_q(t_{q-1}) = x_{q-1}(t_{q-1}),\ q = 2,...,10, \\ &\sigma(k) = \begin{cases} 1, k = 0, \\ 0, k \neq 0. \end{cases} \end{aligned} \quad (20)$$

Accordingly, with procedure [14], for non-linear part of equation (18) $f(x) = x^2$ we calculate over each sub-interval the components A_{kq} of Adomian polynomials and thereon the corresponding components $\widetilde{A}_{kq}$ for replacement by them of components of differential images of non-linear part of equation:

$$\widetilde{A}_{0q} = X_q^2(0),\ \widetilde{A}_{1q} = 2X_q(0)X_q(1),$$

$$\widetilde{A}_{2q} = X_q^2(1) + 2X_q(0)X_q(2),$$

$$\widetilde{A}_{3q} = 2X_q(0)X_q(3) + 2X_q(1)X_q(2),$$

$$\widetilde{A}_{4q} = 2X_q(0)X_q(4) + 2X_q(1)X_q(3) + X_q^2(2),$$

$$\widetilde{A}_{5q} = 2X_q(0)X_q(5) + 2(X_q(2)X_q(3) + X_q(1)X_q(4))$$

Substituting values $\widetilde{A}_{kq}$ in (19) and taking into account (7), we find the approximate solution of equation (18) over each subinterval. Summating given solutions obtain the general solution of equation (18) on the given interval.

Let us find the value of function $x(t)$ in the end point $t = 2,0$. Result obtained shown the following. The exact solution (19) of function $x(t)$ of equation (18) in the point $t = 2,0$ is equal 2,35777. Application of the DTM doesn’t allow to obtain the solution over given interval due to exceeding the value of given interval the radius of convergence of Taylor series by whom the approximate solution is approximated.

The found solution by MsDTM with taking into account first 6 discretes of the differential spectrum and dividing given interval into two sub-intervals (analogue of application of shifted differential transformations) is 2,08641 ($\varepsilon = 1,15 \cdot 10^{-1}$), while at dividing interval into 10 sub-intervals, the approximate solution has the value 2,3577717 ($\varepsilon = 3,19 \cdot 10^{-8}$). The given example is illustrated the effectiveness of the MsDTM application for solving non-linear boundary value problems.

5. Conclusions

The upper bound of error estimate for approximate solution of non-linear boundary value problem by the MsDTM has been offered. It is shown, that upper bound of error estimate of the MsDTM compared with traditional DTM is decreased in p^s time, where s is the quantity of accounted discretes, p is the quantity of intervals, over which the given time interval is divided. The MsDTM gives the principal possibility to get more exact value of random analytic function $x(t)$ on the end of interval at restricted quantity of discretes of differential spectrum compared with the DTM application.

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В. П. Гусинін[1], А. В. Гусинін[2], Е. М. Тачиніна[2]

Оцінка точності наближеного розв’язку нелінійних крайових задач багатоетапним методом диференціальних перетворень

[1] Бінаціональна компанія «Alcântara Cyclone Space»
Av. L3 Norte – Ed. Finatec – Bloco H, Brasilia-DF – Brasil
[2] Національний Технічний Університет України «КПІ» ім. І. Сикорського
пр. Перемоги, 37, Київ, 03056, Україна
[3] Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680
E-mails: [1]viacheslav.gusynin@gmail.com; [2]gusynin@gmail.com; [3]tachinina@mail.ru

Мета: Метою цієї статті є оцінка точності та обґрунтування ефективності застосування багатоетапного метода диференціальних перетворень для розв’язку нелінійних крайових задач. **Методи:** В статті розглянуто багатоетапний метод диференціальних перетворень до розв’язку нелінійної крайової задачі. **Результати:** Запропоновано оцінку зверху точності наближеного розв’язку нелінійних крайових задач багатоетапним методом диференціальних перетворень для випадку урахування обмеженої кількості дискрет диференціальних спектрів. Представлені результати численного розв’язку нелінійної крайової задачі та показана ефективність застосування багатоетапного метода диференціальних перетворень порівняно з основними диференціальними перетвореннями. **Обговорення:** Показано, що оцінка зверху наближеного розв’язку нелінійної крайової задачі багатоетапним методом диференціальних перетворень порівняно з основними диференціальними перетвореннями знижується в p^s раз, де s – кількість дискрет, що враховується, p – кількість підінтервалів, на які розбивається заданий часовий інтервал. Отримано, що застосування метода багатоетапних диференціальних перетворень дає принципову можливість отримати точне значення довільної аналітичної функції $x(t)$ на кінці інтервалу при обмеженій кількості дискрет диференціального спектру.

Ключові слова: багатоетапний метод диференціальних перетворень; верхня та нижня межі оцінки похибки; метод диференціальних перетворень; оцінка точності; моделювання; наближений розв'язок.

В. П. Гусынин[1], А. В. Гусынин[2], Е. М. Тачинина[3]. Оценка точности приближенного решения нелинейных краевых задач многоэтапным методом дифференциальных преобразований

[1] Бинациональная компания «Alcântara Cyclone Space»
Av. L3 Norte – Ed. Finatec – Bloco H, Brasilia-DF – Brasil
[2] Национальный Технический Университет Украины «КПИ им. І. Сикорского»
пр. Победы, 37, Киев, 03056, Украина
[3] Национальный Авиационный Университет
пр. Космонавта Комарова, 1, Киев, 03680, Украина
E-mails: [1]viacheslav.gusynin@gmail.com; [2]gusynin@gmail.com; [3]tachinina@mail.ru

Цель: Целью данной статьи является оценка точности и обоснование эффективности применения многоэтапного метода дифференциальных преобразований для решения нелинейных краевых задач. **Методы:** В статье рассмотрен многоэтапный метод дифференциальных преобразований к решению нелинейной краевой задачи. **Результаты:** Предложена оценка сверху точности решения нелинейных краевых задач многоэтапным методом дифференциальных преобразований для случая учета ограниченного количества дискрет дифференциальных спектров. Представлены результаты численного решения нелинейной краевой задачи и показана эффективность применения многоэтапного метода дифференциальных преобразований в сравнении с основными дифференциальными преобразованиями. **Обсуждение:** Показано, что оценка сверху приближенного решения нелинейной краевой задачи многоэтапным методом дифференциальных преобразований по сравнению с основными дифференциальными преобразованиями снижается в p^s раз, где s - количество учитываемых дискрет, p - количество подинтервалов, на которое разбивается заданный временной интервал. Получено, что применение метода многоэтапных ДТ-преобразований дает принципиальную возможность получить точное значение произвольной аналитической функции $x(t)$ на конце интервала при ограниченном количестве дискрет дифференциального спектра.

Ключевые слова: верхняя и нижняя граница оценки погрешности; метод дифференциальных преобразований; многоэтапный метод дифференциальных преобразований; моделирование; оценка точности; приближенное решение.

Gusynin Viacheslav. Doctor of Engineering.
Acting General Director Ukraine, Binational company «Alcântara Cyclone Space», Brasilia, Brazil.
Education: Taras Shevchenko National University of Kyiv, Kyiv, Ukraine (1973).
Research area: flight dynamics, optimal control, differential transformation.
Publications: more than 210.
E-mail: viacheslav.gusynin@alcantaracyclonespace.com

Gusynin Andrii. Candidate of engineering, associate professor.
Associate professor, National Technical University of Ukraine «Igor Sikorsky KPI»
Education: International Solomon University, Kyiv, Ukraine (2000).
Research area: flight dynamics, automatization, optimal control, differential transformation.
Publications: 105.
E-mail: gusynin@gmail.com

Tachinina Helen. Candidate of engineering, associate professor.
Associate professor, Department of Automation and Energy Management, National Aviation University
Education: National Aviation University, Kyiv, Ukraine (2000).
Research area: flight dynamics, automatization, optimal control
Publications: 80.
E-mail: tachinina@rambler.ru

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Olha Sushchenko

MATHEMATICAL MODEL OF ATTITUDE AND HEADING REFERENCE SYSTEM WITH BIAXIAL HORIZONTAL PLATFORM

National Aviation University
Kosmonavta Komarova avenue 1, 03058, Kyiv, Ukraine
E-mail: sushoa@ukr.net

Abstract

Purpose: *Operation of attitude and heading reference systems in conditions of autonomy and high accuracy requires usage of gimballed platforms. The goal of the paper is detailed research of such systems kinematics and control moments. As result the full mathematical model of the precision attitude and heading reference system with the biaxial horizontal platform was derived.* ***Methods:*** *Obtaining of the mathematical model is based on the theory of gyros in general and corrected gyro compasses and theory of dynamically tuned gyros in particular. The basic laws of theoretical mechanics including concepts of Euler angles and directional cosines were taken into consideration.* ***Results:*** *The full mathematical model of the attitude and heading reference system is developed. The mathematical models of the vertical gyro and directional gyro as components of the researched system are given. The simulation results based on the developed models are presented.* ***Conclusions:*** *The mathematical model of the gimballed attitude and heading reference system including the vertical gyro and directional gyro is derived. The detailed expressions for control (correction) moments are obtained. The full analysis of the researched system kinematics was carried out. The obtained results can also be useful for design of inertial navigation systems of the wide class.*

Keywords: attitude and heading reference system; directional cosines; directional gyro; gimballed platforms; precision navigation systems; vertical gyro.

1. Introduction and Problem Statement

Nowadays the gimballed navigation systems are used when it is necessary to satisfy high accuracy in conditions of autonomous operation. The requirements to the high functional reliability and the ability to function in conditions of external disturbances are given to such systems too [1]. The gimballed systems can be components of guidance, navigation and control systems [2].

The researched attitude and heading reference system (AHRS) includes biaxial horizontal platform, which is stabilized by the vertical gyro signals. The principal axis of the gyro device is aligned by the direction of the local vertical based on accelerometer signals. The system uses the integral correction. In fact the biaxial horizontal platform with gyro devices represents the inertial vertical gyro.

The gimballed AHRS with biaxial horizontal platform has reduced dimensions [3]. Its possibility to rotate around the third axis (in the azimuth plane) is provided by means of a rotator, on which the directional gyro is mounted.

The rotator is stabilized relative to the given plane and can turn on the given angles providing alignment of the gyro. The directional gyro uses as an indicator of direction similar to the azimuth gyro. It can be used also as the gyro compass if stabilization is implemented relative to the meridian plane. The vertical gyro is mounted on the rotator too. Such construction provides calibration of the gyro device and determination of its corrections.

The researched AHRS uses dynamically tuned gyros (DTG) and accelerometers [4]. This system has some features. The first feature is division of control functions. In this case control by the position of the DTG principal axis is implemented by accelerometer’s signals. Stabilizing motors provide coincidence of the axis normal to the stabilized platform with the direction of DTG rotor. Division of functions provides relatively small moments of DTG torque sensors. The second feature of the researched system is usage of the biaxial platform.

In contrast to the traditional triaxial platform such construction provides azimuth motion of the platform together with the vehicle and constant orientation of the outer gimbal to the North. Therefore the system becomes sensitive to disturbances caused by changes of the heading and elliptic shape of the Earth. To compensate such disturbances it is necessary to use information about the linear speed, heading and its changes.

Advantages of the researched system are high accuracy and reduced dimensions in comparison with the triaxial platform.

Development of the model of such system requires usage of the trajectory reference frame. This significantly complicates control of the system.

2. Review of Last Publications

Features of the researched system are presented in [5]. Analysis of the kinematical schemes of gimballed corrected gyro compass and gimballed navigation systems with biaxial and triaxial gyrostabilized platforms is given in [4]. This paper keeps the basic idea proposed in [5] and used in [6]. The idea is to neglect the servo-systems errors and divide the system into the vertical and directional gyros. **The goal of the paper** is to consider the system kinematics and to derive expressions for control moments.

3. System kinematics

To describe the system kinematics it is necessary to introduce the following systems of coordinates:

1) the trajectory system of coordinates O′ζηξ (O′η is directed along the vehicle speed, O′ζ is perpendicular to the horizon plane, O′ξ lies in the horizon plane);

2) the body-axis system of coordinates $Ox_0y_0z_0$ (the axis Oy_0 is directed along the longitudinal axis of the vehicle; the axis Oz_0 is perpendicular to the horizon plane; the axis Ox_0 lies in the horizon plane);

3) the platform-axis system of coordinates $Ox_ny_nz_n$ (the axis Oy_n is directed along the external gimbal; the axis Oy_n is perpendicular to the horizon plane, the axis Ox_n is perpendicular to the axis Oy_0 and lies in the horizon plane);

4) the system of coordinates $Ox_ry_rz_r$, which is connected with Resal axes of DTG carrying out functions of the vertical gyro.

Mutual angular position of introduced systems of coordinates is given in Figures 1–5.

z_0

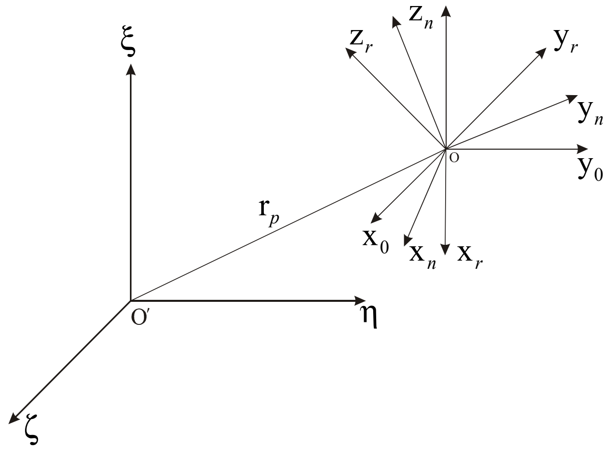


Fig. 1. Mutual position of introduced systems of coordinates: r_p is the radius-vector defining position of coordinate systems origins

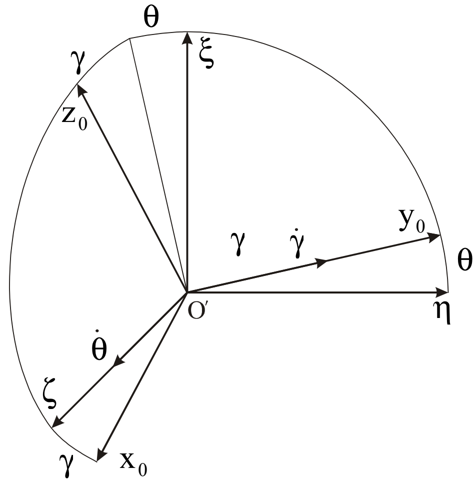


Fig. 2. Mutual location of the trajectory and body-axis systems of coordinates: θ, γ are angles of pitch and roll

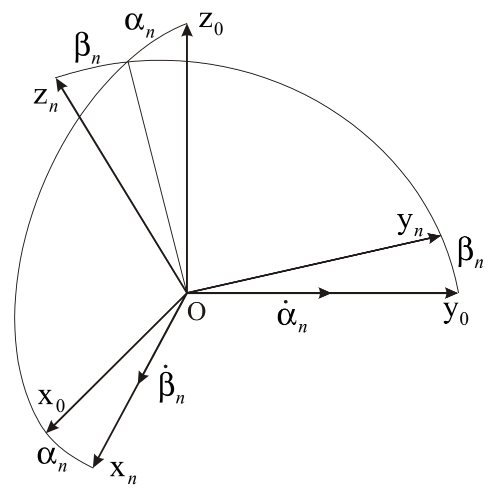


Fig. 3. Mutual location of the body-axis and platform-axis systems of coordinates (α_n, β_n are angles, which determine turn of a platform relative to the body-axis system)

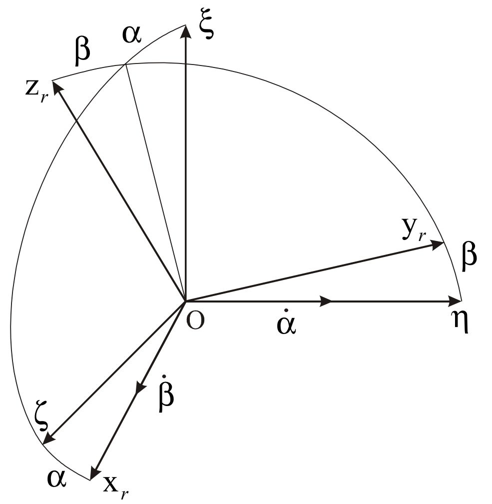


Fig. 4. Resal axes location relative to the trajectory system of coordinates (α, β determine the location of Resal axes relative to the horizon plane)

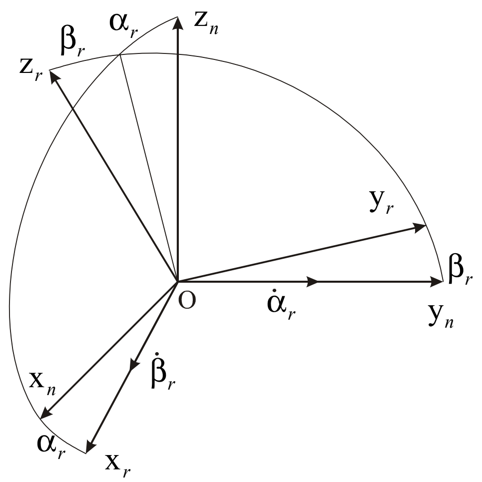


Fig. 5. Resal axes location relative to the platform (α_r, β_r determine the location of Resal axes relative to the platform)

In accordance with Figures 1–5 relations between introduced systems of coordinates can be described in the following way [5, 7]

$$\begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} = \mathbf{A}_1 \begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix}; \quad \begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix} = \mathbf{A}_2 \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix};$$
$$\begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} = \mathbf{A}_3 \begin{bmatrix} \zeta \\ \eta \\ \xi \end{bmatrix}; \quad \begin{bmatrix} x_r \\ y_r \\ z_r \end{bmatrix} = \mathbf{A}_4 \begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix}; \qquad (1)$$

$$\mathbf{A}_1 = \begin{bmatrix} \cos\gamma & \sin\theta\cdot\sin\gamma & -\cos\theta\cdot\sin\gamma \\ 0 & \cos\theta & \sin\theta \\ \sin\gamma & -\sin\theta\cdot\cos\gamma & \cos\theta\cdot\cos\gamma \end{bmatrix}; \qquad (2)$$

$$\mathbf{A}_2 = \begin{bmatrix} \cos\alpha_n & 0 & -\sin\alpha_n \\ \sin\alpha_n\cdot\sin\beta_n & \cos\beta_n & \cos\alpha_n\cdot\sin\beta_n \\ \sin\alpha_n\cdot\cos\beta_n & -\sin\beta_n & \cos\alpha_n\cdot\cos\beta_n \end{bmatrix}; \qquad (3)$$

$$\mathbf{A}_3 = \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ \sin\alpha\cdot\sin\beta & \cos\beta & \cos\alpha\cdot\sin\beta \\ \sin\alpha\cdot\cos\beta & -\sin\beta & \cos\alpha\cdot\cos\beta \end{bmatrix}; \qquad (4)$$

$$\mathbf{A}_4 = \begin{bmatrix} \cos\alpha_r & 0 & -\sin\alpha_r \\ \sin\alpha_r\cdot\sin\beta_r & \cos\beta_r & \cos\alpha_r\cdot\sin\beta_r \\ \sin\alpha_r\cdot\cos\beta_r & -\sin\beta_r & \cos\alpha_r\cdot\cos\beta_r \end{bmatrix}. \qquad (5)$$

It should be noted that there is dependence

$$\mathbf{A}_3 = \mathbf{A}_4 \cdot \mathbf{A}_2 \cdot \mathbf{A}_1 . \qquad (6)$$

The expression (6) allows obtaining relations for determination of angles α_n, β_n.

4. Vertical Gyro Model

For small turn angles it is possible to believe that the gyrostabilized platform motion coincides with motion of the vertical gyro's Resal axes. Accuracy of such supposition is defined by stabilization errors α_r, β_r. Angular motion of DTG, which carries out functions of the vertical gyro, can be described by the differential equations [8]

$$J\ddot{\alpha}_r + d\dot{\alpha}_r - H\dot{\beta}_r - \frac{H}{T}\beta_r + c\alpha_r = J\dot{\omega}_y + H_1\omega_x + $$
$$+ M_{1y} + M_{2y} + M_{3y} + M_{4y} + M_{dist\ y}$$
$$J\ddot{\beta}_r + d\dot{\beta}_r + H\dot{\alpha}_r + \frac{H}{T}\alpha_r + c\beta_r = J\dot{\omega}_x - H_1\omega_y + $$
$$+ M_{1x} + M_{2x} + M_{3x} + M_{4x} + M_{dist\ x} \qquad (7)$$

where H is the kinetic moment; c is the residual rigidity of gimbals; d is the damping coefficient; T is the gyro time constant; $H_1 = H(1-S)$; S=10^{-3}; J is a sum of the equatorial moments of the rotor and gyro gimbals; ω_x, ω_y are projections of the platform angular rates; $\dot{\omega}_x, \dot{\omega}_y$ are projections of platform angular accelerations; $M_{iy} = 1,\ldots,4$, $M_{ix} = 1,\ldots,4$ and $M_{dist\ y}$, $M_{dist\ x}$ are control and disturbance moments acting along axes y, x respectively.

To determine projections of platform angular rates it is necessary to project angular rates of the trajectory reference frame onto platform-axis reference frame. For estimation of the vertical gyro errors it is convenient to represent projections ω_x, ω_y as functions of the angles α, β.

The angles α_r, β_r represent errors of platform stabilization and define position of the vertical gyro axes relative to the horizon plane. In fact they represent errors of vertical line determination. Respectively transformation for small angles α_r, β_r, and α, β using matrices (4) (5) becomes

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \mathbf{A}_4 \cdot \mathbf{A}_3 \begin{bmatrix} \xi \\ \eta \\ \zeta \end{bmatrix}; \qquad (8)$$

here $A_4 A_3 \approx \begin{bmatrix} 1 & 0 & -\alpha+\alpha_r \\ 0 & 1 & \beta\text{-}\beta_r \\ \alpha\text{-}\alpha_r & \text{-}\beta+\beta_r & 1 \end{bmatrix}$.

Using the expression (8) it is possible to write the platform angular rates in the following form

$$\begin{aligned} \omega_x &= \dot\beta - \dot\beta_r + \omega_\xi - \omega_\zeta(\alpha - \alpha_r); \\ \omega_y &= \dot\alpha - \dot\alpha_r + \omega_\eta + \omega_\zeta(\beta - \beta_r); \\ \omega_z &= (\dot\alpha - \dot\alpha_r)\mathrm{tg}\theta + \frac{\alpha - \alpha_r}{\cos^2\theta}\dot\theta + \omega_\zeta. \end{aligned} \qquad (9)$$

Angular rates in the equations (9) are determined with accuracy to the second order of smallness. If the expression (9) is substituted in the equations (7), it is possible to obtain

$$\begin{aligned} &-H_1\dot\beta + H_1\omega_\zeta\alpha = -I\ddot\alpha_r + H\dot\beta_r - c\alpha_r - d\dot\alpha_r + \frac{H}{T}\beta_r + \\ &+ H_1(-\dot\beta_r + \omega_\xi + \omega_\zeta\alpha_r) + I\dot\omega_y + \\ &+ \sum_{i=1}^{4} M_{iy} + M_{\mathrm{d}ist\, y}; \\ &H_1\dot\alpha + H_1\omega_\zeta\beta = -I\ddot\beta_r - H\dot\alpha_r - c\beta_r - d\dot\beta_r - \frac{H}{T}\alpha_r - \\ &- H_1(-\dot\alpha_r + \omega_\eta - \omega_\zeta\beta_r) + I\dot\omega_x + \\ &+ \sum_{i=1}^{4} M_{ix} + M_{\mathrm{d}ist\, x}. \end{aligned} \qquad (10)$$

If stabilization errors are believed to be constant, the relations (10) represent the vertical gyro model. Stabilization errors can be determined based on information about the gyro devices drifts, which can be obtained during operation.

Variables ω_ξ, ω_η, ω_ς in the equations (10) are projections of the angular rates of the trajectory reference frame. In accordance with [9, 10] they can be represented in the following form

$$\begin{aligned} \omega_\xi &= -\frac{V_\eta \sin K + V_\xi \cos K}{R_1}\sin K - \\ &- \frac{V_\eta \cos K - V_\xi \sin K}{R_M}\cos K - \Omega\cos\varphi\sin K; \\ \omega_\eta &= \frac{V_\eta \sin K + V_\xi \cos K}{R_1}\cos K - \\ &- \frac{V_\eta \cos K - V_\xi \sin K}{R_M}\sin K + \\ &+ \Omega\cos\varphi\cos K; \\ \omega_\zeta &= \frac{V_\eta \sin K + V_\xi \cos K}{R_1}\mathrm{tg}\varphi - \dot K + \Omega\sin\varphi, \end{aligned} \qquad (11)$$

where V_ζ, V_η, V_ξ are lateral, longitudinal and vertical projections of the vehicle speed; K is the heading; R_1 is the main radius of curvature of the earth ellipsoid in the plane perpendicular to the meridian; R_M is the main radius of the earth curvature in the meridian plane; Ω is the angular rate of the diurnal rotation; $\dot K$ is rate of heading change.

To determine apparent accelerations projections onto accelerometer sensitive axes it is convenient to neglect the instrumental errors of accelerometer alignment. And accelerometer sensitivity axes are believed to coincide with platform axes. In accordance with [9] the expression for apparent acceleration looks like

$$\mathbf{W}_{cw} = \dot{\mathbf{V}}_{cw} + \boldsymbol{\omega}_{tr} \times \mathbf{V}_{cw} + \boldsymbol{\Omega} \times \mathbf{V}_{cw} - \mathbf{g}, \qquad (12)$$

where $\boldsymbol{\omega}_{tr}$ is the vector of the absolute angular rate of trajectory reference frame; **g** is the gravity acceleration; $\mathbf{V}_{cw}$ is the vector of the mass centre rate relative to the Erath; **Ω** is the vector of the diurnal rotation; φ is the geographical latitude. Projections of the vector equation (12) can be represented in the following form

$$\begin{bmatrix} W_\xi \\ W_\eta \\ W_\zeta \end{bmatrix} = \begin{bmatrix} \dot V_\xi \\ \dot V_\eta \\ \dot V_\zeta \end{bmatrix} + \begin{bmatrix} V_\zeta\omega_\eta - V_\eta\omega_\zeta \\ V_\xi\omega_\zeta - V_\zeta\omega_\xi \\ V_\eta\omega_\xi - V_\xi\omega_\eta \end{bmatrix} + \begin{bmatrix} V_\zeta\Omega\cos\varphi\cos K - V_\eta\Omega\sin\varphi \\ V_\xi\Omega\sin\varphi - V_\zeta\Omega\cos\varphi\sin K \\ V_\eta\Omega\cos\varphi\sin K - V_\xi\Omega\cos\varphi\cos K \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \qquad (13)$$

The acceleration of the point, at which the platform is mounted at the vehicle, can be written as [5, 9]

$$\mathbf{W}_0 = \mathbf{W}_{cw} + \boldsymbol{\omega}_{abs} \times \mathbf{r}_\mathrm{p} + \boldsymbol{\omega}_{abs} \times (\boldsymbol{\omega}_{abs} \times \mathbf{r}_\mathrm{p}); \qquad (14)$$

where $\boldsymbol{\omega}_{abs}$ is a vector of the absolute angular rate of the vehicle; $\mathbf{r}_p$ is the radius-vector of the point of platform setting relative to the centre of the vehicle mass.

Projections of the vector equation (14) onto the body-axis reference frame $Ox_0y_0z_0$ look like

$$\begin{bmatrix} W_{x0} \\ W_{y0} \\ W_{z0} \end{bmatrix} = \mathbf{A}_1 \begin{bmatrix} W_\xi \\ W_\eta \\ W_\zeta \end{bmatrix} + \begin{bmatrix} \dot{\omega}_{x0} z_p - \dot{\omega}_{z0} y_p \\ \dot{\omega}_{z0} x_p - \dot{\omega}_{x0} z_p \\ \dot{\omega}_{x0} y_p - \dot{\omega}_{y0} x_p \end{bmatrix} + \\ + \begin{bmatrix} \omega_{y0}(\omega_{x0} y_p - \omega_{y0} x_p) - \omega_{z0}(\omega_{z0} x_p - \omega_{x0} z_p) \\ \omega_{z0}(\omega_{y0} z_p - \omega_{z0} y_p) - \omega_{x0}(\omega_{x0} y_p - \omega_{y0} x_p) \\ \omega_{x0}(\omega_{z0} x_p - \omega_{x0} z_p) - \omega_{y0}(\omega_{y0} z_p - \omega_{z0} y_p) \end{bmatrix}; \quad (15)$$

where $W_{x_0}, W_{y_0}, W_{z_0}$ are projections of the apparent acceleration onto the body-axis reference frame; $\omega_{x_0}, \omega_{y_0}, \omega_{z_0}$ are projections of the vehicle absolute angular rate; x_p, y_p, z_p are coordinates of point, at which the platform is set at the vehicle; $\mathbf{A}_1$ is the matrix of directional cosines between the trajectory and body-axis reference frames. This matrix is determined by the expression (2).

Projections of the absolute angular rate of the vehicle can be represented in the following form

$$\omega_{x_0} = (\omega_\xi + \dot{\theta})\cos\gamma + \omega_\eta \sin\gamma\sin\theta - \omega_\zeta \sin\gamma\cos\theta;$$
$$\omega_{y0} = \dot{\gamma} + \omega_\eta \cos\theta + \omega_\zeta \sin\theta;$$
$$\omega_{z_0} = (\omega_\xi + \dot{\theta})\sin\gamma - \omega_\eta \cos\gamma\sin\theta + \omega_\zeta \cos\gamma\cos\theta. \quad (16)$$

Based on the equations (15) it is possible to obtain the vector equation

$$\begin{bmatrix} W_x \\ W_y \\ W_z \end{bmatrix} = \mathbf{A}_2 \begin{bmatrix} W_{x0} \\ W_{y0} \\ W_{z0} \end{bmatrix}, \quad (17)$$

where W_x, W_y, W_z are projections of the apparent acceleration onto the body-axis reference frame $Oxyz$; $\mathbf{A}_2$ is the matrix of the directional cosines between the body-axis and platform-axis reference frames. This matrix can be determined by the expression (3).

It should be noted that projections of the trajectory reference frame taking into consideration (1) are determined by relations

$$W_\xi = \dot{V}_\xi + V_\zeta\omega_\eta - V_\eta\omega_\zeta + V_\zeta\Omega\cos\varphi\cos K - V_\eta\Omega\sin\varphi;$$
$$W_\eta = \dot{V}_\eta + V_\xi\omega_\zeta - V_\zeta\omega_\xi + V_\xi\Omega\sin\varphi + V_\zeta\Omega\cos\varphi\sin K; \quad (18)$$
$$W_\zeta = \dot{V}_\zeta + V_\eta\omega_\xi - V_\xi\omega_\eta - V_\eta\Omega\cos\varphi\sin K - \\ - V_\xi\Omega\cos\varphi\cos K - g.$$

The equations (10) supplemented by the expressions (11), (15), (17), (18) represent the model of the inertial vertical. Such model allows researching of the AHRS using the biaxial gyrostabilized platform and the trajectory reference frame.

5. Control of Vertical Gyro

The important component of the vertical gyro model is description of control moments. These moments are formed in computing device and are applied to torque sensors of the vertical gyro. Such approach provides high accuracy of attitude and heading determination.

The researched system is created by the scheme of the nondisturbed inertial vertical with the integral correction. The respective control moments can be described by the expressions

$$M_{1y} = k_i \int_0^t w_y, \quad M_{1x} = k_i \int_0^t w_x, \quad (19)$$

where $k_i = \dfrac{H_1}{R_M}$ is the coefficient of the integral correction; w_x, w_y are projections of apparent accelerations of the point, at which the platform is set. To organize the mode of the inertial vertical it is necessary to give signals to the integrators taking into consideration the corrections on translational and Coriolis accelerations caused by the Earth rotation and vehicle motion; noncoincidence of centre of mass of the vehicle and the point, at which the platform is set; and also vertical acceleration of the vehicle. To simplify these expressions it is necessary to believe that the system is set at the centre of the vehicle. Then expressions for the integral correction become

$$M_{1y} = k_i \int_0^t W_y - \Delta W_y, \quad M_{1x} = k_i \int_0^t W_x - \Delta W_x, \quad (20)$$

here W_x, W_y are readings of accelerometers; ΔW_x, ΔW_y are corrections.

Moments for compensation of trajectory reference frame angular motion can be determined in the following way [9, 10]

$$M_{2x} = H_1 \frac{V_\eta \sin K + V_\xi \cos K}{R_1} \cos K -$$

$$-\frac{V_\eta \cos K - V_\xi \sin K}{R_M}\sin K + \Omega\cos\varphi\cos K;$$

$$M_{2y} = H_1 + \frac{V_\eta \sin K + V_\xi \cos K}{R_1}\sin K + \tag{21}$$
$$+\frac{V_\eta \cos K - V_\xi \sin K}{R_M}\cos K + \Omega\cos\varphi\sin K$$

Control moments, which provide damping of the platform based on the external information v_{Ex}, v_{Ey}, can be determined by the expressions

$$M_{3x} = k_{3x}\int_0^t (v_{Ey} - v_y)/R_M dt;$$

$$M_{3y} = k_{3y}\int_0^t (v_{Ex} - v_x)/R_1 dt, \tag{22}$$

where k_{3x}, k_{3y} are transfer constants, v_{Ey}, v_{Ex} are linear speeds determined by the external aids; v_y, v_x are the vehicle linear speeds calculated based on accelerometers readings.

Control moments, which take into consideration gyro drifts, can be determined in the following way

$$M_{4y} = -I\ddot{\alpha}_r + H\dot{\beta}_r - c\alpha_r - d\dot{\alpha}_r + \frac{H}{T}\beta_r +$$
$$+ H_1(-\dot{\beta}_r + \omega_\zeta\alpha_r); \tag{23}$$
$$M_{4x} = -I\ddot{\beta}_r - H\dot{\alpha}_r - c\beta_r - d\dot{\beta}_r - \frac{H}{T}\alpha_r -$$
$$- H_1(-\dot{\alpha}_r - \omega_\zeta\beta_r).$$

The expressions (19)–(23) represent control moments of the vertical gyro. The gyro drifts can be determined by results of tests. As a rule, the moments due to cross influence of the angular accelerations can not be taken into consideration in the researched systems. But they can be determined in the computing unit.

6. Directional Gyro Model

To create the mathematical description of the directional gyro it is necessary to use the following reference frames: platform-axis reference frame Oxyz; reference frame $Ox_1y_1z_1$ connected with the rotor of the directional gyro; reference frame $Ox_\kappa y_\kappa z_\kappa$ connected with Resal axes of DTG, which carries out functions of the directional gyro.

The mutual location of the platform axes and the rotator of the directional gyro is shown in Fig. 6.

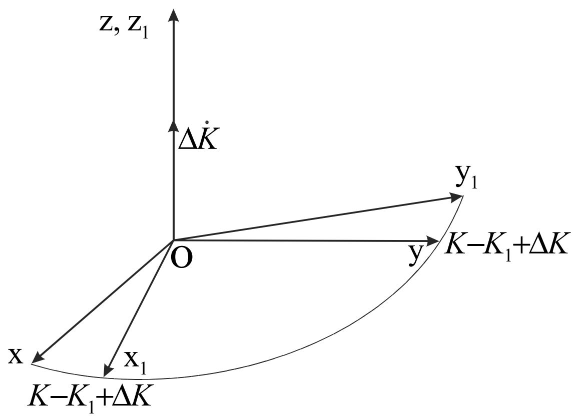


Fig. 6. Mutual location of the platform and the directional gyro

The following notations are used in Fig. 6: K is the heading; K_1 is the given orientation of the directional gyro principal axis; ΔK is error of heading determination. It should be noted that K_1 defines the angular orientation of the directional gyro relative to the meridian plane. Mutual location of the rotator axes and the Resal axes of the directional gyro is given in Fig. 7.

Angles α_K, β_K shown in Fig. 7 characterize an error of directional gyro rotor stabilization and an angle of deviation of the directional gyro principal axis from the simulated horizon plane.

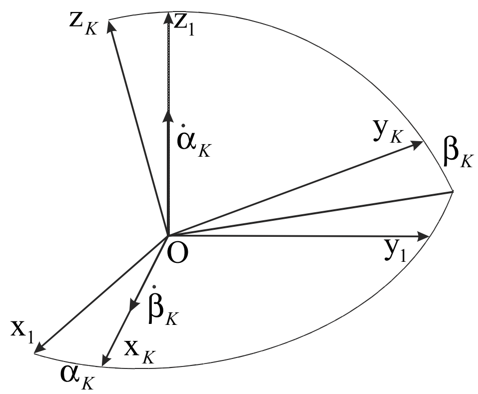


Fig. 7. Mutual location of the rotator axes and Resal axes of the directional gyro

Location of the directional gyro Resal axes can be also defined relative to the reference frame $O\zeta_1\eta_1\xi_1$ turned relative to the trajectory reference frame on an angle $(K–K_1)$ as it is shown in Fig. 8. Here an angle ψ represents the horizontal component of angle defining deviation of the directional gyro principal axis from the given direction K_1.

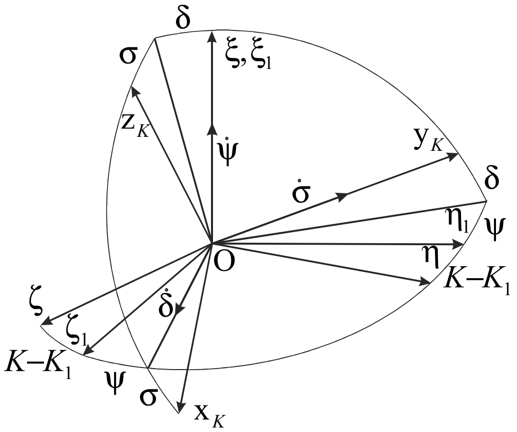


Fig. 8. Mutual location of the directional gyro directional axis relative to the reference frame $O\zeta_1\eta_1\xi_1$

By comparing Figures 6–8 and taking into consideration the matrix $\mathbf{A}_2$ it is possible to write [5]

$$\Delta K = \psi - (\alpha - \alpha_r)\text{tg}\theta - \alpha_K .$$

Equations of the directional gyro can be represented in the following form [8]

$$\begin{aligned} & J\ddot{\alpha}_k + H\dot{\beta}_k + c\alpha_k + d\dot{\alpha}_k + \frac{H}{T}\beta_k = -H_1\omega_{x_1} + M_{z1} + \\ & + M_{z2} + M_{z3} + M_{z4} + M_{dist\,z}; \\ & J\ddot{\beta}_k + H\dot{\alpha}_k - c\beta_k - d\dot{\beta}_k + \frac{H}{T}\alpha_K = H_1\omega_{z_1} + M_{x1} + \\ & + M_{x2} + M_{x3} + M_{x4} + M_{dist\,x}. \end{aligned} \tag{24}$$

Expressions for determination of angular rate projections of the directional gyro rotor look like

$$\begin{cases} \omega_{x_1} = \omega_x \cos(K_1 + \Delta K) + \omega_y \sin(K_1 + \Delta K); \\ \omega_{z_1} = \omega_z + \dot{K} + \Delta\dot{K} \end{cases} \tag{25}$$

where $\omega_x, \omega_y, \omega_z$ are defined by relations (9), where index r is changed by index k.

After substitution of (25) in (24) equations of the directional gyro become

$$\begin{aligned} & J\ddot{\alpha}_k + H\dot{\beta}_k + c\alpha_k + d\dot{\alpha}_k + \frac{H}{T}\beta_k = -H_1\{[\dot{\beta} - \dot{\beta}_k + \\ & + \omega_\xi - \omega_\zeta(\alpha - \alpha_k)]\cos(K_1 + \Delta K) + \\ & + [\dot{\alpha} - \dot{\alpha}_k + \omega_\eta - \omega_\zeta(\beta - \beta_k)]\sin(K_1 + \Delta K)\} + \\ & + M_{z1} + M_{z2} + M_{z3} + M_{z4} + M_{dist\,z}; \end{aligned}$$

$$\begin{aligned} & J\ddot{\beta}_k + H\dot{\alpha}_k - c\beta_k - d\dot{\beta}_k + \frac{H}{T}\alpha_k = H_1\{[(\dot{\alpha} - \dot{\alpha}_k)\text{tg}\theta + \\ & + \frac{\alpha - \alpha_k}{\cos^2\theta}\dot{\theta} + \omega_\zeta] + \dot{K} + \Delta\dot{K}\} + \\ & + M_{x1} + M_{x2} + M_{x3} + M_{x4} + M_{dist\,x}. \end{aligned} \tag{26}$$

After some transformations the relations (26) can be represented in the following form

$$\begin{aligned} & -H_1[(\dot{\beta} + \omega_\xi - \omega_\zeta\alpha)\cos(K_1 + \Delta K) + \\ & + (\dot{\alpha} + \omega_\eta + \omega_\zeta\beta)\sin(K_1 + \Delta K)] = \\ & = J\ddot{\alpha}_k + H\dot{\beta}_k + c\alpha_k + d\dot{\alpha}_k + \frac{H}{T}\beta_k - H_1[(-\dot{\beta}_k + \\ & + \omega_\zeta\alpha_k)\cos(K_1 + \Delta K) - \\ & - (\dot{\alpha}_k - \omega_\zeta + \beta_k)\sin(K_1 + \Delta K)] + M_{z1} + M_{z2} + \\ & + M_{z3} + M_{z4} + M_{dist\,z}; \end{aligned}$$

.

$$\begin{aligned} & H_1(\dot{\alpha}\text{tg}\theta + \frac{\alpha}{\cos^2\theta}\dot{\theta} + \omega_\zeta + \dot{K} + \Delta\dot{K}) = J\ddot{\beta}_k + H\dot{\alpha}_k - \\ & - c\beta_k - d\dot{\beta}_k + \frac{H}{T}\alpha_k + \\ & + H_1(-\dot{\alpha}_k\text{tg}\theta - \frac{\alpha_k}{\cos^2\theta}\dot{\theta} +) + M_{x1} + M_{x2} + \\ & + M_{x3} + M_{x4} + M_{dist\,x}. \end{aligned} \tag{27}$$

The equations (27) represent the directional gyro model.

7. Control of Directional Gyro

The system in the mode of the gyro compass functions as the corrected gyro with appropriate control moments. It is typical for the researched device to use correction by the signal of the angle transmitter, which it is mounted on the inner gimbal of the directional gyro. The appropriate control moments can be described by the expressions

$$M_{x1} = k_{x1}\beta; \; M_{z1} = k_{z1}\beta, \tag{28}$$

where k_{x1}, k_{z1} are transfer constants.

Control moments (28) based on accelerometer signals can be represented in the following form

$$M_{x2} = k_{x2}\frac{A_y}{g}; \; M_{z2} = k_{z2}\frac{A_y}{g}, \tag{29}$$

where k_{x2}, k_{z2} are transfer constants; $A_y = W_y - \Delta W_y$, here W_y is the accelerometer output signal; ΔW_y is a correction taking into consideration influence of translational and Coriolis accelerations, and the vertical acceleration.

Control moments caused by the angular motion of the trajectory reference frame and the rotator are determined by the expressions

$$\begin{aligned} &M_{x3} = H_1(\omega_\zeta + \dot{K} + \Delta\dot{K}); \\ &M_{z3} = -H_1[\omega_\xi \cos(K_1 + \Delta K) + \omega_\eta \sin(K_1 + \Delta K).] \end{aligned} \quad (30)$$

or after substitution of expressions of trajectory reference frame angular rates [5, 11]

$$\begin{aligned} &M_{x3} = H_1\left(V_1 \mathrm{tg}\varphi - \dot{K} + \Omega\sin\varphi + \dot{K} + \Delta\dot{K}\right); \\ &M_{z3} = -H_1\left(-V_1 \sin K - V_2 \cos K - \Omega\cos\varphi\sin K\right)\times \\ &\times\cos(K_1 + \Delta K) - H_1(V_1 \cos K - V_2 \sin K + \\ &+\Omega\cos\varphi\cos K)\sin(K_1 + \Delta K), \end{aligned} \quad (31)$$

here

$$V_1 = \frac{V_\eta \sin K + V_\xi \cos K}{R_1};$$

$$V_2 = \frac{V_\eta \cos K - V_\xi \sin K}{R_M}.$$

The moments taking into consideration gyro drifts are described by the expressions

$$\begin{aligned} &M_{z4} = J\ddot{\alpha}_k + H\dot{\beta}_k + c\alpha_k + d\dot{\alpha}_k + \frac{H}{T}\beta_k - \\ &- H_1\{[-\dot{\beta}_k + \omega_\zeta \alpha_k)]\cos(K_1 + \Delta K) + \\ &+[-\dot{\alpha}_k - \omega_\zeta \beta_k]\sin(K_1 + \Delta K)\}; \quad (32) \\ &M_{x4} = J\ddot{\beta}_k + H\dot{\alpha}_k - c\beta_k - d\dot{\beta}_k + \\ &+\frac{H}{T}\alpha_k + H_1(-\dot{\alpha}_k \mathrm{tg}\theta - \frac{\alpha_k}{\cos^2\theta}\dot{\theta}+). \end{aligned}$$

Equations (27) supplemented by expressions (29)–(32) represent the model of the directional gyro using biaxial gyrostabilized platform.

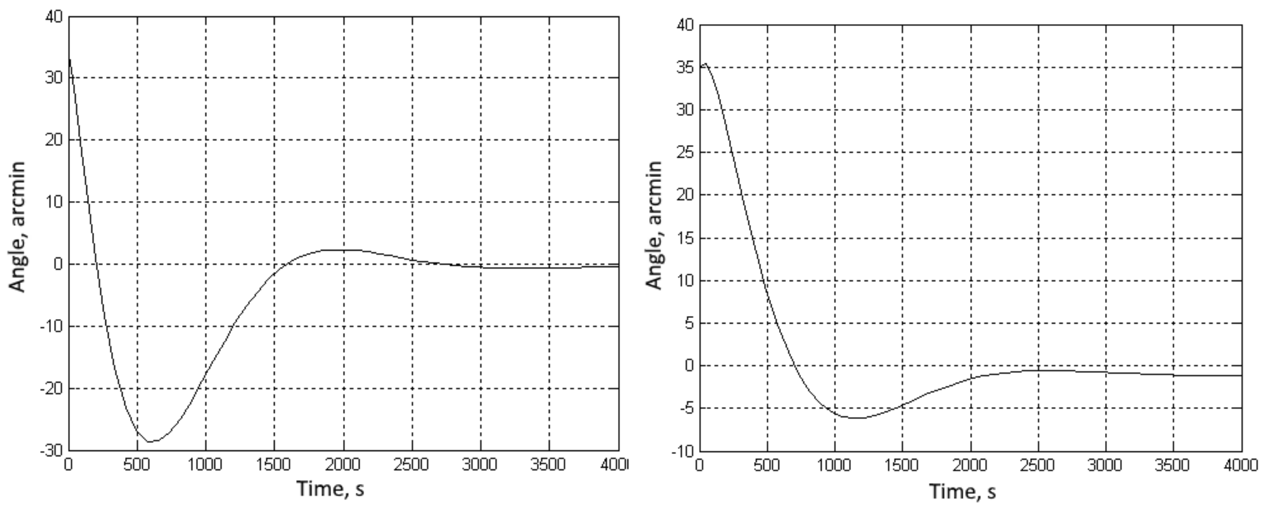
In the mode of the azimuth gyro it is necessary to believe

$$M_{x1} = 0, M_{x2} = 0, M_{z3} = 0.$$

8. Simulation Results and Their Discussion

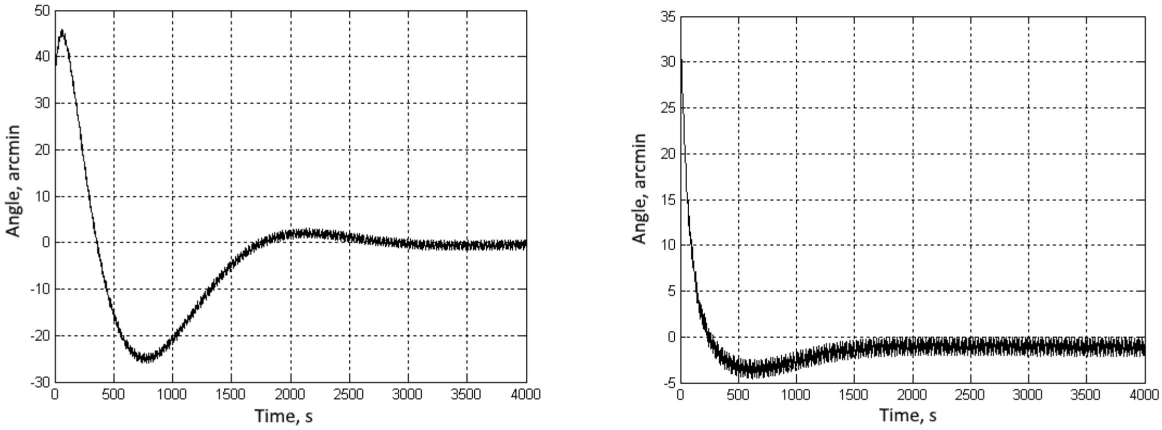
Simulation results are given in Figures 9–11. They represent the transient processes of high-precision attitude determination. It should be noted that simulation was carried out for the AHRS operated on marine vehicles in conditions of autonomy [12].

Fig. 9 presents attitude determination by means of ideal situation, when the external disturbances are absent. Influence of irregular sea wave is shown in Fig. 10.



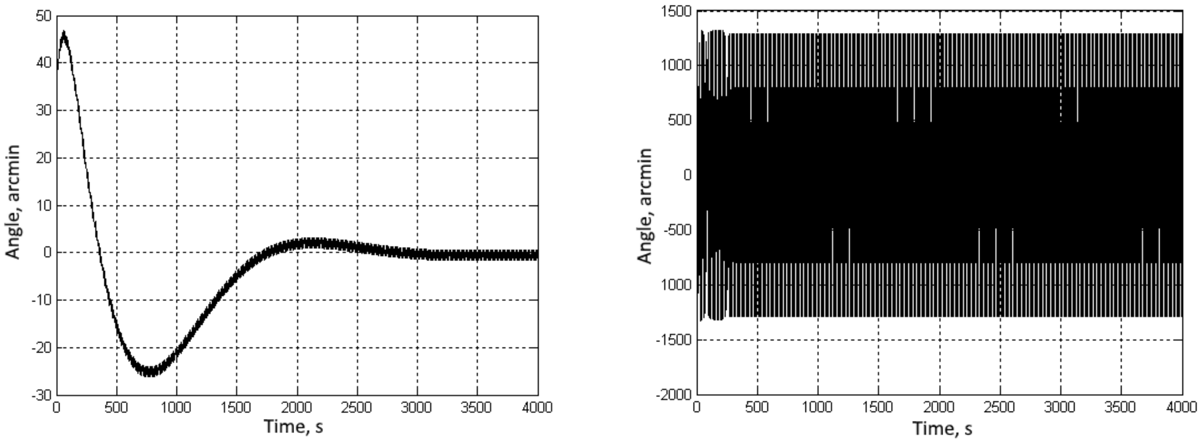
a b

Fig. 9. Transient processes of angles α (a) and β (b) during nondisturbed operation



a b

Fig. 10. Transient processes of angles α (a) and β (b) during disturbed operation (amplitude of irregular sea wave is 12 degrees, period of irregular sea wave is 12,57 s)



a b

Fig. 11. Control with presence (a) and absence (b) of the integral correction

Advantages of the integral correction for AHRS operated in difficult conditions of external disturbances are verified by the simulation results shown in Fig. 11.

Simulation results prove the possibility to achieve high accuracy of attitude and heading determination.

9. Conclusions

The full mathematical model of the gimballed AHRS including the vertical gyro and directional gyro are derived.

The detailed expressions for control moment both for the vertical gyro and for the directional gyro are obtained.

The necessary complex transformations taking into consideration the trajectory reference frame as the initial navigation reference frame are carried out.

The full analysis of the system kinematics is represented. This allows obtaining expressions for errors of attitude and heading determination.

The simulation of attitude and heading processes determination for system operated on the marine vehicles is carried out. Represented results of simulation include situation with nondisturbed motion, and influence of irregular sea waves.

The presented results prove efficiency of integral correction in conditions of the external accelerations influence.

The obtained results can be also useful for design of inertial navigation systems of the wide class.

The obtained expressions of control moments can be useful both for gimballed and for strapdown inertial navigation systems of the wide class.

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О. А. Сущенко

Математична модель системи визначення просторової орієнтації з використанням двоосної горизонтальної платформи.

Національний авіаційний університет, пр. Космонавта Комарова, 1, Київ, Україна, 03058
E-mail: sushoa@ukr.net

Мета: Функціонування системи визначення просторового положення в умовах автономності та високої точності потребує використання платформ у кардановому підвісі. Метою статті є детальне дослідження кінематики та моментів управління такої системи. У результаті досліджень було отримано модель високоточної системи визначення просторової орієнтації з використанням двохосної горизонтальної платформи. **Методи:** Створення математичної моделі здійснювалося на підставі теорії гіроскопів у цілому та теорії коректованих гірокомпасів та динамічно настроюваних гіроскопів зокрема. Було взято до уваги концепцію кутів Ейлера та спрямовуючих косинусів. **Результати:** Представлено повний опис системи визначення просторового положення. Наведено математичні моделі таких складових досліджуваної системи як гіровертикаль та гіроскоп напрямку. Представлено результати моделювання з використанням розробленої моделі. **Висновки:** Отримано математичну модель платформної системи визначення просторової орієнтації, включаючи моделі гіровертикалі та гіроскопа напрямку. Наведено детальні вирази для отримання моментів управління (корекції). Виконано повний аналіз кінематики досліджуваної системи. Отримані результати можуть бути корисними під час проектування інерціальних навігаційних систем широкого класу.

Ключові слова: високоточні навігаційні системи; гіровертикаль; гіроскоп напрямку; платформи у кардановому підвісі; система визначення просторової орієнтації; спрямовуючі косинуси.

О.А. Сущенко

Математическая модель системы определения пространственной ориентации с использованием двухосной горизонтальной платформы.

Национальный авиационный университет, пр. Космонавта Комарова, 1, Киев, Украина, 03058
E-mail: sushoa@ukr.net

Цель: Функционирование системы определения пространственного положения в условиях автономности и высокой точности требует использования платформ в кардановом подвесе. Целью статьи является подробное исследование кинематики и моментов управления такой системы. В результате исследований была получена модель высокоточной системы определения пространственной ориентации с использованием двухосной горизонтальной платформы. **Методы:** Разработка математической модели основывалась на теории гироскопов в целом и теории корректируемых гирокомпасов и динамически настраиваемых гироскопов в частности. Были приняты во внимание концепции углов Эйлера и направляющих косинусов. **Результаты:** Представлено полное описание системы определения пространственного положения. Приводятся математические модели таких составляющих исследуемой системы как гировертикаль и гироскоп направления. Представлены результаты моделирования с использованием разработанной модели. **Выводы:** Получена математическая модель платформенной системы определения пространственной ориентации включая модели гировертикали и гироскопа направления. Приведены подробные выражения для моментов управления (коррекции). Выполнен полный анализ кинематики исследуемой системы. Полученные результаты могут быть полезными при проектировании инерциальных навигационных систем широкого класса.

Ключевые слова: высокоточные навигационные системы; гировертикаль; гироскоп направления; направляющие косинусы; платформы в кардановом подвесе; система определения пространственной ориентации.

Olha Sushchenko. D. Sci., Associate Professor.
Aircraft Control Systems Department, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Polytechnic Institute, Kyiv, Ukraine (1980).
Research area: systems for stabilization of information and measuring devices.
Publications: 120.
E-mail: sushoa@ukr.net

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Yurii Hryshchenko[1]
Viktor Romanenko[2]
Vladimir Tronko[3]
Yurii Hryshchenko[4]

METHODS OF TRAINING OF MODERN AIRCRAFT FLIGHT CREWS FOR INFLIGHT ABNORMAL CIRCUMSTANCES

National Aviation University
Kosmonavta Komarova Avenue 1, 03680, Kyiv, Ukraine
E-mails: [1]hryshchenko8y@gmail.com; [2]v@tronko.kiev.ua; [3]rvg11235@ukr.net; [4]noktinua@gmail.com

Abstract

Purpose: *The purpose of this article is the theoretical justification of the existing methods and development of new methods of training the crews of modern aircraft for inflight abnormal circumstances.* ***Methods:*** *The article describes the research methods of engineering psychology, mathematical statistics and analysis of the correlation functions.* ***Results:*** *The example of the two accidents of aircraft with modern avionics is shown in the problem statement. The pilot made a sharp movement of the steering wheel while go-around, which has led to a sharp diving and impossibility of coming out of it. It was shown that the developed anti-stress training methods allow crews to train a human operator to prevent such events. The theoretical solution of the problem of optimization of the flight on the final approach, considering the human factor, is suggested to solve using the method of analysis of the autocorrelation function.* ***Conclusions:*** *It is necessary to additionally implement methods of teaching the counteracting of factorial overlaps into the training course using the complex modern aircraft simulators. It is enough to analyze a single pitch angle curve of the autocorrelation function to determine the phenomena of amplification of integral-differential motor dynamic stereotype of the pilot.*

Keywords: correlation function; dynamic stereotype; glide path; negative factors.

1. Introduction

Ensuring the flight safety is very important component of the civil aircraft operation. For modern aircraft high level of modern airplane safety depends primarily on the features of the airplane and the training and experience of the flight crew. The functional efficiency of aircraft is determined by its structural and operational excellence, stability, handling and maneuverability, as well as high operational workability of the airframe, engine and equipment. The functional efficiency of the flight crew depends on the theoretical training, knowledge of aircraft and the rules of its operation under regular and extreme conditions, as well as the discipline and diligence of captain and his crew. Statistical analysis of aircraft accidents shows that most of them are caused by the fault of human factor.

2. Problem statement

Let us consider two accidents of the Boeing 737 aircraft during night operations under adverse weather conditions.

Aircraft accident of «Tatarstan» airlines Boeing 737-500 during landing, had place on November 17, 2013 in Kazan International Airport. There was heavy rain with snow and wind gusts of 7 m / s to 16 m / s depending on the altitude, with visibility of 10 km.

Aircraft accident of FlyDubai airlines Boeing 737-800, flying from Dubai (United Arab Emirates), which has crashed at the airport of Rostov-on-Don during the second approach in difficult weather conditions, with a strong side wind and rain.

In both cases the captains made a sharp and disproportionate movements using the steering wheel while go-around, which caused the airplane to dive sharply. In both cases we deal with the problem of controlled flight into terrain (CFIT).

This brings up the question of working out the situation using the complex flight simulator (CFS) to secure the persistent flight crew skill. Of course, it should be done. As much as possible situations are required to be worked out using CFS. But the programs of simulator training are based on the condition of ordinariness, when only one failure is put in from the instructor control panel. In practice it sometimes happens in a different way i.e. we can have 2^Noptions, which deal with the right or wrong action, and N – the number of negative factors, which influence the flight crew. So considering all the situation is almost impossible.

The problem of improving the quality of flight is currently the subject of many scientific publications [1-6].

The purpose of this work is the theoretical justification of application of existing methods of modern aircraft crew training for special conditions of flight and the development of new such methods.

3. Solution for the problem using complex airplane simulator by methods of engineering psychology and mathematical statistics

Now let's investigate the reason of disproportionate integral-differentiated motive actions of human operator. The experiment was carried out using CFS of Tu-154 B2 by staff of Kyiv Institute of Civil Aviation Engineers (National Aviation University nowadays) at the training detachment in 1980-1990. We used the CFS not to work out concrete action (the necessity of this procedure, we do not deny in any case) but to improve the skill of countering the factor overlays (FO), which were simulated by simultaneously acting failures. It was determined that initially 80% of the pilots had no opposition to factor overlays. Recommendations for pilots were based on the theory of the process analysis and factor transitions phenomenon, introduced by Khokhlov E. M., phenomenon of "factor resonance", introduced by Korneyev S. V. (further research was continued by Polozhevets A. A.), where the area with the greatest amplitude of the flight parameter and phenomenon of amplification of integral-differentiated motive dynamic stereotype (PAIDMDS) was examined by Hryshchenko Y. V. It should be noted that these techniques allowed to successfully train pilots to counter FO, but their further implementation has been stopped due to lack of funding.

It should be noted that the above mentioned aircraft pilots would not have made a disproportionate and sharp actions using steering wheel of the aircraft with a high probability in the case of passing the training techniques which were mentioned above [7,8].

Also it was noticed that the burst of accidents has periodic nature each 10 years. This peak takes place this year [8].

The general nature of the industrial cycles is the development of large scale machine industry, such as aviation, is studied in detail by economists. And although economists do not have a single point of view, there are about 500 different points of view about mechanisms and the nature of the industrial cycles, but the fact of existence of these cycles is not already under discussion.

Delta is taken as flight safety level in the conception proposed in work [8], as level for various modal (volumetric) air transportation market indicators (number of flights, takeoffs and landings, the volume of passenger traffic, cargo handling, mail, etc.)

Delta level of flight safety (FS, surplus safety) is a differentially difference level that fixes the positive effect of flights and shows the difference (increment) between the total effect of the flights and the negative effects from them in absolute and relative forms. Of course, the maximum negative effect of flights is an accident and the positive one is flights without remarks.

In other words, unlike established flight safety assessment approaches, this concept offers accounting not only security as a systemic property of the air transport system by the level of danger, but assessment of the increment of flight operation, which provides the result of transportation (delta - safety).

Central strategic goal of scientific research, which controls decisions, can only be decrease of the danger of flights (DF). Such decrease of DF level may be carried out in two phases:

- system method by increasing the decrement of oscillations damping of DF level in cycles of 10 years till "sustainable" level;
- process methods by a factor transition from "sustainable" level of danger to drift near "zero level of accident rate" over human factor.

Process analysis which is based on the general theory of processes, the general theory of statistics is based on the theory of limits, qualitative theory of uncertainties and other theories of process concepts. Knowledge and understanding of the dialectical law of transition from disordered to ordered science is important for understanding the general nature and general points of transition from system to process research, as a general new scientific strategy for the areas of human factors.

Civil aviation companies are complex automated manufacturers. The scale of air transportation, the number of people and equipment that are involved in this type of transport are increasing every year. One of the major problems of civil aviation is ensuring the high level of flight safety. This problem has many aspects as flight safety depends on complex factors, including the level of technical dependability of the aircraft and its systems, level of professional staff training, organization of work of flight, technical and medical services, discipline of flight and technical staff, human interaction with technology and among themselves, intensity and conditions of flights and many other things.

The problem of improving the flights safety is complex and can be solved by consistent efforts of flight, engineering, medical staff, as well as scientists, designers and specialists from other professions. However psychophysiology knowledge is essential for improving the flights safety.

Depending on the level of automation of process management there are two main processes: automatic and ergatic. In ergatic process human operator is a center that receives information, processes it, makes decisions and carries out specific actions on management. But the full automation of the production process in aviation cannot always be done, or is not always needed. This significantly causes that ergatic production processes are very extensive class of processes and ergatic systems are essentially the main processes in aviation.

Let us consider glide path with taking into account PAIDMDS.

4. The theoretical solution for the problem of optimization of the flight on the final approach with taking into account the human factor

Let us define integral difference between the set and realized flight paths.

Flight path deviation from the intended course is characterized by the correlation function between the set and realized flight paths [9, 10]. The physical sense of the correlation function is analyzed in this work. Relationship of correlation function with the difference between scheduled and actual flight paths is determined.

The square of the integral difference between flight paths (scheduled and real) in the specific area equals

$$\Delta = \int_{x_1}^{x_2} \left[Z_s(x) - Z_r(x) \right]^2 dx, \tag{1}$$

where $Z_s(x)$ is scheduled flight path,

$Z_r(x)$ is real flight path.

Flight path takes place in a plane $y = const$. Coordinate Z depends on x, Z(x), i.e. it is the height of flight path in the Cartesian coordinate system.

x_1, x_2 are starting and ending points of reference of flight path in the horizontal plane.

Let's compute the expression (1)

$$\Delta = \int_{x_1}^{x_2} Z_s^2(x)dx - 2\int_{x_1}^{x_2} Z_s(x) Z_r(x)dx + \int_{x_1}^{x_2} Z_r^2(x)dx, \tag{2}$$

Let us designate the components of the equation (2):

$$\Delta = \int_{x_1}^{x_2} Z_s^2(x)dx = L\rho_3,$$

$$\int_{x_1}^{x_2} Z_s(x) Z_r(x)dx = L\rho_{3p},$$

$$\int_{x_1}^{x_2} Z_r^2(x)dx = L\rho_r,$$

where $L = x_2 - x_1$, functions ρ_s, ρ_{sr}, ρ_r are respectively autocorrelation function of the scheduled flight (ρ_s), function of correlation between the scheduled path and the real path (ρ_{sr}) and ρ_r are autocorrelation function of actual flight path. In this case expression (1) takes the form

$$\Delta = L\rho_s - 2L\rho_{sr} + L\rho_r, \tag{3}$$

Autocorrelation functions ρ_s and ρ_r are approximately equal to each other. Let's consider the case, where

$$\rho_s \approx \rho_r \approx \rho_A, \tag{4}$$

and ρ_A is autocorrelation function of scheduled and implemented process. That is, when the correlation function of the scheduled and realized the flight path differ insignificantly.

Let's rewrite formula (3) with considering (4)

$$\Delta = 2L(\rho_A - \rho_{sr}), \tag{5}$$

$$\rho_{sr} = \rho_A - \frac{\Delta}{2L}.$$

From (5) it is clear that if the paths are same $\Delta=0$, then $\rho_{sr} = \rho_A$.

Integral error value per unit of length $\frac{\Delta}{L}$ equals to the difference of the function of autocorrelation ρ_A and correlation ρ_s. Let us calculate these three functions for different types of paths.

5. Flight paths on the glide path

Let us consider Flight paths on the glide path (fig. 1), which is defined by the equation

$$Z_s(x) = h - \frac{h}{L}x, \tag{6}$$

where h is initial altitude of flight on the glide path, L is the length of flight on the glide path.

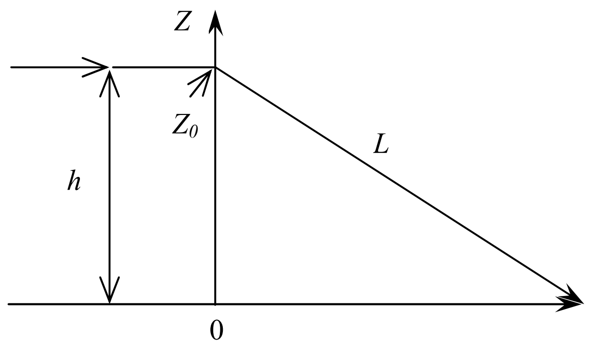

Fig. 1. Glide path trajectory.

L is the glide path length (l≈12000,00002m), h is the initial altitude at the moment of landing.

Let us consider the special case of delay of landing trajectory.

$$Z_p = h - \frac{h}{L}(x - \chi). \tag{7}$$

Where χ is value of the delay.

Then correlation and autocorrelation functions are equal to

$$\rho_s = \frac{1}{L}\int_0^L \left(h - \frac{h}{L}x\right)^2 dx = \frac{h^2}{3}, \tag{8.1}$$

$$\rho_{rs} = \frac{1}{L}\int_L^0\int_0^L \left[\left(h - \frac{h}{L}x\right)\left(h - \frac{h}{L}(x - \chi\right)\right]dx =$$

$$= \frac{h^2}{3} + \frac{h^2}{2L}\chi, \tag{8.2}$$

$$\rho_k = \frac{1}{L}\int_L^0 \left[h - \frac{h}{L}(x - \chi)\right]^2 dx =$$

$$= \frac{h^2}{3} + \frac{h^2}{L}\chi + \frac{h^2}{L^2}\chi^2. \tag{8.3}$$

Further we denote $\rho(-\chi)$.

Substitute values of (8.1, 8.2, 8.3) into formula (3) and we find the integral difference between the two paths

$$\Delta = L\frac{h^2}{3} - 2L\frac{h^2}{3} - h^2\chi + \frac{h^2L}{3} - \frac{h^2}{L}\chi^2 + h^2\chi^2 =$$

$$= \frac{h^2}{L}\chi^2, \tag{9}$$

while χ=0, Δ=0, $\chi=L$, $\Delta=h^2L$. (9.1)

Let us write (9) in such a way

$$\Delta = h^2L\left(\frac{\chi}{L}\right)^2. \tag{10}$$

The formula (8) shows that with increasing of χ from 0 to L the value of Δ increases.

Outrunning flight path on the glide path equals

$$Z(x+\chi) = h - \frac{h}{L}(x+\chi). \tag{11}$$

Let us split the range (0, L) into two parts (0, $L-\chi$) and (0, $L+\chi$). Outrunning function at part ($L-\chi$, L) equals zero: $Z(x+\chi)=0$. Consequently, the outrunning correlation function is determined by integrating only in the interval of (0, $L-\chi$)

$$\rho_{sr} = \rho(+\chi) = \frac{1}{L}\int_0^{L-\chi}\left(h - \frac{h}{L}x\right)\cdot\left[h - \frac{h}{L}(x+\chi)\right]dx =$$

$$= \frac{h^2}{3} - \frac{h^2}{2L}\chi. \tag{12}$$

By comparing the expressions (8.2) and (12)

$$\rho(-\chi) - \rho(+\chi) = \frac{h^2}{L}\chi.$$

It can be concluded that

$$\rho(-\chi) > \rho(\chi)^*.$$

Autocorrelation function of outrunning path is equal to

$$\rho_k(+\chi) = \frac{1}{L}\int_0^L\left[h - \frac{h}{L}(x+\chi)\right]^2 dx =$$

$$= \frac{h^2}{L}\int_0^L\left[1 - \frac{x+\chi}{L}\right]^2 dx = \frac{h^2}{3} - \frac{h^2\chi}{L} + \frac{h^2}{L^2}\chi^2. \tag{13}$$

$\rho(-\chi) - \rho(+\chi)=0$ as long as $\chi=2L$, that is unreal condition when the aircraft has not landed.

If L»χ, the delay value is much less than the length of the glide path, which is quite real, the autocorrelation function is equal to the outrunning path

$$\rho_k(+\chi) = \frac{1}{3}h^2 \tag{14}$$

Let us substitute values ρ_s, $\rho_k(+\chi)$ and $\rho_{sk}(+\chi)$ into the equation (3) and get (fig. 2):

$$\frac{\Delta}{L}=\frac{1}{3}h^2-\frac{2h^2}{3}+\frac{h^2}{L}\chi+\frac{h^2}{3}+$$
$$+\frac{h^2}{L^2}\chi-\frac{h^2}{L}\chi+\frac{h^2}{L^2}\chi=\frac{h^2}{L^2}\chi.$$

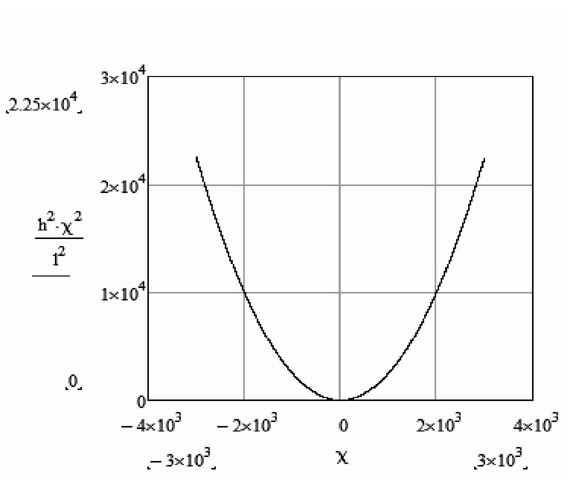

Fig. 2. Graph of relation between $\frac{\Delta}{L}$ and χ (χ is within the range from -3000 m to 3000 m).

This figure shows that in the case of the glide path entrance delay, the probability of hitting the threshold level of runway increases.

The probability of the preconditions for occurrence of aircraft accident increases. Therefore measurement error will be less than this one.

6. Conclusions

1. It is necessary to further implement a training course using CFS training methodology of countering FO.
2. To determine PAIDMDS enough for the pilot to have analysis of one curve of the autocorrelation function on the glide path during "flight" using CFS.
3. To implement the proposed method it is necessary to develop and create the equipment for comparing the predetermined and realized glide paths. Most likely polarimetric devices will be used, allowing to register the above mentioned the glide paths and analyze quickly and accurately.

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Грищенко Ю.В.[1], Романенко В.Г.[2], Тронько В.Д.[3], Грищенко Ю.Ю.[4]

Методи підготовки екіпажів сучасних літаків до особливих ситуацій польоту

Національний Авіаційний Університет
пр. Космонавта Комарова, 1, Київ, 03680, Україна
E-mails: [1]hryshchenko8y@gmail.com; [2]v@tronko.kiev.ua; [3]rvg11235@ukr.net; [4]noktinua@gmail.com

Мета: Метою даної статті є теоретичне обґрунтування застосування існуючих і розробки нових методів підготовки екіпажів сучасних літаків до особливих ситуаціям польоту. **Методи:** У статті розглянуто методи досліджень інженерної психології, математичної статистики та аналізу кореляційних функцій. **Результати:** При постановці завдання наведено приклад двох катастроф літаків із сучасною авіонікою. При виході на друге коло пілот допустив різкі рухи штурвалом, що призвело до різкого пікірування і неможливості виходу з нього. Показано, що розроблені методи антистресової підготовки екіпажів дозволяють навчити людину-оператора недопущенню таких подій. Теоретичне рішення задачі оптимізації польоту на глісаді з урахуванням людського чинника запропоновано вирішити методом аналізу автокореляційної функції. **Висновки:** На комплексних тренажерах сучасних літаків необхідно додатково вводити в курс підготовки методики навчання протидії факторним накладкам. Для визначення явища посилення інтегро-диференційованого рухового динамічного стереотипу у пілота досить провести аналіз однієї кривої автокореляційної функції тангажу.

Ключові слова: глісада, функція кореляції, динамічний стереотип, негативні чинники.

Грищенко Ю.В., Романенко В.Г., Тронько В.Д., Грищенко Ю.Ю.

Методы подготовки экипажей современных самолетов к особым ситуациям полета

Национальный Авиационный Университет
пр. Космонавта Комарова, 1, Киев, 03680, Украина
E-mails: [1]hryshchenko8y@gmail.com; [2]v@tronko.kiev.ua; [3]rvg11235@ukr.net; [4]noktinua@gmail.com

Цель: Целью данной статьи является теоретическое обоснование применения существующих и разработки новых методов подготовки экипажей современных самолетов к особым ситуациям полета. **Методы:** В статье рассмотрены методы исследований инженерной психологии, математической статистики и анализа корреляционных функций. **Результаты:** При постановке задачи приведен пример двух катастроф самолетов с современной авионикой. При уходе на второй круг пилот допустил резкие движения штурвалом, что привело к резкому пикированию и невозможности выхода из него. Показано, что разработанные методы антистрессовой подготовки экипажей позволяют обучить человека-оператора недопущению таких событий. Теоретическое решение задачи оптимизации полета на глиссаде с учетом человеческого фактора предложено решить методом анализа автокорреляционной функции. **Выводы:** На комплексных тренажерах современных самолетов необходимо дополнительно вводить в курс подготовки методики обучения противодействию факторным накладкам. Для определения явления усиления интегро-дифференцированного двигательного динамического стереотипа у пилота достаточно провести анализ одной кривой автокорреляционной функции тангажа.

Ключевые слова: глиссада, функция корреляции, динамический стереотип, негативные факторы.

Hryshchenko Yurii (1958). Candidate of Engineering. Associate Professor.
Associate Professor of the Department of avionics, National Aviation University, Kyiv, Ukraine.
Education: National Aviation University, Kyiv, Ukraine (1987).
Research area: flight safety and dependability of technical and ergonomics systems.
Publications: 40.
E-mail: hryshchenko8y@gmail.com

Romanenko Viktor (1964). Candidate of Engineering. Associate Professor
Associate Professor of the Department of avionics, National Aviation University, Kyiv, Ukraine,
Education: Kyiv Civil Aviation Engineers Institute, Kyiv, Ukraine (1988).
Research area: cavitation in liquid systems and optoelectronics.
Publications: 60.
E-mail: rvg11235@ukr.net;

Tronko Vladimir (1939). Doctor of Physics and Mathematics . Professor.
Professor of the Department of avionics, National Aviation University, Kyiv, Ukraine.
Education: Kyiv State Taras Shevchenko University, Ukraine (1962).
Research area: optoelectronics and laser technique and avionics link.
Publications: 250.
E-mail: v@tronko.kiev.ua

Hryshchenko Yurii (1994). Master.
Education: National Aviation University, Kyiv, Ukraine (Master, 2017).
Senior engineer. Department of intelligent control, International Research and Training Center for Information Technologies and Systems of NAS of Ukraine and MES of Ukraine.
Research area: flight safety and dependability of technical and ergonomics systems.
E-mail: noktinua@gmail.com

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Dmytro Prusov[1]
Mykhaylo Matiychyk[2]
Oleksiy Mykhatskyi[3]

COMPARATIVE ANALYSIS OF AVIONICS SAMPLES AND COMPONENTS DUE TO DEVELOPING A METHODOLOGY OF THE UAV INTEGRATED AVIONICS SYNTHESIS

National Aviation University
Kosmonavta Komarova avenue 1, 03058, Kyiv, Ukraine
E-mails: [1]prusov@nau.edu.ua; [2,3]nvcba@nau.edu.ua

Abstract

The article is devoted to analysis of avionics components samples with a view to creating an integrated avionics synthesis methodology remotely piloted and unmanned Aerospace Dynamic Objects (ADO), which provides a comprehensive solution of problems of navigation and synergistic control ADO air navigation in space. ***Methods:*** *The analysis and setting objectives are the basis for the development of modern techniques for combining and processing primary data, methods to solve navigation problems, methods of solving problems in the management of complex integrated avionics ADO. In particular, this invariant compensation method for combining primary sources of information, complete correlation-extreme methods of navigation, control method synergistic ADO.* ***Results:*** *Using these techniques will increase the effectiveness of solving problems of navigation and control both civilian and military ADO, in terms of accidental and intentional interference, the failures of avionics.* ***Discussion:*** *Based on the provisions set a prototype integrated avionics for ADO navigation and control synergistic with current approaches has been developing.*

Keywords: navigation and control; integrated avionics system; unmanned aerial vehicles.

1. Introduction

The rapid development of aviation and space technology, which is observed in recent decades contributes fundamentally review the operation concepts of aerospace systems in the same space of Air Navigation [1, 2]. Formation of new fundamental concepts such as the concept CNS/ATM, Free Flight, A3 etc., leading to the nomination of the new requirements on the structure and principles of modern avionics ADO. Despite the fact that Ukraine is a state aircraft, aircraft industry domestic enterprises do not have sufficient experience developing and manufacturing advanced avionics systems. Usually avionics for unmanned aircraft Ukraine shipped from abroad, which were purchased in the leading European manufacturers of avionics. Research and development of such systems in Ukraine is spontaneous and decentralized. Along with that there are no domestic theoretical work on the synthesis of integrated avionics. Thus, in Ukraine there was a problem situation, which is the need to equip local ADO avionics systems of its own design and production system and lack of a unified methodology of hardware and software systems integrated avionics ADO [3].

2. Analysis of the latest research and publications

The staff of the National Aviation University have made a significant contribution to the development of the theory of synthesis of integrated avionics systems, particularly invariant developed the concept of integration of navigation aids - so-called invariant compensation scheme for integration of navigational aids based on nonlinear discrete filter; the method of complex correlation-extreme navigation compatible with processing information and navigation data evaluation; Energy-developed potential method for solving the poly-conflicts of aircraft in free flight conditions [4].

In this direction is planned to further develop and improve invariant compensation scheme through the use of special operation entry "acceleration" scheme based on regression algorithm using the device sensitivity theory; expansion methods correlation-extreme navigation. Requires further development and improvement of methods avionics system integration ADO for solving navigation and synergistic management on common methodological basis, in conditions of uncertainty, lack of information, intentional interference and random failures.

From the standpoint of the theory of complex dynamic systems in the work expected to address the problem at two levels of theoretical research: level navigation tasks solution to improve the accuracy and reliability of the definition phase coordinates ADO and synergistic management level synthesis formations ADO.

The basic idea of the first level investigation is to improve existing and develop new methods of primary processing, methods to solve navigation problems, methods of information integration and their system use in an integrated avionics [5].

The basic idea of the second level investigation is to create a virtual environment, giving it synergistic properties of objects real physical systems, determining parameters of traffic of objects in the virtual environment and use of derived parameters for the synthesis of synergetic self management group or traffic manned, remotely piloted and unmanned ADO in the CNS/ATM environment.

The relevance of confirmed new requirements for avionics systems ADO, due to the current global trends:

- increasing intensity of aircraft flight and increase the number of conflicts between them;
- nomination global aviation community requirements the transition from regulated flight trajectories to their free flight autonomy and board;
- simultaneous use of a single aeronautical space heterogeneous dynamic objects (manned, remotely controlled, unmanned);
- increasing use of remotely piloted and unmanned aerial vehicles to solve problems and civilians in areas of armed conflict.

The above trends impose strict requirements for methods of navigation and control their implementation in modern integrated complex avionics ADO. Complex solution of this problem is not only crucial, but in theoretical terms is classified as high complexity tasks.

3. Research tasks

The problem of designing prospective avionics today refers to the priority areas of the aviation industry. Basic scientific research in this area are carried out by experts of Aviation in the search for new concepts of designing hardware and software within the framework of the implementation of new technologies, materials and element base in the aviation product samples. The search for new concepts of designing hardware and software aimed at improving the structural organization of the on-board systems to meet the continuously increasing demand [6].

4. Integrated Modular Avionic concept

The introduction of new technologies, materials and element base in the aviation product samples aimed at changing technical and economic parameters of avionics in order to make on-board systems of the new qualities or to improve the quantitative performance of the existing equipment. At the present stage avionics developers some progress in addressing the particular problems of designing individual components due to the introduction in the development of promising functional technology, hardware and software integration equipment, but the problem of building integrated avionics computer systems remains unresolved fully up to date. The purpose of this article is to present a wide range of issues of design professionals integrated computer systems that make up the core of advanced computing systems avionics. The reader will find a brief overview of the results now achieved by developers and proposed for more detailed acquaintance modern approach to the design of the avionics perspective - an approach based on the introduction of on board UAV structures integrated modular avionics [6].

The main result of the international experts in the development of architecture and components of the avionics is now approved by ARINC (Aeronautical Radio Inc., USA) and developing the concept of integration of national experts on-board equipment - the IMA concept (Integrated Modular Avionic), the foundations of which are set out in the standard ARINC 651 «Design Guidance for Integrated Modular Avionic». The standard has defined a new direction in the improvement of aviation instrument and outlined the prospects for the development of the aviation industry for decades to come. ARINC 651 is a coherent and legally approved in the United States view the representatives of airlines, operators of aircraft, aircraft manufacturing companies and the US aviation equipment and a number of other countries on the approach to the systematization of avionics design.

IMA concept covers the following groups of design problems aircraft instrument:

– the establishment and implementation of IMA in the development of the avionics;

– used in the development of avionics technology;

– implementation of fault tolerance of onboard equipment;

– principles of the on-board network of information exchange (on-board data network);

– architecture of avionics;

– software architecture of avionics and its components;

– development certification (avionics hardware and software);

– testability and maintainability of avionics and object a whole;

– range of sources and data consumers (subscribers on-board local data network).

IMA concept involves the separation of the functional components of avionics into three hierarchical levels:

– the lower level of the hierarchy form a unified structural and functional modules for different purposes, with their own computing devices in a compact standardized design;

– the average level of the hierarchy form a multi-processor computer systems, modules created from the lower level and constructively performed in a standardized package;

– the highest level of the hierarchy is an onboard local area network based on the network interface of the central high bandwidth computing means integrating racks midrange.

For the organization of the central on-board network interface high bandwidth enterprises today aircraft instrument experts worked out a constructive and technological solutions for the implementation on the aviation and space ADO for new or existing:

– intersystem interface Fiber Channel (ANSI X3T11); Scalable Coherent Interface (ANSI / IEEE Std 1596-1992); Myrinet; Gigabit Ethernet; ARINC 664; Asynchronous Transfer Mode; FireWire (IEEE 1394) etc.;

– intrasystem interfaces Scalable Coherent Interface – SCI (ANSI / IEEE Std 1596-1992); Fiber Channel – ANSI X3T11; VME; PCI Compact; SKY Channel Packet Bus; LVDS (TIA / EIA 644) etc. [6]

Among foreign avionics projects carried out in accordance with the basic provisions of the IMA concept, deserve the attention of the following systems, a review is given below.

5. MicroPilot components

MicroPilot serves UAV manufacturers who maintain high standards for both the hardware they integrate into their systems and the software that drives them. Our customers require products that are reliable, scalable and customizable. MicroPilot has a solid reputation that supplies consistent products, services, and support [7]. Incorporated in 1994, MicroPilot has served over 850 clients in over 70 countries during its 20+ years in business. With such a stronghold and longevity in the industry, MicroPilot has maintained itself as the world leader in professional autopilots for UAVs and MAVs. MicroPilot serves small UAV manufacturers, large-scale defense and research enterprises, and all that exists between. Some of the organizations we serve include NASA, Raytheon, and Northrop Grumman.

Customizable Products.

MicroPilot offers a family of lightweight UAV autopilots that fly fixed-wing, transitional, helicopter, and multi-rotor UAVs. Some of our autopilots' popular features include:

- Airspeed and altitude hold;
- Turn coordination;
- GPS navigation;
- Vertical takeoff and landing (VTOL);
- Autonomous operation from launch to recovery.

Circuit Board Autopilots.

MP2x28 Series Autopilots

Since the company began in 1994, MicroPilot autopilots have been compact, lightweight, and powerful. They have flown everything from one-pound MAVs/backpacks to high-speed, turbine-powered drones. MicroPilot offers more flexibility and selection in autopilots than ever before to meet clients' needs, ranging from sophisticated data and imaging UAV systems to entry-level or single-use applications. From our single-use autopilot (MP2x28^{xp}) all the way up to our powerful VTOL autopilot (MP2128^{HELI2}), MicroPilot provides a seamless upgrade path. No other autopilot manufacturer offers such adaptable technology or such a range of autopilot options at quantity pricing. This makes MicroPilot the single-vendor solution for all autopilot hardware, software, and accessory needs. This also positions to grow and adapt at a fraction of the cost so that newly developed UAVs can get in the air faster with better autopilot control.

MP2128^{HELI2}. Incorporates all the functionality need to fly both VTOL and fixed-wing UAVs in an ultra-small autopilot. Based on proven MicroPilot autopilot technology, it flies fixed-wing and heli UAVs. Upward-compatible with the MP2x28^{g2} series of autopilots. Includes Ublox 4 Hz

GPS module and compass module. Supports fully autonomous flight from takeoff to landing.

MP2128^{g2}. Comparable in size to the MP2028^{g2} but with 50 times the processing power. Offering upward compatibility with the popular MP2x28^{g2}, MicroPilot's MP2128^{g2} provides a 50-fold increase in processor power, double the memory, and twice the input/output channels. The MP2128^{g2} is MicroPilot's premium autopilot and the autopilot of choice for high-performance miniature UAV.

MP2028^{g2}. The autopilot that will take miniature UAV from vision to reality. The MP2028^{g2} established a new benchmark for lightweight UAV autopilots. Weighing only 28 grams, including all sensors and a GPS receiver, this UAV autopilot is the smallest in the world. With a proven track record, the MP2028^{g2} packs everything need into one powerful UAV autopilot.

MP1028^{g2}. Bringing MP2028^{g2} performance to the entry-level UAV operator. The MP1028^{g2} is the lowest-cost member of the MicroPilot family of UAV autopilots. With the same small size and weight as the MP2028^{g2}, the MP1028^{g2} offers all of the reliability and the most important features of the MP2028^{g2}. The MP1028^{g2} autopilot is suitable for entry-level UAV applications where cost is the overriding consideration.

trueHWIL^{mp}. The highest fidelity available in UAV autopilot simulators. MicroPilot's new True Hardware-in-the-Loop (trueHWIL^{mp}) simulator offers UAV integrators and researchers the highest-fidelity UAV autopilot simulation available on the market today.

Existing quasi-hardware-in-the-loop simulators approximate a UAV's flight by exchanging sensor and control surface position information with the autopilot over a serial port or CAN bus. This form of simulation introduces inaccuracies as an autopilot in flight reads this information directly from its sensors instead of a serial port or CAN bus. MicroPilot's trueHWIL^{mp} offers a dramatic improvement in simulator fidelity by electrically simulating all sensor outputs using an analog-to-digital converter, signal conditioning, and PWM interface boards. MicroPilot's trueHWIL^{mp} allows our customers to replicate the conditions their UAVs experience in flight, offering superior on-the-ground validation of autopilot setup and integration.

MP2128^{3X} Triple Redundant. Three complete autopilots, advanced voting logic, carrier phase GPS, helicopter and fixed-wing. Triple redundancy (3X) gives autopilot technology the reliability necessary to safely carry out sensitive flight missions and transport valuable payloads. A triple redundant arrangement is comprised of three similar software and hardware systems. If any one of the three systems fails, the remaining two take over, offering a double redundancy arrangement. If one of the other two systems should fail, the third takes over. An additional mechanism is also included to oversee these three systems. Triple redundant systems are highly tolerant of autopilot hardware failures.

Triple redundant autopilots are not new. Military aircrafts such as the RAF's Trident fleet, used a triple redundant autoland system in the early 1960's. Ten years later, the Aérospatiale-BAC Concorde took advantage of 3X technology in its flight control system. Presently, triple redundancy is used in several manned military and commercial aircrafts.

Although triple redundant technology is established within the aviation industry, triple redundant autopilots are a relatively new addition to unmanned aerial vehicles (UAVs). MicroPilot, the leading UAV autopilot manufacturer, is setting the benchmark for triple redundant UAV autopilots. MicroPilot, based in Canada, has been designing autopilots for fixed-wing, transitional and helicopter UAVs since 1994. In 2006 MicroPilot started designing a triple redundancy autopilot for helicopter and fixed-wing UAVs.

The MP2128^{3X} is comprised of three MicroPilot MP2128^{HELI2} autopilots, mounted on an adapter board, or redundancy board. The three MP2128^{HELI2}s are prioritized. At the start, the autopilot in position one flies the airframe. If this autopilot should fail, the MP2128^{HELI2} in position two takes over, and so on. The redundancy board provides several input/output (I/O) ports. The board also includes two RS232 serial ports designed to communicate with a ground control system via radio modems. As a result of this design, users never need to work directly with bare circuit boards. Additionally, the autopilots do not have an individual casing, keeping overall weight to a bare minimum; however, the entire redundancy board is enclosed to protect the system.

Features:

- Fly both fixed-wing and helicopter UAVs.
- Multiple communication links for onboard devices such as cameras and aircraft transponders.
- Redundant datalinks to ground control station.
- Configuration, state and waypoint synchronization among all three autopilots.
- 11 serial ports including RS232 and RS485.
- 16 independently-generated servo signals.

• 8 high current drivers controlled independently by each autopilot.

• Pass or fail voting logic reliably selects the appropriate autopilot.

• HORIZON^{mp} ground control station software with built-in software in the loop simulator.

• Feedback loop synchronization ensures smooth transition when switching autopilots.

HORIZON^{mp}

Ground control software that consistently takes UAV from the ground to the air. The choice of over 850 clients in 70 countries, HORIZON^{mp} ground control software offers a user-friendly, point-and-click interface. Developed by MicroPilot for the MP2x28 series of autopilots, HORIZON^{mp} runs on a Windows computer or laptop.

HORIZON^{mp} allows the operator to monitor the autopilot, change waypoints, upload new flight plans, initiate holding patterns, and adjust feedback loop gains all while the UAV is flying.

INFORMATIVE

HORIZON^{mp} allows both the UAV developer and the end user to access critical information in real time. Up to eight user-defined sensors can be configured and displayed in three formats:

• Current sensor values are displayed in an easy-to-read gauge format; warning and danger levels can be set for each gauge

• The Strip Chart graphs sensor-specific variations over time

• The Trace Route displays sensor data variations along the UAV's flight path

Data from the autopilot is also recorded for post-flight analysis.

MP2128^{LRC2} MP2128$^{HELI-LRC2}$

Providing the best MicroPilot 2128 series products in one convenient autopilot package. As world leaders in miniature UAV autopilots, MicroPilot continually develops dynamic new systems to serve RPAS, MAV, UAS, UAV, drone, and certain unmanned vehicles. The MP2x28 and MP2128 are the autopilots of choice for UAV operators who need a reliable, integrated system that performs in a variety of scenarios. Equipped with full airside and groundside UAV system components, the MP2128^{LRC2} is MicroPilot's premium UAV autopilot package. This long-range communication (LRC) autopilot provides an integrated, redundant, long-range data communication link. With this feature, operators benefit from greater distance and flexibility.

The LRC ground unit uses standard, off-the-shelf radio modems with three popular frequency band choices (see below), as well as versions for either fixed-wing or helicopter. This product adds RC control information to the existing GCS datalink and a second redundant datalink, which reduces possible failure modes. In addition, LRC units provide automatic emergency override. The LRC is lightweight, yet enclosed in a rugged aluminum housing that protects its sensitive electronics. What's more, these electronics are convenient to install on a variety of airframes.

XTENDER^{mp}

Take UAV to the next level with this power solution XTENDER^{mp} taps into the power of a world-recognized autopilot and expands it to fill the gap between standard autopilot functionality and specific requirements.

MP plug-ins are code modules that execute at the same time as the autopilot code and allow customers to add functionality to the autopilot to differentiate their products and close the gap between the standard autopilot functionality and their custom requirements

• MP plug-ins can access 64k RAM for data and 64k Flash for code

• MP plug-ins run under the autopilot simulator to simplify testing and speed development

• MP plug-ins can access all autopilot state fields

• MP plug-ins can provide customer-specific servo mixing

• Customer-defined control laws can replace any or all existing MP2x28 control laws

• MicroPilot plug-ins can access unused autopilot hardware for custom payload control and data collection

• Up to 9 I/O channels are available for MicroPilot plug-in. Each I/O channel can be configured as one of: serial input, serial output, PWM in, PWM out, single-bit input, or single-bit output

SIMULATOR

XTENDER^{mp} includes a "software in the loop" 6-DOF simulator linked to autopilot code.

• Simulator update rate: 150 Hz

• Accepts autopilot commands via PC serial port; speeds development of embedded payload/mission controllers

• Simulates communication, engine failure, loss of GPS lock, loss of RC signal, loss of communications, and low-battery failures

• Availability of simulator gives end-product training mode

XTENDER^{validate}

Build quality systems that meet high-level expectations. Develop high-level requirements and easily decompose them into appropriate lower level requirements with XTENDER^{validate}, the world's first available design life-cycle tool for UAVs. Systematically link flight, user, and simulator testing validation data to requirements. Likewise, link requirements to autopilot options and GCS settings. Additionally, XTENDER^{validate} incorporates a failure analysis tool that helps identify subsystem failure modes and links them to requirements. With XTENDER^{validate}, clearly satisfy requirements via autopilot options, ground control station options, UAV design, and more. Auto-generate electronic test cards, complete with descriptions for each test, indicators for severity, and schedule dates. Automate documentation for each requirement and its implementation, with this design life-cycle tool. XTENDER^{validate}offers a flexible means of satisfying requirements and provides progress and fulfillment reporting.

Features:

• Freeze and roll back requirements and implementation capability;

• Requirement linking to autopilot options and GCS settings;

• System and subsystem decomposition tool;

• Share requirement subsets among multiple UAVs capability;

• Integrated failure modes analysis and mitigation tool;

• Auto-generated electronic test cards from requirements;

• Validation data linking to requirements;

• Requirements and implementation change history;

• Progress tracking for satisfying and validating requirements [7].

6. RVOSD components

RVOSD6 Autopilot & Telemetry + LRS

RangeVideo RVOSD6 with RVLINK receiver module and airspeed sensor [8], includes:

• RVOSD6

• RVLINK Rx module + antenna

• GPS

• Current sensor

• IR remote

• Servo cables.

Requires: RVLINK Transmitter

Capabilities:

OSD: F16 style graphical OSD; Battery voltage & current; Airspeed; Ground Speed; Altitude; Variometer; Heading; AHI; 3 different OSD displays: F16, simple, or radar screen.

Autopilot:

– Variable throttle control based on airspeed and power.

– 16 waypoints (coordinates and altitude). Autopilot will fly the programmed path.

It can be override the mission at any time, with the following auxiliary modes:

– Position hold (circle flight path above any point– loiter diameter can be set);

– Fly-By-Wire (semi-automatic stabilized manual flight);

– Heading hold (maintain constant heading course);

– Return to home(return to take-off location and circle flight path at pre-set altitude).

Other Features:

Supports up to 6S battery; 100A current sensor with XT60 plugs; Filtered power supply for video camera and transmitter; 1A 5V PSU to power camera or vtx.

RVLINK UHF Control Relay (receiver is included in the RVOSD) 430MHz 800mW; 20-40km range; Spectrum analyzer mode.

RVGS(Optional)

Antenna tracker; Video diversity controller; Video splitter.

The RVOSD autopilot relies on a combination of gyros and accelerometers to sense the airplane's pitch and roll. The most important function of the autopilot is to return the airplane back home when R/C signal is lost. The RVOSD5 can also stabilize(fly-bywire mode) and autonomously(by waypoints) fly the aircraft.

Aircraft Compatibility. The RVOSD autopilot can control these types of aircraft:

– Stable trainer aircraft. Throttle, elevator, and rudder.

– Low wing Aerobatic aircraft. Throttle, elevator, and ailerons.

Autopilot Flight Modes RTH (return to home) This autopilot mode will engage automatically when R/C link lost is detected, and will fly the model back to the takeoff spot. Level flight The autopilot will keep the attitude of the model leveled on the pitch and roll axes. Heading hold The autopilot will keep the heading of the plane at the moment this of activation; it will also try to keep the actual altitude.

Position hold The autopilot will fly figure eight patterns around the GPS coordinates at the moment of activation; it will also try to keep the actual altitude. Fly-by-wire The control of the plane is given up to the OSD computer. It will check for user stick traffics and will translate to model desired attitudes. Control sticks are interpreted from 0 to full as 0-60° on each axis. Waypoint navigation (this mode is disabled outside of North America)

Hardware Overview.

RVOSD5. The RVOSD performs all of the text and graphic overlay, navigation, autopilot control, and power management. A custom graphics engine draws a flicker free overlay. Two microprocessors handle all of the tasks. The RVOSD5 contains an onboard Barometric Pressure Sensor for measuring aircraft altitude.

GPS Receiver. The included 10Hz GPS with SAW filter is immune to jamming from video transmitters. It is WAAS enabled, and has an accuracy of < 2m. It has a lithium backup battery to retain GPS settings for quicker satellite acquisition times. GPS data provides ground speed, ground track, and latitude and longitude.

Current Sensor. The current sensor measures the current consumption of electric motor system from 6-25VDC, 70A maximum.

External Temperature Sensor. If the external temperature sensor is left disconnected, then RVOSD will display the onboard temperature sensor reading. Temperature sensor operating range:

onboard temp sensor MCP9700 -40 to +150 degrees Celsius.

Remote Control. The IR remote is used to navigate the RVOSD menus. The IR signal is powerful enough to penetrate foam and balsa; there is no need to remove the RVOSD from the model.

Wiring. Cables to connect video in, video out, GPS, current sensor, R/C receiver, are all included.

Video Camera. A video camera is not included with the RVOSD5. The RVOSD will not provide a video output without a valid video input. Use the included cables to connect camera to the RVOSD. There are cables for the KX131/KX191, KX171, and DX201. RVOSD is compatible with both PAL and NTSC composite video formats

Video Transmitter. A video transmitter is not included with the RVOSD5. The RVOSD5 will send the combined camera video and OSD to the connected video transmitter so the video can be sent down to on the ground for monitoring.

The video out connector is the video signal with the graphic/text data overlay. It can be connected directly to a TV monitor, DVR, or wireless video transmitter. Use the included male to male servo cable to connect the video out to a RangeVideo Aerial Video System transmitter.

Video Receiver. A video receiver is not included with the RVOSD. It will need a video receiver that operates on the same frequency as video transmitter. The video receiver will receive the transmitted video with RVOSD5 overlays. Connect the video receiver output to a video monitor to watch the video in real-time

Video Monitor. It will need a video monitor (not included with RVOSD5) to view the video being received by the video receiver.

Main Battery. The electric aircraft already has a battery to power the motor and electronics. The RVOSD5 and related components can use this existing battery as a power source. The Main Battery voltage and current can also be monitored and displayed on the OSD. A video transmitter and video camera can also be powered from the main battery via RVOSD5 connections.

Auxiliary Battery. The Auxiliary (Aux) Battery is optional and not included with the RVOSD5. The input range is 6-35 VDC [8].

7. Pixhawk Autopilot

PIXHAWK is a high-performance autopilot-on-module suitable for fixed wing, multi rotors, helicopters, cars, boats and any other robotic platform that can move. It is targeted towards high-end research, amateur and industry needs and combines the functionality of the PX4FMU + PXIO [9].

PX4 Autopilot. PX4 is platform independent autopilot software (or a software stack / firmware) that can fly or drive Unmanned Aerial or Ground Vehicles (UAV / UGV). It is loaded (flashed) on certain hardware and together with Ground Control Station it makes a fully autonomous autopilot system. PX4 ground control station is called QGroundControl and is integral part from the PX4 Autopilot System. QGroundControlcan run on Windows, OS X or Linux. With the help of QGroundControl it can load (flash) the PX4 on to the hardware, it can setup the vehicle, change different parameters, get real-time flight information and create and execute fully autonomous missions.

Today the PX4 Project and 3D Robotics announced Pixhawk□—□an advanced open-hardware autopilot design for multirotors, fixed-wing aircraft, ground rovers and amphibious vehicles. Pixhawk is designed for improved ease of use and reliability while offering unprecedented safety features compared to existing solutions.

Pixhawk is designed by the PX4 open-hardware project and manufactured by 3D Robotics. It features the latest processor and sensor technology from ST Microelectronics® which delivers incredible performance and reliability at low price points.

The flexible PX4 middleware running on the NuttX real-time operating system brings multithreading and the convenience of a Unix/Linux-like programming environment to the open-source autopilot domain. Advanced PX4 firmware layers ensure tight timing of operations and allow the addition of completely new functionalities like direct programmatic scripting of autopilot operations.

The flagship Pixhawk module will be accompanied by new peripheral options, including support for a digital airspeed sensor, external multi-color LED indicator and external magnetometer. All peripherals are automatically detected and configured.

PX4 is an open-source, open-hardware project aimed at providing a high-end autopilot to the academic, hobby and industrial communities at low costs with high availability. It is backed by volunteers of the Pixhawk Project hosted at the Computer Vision and Geometry Lab of ETH Zurich (Swiss Federal Institute of Technology) and supported by the Autonomous Systems Lab and the Automatic Control Laboratory of ETH as well several excellent individuals internationally.

3D Robotics is the leading open-source unmanned aerial vehicle technology company. It was founded in 2009 by Chris Anderson (founder of DIY Drones) and Jordi Muñoz. Today, 3D Robotics is a seasoned, venture-backed enterprise with more than 80 employees focused on delivering the most advanced, full-featured autonomous technologies at the most competitive prices.

3D Robotics and PX4 continue their partnership to mutually support the further development of the Pixhawk platform and provide all PX4 source code and hardware under BSD/Creative Commons licensing.

- Manufactured by 3D Robotics
- Aautopilot system designed by the PX4 open-hardware project
- Advanced 32 bit ARM Cortex® M4 Processor running NuttX RTOS

• 14 PWM/servo outputs (8 with failsafe and manual override, 6 auxiliary, high-power compatible)

• Abundant connectivity options for additional peripherals (UART, I2C, CAN)

• Integrated backup system for in-flight recovery and manual override with dedicated processor and stand-alone power supply

• Backup system integrates mixing, providing consistent autopilot and manual override mixing modes

• Redundant power supply inputs and automatic failover

• External safety button for easy motor activation

• Multicolor LED indicator

• High-power, multi-tone piezo audio indicator

• MicroSD card for long-time high-rate logging

Features

• 32 bit ARM Cortex® M4 Processor running NuttX RTOS;

• 14 PWM/servo outputs (8 with failsafe and manual override, 6 auxiliary, high-power compatible);

• Abundant connectivity options for additional peripherals (UART, I2C, CAN);

• Integrated backup system for in-flight recovery and manual override with dedicated processor and stand-alone power supply;

• Redundant power supply inputs and automatic failover;

• External safety switch;

• Multicolor LED visual indicator;

• High-power, multi-tone piezo audio indicator;

• microSD card for extended-time high-rate logging.

Specifications.

Microprocessor:

• 32-bit STM32F427 Cortex M4 core with FPU;

• 168 MHz/256 KB RAM/2 MB Flash;

• 32 bit STM32F103 failsafe co-processor.

Sensors:

• ST Micro L3GD20 3-axis 16-bit gyroscope;

• ST Micro LSM303D 3-axis 14-bit accelerometer / magnetometer;

• Invensense MPU 6000 3-axis accelerometer / gyroscope;

• MEAS MS5611 barometer.

Interfaces:

• 5x UART (serial ports), one high-power capable, 2x with HW flow control;

• 2x CAN;

- Spektrum DSM / DSM2 / DSM-X® Satellite compatible input up to DX8 (DX9 and above not supported);
- Futaba S.BUS® compatible input and output;
- PPM sum signal;
- RSSI (PWM or voltage) input;
- I2C®;
- SPI;
- 3.3 and 6.6V ADC inputs;
- External microUSB port.

Power System:

- Ideal diode controller with automatic failover;
- Servo rail high-power (7 V) and high-current ready;
- All peripheral outputs over-current protected, all inputs ESD protected.

Weight and Dimensions:

- Weight: 38g (1.31oz);
- Width: 50mm (1.96");
- Thickness: 15.5mm (.613");
- Length: 81.5mm (3.21").

Radio connections (range to 30km):

- Telemetry: 915 MHz;
- Digital video: 5.1-5.9 GHz [9].

8. Autopilots MNAV and Kestrel

Autopilot MNAV + Stargate has average size and not light enough for use on small ADO. Autopilot advantage of this is that the original software into the Linux open-friendly. In addition, Stargate is a powerful CPU and IO-ports MNAV Stargate and provide users with a great opportunity to install individual extensions.

Autopilot Procerus Kestrel has a much smaller size and weight that is acceptable for small ADO. Autopilot contains processor Rabbit 3000 with a frequency of 29 MHz, and a set of sensors, similar to the autopilot MNAV. All sensors are integrated with the processor, except for receiver GPS. In autopilot built to perform autonomous takeoff, landing and flight route, and provides pre-flight inspection of sensors. Autopilot algorithm is based on the traditional PID controller. Autopilot contains some controllers handlebar height, engine throttle and ailerons.

Autopilot provides automatic flight route as control points with three dimensions (latitude, length, height). Autopilot can use to ADO with bands such air speeds (km / h), the bottom 25 ... 150; normal 35 ... 250 the top 45 ... 450.

Apart from the autopilots, there are many commercial standard autopilots, such as the AP50 autopilot of UAV Flight Systems, 3400 the company UNAV autopilot, autopilot Microbot of Microbotics Inc. and others.

Mini ADO put strict requirements for autopilots for their physical size, weight and minimal power consumption. Comparison of these characteristics are given in Table 1. Information on the availability of sensors as parts of autopilots MNAV, Kestrel and MicroPilot are shown in Table 2.

Table 1

Specifications of autopilots

Parameter	MNAV	Kestrel	MicroPilot
Temperature, ◦C	-5 ... +45	-40 ... +85	–
The angular velocity, deg/s	±200	±300	±150
Acceleration, m/s2	±2	±10	±2
Magnetic induction, nT	±0,75	±1	–
Height, m	0 ... 5000	-13,7...3414	0 ... 12000
Air speed, mil/h	0 ... 180	0 ... 130	0 ... 311

Table 2

Comparing weight and dimensions performance and cost autopilots

Autopilot	Size, cm	Weight, g	Energy consumption	Cost, thous.doll.
MNAV	5.7×4.5×1.1	33	<0.8 W (5V)	1.5
Stargate	9.53×6.33×2.81	80.47	<500 mA	0.9
Kestrel 2.2	5.08×3.5×1.2	16.7	500 mA (3.3…5V)	5
MicroPilot	10×4×1.5	28	–	1.7…6
Piccolo LT	11.94×5.72×1.78	45	–	–
UNAV 3400	10.16×5.08×4.06	84	180 mA (5.5…7.5V)	5

Most commercial autopilots using PID regulators. Autopilot based PID controllers have a simple design and can easily be implemented to control the ADO. However, the autopilot is not optimal and have low reliability. In addition, some airplane mode settings PID controller can cause serious difficulties. Therefore, the current research is the application of modern methods of control theory for the synthesis of control laws ADO.

9. Development and production of integrated navigation system of unmanned aerial vehicles

Currently, the main and most common option is a navigation system UAV is the Inertial-Satellite Navigation System (ISNS), which is based Inertial System Platformless Type (ISPT). In ISPT sensors as the primary information used accelerometers and angular rate sensors. ISPT navigation systems are high, issuing evaluations of almost all parameters necessary for traffic control aircraft (components of linear and angular speeds, coordinates and orientation parameters) with high refresh rate information [10]. ISPT usually seen as the main source of navigation data and information coming from the receiver SNA, is used for correcting INS.

In evaluating parameters of spatial traffic of the aircraft should be aware that vertical channel INS unlike horizontal channels are structurally unstable, because it is no integrated contour correction. So usually expected to have an additional source of information – barometric altimeter that provides, first, linking the measurements to a reference level (to the average sea level), and secondly, a correction of this channel to restore the stability of the system.

Also note that in the SNA are no angular orientation, and ISPT error of course, as opposed to errors of calculation roll and pitch rapidly increasing. In this case, usually of the INS include magnetometer, which azimuthally adjusting channel ISPT, reduces error determination of the UAV.

So in addition to classic board sensors are more ISPT: magnetometer sensor and receiver static pressure, which provides the measuring barometric altitude. It is proposed to use these sensors to build an additional information system to improve reliability UAV flight navigation support.

Due to the different nature and different physical principles forming the navigation algorithm software ISPT and SNA well complement each other. Their sharing allows, on the one hand, to limit the increase in errors INS, and, on the other hand, to reduce the noise component errors SNA, increase the rate of delivery of information to consumers onboard, significantly raise the level of hurt-protection. But the real conditions of use Navigating consumers indicate that many gauges and, above all, the satellite radio navigation system, not always in working condition. In reality there is often failure tracking satellite signals, particularly because multi-beam action and other interference, and error signals capture etc.

In the article additional hardware devices without involving is proposed to create on the basis of existing equipment onboard the UAV navigation system that will support the work of SINS radio silence during the SNA, that is in turn ISSN integrated navigation system (INS). For truncated algorithms system of air signals, using information about the static and dynamic pressure, in addition to barometric altitude can be calculated true air speed.

Basically mode navigation system in calculators about the estimated components of the ground speed using the calculated value of the true air speed and the current rate is calculated and stored wind speed and direction. For short-range UAV flight parameters of the wind can be administered according to weather stations. Availability of information on the options wind allows aeromagnetic-metric calculation algorithm of navigation parameters.

To improve the reliability of measurements of angular orientations proposed use information not only on inertial system, but also from alternative sources not gyroscopic this information. Upon receipt of this information can be used magnetic-metric, aerodynamic, accelerate-metric measurement methods and pitch angles. The presence of additional flight and navigation information can significantly improve the reliability of the navigation software and the disappearance or noise signals SNS and continue further implementation of the flight mission, realizing inertial course-air method of infinite coordinates.

Thus, the main navigation tasks that will solve a navigation system is the problem of inertial and satellite navigation. The main mode of the complex is the mode of inertial-satellite navigation. The period of radio silence SNA complex moves to autonomous mode of inertial and aeromagnetic-metric systems [10, 11].

10. Automatic landing system of UAV

Tasks flight control automation is currently valid in connection with the global development of unmanned aircraft. The most responsible of all the list of tasks automation is the process of landing unmanned aircraft. Although you can find general information about individual achievements in this field in the world practice, however, this information does not include data on specific ways to solve this problem. The analysis of existing methods of planting the parameters guidance during the approach and landing. With the help of analytic geometry developed algorithms for calculating parameters guidance and control integrity. Based on algorithms developed software for mathematical modeling. To test the hypothesis to improve the accuracy of navigation based on an equipment navigation receivers leading manufacturers developed subsystem models and differential treatment for technology GBAS EGNOS [12, 13].

Requirements for the UAV landing systems.

According to the general concept of UAV flights should operate in accordance with the standards of ICAO, which are designed to fly with a pilot on board. Thus, UAVs, carrying out direct flights visibility must meet the requirements that apply to of systems communication, navigation and surveillance in the airspace.

According to the navigation strategy states of the European Conference on Civil Aviation for the European region has further development:

- gradual extension of area navigation (RNAV);
- heavy use of GNSS navigation;
- gradual decommissioning of navigational aids NDB and VOR.

The most promising landing UAV systems should be considered landing system using area navigation and satellite navigation systems, as evidenced navigation strategy states of the European Conference on Civil Aviation, which involves increasing the accuracy of satellite landing the third category (GBAS Cat I/II/III).

It should be noted that the use of GNSS and RNAV involve the use of algorithms receiver autonomous integrity monitoring (RAIM or FDE). In order to meet a specified level of continuity of operation should apply a system of functional additions: GBAS and / or SBAS with ABAS. When landing using GNSS must perform separate RAIM - forecast. Application of GNSS systems, along with functional supplement allows you to perform operations on the basis of appropriate type RNP.

The base receiver GNSS must comply to the requirements of Volume 1 Annex 10 ICAO and specifications RTCA DO-208 (Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using Global Positioning System) and EUROCAE ED-72A (MOPS for Airborne GPS Receiving Equipment used for Supplemental Means of Navigation) with amendments TSO-C129A (Airborne Supplemental Navigation Equipment Using the Global Positioning System). These documents define the minimum requirements to be met by the receiver GNSS (integrity control, prevent reversals, the use of electronic navigation data bases).

The board equipment SBAS must comply to the requirements of Volume 1 Annex 10 ICAO and specifications RTCA DO-229C (Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment).

Standards for SBAS avionics features include three levels of approach:

- LPV (the approach beacon on the course with a vertical input);
- LNAV/VNAV (side / vertical navigation);
- LNAV (side navigation).

There are four separate classes onboard equipment SBAS. Different classes of equipment provide different functionality. Minimum functionality is Class I. This equipment provides flights on routes near the airfield and landing LNAV. Class II SBAS equipment in a position to Class I and provides Approaches LNAV / VNAV. Class III and IV has the capabilities of the hardware and Class II SBAS provides Approaches LPV.

Basic requirements for SBAS equipment onboard during landing formulated as follows. Board equipment SBAS calculates the exact location and provide information about the integrity of the calculated provision for this type of approach. The required level of integrity for each of the types of approaches specific set alarm thresholds in the horizontal and vertical planes, called HAL and VAL. These thresholds similar control limits for ILS. These alarm thresholds form a region of maximum error that meets the requirements of integrity for this type of approach.

SBAS-board equipment ensures the integrity of information intended location for this type of approach via continuous calculation of levels of protection in the horizontal and vertical planes (HPL and VPL) and comparing the calculated values according to HAL and VAL. If HPL or VPL exceeds the limits alarm (HAL or VAL) for a specific type of approach, the pilot warned of the need to interrupt at this point performed the operation. The pilot takes only warning and does not perform the function of monitoring VPL or HPL.

The board equipment GBAS must comply to the requirements of Volume 1 Annex 10 ICAO and specifications RTCA DO-253A (Minimum Operational Performance Standards for GPS Local Area Augmentation System Airborne Equipment) and DO-246B (GNSS Based Precision Approach Local Area Augmentation System Signal-in-Space Interface Control Document).

At minimum requirements for onboard equipment GBAS no provisions relating to RNAV. GBAS can produce vector position, velocity and time (PVT). In cases where the GBAS ground station provided this service, it is called GBAS service to determine the location. PVT vector is intended for introduction into an existing board navigation equipment. However, the requirements for RNAV equipment computer equipment available. No demand and to provide onboard equipment GBAS pointing out at the second round. Minimum display functionality similar to ILS deviations and provide an indication of the rate indication deviation in the vertical plane, about the distance to the runway threshold and flags signaling failures. With no navigation equipment on board the pilot not provided information on the spatial position of the PC. Its provided only information that provides guidance for the course and glideslope on final approach phase.

Monitoring the integrity of navigation information performs receiver GNSS, using RAIM function.

UAV, equipped with facilities multisensory RNAV, can and using sensors monitoring the integrity of GNSS, with built-in algorithm RAIM. The implementation RAIM integrity monitoring functions based only on satellite signals. Interruptions RAIM may occur due to insufficient number of satellites or their unfavorable location, which leads to a very large error determining spatial position. The loss of the satellite signal and a warning given by the RAIM, may also occur due to traffic. Installation antennas for UAV, satellite positions relative to the horizon and spatial position UAV can affect reception of signals of one or more satellites. Since the relative position of the satellites are constantly changing, resulting in this airport's previous experience does not guarantee the sustainability of signal reception, and in this regard should always check the readiness RAIM. In the absence of minimal conditions for RAIM must use a different type of navigation and approach, choose another destination or delay the flight until as predicted will be provided willingness to RAIM the arrival. In carrying out long flights should provide pilots during flight of revalidation RAIM prediction of destination. It can advance to obtain information that after takeoff, there was an unexpected break in satellite signal. Interruptions in readiness mode RAIM approach will have a greater frequency compared with the flight route as a result of more stringent threshold alarm. Since factors such as spatial position and UAV antenna location may affect reception of signals from one or more satellites, and also due to unplanned outages satellites willingness to RAIM predictions can not be 100% accurate.

GNSS receiver has three modes: the flight route, flight in the terminal area and approach mode. Limits RAIM alarm automatically brought into line with the modes of the receiver and are ± 3,7 km (2,0 m. Mile) route mode, ± 1,9 km (1,0 m. Miles) area of the airfield mode and ± 0.6 km (0.3 m. miles) mode precision approach.

Sensitivity indicator deviation Exchange automatically consistent with the mode of operation of the receiver. Sensitivity is: ± 9,3 km (0,5 m. Mile) route mode, ± 1,9 km (1,0 m. Miles) area of the airfield mode and ± 0,6 km (0,3 m. Miles) mode approach.

Approach on GNSS traditional event like the landing and is a flight with guidance on appropriate terms and is independent from any terrestrial navigation aids, except accurate approach in which the use GBAS.

The following are excerpts from the Doc. 8186, describing the features of the implementation approach for satellite navigation systems.

Approach can be performed if the database onboard equipment:

- includes all points the way indicated in the diagram future approach;
- presents them in the same order in which they are marked on the map scheme;
- contains updated information for the current AIRAC cycle.

To ensure the accuracy of mapping databases GNSS pilots should check the admissibility of data displayed for an approach based on GNSS after loading scheme in the current flight plan and flight performance under this scheme.

The main modes and functions of the system's hardware landing UAV, turn on and initialization, the creation of-flight (FPL), navigation (NAV), the choice of types of navigation points procedures (WPT), calculation (CALC), enter additional information (AUX), the approach (APP) [12, 13].

11. Automated system for optimal control of remotely controlled aircraft system

The main requirement is that the current development of aviation technology refers to traffic control facilities for different purposes, is the greatest attainable accuracy of the object it designated traffics in each normal mode of operation. That object precision traffics necessary quality control is the equivalent of the specified object and determines its level of competitiveness of the developed or the modernizes my moving object. How to view moving objects of aircrafts (airplanes, missiles, unmanned aerial vehicles, etc.), various ground transport tools and moving simulators and training devices, which are equipped with the above items [14].

The successful use of unmanned aerial aircraft is extremely important so-called stabilization modes. In the process of stabilizing one of the basic and complex types of motion control, object held in the space in a state close to the set for a sufficiently long time. When given of the facility means a series of software components values of the state vector object. These components can be not only constant, but also deterministic or random functions of time with known statistical characteristics. Automated tools that keep the object in a state close to the set (software) called Stability and they're the regulators that are normally in the feedback to stabilize the object. When the program is a function of time, the system of "object-regulator" called tracking system. Typically, the formation of law stabilization using only information about the current and / or past state of the object. This mode is called stabilization system for deviation. When in the formation of law stabilization using, in addition, information on external disturbing factors act to stabilize the facility, then it is for the stabilization and disturbance rejection.

Stability intended, first, to ensure the stability of the system "object-regulator" with unstable or no-minimum-phase facility, and, secondly, to parry the impact of disturbing factors and obstacles that are in the loop stabilization . Disturbing factors and disturbances in the circuit are stabilizing as deterministic and random. In many cases, the impact of deterministic factors may fully compensate, for example, from the standpoint of the theory of invariance.

Linear stochastic optimal control stand-simulator known traffics can be solved as the problem of multidimensional dynamic stabilization facility taking into account only random measurements in famous productions using the so-called theorem section and without. The task of designing analytical and objectives of sustainable stabilization facility at the disturbance of the "white noise" and perfect measurement vector of the facility are identical. However, the task of stabilization allows you to get the best solutions for arbitrary dynamic properties of the object, but also take into account interference and perturbation measurements.

In practical formulation of the problem of synthesis of stabilizing traffics UAV must also take into account the fact that the waste traffic UAV created not only the initial conditions of work, but also deterministic and random disturbances constantly acting on the UAV in flight, deterministic and random obstacle of measurement conditions UAV. Such measurements are often incomplete and facilities management systems or meters can be volatile. Often management system moving objects that are being developed, and to include the so-called adaptation contours [14].

Thus, the problem of ensuring efficiency, safety, regularity and quality of UAV flight accompanied by major scientific and technical challenge. One of the main ways to solve this problem, obviously, is full automation of mission control. The accuracy depends on the quality control tasks on flights performed. In many cases of practical importance the concept of "accuracy" can be the equivalent of the concept of "quality" and the accuracy rate system could be a criterion of quality. For example, the average square error criterion adopted to determine the quality mode navigation and stabilization of different types of UAV flight.

Thus, the problem of maximizing precision motion control is one of the basic side problems of efficiency, safety, regularity and quality of flights and can be solved in a complex where motion control is optimal for accuracy, the impact of disturbing factors and quality control will be constantly assessed a special board system and using a special system update (adaptation) quality is maintained at extreme values.

Performance Based Navigation Area navigation (RNAV) is a method of Instrument Flight Rules (IFR) navigation that allows an aircraft to choose any course within a network of navigation beacons, rather than navigating directly to and from the beacons. This can conserve flight distance, reduce congestion, and allow flights into airports without beacons. RNAV began as a means of navigation on a flight path from any point, or fix, to another. These fixes could be defined by a latitude and longitude, and an airplane's position relative to them could be established using a variety of navaids. RNAV facilitated a type of flight operation and navigation in which the flight path no longer had to be tied directly to overflight of ground navigation stations. Performance Based Navigation concept specifies that aircraft RNAV system performance requirements be defined in terms of accuracy, integrity, availability, continuity and functionality required for the proposed operations in the context of a particular airspace concept, when supported by the appropriate navigation infrastructure. Performance Based Navigation concept identifies three components: – the NAVAID Infrastructure; – the Navigation Specification; – the Navigation Application [15].

European aviation community is currently looking for the right steps in order to increase airspace capacity and airspace flexibility along with enhancement of operator's efficiency.

12. Conclusions

Based on the provisions set a prototype integrated avionics for ADO navigation and control synergistic with current approaches has been developing [16, 17].

The further implementation of scientific research and development work activities include such tasks:

1. Improve existing and develop new concepts and methods of system integration of avionics ADO for solving navigation and synergistic management, namely:

- to develop a new compensation invariant concept and method for combining primary sources of information in an integrated ADO avionics;
- to develop new methods for complex correlation-extreme ADO navigation;
- to develop a new concept of synergistic motion control ADO formations;
- to improve energy-potential method guaranteed solution of poly-conflict dynamic objects for solving synergistic control ADO formations;
- to improve methods of ensuring reliability ADO avionics;
- to improve methods of communication and information transfer between elements ADO avionics.

2. To develop algorithmic software integrated ADO avionics, namely:

- algorithms implementing basic operations invariant compensation scheme combining treatments based on nonlinear filtering theory and sensitivity;
- allocation algorithms characteristics of real-time and their comparison with the standards;
- algorithms for tracking target image characteristics of the video sequence;
- processing algorithms compatible data inertial navigation system and the correlation extreme navigation system using nonlinear models and Gaussian filter point.

3. To create a prototype integrated avionics ADO and evaluate the effectiveness of the its operation in a high probability of operational and intentional failures, the suppression of radio subsystems.

In the course of further work must be obtained new results:

- invariant compensation concept and method for combining primary sources of information in an ADO integrated avionics;
- complex methods of correlation-extreme ADO navigation;
- concept synergistic traffic control ADO formations;
- advanced ENERGY-potential method guaranteed solution of poly-conflict dynamic objects for solving synergistic control ADO formations;
- improved methods of ensuring reliability ADO avionics;
- improved methods of communication and information transfer between elements ADO avionics;
- algorithms implementing basic operations invariant compensation scheme combining treatments based on nonlinear filtering theory and sensitivity;
- mapping algorithms base reference surface and image processing methodology for the selection of the characteristics, the characteristics allocation algorithms in real time and their comparison with standard algorithms for tracking target image characteristics of the video sequence;
- methodology compatible data processing inertial navigation system and the correlation extreme navigation system using nonlinear models and Gaussian filter point;
- assessment methodology required amount of computation depending on hardware configuration ADO avionics;

- method of improving reliability models integrated ADO avionics;
- algorithms of systems connection between ADO elements avionics;
- axioms and laws synergistic motion control in a single ADO limited navigation environment;
- stand for ADO avionics testing;
- testing methods elements integrated avionics ADO, methods of testing complex integrated avionics ADO, methods of evaluating the effectiveness of the proposed compensation invariant concept of integration of navigational aids ADO, methods of assessing the effectiveness of laws synergistic management of extreme correlation navigation system of channels that are resistant to intentional interference.

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Д.Е. Прусов[1], М.П. Матійчик[2], О.Ю. Михацький[3]

Порівняльний аналіз зразків авіоніки і їх компонентів стосовно до створення методології синтезу інтегрованої авіоніки БПЛА

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03058.
E-mails: [1]prusov@nau.edu.ua; [2,3]nvcba@nau.edu.ua

Мета: Метою цієї роботи є аналіз зразків авіоніки та їхніх компонентів з огляду на створення методології синтезу інтегрованої авіоніки дистанційно-пілотованих та безпілотних аерокосмічних динамічних об’єктів (АДО), яка забезпечує комплексне розв’язання завдань навігації та синергетичного управління АДО в аеронавігаційному просторі. **Методи дослідження:** Аналіз та постановка завдань є основою для розробки сучасних методів комплексування та обробки первинної інформації, методів розв’язання навігаційних задач, методів розв’язання задач керування в комплексах інтегрованої авіоніки АДО. Зокрема це неінваріантний компенсаційний метод комплексування первинних джерел інформації, комплексні методи кореляційно-екстремальної навігації, метод синергетичного управління АДО. **Результати:** Використання цих методів дозволить підвищити ефективність вирішення задач навігації і управління як цивільних так і військових АДО, в умовах дії випадкових і навмисних завад, при відмовах елементів авіоніки. **Обговорення:** Виходячи з наведеного аналізу, можна встановити вимоги до прототипів інтегрованої авіоніки, що розробляється для навігації і управління АДО.

Ключові слова: безпілотні літальні апарати; інтегрована система авіоніки; навігація і управління.

Д.Э. Прусов[1], М.П. Матийчик[2], А.Ю. Михацкий[3]

Сравнительный анализ образцов авионики и их компонентов применительно к созданию методологии синтеза интегрированной авионики БПЛА.

Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03058.
E-mails: [1]prusov@nau.edu.ua; [2,3]nvcba@nau.edu.ua

Цель: Работа посвящена анализу образцов авионики и их компонентов с учетом создания методологии синтеза интегрированной авионики дистанционно-пилотируемых и беспилотных аэрокосмических динамических объектов (АДО), которая обеспечивает комплексное решение задач навигации и синергетического управлиния АДО в аэронавигационных пространстве. **Методы исследования:** Анализ и постановка задач является основой для разработки современных методов комплексирования и обработки первичной информации, методов решения навигационных задач, методов решения задач управления в комплексах интегрированной авионики АДО. В частности это неинвариантны компенсационный метод комплексирования первичных источников информации, комплексные методы корреляционно-экстремальной навигации, метод синергетического управления АДО. **Результаты:** Использование этих методов позволит повысить эффективность решения задач навигации и управления как гражданских так и военных АДО, в условиях действия случайных и преднамеренных помех, при отказах элементов авионики. **Обсуждение:** Исходя из приведенного анализа можно установить требования к прототипам интегрированной авионики, разрабатываемой для навигации и управления АДО.

Ключевые слова: беспилотные летательные аппараты; интегрированная система авионики; навигация и управление.

Prusov Dmitry. Doctor of Technical Sciences (Prof.Dr.Habil.Eng.), Associate Professor.
Senior Research Analyst,, Scientific Research Administration, National Aviation University, Kyiv, Ukraine.
Education: Kyiv National University of Construction and Architecture (1997).
Research area: Development the new concepts, creation of theoretical principles and new methodologies for objects research and processes mathematical modeling.
Publications: 121.
E-mail: prusov@nau.edu.ua

Matiychyk Mykhailo. Candidate of Technical Sciences (Ph.D.), Associate Professor.
Director of the Scientific and Production Center of Unmanned Aviation "Virazh".
Education: Ternopil National Technical University (1985).
Research area: development and designing of modern competitive unmanned aerial vehicles and unmanned aircraft systems.
Publications: 71.
E-mail: nvcba@nau.edu.ua

Mykhatskyi Oleksiy. Candidate of Technical Sciences (Ph.D.). Senior Researcher.
Senior designer of the Scientific and Production Center of Unmanned Aviation "Virazh".
Education: The National Technical University of Ukraine "Kyiv Polytechnic Institute" (1985).
Research area: development and designing of modern competitive unmanned aerial vehicles and unmanned aircraft systems.
Publications: 50.
E-mail: nvcba@nau.edu.ua

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Sergii Filonenko

ACOUSTIC EMISSION AT TREATING TOOL WEAR WITH A NOT CONTROLLED CUTTING DEPTH

National Aviation University
Kosmonavta Komarova avenue 1, 03680, Kyiv, Ukraine
E-mail: fils0101@gmail.com

Abstract

Purpose: *The aim of this article is to research of acoustic emission at composite material machining with not controlled cutting depth and cutting tool from composite material wear.* ***Methods:*** *In the basis of researches lies the simulation acoustic radiation, which appears at destruction of treated composite material surface layer and treating tool wear. The case of prevailing treated composite material mechanical destruction surface layer was esteemed, and tool wear descends without change of cutting depth. The statistical processing of acoustic emission amplitude parameters for want and originating treating composite material wear was conducted. The analysis of acoustic emission amplitude parameters legitimacies change, and as their sensitivity to treating composite material wear at not controlled machining depth was conducted.* ***Results:*** *Is determined, that the ascending of treating composite material wear is accompanied by decreasing of acoustic emission statistical amplitude parameters - amplitude average level, its standard deviation and dispersion. Are obtained of acoustic emission amplitude parameters regularity decreasing at increasing of treating composite material wears. The acoustic emission amplitude parameters percentage decreasing at ascending of treating composite material wear, in relation to their values without tool wear is determined. It is shown, that the decreasing of acoustic emission amplitude average level dispersion advances decreasing of amplitude average level and its standard deviation.* ***Discussion:*** *The simulation of acoustic radiation at prevailing mechanical destruction treated composite material surface layer with a not controlled cutting depth and treating composite material wear is conducted. It is shown, that the ascending of tool wear results in decreasing acoustic radiation statistical amplitude parameters. Is determined, that decreasing of acoustic emission signals amplitude average level dispersion advances decreasing of amplitude average level and its standard deviation. The decreasing of acoustic radiation amplitude average level and its spread values is conditioned by the different contribution of acoustic emission signals components, which appears at treated material destruction and treating composite material wear. Apparently, that at decreasing of treated composite material area destruction the arising signals amplitude parameters decreasing advances ascending of signals amplitude parameters, which appear at increase of treating composite material wear. The outcomes of the conducted researches can be used at mining of cutting tool condition verification methods and control of technological process machining parameters. These methods are of interest in the robotic technological processes, the monitoring and control by which one is possible for conducting through neuronal networks.*

Keywords: Acoustic emission; amplitude; composite material; machining; statistical characteristics; wear.

1. Introduction

The conventional methods of testing's composite materials (CM) machining processes allow to conduct measurements and analysis of cutting forces, temperature, chattering parameters and other characteristics. The researches are directed on optimization the technological processes and mining the methods of their control and monitoring. One of the relevant directions is the cutting tool state estimation.

The conventional methods have a low sensitivity to internal processes descending in treated and treating materials at different levels. It reduces veracity the control and monitoring of technological processes for obtaining the items given quality.

The method of acoustic emission (AE) falls into not to conventional methods. The outcomes of researches demonstrate a sharp response the method to change interplay conditions of treated and treating materials. However advantage of AE method result to the problem registered information interpretation. The problem is aggravated by influencing on AE the machining CM technological parameters, and as treated and treating materials properties. It complicates looking up the legitimacies of AE parameters change for mining the methods verification and monitoring of technological processes.

The solution this problem is possible on the basis of acoustic radiation analytical investigations at CM machining. The models and simulation of AE radiation processes, with allowance of different factors operating, are the basis in definition of acoustic radiation parameters legitimacies change, and, as a consequent, basis in mining the methods verification and monitoring of CM machining technological processes. One of the influential factors is the treating tool wear. Analysis of its influencing on acoustic radiation parameter, unconditionally, introduces scientific and practical concern.

2. Analysis of the latest research and publications

The AE method will widely be used for research of CM machining processes and mining the methods of their control and monitoring. The special value such researches have at automation CM machining processes and monitoring of cutting tool status with neural networks usage.

At researches of AE, that registered during CM machining, is carried out processing mean or root mean square (RMS) AE signals amplitudes, stored RMS AE amplitudes, low frequency and high frequency components in spectra AE signals, statistical amplitude characteristics AE signals, amplitude and power AE signal distributions and other parameters [1-4]. The parameters of AE signals analyze in interconnection with parameters of CM machining technological processes, and as with cutting tool wear.

The outcomes of the conducted researches demonstrate composite nature of acoustic radiation at CM machining. However influencing of treating tool wear or damage on AE is discordant. In articles [5, 6] is shown, that at originating wear or damage of the treating tool there is ascending amplitude or RMS amplitude of AE signals. In article [7] is marked, that at originating tool wear there is ascending average value of AE signal amplitude, and at further tool wear increase AE signal amplitude average value decreases. The decreasing of AE signals amplitude average level, its standard deviation and amplitudes distribution coefficient at increase of treating tool wear is shown in article [3]. However connection of AE amplitude parameters with the treating tool wear has composite and not steady nature. Thus is marked, that to ascending of wear there is decreasing the main carrier frequency amplitude in a spectrum of AE registered signals. In articles [8, 9] is shown, that wear or damage of the treating tool result in decreasing of AE signals RMS amplitudes and value of their deviation. Thus ascending speed of amplitudes low frequency and high frequency components change in spectra of AE signals is watched. In article [4] is marked, that at ascending of treating tool wear there is decreasing *b*-parameter, describing β-distribution of AE signals amplitudes. At the same time, in article [1] is shown, that ascending of tool wear results in sharp ascending of AE signals stored amplitude.

The analytical investigations of AE amplitude parameters at cutting tool wear and controlled cutting depth are conducted in article [10]. The model of AE resultant signal is reviewed, in the basis by which one lays the formation of AE signals U_j and U_i at destruction, accordingly, elementary areas treated CM and treating CM wear

$$U_j(t) = u_0 t\alpha\upsilon_0 e^{r\alpha t} e^{-\frac{\upsilon_0}{r\alpha}(e^{r\alpha t}-1)}, \quad (1)$$

$$U_i(t) = U_0 V_0 \sigma e^{R\sigma} e^{-V_0 \int_{t_0}^{t} e^{R\sigma} dt}, \quad (2)$$

where u_0 - the maximum elastic displacement at instantaneous destruction of the given treated CM area consisting from N_0 single elements; α – the loading speed; υ_0, r - constant, determining properties of treated CM; U_0 – maximum elastic displacement at instantaneous destruction of the given treating CM area consisting from N_1 single elements; V_0, R – constants, dependent on the treating CM characteristics; $\sigma = \alpha t(1-\alpha t)(1-g\sqrt{\alpha t}) - \alpha t_0(1-\alpha t_0)(1-g\sqrt{\alpha t_0})$;

t, t_0 – running time and time the beginning of CM elements destruction; g – coefficient, dependent on the geometrical sizes of CM elements.

Is conducted the simulation of AE signals, reshaped at CM machining with controlled cutting depth, for want of wear and with wear of the treating tool. It is shown, that the increase of treating tool wear and controlled cutting depth results in increasing of all AE resultant signal amplitude parameters (amplitude average level, amplitude average level standard deviation and amplitude average level dispersion). Thus with increasing of treating CM wear the increase of AE signal amplitude average level advances increase of amplitude average level standard deviation and amplitude average level dispersion.

In the actual CM machining technological processes the cutting depth is constant (not controlled). For a case of not controlled cutting depth, with allowance researches, reviewed in article [10], it is possible to conduct the analysis of influencing treating CM tool wear on the AE signals parameters. Such research introduces scientific and practical concern.

3. Research tasks

The purpose of article is the research of AE at CM machining with a not controlled cutting depth and a cutting tool wear from CM.

For achievement the purpose of article the following problems were put: - to conduct simulation of acoustic radiation at cutting tool from CM wear, arising during CM machining with a not controlled cutting depth; - to conduct statistical processing of AE amplitude parameters for want and wear of treating tool from CM, arising at CM machining with a not controlled cutting depth; - to determine regularity of AE amplitude parameters change at increasing the treating tool from CM wear, arising at CM machining with a not controlled cutting depth.

4. Researches results

For realization researches we shall accept CM machining conditions and conditions of acoustic radiation formation, as well as in article [10]. The acoustic radiation without cutting tool wear is reshaped at sequentially destruction of treated CM elementary areas. The acoustic radiation with cutting tool wear is reshaped at sequentially destruction of treated CM elementary areas and sequentially wears of treating CM elementary areas. In other words, the acoustic radiation is reshaped at the expense of AE signals pulse appearance at weep of two processes - at sequentially destruction of treated CM elementary areas and sequentially wears of treating CM elementary areas.

The resultant AE signal, agrees [10], it is represented by the way

$$U_p(t) = \sum_j U_j(t - t_j) + \sum_i U_i(t - t_i), \quad (3)$$

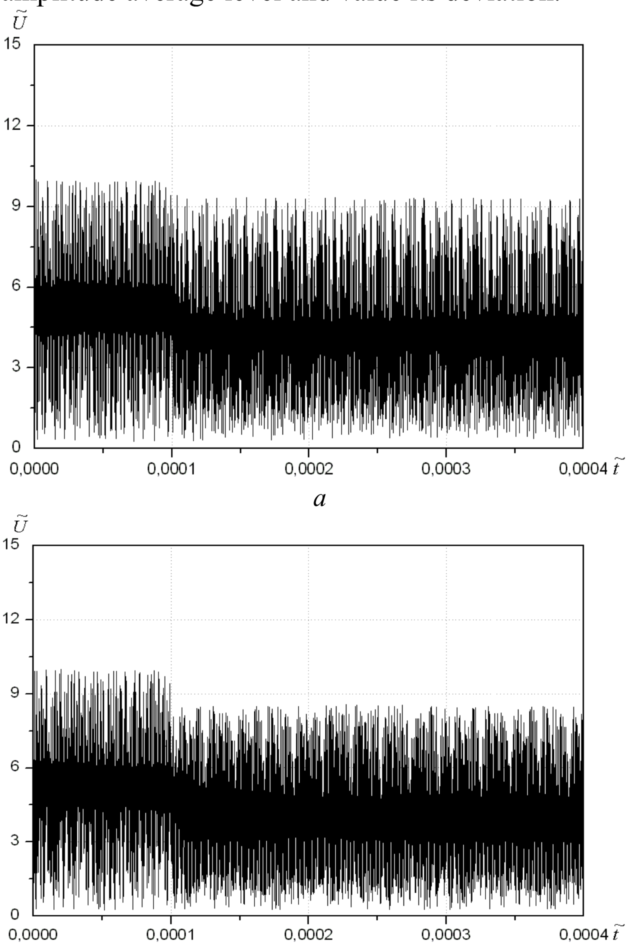
where $t_j = j\Delta t_j \pm \delta_1$ - instants of AE signals U_j appearance at destruction of elementary CM treated area; $t_i = i\Delta t_i \pm \delta_2$ - instants AE signals U_i appearance at wear (destruction) of elementary CM treating area; j - number of CM treated destruction areas or numbers of reshaped AE pulse signals U_j (j = 0,……, n); i - number of CM treating destruction areas or numbers of reshaped AE pulse signals U_i (i = 0,……, m); Δt_j - time interval between the beginning of the subsequent AE pulse signal U_j formation in relation to the previous signal; Δt_i - time interval between the beginning of the subsequent AE pulse signal U_i formation in relation to the previous signal; δ_1 - random component in an instant of each subsequent AE pulse signal U_j appearance; δ_2 - random component in an instant of each subsequent AE pulse signal U_i appearance.

The simulation of AE signals, agrees (3), we shall conduct under condition of absence and availability of treating tool wear in relative units. At simulation we shall consider, that treating tool wearing appear in some time t_0. As we shall consider, that the cutting depth is not controlled, i.e. increase of wear (CM treating destruction area) results in proportional decreasing of CM treated destruction area. The parameters u_0 and U_0 are proportional to the treated and treating CM elementary destruction areas (are proportional to quantity of N_0 and N_1 destruction elements). For want of treating tool wear the values of parameters u_0 and U_0 we shall accept equal: $\tilde{u}_0$=1, $\tilde{U}_0$=0. At appearance of treating CM wear in the moment of time t_0 values of parameters u_0 and U_0 we shall accept equal: $\tilde{u}_0$=0,9, $\tilde{U}_0$=0,1; $\tilde{u}_0$=0,8, $\tilde{U}_0$=0,2; $\tilde{u}_0$=0,7, $\tilde{U}_0$=0,3; $\tilde{u}_0$=0,6, $\tilde{U}_0$=0,4.

For realization of simulation all parameters, which one enter in expressions (1), (2) and (3), we shall put to non-dimensional values, and their values we shall accept same as well as in article [10]: $\widetilde{\upsilon}_0$ = 1000000; $\widetilde{r}$ = 10000; $\widetilde{V}_0$=1000000; $\widetilde{R}$=14000; $\widetilde{\alpha}$=10; $\widetilde{t}_0$=0,0001; $\widetilde{g}$=0,1; $\widetilde{\sigma}_0$=0,000995840884617491 7; $\widetilde{\Delta t}_j$=0,0000015; $\widetilde{\Delta t}_i$=0,0000015. Initial values of parameters $\widetilde{\delta}_1$ and $\widetilde{\delta}_2$ we shall change in range of sizes, accordingly, from 0 up to 0,0000049 and from 0 up to 0,0000049 arbitrarily.

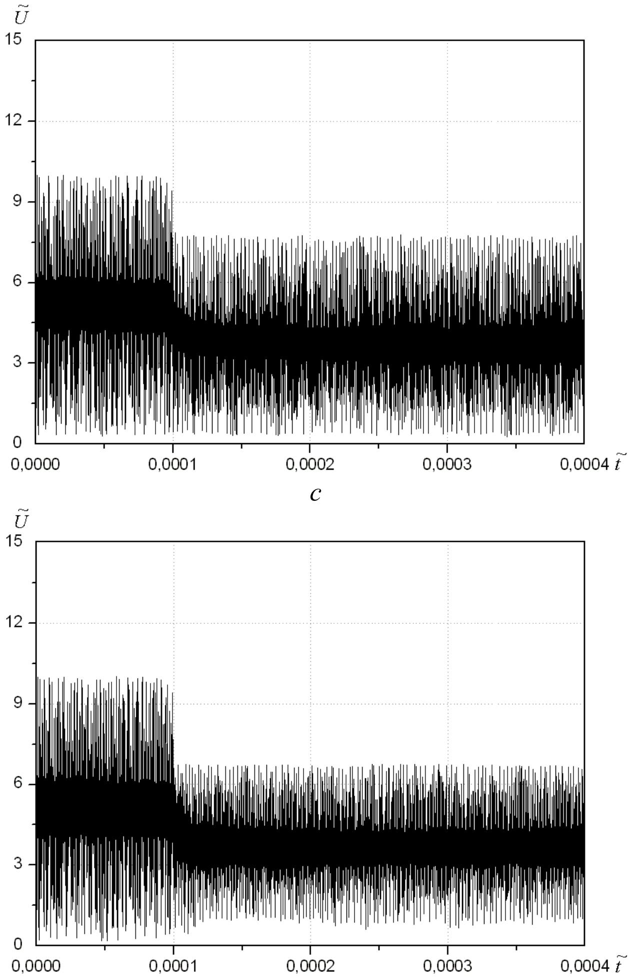
At simulation the calculations 5000 values of AE signal amplitudes for each pair values of parameters u_0 and U_0 were conducted. According to the conducted calculations for adopted conditions of simulation, in a fig. 1 the relations of AE signals amplitude change in time in normalized units are shown.

The conducted simulation has shown (fig. 1) that the CM treating wearing appearance and increase for a case of not controlled cutting depth not influences of acoustic radiation nature. The increase of treating tool wear results to decreasing of AE signals amplitude average level and value its deviation.



a

b



c

d

Fig. 1 - Relations of AE signals amplitudes change in relative units in time at CM machining with treating tool from CM wear. Time periods: 0 … .0,0001 - absence of tool wear; 0,0001 ….. 0,0004 - availability of tool wear. The values of parameters $\widetilde{u}_0$ and $\widetilde{U}_0$: on a time period 0….0,0001 - $\widetilde{u}_0$=1, $\widetilde{U}_0$=0; on a time period 0,0001…..0,0004 - *a* - $\widetilde{u}_0$=0,9, $\widetilde{U}_0$=0,1; *b* - $\widetilde{u}_0$=0,8, $\widetilde{U}_0$=0,2; *c* - $\widetilde{u}_0$=0,7, $\widetilde{U}_0$=0,3; *d* - $\widetilde{u}_0$=0,6, $\widetilde{U}_0$=0,4

As have shown outcomes data processing for want of treating tool wear AE signal amplitude average level ($\overline{\widetilde{U}}$), its standard deviation ($s_{\widetilde{U}}$) and dispersion ($s^2_{\widetilde{U}}$) in relative units make: $\overline{\widetilde{U}}$ =5,04126; $s_{\widetilde{U}}$=2,49876; $s^2_{\widetilde{U}}$=6,2438. At appearance of treating tool wearing, the value makes which one 0,1, there is decreasing of AE signal amplitude average level ($\overline{\widetilde{U}}$), its standard deviation ($s_{\widetilde{U}}$) and dispersion ($s^2_{\widetilde{U}}$) in relation to their values without tool wear, accordingly: in 1,17825 times, in 1,09083 times and in 1,18991 times. The increase of treating tool wearing up to 0,2 (in 2 times) results in decreasing of AE signal amplitude average level ($\tilde{\tilde{U}}$), its standard deviation ($s_{\tilde{\tilde{U}}}$) and dispersion ($s^2_{\tilde{\tilde{U}}}$) in relation to their values without tool wear, accordingly: in 1,25704 times, in 1,13627 times and in 1,29111 times. As have shown outcomes data processing at increasing tool wear up to 0,3 (in 3 times) the values of AE signal amplitude parameters $\tilde{\tilde{U}}$, $s_{\tilde{\tilde{U}}}$ and $s^2_{\tilde{\tilde{U}}}$ decrease, accordingly: in 1,32833 times; in 1,36966 times and in 1,87598 times. At increasing of tool wear up to 0,4 (in 4 times) the values of AE signals amplitude parameters $\tilde{\tilde{U}}$, $s_{\tilde{\tilde{U}}}$ and $s^2_{\tilde{\tilde{U}}}$ decrease, accordingly: in 1,3633 times, in 1,8275 times and in 3,33977 times.

The outcomes statistical data processing by the way of relations of AE signals amplitude parameters change at treating tool wear increasing and their percentage decreasing, in relation to AE signals parameters without tool wear, are shown in fig. 2.

From fig. 2, *a* it is visible, that increasing of CM treating tool wear results to not a scaling down statistical AE signals amplitude parameters. With increasing of tool wear decreasing of AE signals amplitude average level speed change is watched. At the some time, AE signals amplitude average level standard deviation speed change and AE signals amplitude average level dispersions speed change are augmented. Thus the percentage decreasing of AE signals amplitude average level standard deviation advances percentage decreasing of AE signals amplitude average level (fig. 2, *b*).

At the same time, the percentage decreasing of AE signals amplitude average level dispersion advances percentage decreasing of AE signals amplitude average level and its standard deviation (fig. 2, *b*).

The outcomes of the conducted researches demonstrate, that at CM machining with a not controlled cutting depth the originating of treating tool wear from CM does not influence on acoustic radiation nature. However is watched decreasing of AE signal amplitude average level and value of its deviation. The obtained outcomes will be agreed experimental data by the obtained different writers [8, 9]. The processing of outcomes simulation has shown that at increasing tool wear all statistical AE amplitude parameters decrease. Thus the decreasing of AE signals amplitude average level dispersion advances decreasing of AE signals amplitude average level its standard deviation. So, at increase of treating tool wear in 2 times percentage decreasing of AE signals amplitude average level, its

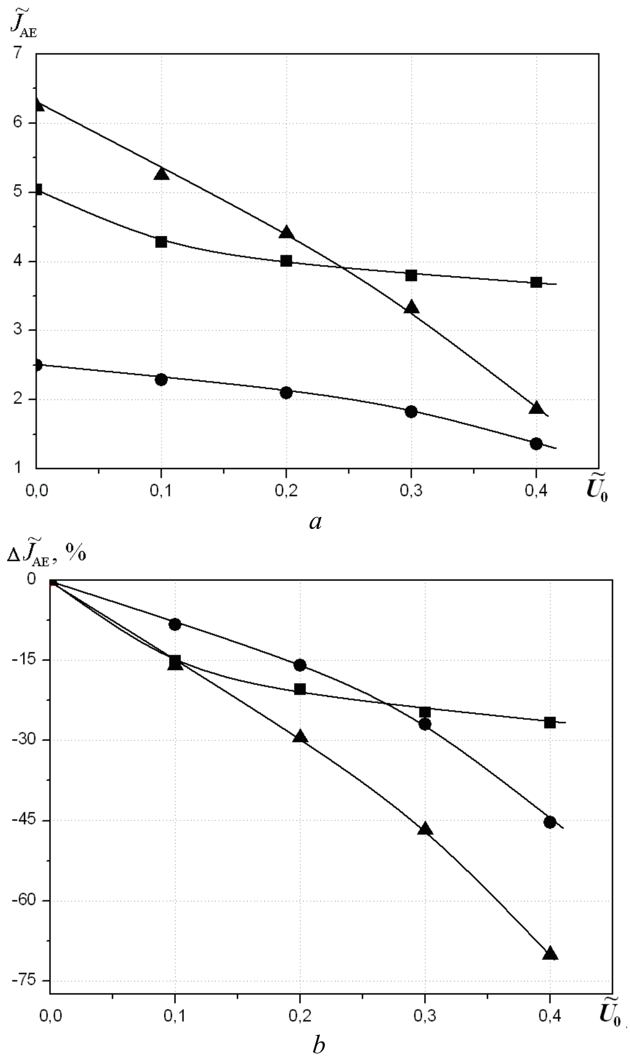


Fig. 2 - The graphs of AE signals amplitude parameters change (*a*) and their percentage decreasing (*b*) at CM machining with a not controlled cutting depth depending on treating tool from CM wear $\tilde{U}_0$: ■ - AE signals amplitude average level ($\tilde{\tilde{U}}$); ● - standard deviation ($s_{\tilde{\tilde{U}}}$) of AE signals amplitude average level; ▲ - dispersion ($s^2_{\tilde{\tilde{U}}}$) of AE signals amplitude average level

standard deviation and dispersions, accordingly, make: 20,448 %, 15,995 % and 29,431 %. At increase of treating tool wear in 4 times percentage decreasing of AE signals amplitude average level, its standard deviation and the dispersions, accordingly, already make: 26,649 %, 45,281 % and 70,059 %.

The decreasing of AE signal amplitude average level and value of its deviation is conditioned by the different contribution of AE signals components from CM treated destruction and treating wear in resultant acoustic radiation. Apparently, that dip of AE signals amplitude parameters at decreasing the CM treated destruction area advances increasing of AE signals amplitude parameters at increase of CM treating wear.

6. Conclusions

One of the tasks in a problem maintenance the given quality items from CM at their machining is the control and monitoring a cutting tool condition. For the solution a problem the control and monitoring of cutting tool condition usage AE method is possible.

The simulation of acoustic radiation at cutting tool wear from a CM, which one arises during CM machining with a not controlled cutting depth is conducted. The statistical processing of outcomes simulation with definition the AE signal amplitude average level, its standard deviation and dispersion values for want and availability treating tool wear from CM and not controlled cutting depth is made. AE signals amplitude parameters regularity change at increase of treating tool wear, for a case of not controlled cutting depth, are obtained. The relations of AE signals amplitude parameters percentage decreasing at increase of treating tool wear in relation to their values for want of wear are determined. It is shown, that at increase of tool wear decreasing of AE signals amplitude average level dispersion advances decreasing AE signals amplitude average level and value of its standard deviation.

The outcomes of conducted researches can be used at mining the methods verification cutting tool condition and control the CM machining parameters. These methods are of interest in the robotic technological processes, the monitoring and control by which one is possible for conducting through neuronal networks. It is necessary to conduct further AE researches, under a not controlled cutting depth condition, with the analysis of influencing cutting tool wearing on AE signals energy parameters.

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С.Ф. Філоненко

Акустична емісія при зносі обробного інструменту з не керованою глибиною різання

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680
E-mail: fils0101@gmail.com

Мета: Метою роботи є дослідження акустичної емісії при механічній обробці композиційного матеріалу з не керованою глибиною різання і зносі ріжучого інструменту з композиційного матеріалу. **Методи дослідження:** В основі досліджень лежить моделювання акустичного випромінювання, яку виникає при руйнуванні поверхневого прошарку оброблюваного композиційного матеріалу і зносі обробного інструменту. Розглядався випадок переважного механічного руйнування поверхневого прошарку оброблюваного композиційного матеріалу, а знос інструменту відбувається без зміни глибини різання. Була проведена статистична обробка амплітудних параметрів акустичної емісії при відсутності і виникненні зносу обробного композиційного матеріалу. Був проведений аналіз закономірностей зміни амплітудних параметрів акустичної емісії, а також їх чутливості до зносу обробного композиційного матеріалу при не керованій глибині механічної обробки. **Результати:** Визначено, що зростання зносу обробного композиційного матеріалу супроводжується зменшенням статистичних амплітудних параметрів акустичної емісії – середнього рівня амплітуди, його стандартного відхилення та дисперсії. Отримано закономірності зменшення амплітудних параметрів акустичної емісії при зростанні зносу обробного композиційного матеріалу. Визначено процентне зменшення амплітудних параметрів акустичної емісії при зростанні зносу обробного композиційного матеріалу, по відношенню до їх значень без зносу інструменту. Показано, що зменшення дисперсії середнього рівня амплітуди акустичної емісії випереджає зменшення середнього рівня амплітуди и його стандартного відхилення. **Обговорення:** Проведено моделювання акустичного випромінювання при переважному механічному руйнуванні поверхневого прошарку оброблюваного композиційного матеріалу з не керованою глибиною різання і зносі обробного композиційного матеріалу. Показано, що зростання зносу інструменту приводить до зменшення статистичних амплітудних параметрів акустичного випромінювання. Визначено, що зменшення дисперсії середнього рівня амплітуди сигналів акустичної емісії випереджає зменшення середнього рівня амплітуди і його стандартного відхилення. Зменшення середнього рівня амплітуди акустичного випромінювання і величини його розкиду обумовлено різним вкладом складових сигналів акустичної емісії, які виникають при руйнуванні оброблюваного і зносі обробного композиційних матеріалів. Очевидно, що при зменшенні площі руйнування оброблюваного композиційного матеріалу зменшення амплітудних параметрів виникаючих сигналів випереджає зростання амплітудних параметрів сигналів, які виникають при зростанні зносу обробного композиційного матеріалу. Результати проведених досліджень можуть бути використані при розробці методів контролю стану ріжучого інструменту і управлінні параметрами технологічного процесу механічної обробки. Дані методи представляють інтерес в роботизованих технологічних процесах, контроль і управління якими можливо проводити через нейронні мережі.

Ключові слова: акустична емісія; амплітуда; знос; композиційний матеріал; механічна обробка; статистичні характеристики.

С.Ф. Филоненко

Акустическая эмиссия при износе обрабатывающего инструмента с не управляемой глубиной резания

Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03680
E-mail: fils0101@gmail.com

Цель: Целью работы является исследование акустической эмиссии при механической обработке композиционного материала с не управляемой глубиной резания и износе режущего инструмента из композиционного материала. **Методы исследования:** В основе исследований лежит моделирование акустического излучения, которое возникает при разрушении поверхностного слоя обрабатываемого композиционного материала и износе обрабатывающего инструмента. Рассматривался случай преобладающего механического разрушения поверхностного слоя обрабатываемого композиционного материала, а износ инструмента происходит без изменения глубины резания. Была проведена статистическая обработка амплитудных параметров акустической эмиссии при отсутствии и возникновении износа обрабатывающего композиционного материала. Был проведен анализ закономерностей изменения амплитудных параметров акустической эмиссии, а так же их чувствительности к износу обрабатывающего композиционного материала при не управляемой глубине механической обработки. **Результаты:** Определено, что возрастание износа обрабатывающего композиционного материала сопровождается уменьшением статистических амплитудных параметров акустической эмиссии – среднего уровня амплитуды, его стандартного отклонения и дисперсии. Получены закономерности уменьшения амплитудных параметров акустической эмиссии при возрастании износа обрабатывающего композиционного материала. Определено процентное уменьшение амплитудных параметров акустической эмиссии при возрастании износа обрабатывающего композиционного материала, по отношению к их значениям без износа инструмента. Показано, что уменьшение дисперсии среднего уровня амплитуды акустической эмиссии опережает уменьшение среднего уровня амплитуды и его стандартного отклонения. **Обсуждение:** Проведено моделирование акустического излучения при преобладающем механическом разрушении поверхностного слоя обрабатываемого композиционного материала с не управляемой глубиной резания и износе обрабатывающего композиционного материала. Показано, что возрастание износа инструмента приводит к уменьшению статистических амплитудных параметров акустического излучения. Определено, что уменьшение дисперсии среднего уровня амплитуды сигналов акустической эмиссии опережает уменьшение среднего уровня амплитуды и его стандартного отклонения. Уменьшение среднего уровня амплитуды акустического излучения и величины его разброса обусловлено различным вкладом составляющих сигналов акустической эмиссии, которые появляются при разрушении обрабатываемого и износе обрабатывающего композиционного материалов. Очевидно, что при уменьшении площади разрушения обрабатываемого композиционного материала уменьшение амплитудных параметров возникающих сигналов опережает возрастание амплитудных параметров сигналов, которые возникают при увеличении износа обрабатывающего композиционного материала. Результаты проведенных исследований могут использоваться при разработке методов контроля состояния режущего инструмента и управления параметрами технологического процесса механической обработки. Данные методы представляют интерес в роботизированных технологических процессах, контроль и управление которыми возможно проводить через нейронные сети.

Ключевые слова: акустическая эмиссия; амплитуда; износ; композиционный материал; механическая обработка; статистические характеристики.

Filonenko Sergii. Doctor of Engineering. Professor.
Director of the Institute of Information-Diagnostic Systems, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Polytechnic Institute, Kyiv, Ukraine (1977).
Research area: diagnostics of technological processes and objects, automatic diagnostic systems.
Publications: 285.
E-mail: fils0101@gmail.com

ENVIRONMENT PROTECTION

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Inna Gosudarska

ANALYSIS RESULTS OF DISTRIBUTION FUNCTIONS FOR PROBABILITY DENSITY ASSESSMENT OF ACCIDENT LOCATIONS IN THE VICINITY OF THE AIRPORT

National Aviation University
Kosmonavta Komarova avenue 1, 03680, Kyiv, Ukraine
E-mail: gil_@mail.ru

Abstract

This paper contains the results of processing and statistical analysis of accident location data from the period 1973-2013 involving different types of large and light aircraft. The distribution of accident site locations which occurred during various phases of flight near-airport is presented. The analysis results of distribution functions are shown to estimate the probability density of accident locations during departures and arrivals. It is defined that the Weibull distribution and Gamma distribution are the most plausibly corresponded to describe the probability density of the accident site locations along the longitudinal and lateral coordinates relative to the runway centerline. The statistical characteristics of accident locations have obtained which took place in the vicinity of airports during take-off and landing phases of flight.

Keywords: aircraft accident location; airport; environment; Gamma distribution; probability density function; runway; Weibull distribution.

1 Introduction

The countries as well as airlines and the International Society have done so much to prevent and reduce the damages for different environment objects due to using of civil aviation. However, today the existing hazards and risks are still high that create the adverse conditions in the vicinity of airports that have resulted the loss of ecological and material resources including death of people. The great majority of aircraft accidents occur during final approach and the initial climb phases of a flight that take place in or immediately adjacent to the airport. All this leads to additional technogenic impact and can be cause disastrous consequences for people in the vicinity of the airport.

2 Analysis of the research and publications

The current approaches for estimating the probability density of accident site locations in the vicinity of airports (the NLR method [1], the DOE method [2] and the ACRAM method [3]) were analysed. Each method includes certain disadvantages and has differences because of the different selection criteria used.

The statistical data of the accident locations involving different types of large and light aircraft were collected for improving the accident location model. The analysis of accident location data was performed for an 40-period (1973-2013) which happened within runways and in the vicinity of airports related to different phases of a flight:

- takeoff phase that includes the takeoff roll and the initial climb,
- landing phase that includes the landing approach and the landing roll.

Finding data with details of aircraft type and by accident site locations was a more difficult task. The data was compiled from a large amount of accident reports published by Federal Aviation Administration [4], the National Transportation Safety Board [5], UK Civil Aviation Authority [6], the Bureau d'Enquêtes et d'Analyses [7], UK Air Accidents Investigation Branch [8]. A vast amount of data on accident locations including information on aircraft type and airport has been collected from the ASN Aviation Safety database [9] and the Transportation Safety Board of Canada database [10]. The ADREP (the International Civil Aviation Organization) database [11] was the preferred source for data because allows the accurate location data to obtain. Data was gathered from reviews of national organisation (the State Aviation Administration of Ukraine) [12] and international organisation (the Interstate Aviation Committee) [13] containing the complete record of the board's investigation of each accident. So, a selection of a certain number of data includes the review different types of aircraft accidents (such as take-off overruns, undershoots, overshoots, lateral veer-offs, landing overruns and etc.) which associated with the various operational phases near-airport. A sufficient number of accident site location data has been found to perform the calculations and for improving the accident location model.

3. Task

The task is to establish trends of accident site locations in the vicinity of airports and determine the distances of accident locations relative to the runway ends by using data set from different sources. Moreover, the estimating the probability density of take-off and landing accident locations for large and light aircraft based on accurate location data.

4. The distribution of take-off and landing accident locations in the vicinity of airports

The function of the accident site location for large and light aircraft is estimated in the form of dependency probability densities [14]:

$$f(x, y) = f(x) \cdot f(y, x),$$

where f (x) is the function of the longitudinal location along the runway and its the extended centerline;

f (y, x) is the function of the lateral distribution perpendicular to the runway centerline.

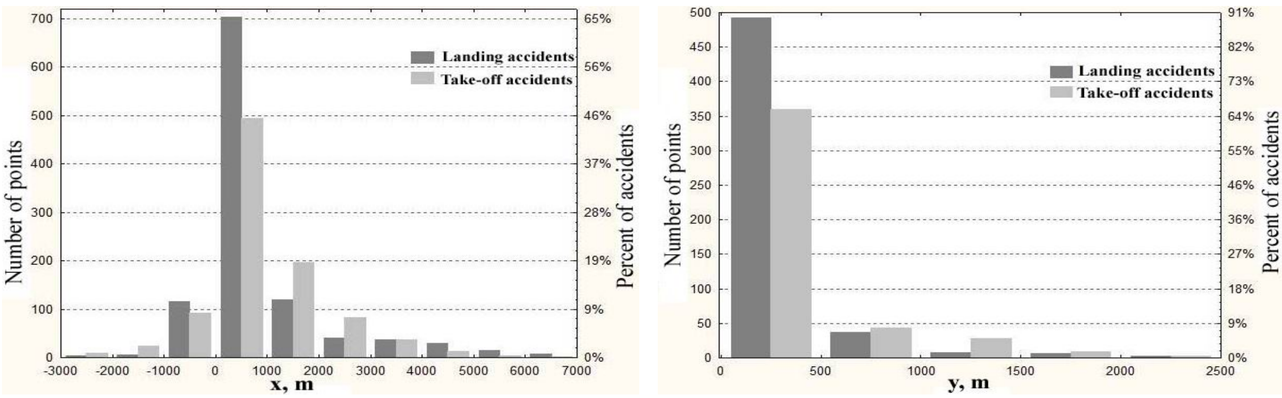
The accident location model for function of accident location has been investigated in form of two-dimensional probability density for longitudinal and lateral coordinates of accident sites during take-off and landing phases of flight. Results of processing of accident location data which happened within runways and areas around airports are represented in Figure 1.

Figure 1 shows the distribution of accident locations which occurred during various phases of flight near-airport in two dimensions:

the longitudinal distribution of locations from the runway end,

the lateral distribution of locations from the runway centerline.

The database resulting from this research contains a total of 2030 aircraft accidents which happened in one of the flight phases: overshoots (5 %), undershoots (26 %), take-off overruns (9 %), landing overruns (26 %), lateral veer-offs (14 %) and other uncategorized (20 %). The processing of statistical data and necessary calculations was performed by a computer system STATISTICA 8.0 [15].



a *b*

Fig. 1. The distribution of accident locations which happened during take-off and landing phases of flight: *a* – along runway centerline; *b* – perpendicular to the runway centerline

The statistical characteristics of the aircraft accident locations were obtained which occurred on the runways and in the vicinity of airports:

- landing accidents (the zero point on the axes is the landing end of the runway): arrival accident sites are concentrated within 1 km laterally from the runway centerline and extending outward to approximately 5-6 km of the runway end; the 65 % of the points lie within an area 500 m wide and extending some 1 km from the runway end;

- take-off accidents (the zero point on the axes is the take-off end of the runway): departure accident sites are spread within 1.5 km laterally from the runway centerline and extending outward to approximately 4-5 km of the runway end; the 46 % of the points are concentrated within an area 500 m wide and extending some 1 km from the runway end.

The analysis of the statistical data related to the accident sites has allowed to define that the great majority of aircraft accidents take place on or immediately adjacent to the runway. It was found that landing accidents tend to be concentrated close to the runway centerline. Furthermore, take-off accidents tend to be concentrated near the runway end, but are not as located close to the runway centerline as are the landing accidents. Since the landing manoeuvres are performed at "approach zone", so the arrival accident sites tend to be most closely bunched around the landing threshold. A comparison of the two images in Figure 1 indicates that arrival accidents sites tend to concentrated farther from the end of the runway than departure accident sites. The majority of departure accident sites in which the aircraft impacted with the ground are widely scattered relatively to the runway end.

The results of the investigation have showed that the probability of an aircraft accident during take-off and landing phases of flight in the proximity of the runway ends is higher than at larger distances from the runway end.

5 Estimating the probability density of take-off and landing accident locations for large aircraft

The distribution functions were used: the Weibull function, the Gamma function, the Log-normal function, the Normal function, the Poisson function, the Chi-Square function and Binominal function. These functions were used for statistical estimation the probability density of accident site locations. The range in values of the longitudinal and lateral coordinates (x, y) of accident site locations was broken into intervals with interval of 1 km and 0.5 km which corresponded to the number data set. Then the number of points were calculated which concentrated at i interval and the statistics Chi-Square was estimated to compare the probability density of accident site locations. The smaller value for the Chi-Square statistic means that more likely hypothesis is true. The larger Chi-Square value the greater the difference between observed and expected data. The Kolmogorov-Smirnov test and Chi-Square test were used to check the hypothesis.

The following Table I presents the analysis results of distribution functions to estimate the probability density for longitudinal coordinate of take-off and landing accident locations due to large aircraft.

As seen in Table 1, the Gamma distribution is the most correspond to describe the probability density of the accident site locations along the longitudinal coordinates in phase of take-off due to large aircraft (Table 1). The value of the Chi-Square statistics is 9.119 which supports this hypothesis. Since a p-value of 0.823 means that the observed data are consistent with hypothesis of the Gamma distribution (Fig. 2).

Table 1

Probability density assessment of longitudinal coordinate of accident site locations due to large aircraft

Assessment, distance	Distribution						
	Binominal	Poisson	Chi-Square	Log-normal	Gamma	Weibull	Normal
Take-off							
Kolmogorov-Smirnov distance							
Interval 0.5 km	0.455	-	0.512	0.067	0.025	0.043	0.086
Interval 1 km	0.303	-	0.343	0.062	0.023	0.026	0.079
Chi-Square test							
Interval 0.5 km	254.723	-	296.534	26.128	9.119	22.276	870.034
Interval 1 km	136.933	-	163.991	20.042	3.645	14.045	745.688
Landing							
Kolmogorov-Smirnov distance							
Interval 0.5 km	0.536	0.679	0.536	0.056	0.044	0.039	0.188
Interval 1 km	0.389	0.371	0.325	0.032	0.028	0.021	0.188
Chi-Square test							
Interval 0.5 km	231.229	546.734	226.242	43.698	23.809	28.048	441.981
Interval 1 km	357.631	321.64	252.17	17.237	13.668	12.223	271.623

Based on result of researches it was found that the Gamma distribution is more closely correspond to describe the probability density of the accident site locations along the longitudinal coordinates in phase of landing due to large aircraft (Table 1) and the Weibull distribution is for lateral coordinates. The calculated value of $\chi^2 = 1.017$ (Table 2) and the significance level of 0.961 support this hypothesis.

Table 2

Probability density assessment of lateral coordinate of accident site locations due to large aircraft

Assessment, distance	Distribution						
	Binominal	Poisson	Chi-Square	Log-normal	Gamma	Weibull	Normal
Take-off							
Kolmogorov-Smirnov distance							
Interval 0.5 km	0.257	0.254	0.213	0.053	0.024	0.039	0.143
Interval 1 km	0.137	0.137	0.137	0.033	0.013	0.021	0.143
Chi-Square test							
Interval 0.5 km	994.746	600.141	60.935	29.935	8.157	3.719	620.328
Interval 1 km	6.973	6.973	6.973	16.297	0.638	0.776	282.7
Landing							
Kolmogorov-Smirnov distance							
Interval 0.5 km	0.148	-	-	0.099	0.018	0.101	0.293
Interval 1 km	0.052	-	-	0.026	0.009	0.021	0.192
Chi-Square test							
Interval 0.5 km	8.461	-	-	20.884	11.067	1.017	324.348
Interval 1 km	1.042	-	-	8.862	5.403	0.438	189.967

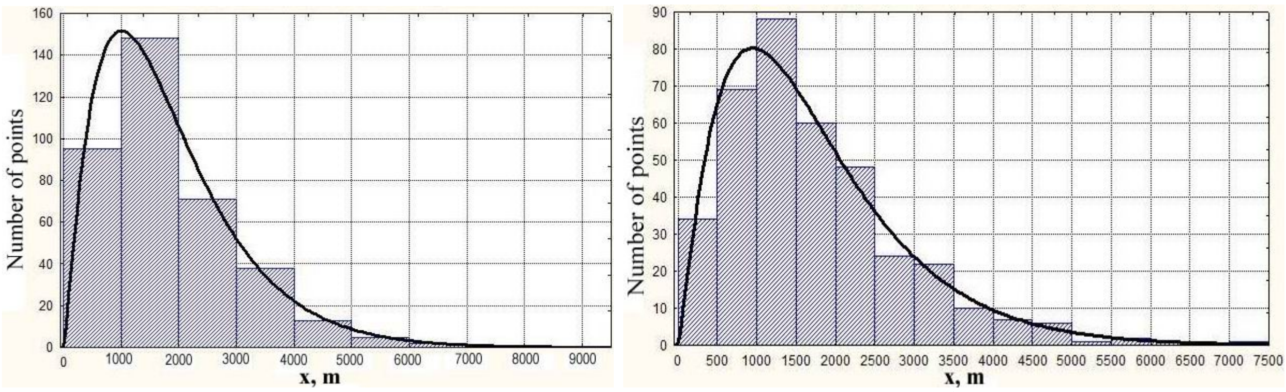


Fig. 2. The probability density of the Gamma distribution of longitudinal location for take-off accidents due to large aircraft: *a* – interval 1 km, *b* – interval 0,5 km

6. Estimating the probability density of take-off and landing accident locations for light aircraft

The analysis results of distribution functions to estimate the probability density for longitudinal coordinate of take-off and landing accident locations due to light aircraft are shown in Table 3.

From the obtained results it was deduced that the Gamma distribution is more closely correspond to describe the probability density of the accident site locations along the longitudinal coordinates due to light aircraft during take-off phase of flight.

Table 3

Probability density assessment of longitudinal coordinate of accident site locations due to light aircraft

Assessment, distance	Distribution						
	Binominal	Poisson	Chi-Square	Log-normal	Gamma	Weibull	Normal
1	2	3	4	5	6	7	8
Take-off							
Kolmogorov-Smirnov distance							
Interval 0.5 km	0.543	0.298	0.247	0.038	0.036	0.034	0.101
Interval 1 km	0.264	0.2	0.2	0.038	0.009	0.027	0.101

Table 3 (continued)

1	2	3	4	5	6	7	8
Chi-Square test							
Interval 0.5 km	248.402	832.332	121.98	20.175	6.283	7.351	182.768
Interval 1 km	29.336	16.8	16.8	19.12	1.848	0.077	104.349
Landing							
Kolmogorov-Smirnov distance							
Interval 0.5 km	0.575	-	0.575	0.057	0.056	0.052	0.218
Interval 1 km	0.204	-	0.154	0.049	0.027	0.024	0.181
Chi-Square test							
Interval 0.5 km	322.472	-	302.783	80.849	41.78	29.082	875.661
Interval 1 km	30.738	-	11.766	52.799	13.814	17.619	434.371

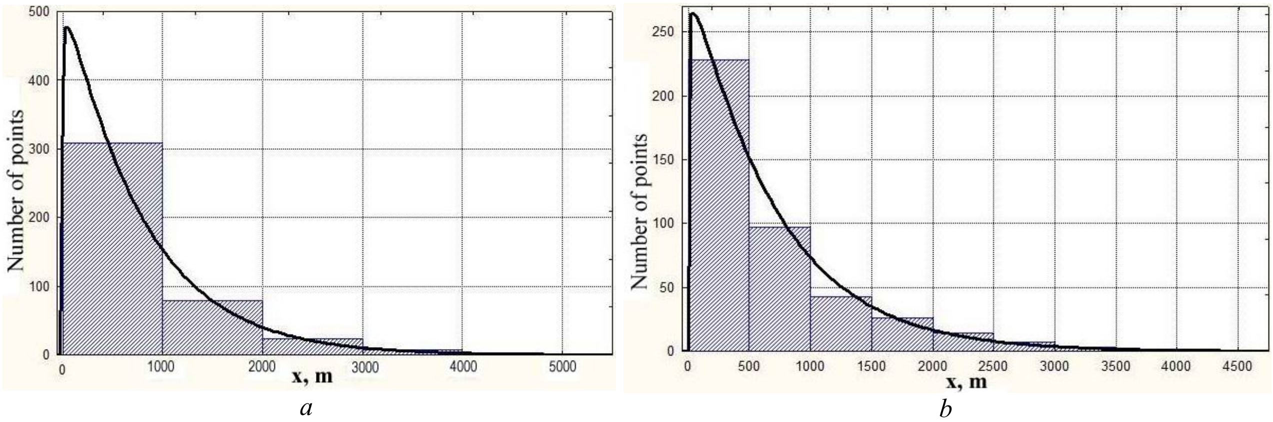


Fig. 3. The probability density of the Gamma distribution of longitudinal location for take-off accidents due to light aircraft: *a* – interval 1 km, *b* – interval 0,5 km

The chi-square calculated value is 6.283 which supports this hypothesis (Table 3). Since a *p*-value of 0.392 indicates that the observed data have not rejected the hypothesis of the Gamma distribution (Figure 3).

It was defined that the Gamma distribution and Weibull distribution are the most plausibly corresponded to describe the probability density of the accident site locations along the longitudinal coordinates due to light aircraft during landing phase of flight (Table 3).

The analysis results of distribution functions for probability density assessment of lateral coordinate for take-off and landing accident locations due to light aircraft are approximately the same.

6. Results

The longitudinal and lateral distribution of take-off and landing accident locations due to large and light aircraft are modelled using the Weibull function (Figure 4 and Figure 5).

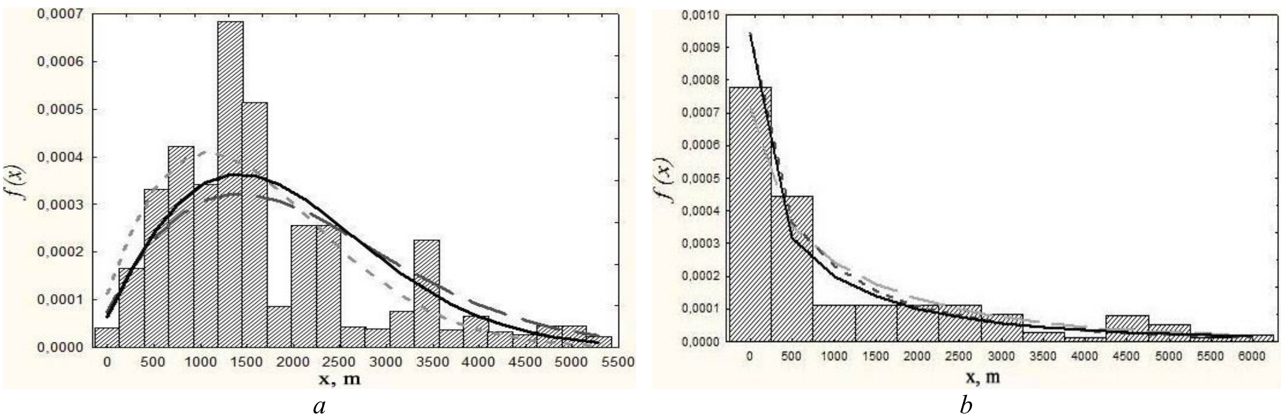


Fig. 4. Weibull distribution to describe the longitudinal coordinates of accident locations due to large aircraft: *a* – take-off, *b* – landing

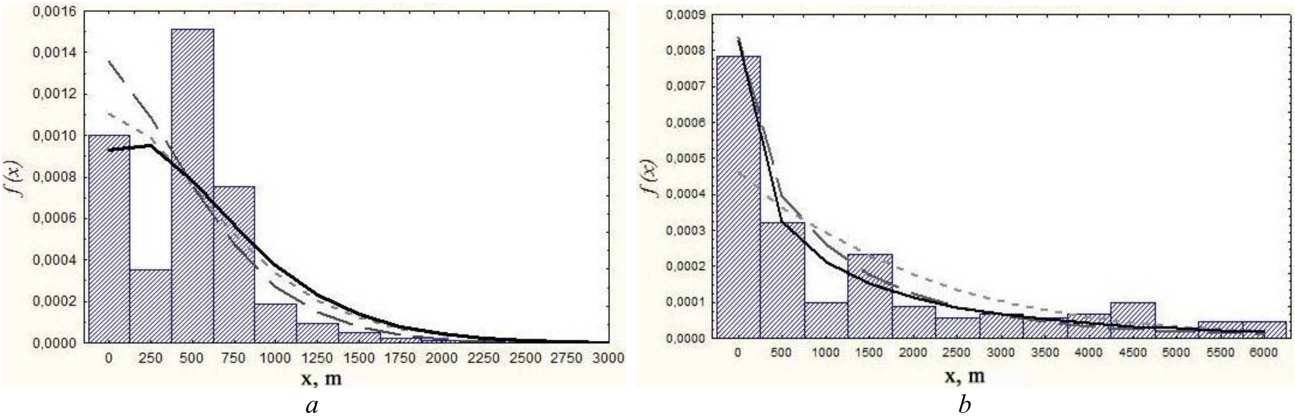


Fig. 5. Weibull distribution to describe the longitudinal coordinates of accident locations due to light aircraft: *a* – take-off, *b* – landing

The longitudinal distribution of accident locations due to large and light aircraft along the runway and its extended centerline are modelled using the Gamma function.

As a result, it was concluded that the Gamma distribution (1) and Weibull distribution (2) are the most plausibly corresponded to describe the probability density of the accident site locations along the longitudinal and lateral coordinates of aircraft accidents due to large and light aircraft during take-off and landing phases of flight:

$$f(x,\alpha,\beta)=\frac{1}{\beta^{\alpha}\Gamma(\alpha)}x^{\alpha-1}exp\left[-\left(\frac{x}{\beta}\right)\right] \qquad 1$$

$$f(x,\alpha,\beta)=\frac{\alpha}{\beta^{\alpha}}x^{\alpha-1}exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right] \qquad 2$$

7. Conclusions

The accident location data involving different types of large and light aircraft has been collected. The analysis of worldwide aircraft accidents related to take-off and landing phases of flight has been performed for the period 1973 to 2013 which occurred within runways and in the vicinity of airports. The processing of data points has been performed by the computer system STATISTICA 8.0 that include the following accident types: the lateral veer-offs, the overshoots, the undershoots, the take-off overruns and landing overruns. Based on result of researches, it is found that a vast amount of aircraft accident sites tend to be concentrated close to the runway ends and relatively near the extended centerline.

From an analysis of the obtained results it was determine that accident probability density decreases with increasing distance from the runway. The 60 % of the arrival accidents points are plotted within a narrow strip, approximately 500 m wide and extending some 1 km from the runway end. Also, almost 45 % of the departure accident points lie within an area 500 m wide and extending some 1 km from the runway end.

The analysis of distribution functions has been performed to estimate the probability density of accident locations due to large and light aircraft during take-off and landing phases of flight. The results of investigation have allowed to deduce that the Gamma distribution and Weibull distribution are the most plausibly corresponded to describe the probability density of the accident site locations along the longitudinal and lateral coordinates of aircraft accidents due to large and light aircraft during take-off and landing phases of flight.

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І.Л. Государська

Результати аналізу функцій розподілу для оцінки густини ймовірності розміщення місць авіаційних подій в околиці аеропорту

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680.
E-mail: gil_@mail.ru

Стаття містить результати обробки та статичного аналізу даних про місця розміщення авіаційних подій важких та легких повітряних суден, які сталися протягом 1973–2013 рр. Представлено розподіл розміщення місць авіаційних подій під час виконання різних етапів польоту поблизу аеропорту. Показано результати аналізу функцій розподілу для оцінки густини ймовірності розміщення місць авіаційних подій під час зльоту і посадки. Розподіли Вейбула і Гама визначені як такі, що з найбільшою достовірністю відповідають опису густини ймовірності розміщення місць авіаційних подій уздовж поздовжніх і поперечних координат відносно вісі злітно-посадкової смуги. Отримані статистичні характеристики місць, де трапляються авіаційні події під час зльоту і посадки повітряних суден в околиці аеропортів.

Ключові слова: аеропорт; довкілля; злітно-посадкова смуга; розміщення місця авіаційної події; розподіл Вейбула; розподіл Гама; функція густини ймовірності.

И.Л. Государская

Результаты анализа функций распределения для оценки плотности вероятности размещения мест авиационных происшествий в окрестности аэропорта

Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03680.
E-mail: gil_@mail.ru

Статья содержит результаты обработки и статического анализа данных про месторасположения авиационных происшествий тяжелых и легких воздушных судов, которые произошли на протяжении 1973–2013 гг. Представлено распределение размещения мест авиационных происшествий при выполнении различных этапов полета вблизи аэропорта. Показаны результаты анализа функций распределения для оценки плотности вероятности размещения мест авиационных происшествий во время взлета и посадки. Определено, что распределения Вейбулла и Гамма с наибольшей достоверностью соответствуют описанию плотности вероятности размещения мест авиационных происшествий вдоль продольных и поперечных координат относительно оси взлетно-посадочной полосы. Получены статистические характеристики мест, где совершаются авиационные происшествия во время взлета и посадки воздушных судов в окрестности аэропортов.

Ключевые слова: размещение места авиационного происшествия; аэропорт; взлетно-посадочная полоса; окружающая среда; распределение Вейбулла; распределение Гамма; функция плотности вероятности.

Gosudarska Inna (1979). Candidate of Engineering.
Department of Safety of Human Activities, National Aviation University, Kyiv, Ukraine.
Education: National Pedagogical Dragomanov University, Kyiv, Ukraine (2002).
National Aviation University, Kyiv, Ukraine (2004, 2008).
Research area: methods of third party risk assessments in the vicinity of the airports, ensuring ecological safety of airports.
Publications: 27.
E-mail: gil_@mail.ru

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Genadiy Yun[1]
Maxim Mazur[2]
Yuri Pederii[3]

ROLE OF UNMANNED AERIAL VEHICLES IN PRECISION FARMING

National Aviation University
Kosmonavta Komarova Avenue 1, 03680, Kyiv, Ukraine
E-mails: [1]yun@ua.fm; [2]maxtomas79@gmail.com; [3]ypederi@microsoft.com

Abstract

Purpose: *By 2050, world population will exceed 9 billion people. According to some projections to feed the world's population, the agricultural sector must increase production by 70%. The number of resources suitable for use in agriculture - land, water, energy - will decline. Here the farmers have to rely primarily on support of new technologies that not only increase production with limited resources, but also improve its effectiveness. Increased yields in crop production - a strategic task for Ukraine.* ***Discussion***: *The object of research is the comparative analysis of the market of production and export of wheat in leading countries of the world is carried out. As well as advanced direction of crop capacity increasing in agriculture with help of Unmanned Aviation System is considered.* ***Results:*** *Practice shows that rural aircraft exceeds the performance processing ground equipment several times. It allows you to quickly carry out crops and their processing by pesticides, toxic chemicals, to make fertilizer, to monitor. The use of modern unmanned aerial vehicles will extend the benefits of small aircraft.*

Keywords: agriculture; airplane; crop protection; perspective; technologies; pest control; productivity; unmanned aerial vehicle; unmanned aircraft systems; wheat.

1. Introduction

Ukraine has been playing significant role on global agriculture arena for decades being among top 10 exporters of agriculture products with 32.5M hectares of arable land producing 90-100M tons of cereal every year. In addition, Ukraine has 30% of world "chernozem" or black soil, one of the most fertile soils worldwide. From economical perspective, every second hryvna in Ukrainian GDP comes from agriculture sector that employs around 20% of its population.

In 2015 World Bank predicted that the global population will increases to 9 billion people by 2050 mostly driven by emerging countries like Brazil, India, China and Africa. According to some projections, to feed the growing population, the agricultural sector must increase production by 70%. The key challenge is that the number of resources available for use in agriculture will be reduced. Areas of arable land are relatively stable and global warming puts significant restriction on use of water and energy to produce incremental crop.

This challenge puts a lot of responsibilities and pressure on Ukrainian agriculture sector. Increasing yields in crop production is a strategic task for Ukraine. The current methods of cultivation used in Ukraine and other countries limited to traditional technologies are inefficient and prevent from reaching the goal to address the problem. The current methods used for land cultivation that rely on land machines and traditional aircrafts have many shortfalls in productivity, efficiency and flexibility.

2. Previous research and publications

The solution to this problem is possible on the basis of the creation of new high-yield crop varieties and new technologies of their cultivation; introduction of advanced and high-performance equipment, new forms of work organization in the agricultural sector. At the heart of the solution is precision agriculture concept that is a set knowledge intensive technologies, maximizing the use of agricultural resources, while reducing the cost of production to maximize performance and increase the profitability of land use. In mature agriculture countries precision agriculture is used for planning the workload, chartering of farmland, accounting field areas, monitoring of plant health condition and discriminatory application of fertilizers.

3. Research tasks

Various methods of information gathering, in particular from the aircraft, provide agronomic service relevant and reliable information on the field state: the problem areas, the development of plants, the effectiveness of fertilizers and herbicides use, efficiency and quality of agricultural machinery work, etc. Collected on a regular basis data form the basis for the solution of one of the most important tasks of agronomy that is forecasting yields.

4. Research results

Practice shows that agricultural aviation has advantages over ground equipment on the efficiency of field processing up to twelve times. It allows you to carry out aero seeding of some plants quickly, pesticides and other agriculture chemicals spraying, applying fertilizers, and carrying out monitoring. Furthermore, unlike conventional ground equipment, aircraft do not damage crops, and do not reserve the wheel track. This ensures additional harvest up to 6% and allows farmers to apply to spray crops when land machines cannot work in the field. For example, early spring or immediately after rainfalls, when soil is wet and wheeled vehicles simply cannot get in the field or late summer when crops are high (over 1 m) and tractors can damage the plants.

For timely sowing treatments needed either availability of technical equipment of farms with a large number of workers, or modern equipment with high-performance work. Timely processing of farmlands substantially limits the adverse weather conditions. In bad weather because of equipment downtime the best time for application of plant protection products is missed. So, it is extremely difficult to select herbicides which according to their mechanism of action do not relate to the dominant inhibitors in sowing of cereal crops for early spring application in a narrow temperature window.

Thus, in many cases, there is no alternative method to aviation. Its main advantage is high performance and efficiency of work, which allows optimal deadlines to process the field.

Currently the main air vehicle for crop spaying in Ukraine are airplanes An-2 and helicopters Mi-2. Most of the planes and helicopters of these models have long outlived their air worthiness, but even this equipment is in very short supply in domestic agriculture. The areas of farmland which need agricultural aviation spraying, account for about 30 722.2 thousand ha. One plane An-2 replaced the work of 5 – 10 tractor sprayers, processing 40 – 50 times more crops than a tractor sprayer per day. In addition, it saved 80 - 90% of labor costs. Agricultural aircraft operates in extremely difficult conditions. For better treatment of the plants in foreign practice may be used flights at a height of 1 – 2 meters from the ground and turns with banking angle up to 60°. It verges on the aerial acrobatics, exhausts a pilot and often leads to serious flight accidents. In the Soviet Union air spraying works were carried out without much damage to their quality at a height of 5 – 10 meters and followed by a climb and turn around maneuvers.

Advantages of the aircraft in the agricultural work are undeniable, if it flies over the flat field. Mountain slopes, broken ground, small fields require more maneuverable unmanned aerial vehicle (UAV). Its advantages are particularly valuable where it is impossible to arrange the runway, even for very light aircraft. Perfect landing characteristics of UAVs allow move the runway closely to the treated area. The advantages are obvious [1].

Efficiency of air assistants directly depends on the design features of the aircraft. One would think, does it matter what we use to spray fertilizers or chemicals? However, aircraft and high-performance chemicals made according to the latest requirements of farming, themselves do not provide economical and rapid processing of crops from the air. The chemical substance can be useful only if it is distributed evenly with a desired concentration on the treated surface. Meanwhile, the increase in the wing bearing capacity, or as they say in aerodynamics, increase the downwash flow, improves evenness of the chemical distribution on the surface to be treated. The lift in helicopter is created by dropping vertically down a large mass of air. Reflecting from the ground, such flow evenly covers both sides of the paper plant by pesticides, which is especially important in the processing of gardens and vineyards: pests of fruit crops usually nest on the underside of the leaf. At the same time this effect is limited to the speed of up to 40 km/hour and when helicopter flies above that speed the spraying characteristics are similar to those of fixed wing aircrafts. [2]

UAVs are produced in many countries of the world: the United States, Israel, Germany, France, Japan, China are the leaders. The majority of the UAV are military ones, and a pioneer in use of UAVs for agricultural purposes is Japan. Purposes of UAV usage are various – scaring the birds, spraying of areas, theft protection, creation of fields' maps, monitoring the evenness of germination and analysis of all the necessary nutrients to plants availability over a large area. With the help of the UAV you can fix the spread of plant diseases on time, purposefully apply fertilizers or spray chemicals against pests.

Back in the 80s of the last century, Japanese scientists have found that the planes over fields of farmers are not the best solution. Their use is limited by difficult terrain, power lines, trees, populated localities. Researchers concluded that the most effective are not big vehicles, controlled by people on board, but small flying robots, in other words – UAVs. Since then, the Ministry of Agriculture of Japan has been actively promoting this idea. Several models of UAVs that are used to monitor crops are developed in Japan. Then, in 1990 an unmanned helicopter Yamaha RMAX was introduced as a modern means for spraying crops. A small, of the size of a motorcycle, remotely controlled helicopter equipped with a 2.4-liter two-stroke engine is capable of carrying a working load of up to 28 kg and spraying chemicals at a speed of 24 km/h [3-4].

Table 1 provides a comparison of the UAV and aircraft An-2.

According to constructive features the UAVs are divided into the following types: airplane, helicopter.

According to flight time UAVs are divided into: short-range (1-2 hours), average (6-12 hours), and long-range (24-48 hours).

According to take-off weights they are divided into: ultralight (up to 5 kg); light (up to 200 kg); medium (up to 1000 kg) and heavy (over 1000 kg);

According to altitude they are divided into: low-altitude – up to 1000 m, medium-altitude – up to 10,000 m, altitude – up to 20 000 m.

Typical UAV system is equipped with modern onboard and ground equipment:

• autopilot, which allows you to perform agricultural work in automatic mode with the help of satellite navigation system GPS both day and night;

• special sprayer with rotary nozzles, with adjustable optimum dispersion spraying of the working fluid (from monodisperse mist to atomizing rain);

• equipment for scanning of the cultivated area and transmission of information on the phytosanitary condition of crops to a personal computer or the Internet, which make it possible to specify and adjust the flight mode and work in the system of "precise deceleration."

UAVs do not need specially prepared permanent or temporary airfields. Takeoff and landing of the aircraft is possible on flat ground, not larger than 150x15m, which should have open approaches. Furthermore, they can take off from crops during germination development, particularly those which need to be processed. UAV is equipped with a radio-controlled braking and taxiway systems for its exact movements on the ground. Flight altitude on the field (from 5m during daytime to 10 – 20m at night) is regulated and controlled by 4 systems (barometric, GPS, ultrasonic and laser-guided), which guarantees high safety of flight and quality of the spray. The problem of rapid evaporation of the drops with ultralow spraying in hot weather conditions (30 degrees Celsius and above) is solved by dilution of preparations in anti-evaporation agents, for example, using aqueous solutions of nitrogen fertilizers (carbomide-ammonium mixture, etc.) or a fertilizer with a high content of amino acids (Megafol, Megafol protein, izabion). It should be also taken into account that density of some agents like carbomide-ammonium is 1.4 of density of water that can impact the amount of spray liquid that UAV can carry and spray[5]

For several years the domestic UAV flight tests took place and the vehicles are almost ready for the implementation of the integrated use of modern pesticides and agrochemicals permitted for aircraft use in Ukraine.

Almost all kinds of work in agriculture, previously recommended for aviation method, can be performed using the UAV but, so far, sieving of mineral fertilizers and ameliorants with high application rate.

Table 1

Advantages of application Airplane An-2 and UAVs in the agricultural sector

An-2	UAV
- Large airborne time; - High load capacity; - High resistance to sharp wind changes;	- The possibility of taking off in almost any terrain without the preparatory engineering work; - The ability to stay in the high readiness practically unlimited time; - Shorter and cheaper training of operators of the UAV ground control stations as compared with the preparation of the crews of manned aircraft; - Significantly lower cost (for one or two orders less, depending on the purpose and parameters of UAV) and opening times of mass production; - Possibility of providing information to consumers in near real time; - Ability to work under high radiation, chemical and bacteriological pollution of air and ground, as well as adverse weather conditions as well as night operations - UAVs do not need specially prepared permanent or temporary airfields; - There is no danger to lose the pilot; - A more accurate radius spraying; - Low cost of operation.

With their help it is possible to apply modern herbicides, insectoacaricides, fungicides, growth retardants, macro and micronutrient fertilizers for foliar application, and other growth-regulatory substances. Also it is possible to apply biological plant protection products, in particular sieving over crops of beneficial insects (Trichogramma etc.). As an example, it is to be recalled that the massive losses of cereal crops because of Fusarium and Septoria during long continuous rains in growing season in 2014, when tractors could not go in the field for weeks, managed to escape thanks to the aircraft. All of these types of work require the use of agrochemicals in reasonably short windows of time, in the proper physical phase, with high quality spraying at the minimum allowable expenses of expensive drugs and with high hygienic and environmental safety.

Having analyzed the market of unmanned aerial vehicles which can fertilize a relatively large planting acreage, we should conclude the average processing acreage by these devices. Unmanned ultralight aircraft weighing up to 40 kg with a load capacity from 20 to 35 kg are designed for low-volume spraying with the norm of the working fluid flow rate from 1 to 10 l/ha, instead of 50 – 400 l/ha in normal conventional spraying of land machines, with a working speed of 80 – 120 km/h, with a spray width of 15 – 25 m, and in some cases – up to 100 m with onboard fogging machines. UAV performance under low-volume spraying is high: 60 – 100 ha/h, 600 – 1000 ha/day, which is higher than that of off-market An-2.

It should also be said about the economic benefits of the treatments associated with a sharp fall in transportation of water (50 – 100 times), preparation and loading of working fluid in the sprayer tank, decrease in the number of auxiliary workers. But it is especially important to the reduction of energy consumption by using UAVs: for the treatment of 1 hectare of crops is enough from 10 to 200 ml of fuel. In such a case the cost of crops treatment is significantly lower than when using ground sprayers. They are able to introduce fertilizers and pollinate pests with small doses of chemicals that reduce the consumption of chemicals by about a third. Due to the greater maneuverability, some UAVs spray the crops almost without leaving the field. [8]

Other UAVs equipped with camera and weighing less than 700 grams can stay in the air for up to 45 minutes. During this period they are able to carry out aeroplane mapping (aerial photography, aerial mapping) of an area of size from 1.5 to 10 square kilometers. Cruising speed ranges from 36 to 57 km/h, radio contact with the operator can be kept at a distance of 3 km. UAV is able to withstand wind gusts of up to 12 m/s.

If we compare relatively low cost of UAV with enormous economic benefits that we get from the use of this miracle of technology, it becomes clear how popular will the UAVs be in the near future. This "robotics" of agriculture first of all will get interested the owners of large farms, where is difficult to keep track of how each leaf looks like, how is the growth of plants going, how is the color of the soil changing.[6-7]

Today, to manage a large farm is not easy. Because of the immensity of the fields, farmers may not know the condition of the land in each area and process all fields the same as required. For example, in June, all the fields are sprayed with the preparation fungicide against fungi, regardless of whether they appear in July or not. UAVs can solve this problem without big expenses, flying over farms and making high-quality images. [9]The navigation system of UAV accurately identifies and indicates the coordinates of the area on the captured images. Then, using this data, it is possible to collect the whole picture and get an idea about the state of the fields. UAVs also notice the farmer of early harvest loss. First signs of the disease in plants appear in a change of chlorophyll, the green pigment involved in photosynthesis. With the help of infrared images diseased plants can be noticed in time and prevent crop damage.

5. Conclusion

Precision agriculture is one of the "hottest" topics in agricultural and IT-specialists circles, as Forbes writes [10]. Since the fourth quarter of 2013, investments in clean technology increased significantly – writes Forbes, citing data from research company “Cleantech Group” [11].

According to the Ukrainian “IST Agro Service” Company (Chernihiv region, Varva), the use of innovative UAV technologies in agriculture can improve productivity, reduce costs, make better use of resources, automatize and control manufacturing processes. As a result we can save up to $150/ha.

AeroDrone startup develops, manufactures and operates UAV systems for crop protection. In 2016 2 UAV systems with payload of 20 and 50 kg (Fig. 1) started operations on the real fields spraying insecticides, herbicides for winter crops of wheat, corn and sunflower. The first results are confirming the key conclusions in this article regarding spray productivity, costs, infrastructure, and so on. The team also got a good learnings on the spray process, UAV refilling between flights, spraying strategy and ready to apply this knowledge, scale production and operations in 2017.

End-user is interested in the effectiveness of the product and price policy. What you need to consider, intending to buy an unmanned aircraft systems (UAS)? In any case it is necessary to take into account all the factors: the cost of the UAS components, the cost of one minute work of the complex, its reliability, etc., that affect the final result of a system operation. Another important factor should also be taken into account– technical staff for the system maintenance, which still needs to be appropriately trained. However, these costs will be paid back quickly by the results of work of the system and savings.

Fig. 1. Agricultural UAV “PAM-20”

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Г.Н. Юн[1], М.С. Мазур[2], Ю.А. Педерий[3]

Роль безпілотних літальних апаратів під час виконання сільськогосподарських робіт

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680.
E-mails: [1]yun@ua.fm; [2]maxtomas79@gmail.com; [3]ypederi@microsoft.com

Мета: До 2050 року населення Землі перевищить 9 мільярдів чоловік. За деякими прогнозами, щоб прогодувати населення планети, аграрному сектору доведеться збільшити виробництво на 70%. При цьому кількість ресурсів, придатних для використання в сільському господарстві - земля, вода, енергія, - буде скорочуватися. Тут аграрним виробникам доводиться сподіватися, перш за все, на допомогу нових технологій, що дозволяють не тільки збільшувати обсяги виробництва в умовах обмеженості ресурсів, а й підвищувати його ефективність. Підвищення врожайності культур в рослинництві - стратегічне завдання для України. **Результати:** Об'єктом дослідження виступає порівняльний аналіз ринку виробництва і експорту пшениці в провідних країнах світу, а також розглядаються перспективні напрямки підвищення врожайності зернових в сільському господарстві за допомогою безпілотних авіаційних комплексів. **Обговорення:** Практика показує, що сільгоспавіація перевищує по ефективності обробки наземну техніку в кілька разів. Вона дає можливість в короткі терміни проводити посів культур, їх обробку пестицидами, отрутохімікатами, вносити добрива, вести моніторинг. Використання сучасних безпілотних літальних апаратів розширить переваги малої авіації.

Ключові слова: безпілотний літальний апарат; безпілотні авіаційні системи; боротьба зі шкідниками; засоби захисту рослин; літак; перспективні; технології; продуктивність; пшениця; сільське господарство.

Г.Н. Юн[1], М.С. Мазур[2], Ю.А. Педерий[3]

Роль беспилотных летательных аппаратов при выполнении сельскохозяйственных работ

Национальный авиационный университет, ул. Космонавта Комарова, 1, Киев, Украина, 03680.
E-mails: [1]yun@ua.fm; [2]maxtomas79@gmail.com; [3]ypederi@microsoft.com

Цель: К 2050 году население Земли превысит 9 миллиардов человек. По некоторым прогнозам, чтобы прокормить население планеты, аграрному сектору придется увеличить производство на 70%. При этом количество ресурсов, пригодных для использования в сельском хозяйстве - земля, вода, энергия, - будет сокращаться. Здесь аграрным производителям приходится надеяться, прежде всего, на помощь новых технологий, позволяющих не только увеличивать объемы производства в условиях ограниченности ресурсов, но и повышать его эффективность. Повышение урожайности культур в растениеводстве - стратегическая задача для Украины. **Результаты:** Объектом исследования выступает сравнительный анализ рынка и экспорта пшеницы в ведущих странах мира, а также рассматриваются перспективные направления повышения урожайности зерновых в сельском хозяйстве с помощью беспилотных авиационных комплексов. **Обсуждение:** Практика показывает, что сельхозавиация превышает по эффективности обработки наземную технику в несколько раз. Она дает возможность в короткие сроки проводить посев культур, их обработку пестицидами, ядохимикатами, вносить удобрения, вести мониторинг. Использование современных беспилотных летательных аппаратов расширит преимущества малой авиации.

Ключевые слова: беспилотный летательный аппарат; беспилотные авиационные системы; борьба с вредителями; средства защиты растений; самолет; перспективные; технологии; производительность; пшеница; сельское хозяйство.

Gennadiy Yun (1938) DS (Engineering), Professor.
Acting Dean of Transport Technologies Faculty of National Aviation University Kyiv, Ukraine.
Education: Kharkov Aviation Institute, Ukraine (1962).
Research area: Mathematical modeling and optimization of transport systems and technologies. Application of UAV in different sectors of economics.
Publications 130.
E-mail: yun@ua.fm.

Maxim Mazur (1993). Postgraduate student.
Education: National Aviation University of Kyiv, Ukraine (2015).
Department of Air Transportation Management Department, National Aviation University, Kyiv, Ukraine.
Research area: Role of unmanned aerial vehicles in agriculture
Publications: 4.
E-Mail: maxtomas79@gmail.com

Yuri Pederi (1976) BS, MBA. CEO and Founder AeroDrone enterprise.

Education: National Aviation University, Ukraine (1999),
Central European University and York University.
Research area: Crop sprying.
Publications: 4.
E-mail: ypederi@microsoft.com.

CHEMMOTOLOGY AND CHEMICAL TECHNOLOGY

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Sergii Boichenko

PHENOMENOLOGICAL CONCEPT OF CHEMMOTOLOGY

National Aviation University
Kosmonavta Komarova ave. 1, Kyiv, Ukraine, 03058
E-mail: chemmotology@ukr.net

Abstract

Aim: *of the article is consideration of goals and objectives of Chemmotology science. The paper presents a modern interpretation of science, its role in the development of technology and society.* ***Methods,*** *which were used for preparing the work include system analysis, systemology, formalization, hypothetic and abstract-logical methods.* ***Results:*** *It is shown that with the development of the range of modern fuel and lubricants, the development and promotion of alternative fuels, consideration of Chemmotology problems is impossible without systematic approach. In addition to the theoretical part of Chemmotology science, it is an integral component of the application, and whose task is to ensure energy and environmental security of the country's economy, rational use of traditional and alternative fuels and lubricants in the operation of a modern and advanced equipment.* ***Discussion:*** *The article focuses on the fact that in recent years one of the most important issues is the ecological constituent of Chemmotology, which is aimed on maximally possible minimization of the negative impact of fuel lubricants and technical liquids on ecosystems. Also processes of regeneration, restoration of quality, disposal and recycling of fuel and lubricants become highly relevant. In conclusion, this work shows that the fundamentality of Chemmotology science is the manifestation of systematic methodological characteristics in solving modern engineering problems in technical development and the development of energy sources for motor vehicles.*

Keywords: chemmotology; exploitation; fuels & lubricants; quality; system approach; technics.

1. Introduction

Rational use of fuel and lubricants, energy efficiency and environmental safety are among the most important problems of our time. Their solution largely determines the sustainable development of the world economy and the preservation of human comfortable conditions.

Science that became responsible for ensuring integrity in dealing with a variety of tasks connected to these problems, is Chemmotology [1–3].

2. Analysis of the research and publications

Encyclopedic concept of science defines it as a sphere of human activity, the function of which is the development and theoretical systematization of objective knowledge of reality [4, 5]. The direct goals of the science are description, explanation and prediction of the processes and phenomena of reality, which are the subject of its study on the basis of public law, i.e. the theoretical reflection of reality. Chemmotology possesses all these features [5–7].

The modern definition of Chemmotology is interpreted as following: *This is the science about the technological processes, properties, quality and methodology for the rational use of fuels, oils, lubricants and technical liquids in the operation of machinery* [8, 9]. It is necessary to consider both conventional and alternative fuels and lubricants.

Knowledge of technology involves not only knowledge of the design, kinematic, dynamic, temperature characteristics, but also the physical and chemical properties of construction materials needed for the analysis and prediction of physico-chemical processes during the application of a specific fuels and lubricants [2, 6, 10–12].

For example, the aircraft is a huge amount of metallic and composite parts, which are flying at a speed of 900 km/h (0.85 from the speed of sound, it is a typical speed of the Boeing 787 Dreamliner) at an altitude of 10 km. A couple of million parts are manufactured and assembled into one product and aircraft flies, providing comfort for passengers and profit for owners (Fig. 1).

Providing reliable and economical joint flight of these details, linking the most different requirements (load capacity, fuel consumption, flight range, noise during takeoff and landing, the requirements for the length of the takeoff and landing, the need for easy maintenance on the ground, the lack of icing, the safety of people on board and so on) is possible only with the help of system engineering approach, taking into account the requirements of a variety of specialists, representing a variety of professional and community groups [13, 14].

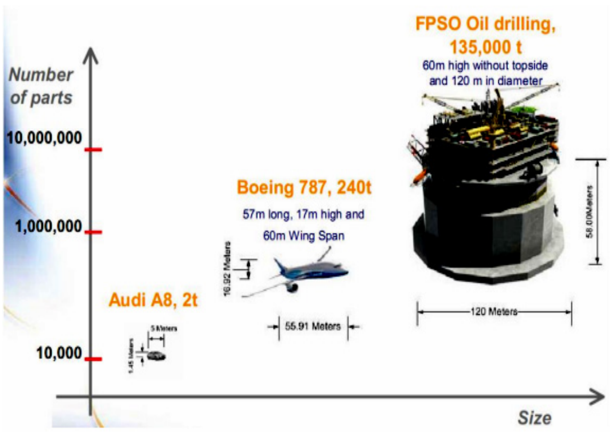

Fig. 1. Number of details and weight of some engineering constructions

Generalized utility function of fuels and lubricants as socially useful products (as opposed to a generalized function of vehicles) can not be described by the appropriate design documentation and drawings [8, 16]. Exactly this fundamental difference between the fuels and lubricants from mechanical engineering products objectively led to the emergence Chemmotology [2–5].

3. Main material

As we know from the classical scientific papers on Chemmotology [6, 12, 14–18], there is a universal four-tier Chemmotology system in any kind of machinery and equipment, which use fuel, lubricants and technical liquids (Fig. 2). This system takes into account the relationship between the quality of the fuels and lubricants, the reliability of equipment and the conditions of its operation [12, 15]. It can also be seen in Fig. 3 that shows an improved Chemmotology system.

Initially Chemmotology science is characterized by systematicity. Chemmotology, as well as system technology and system engineering, has such methodological tools in science and technology, which covers the design, development, testing and operation of complex systems. A certain extent it is an applied embodiment of systems theory in which the term "system" is used in a special way, referring to the way of thinking to explain coherent links between elements of the system, synergy and emergence. Here, the "system" expresses not only the essence, but also related to the nature of the object, emphasizes the class properties interesting point of view from here diversity of definitions and a huge number of possible ways the system decomposition and release of subsystems [18, 19].

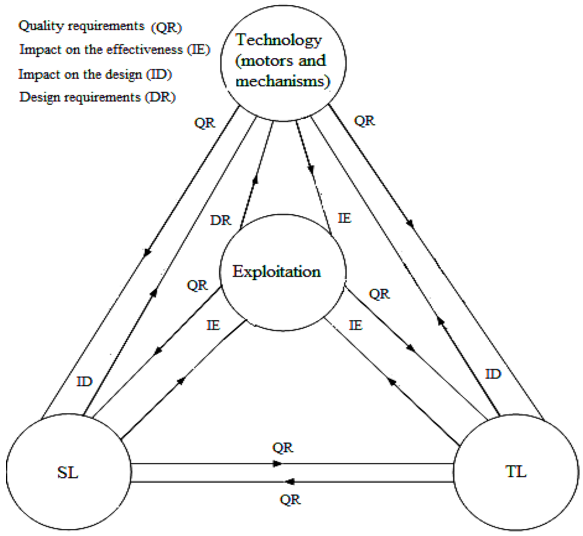

Fig. 2. Improved four-tier Chemmotology system

These thoughts can be seen in Fig. 3. It illustrates the integrated interdisciplinarity of Chemmotology, science system itself, it hierarchy, Chemmotology coherent connections, structure, nature, synergy and emergence [19–21]. It is clearly shown how the interaction of elements and coherent processes on the example of an aircraft engine result in synergistic and emergent effects: ecological compatibility, efficiency, reliability and durability of the equipment.

Currently, consideration of problems of Chemmotology beyond a systematic approach to knowledge is not possible. This is qualitatively higher than just a substantive way of knowing. (Synergies is summarizing effect of the interaction of two or more factors, characterized by the fact that their effect is much greater than the effect of each individual component in the form of a simple sum).

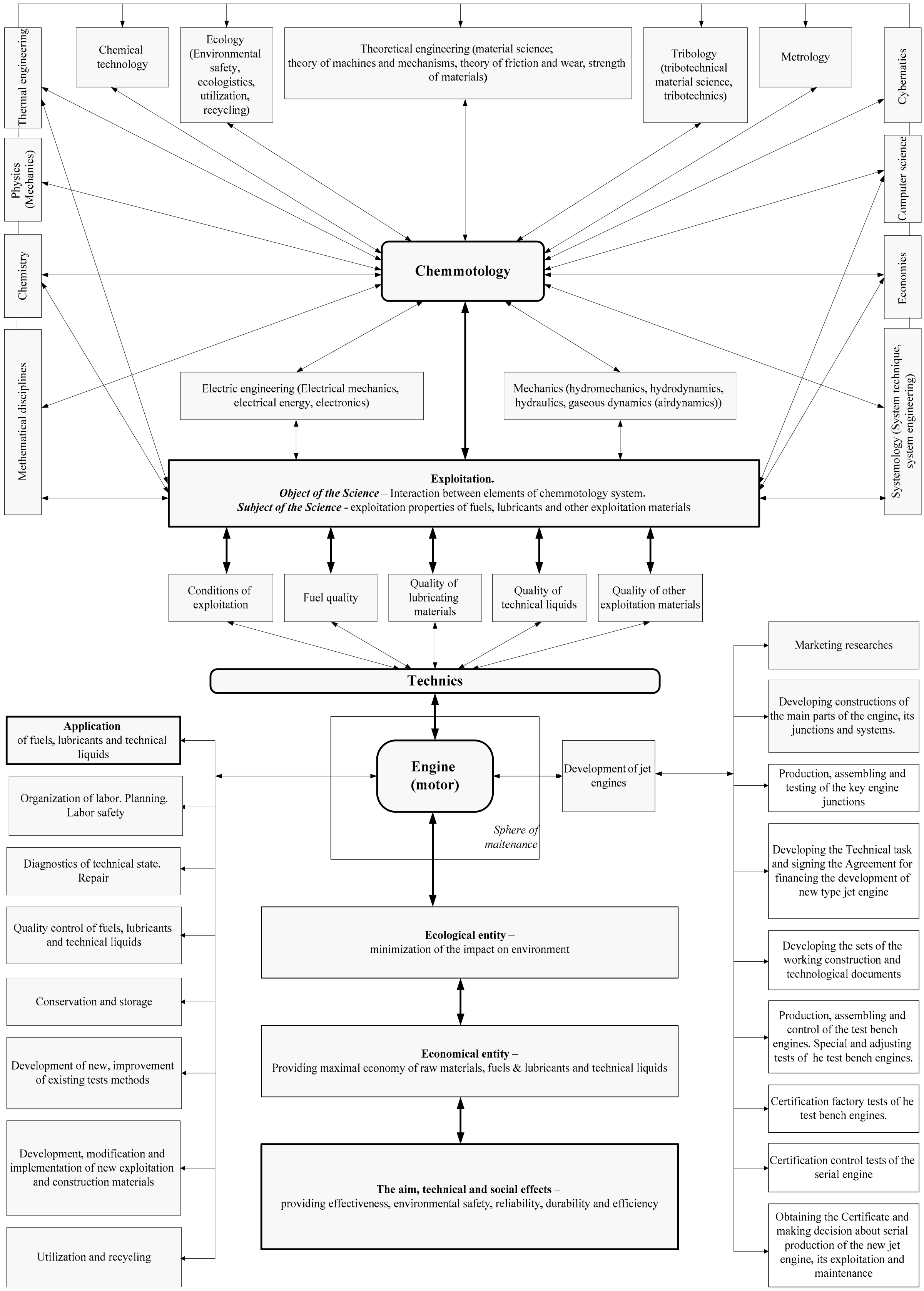

Fig. 3. The phenomenological scheme (model) of Chemmotology

"Emergence is quality, property of the system, which is not inherent in its elements separately, but instead rises by combining these elements into a single, integrated system."

From a philosophical point of view, we can easily state that Chemmotology science makes the consolidating function of system, integration of communication scholars and practitioners of engineering, chemical, oil-refining and petrochemical sectors of the economy, together with operators technique for solving evolution problems of scientific and technological progress. For example, refiners produce gasoline, diesel and other fuel, for further use in engines [22]. Knowing fuels, lubricants and technical liquids is to have a clear understanding of the relationship of indicators characterizing the quality of a physico-chemical and energy processes that occur during their use in specific conditions, and the relationship with their chemical and group composition.

The lack of such an analysis and forecasting makes it impossible to achieve the objective, technical and social effects. This is another clear evidence of synergy effects in the operation of Chemmotology system [22–24]. Quality control of fuels, lubricants and technical liquids plays a special role in Chimmotology on the way from their producer to consumer [25]. As we can see from Fig. 3 quality of exploitation materials is included into the parameter of the system itself. Practice has proved that the use of fuels, lubricants and technical liquids with the overestimated indicators of quality (quality level) leads to excess of costs in their production, and with reduced to cost escalation in mechanical engineering and operation of equipment.

As it is known consider any scientific problem is impossible without a coherent ideological system. Worldview, which selects a particular civilization, defines the whole character of the activities of society and its impact on the environment. On this basis, the ***environmental essence*** of Chemmotology is as far as possible to minimize the negative impact of fuels, lubricants and technical liquids on ecosystems [24–26].

The importance of tasks solved by the Chemmotology is shown by its role as an applied science: ensuring energy and environmental safety of the country's economy, rational use of traditional and alternative fuels, lubricants and technical liquids in the operation of a modern and advanced equipment [27].

Deterioration of fuels, lubricants and technical liquids quality is also typical for operation of technique in a result of evaporation, oxidation products accumulation, precipitation and leaching of some additives, mixing fuels, lubricants and technical liquids of different brands et al. (Fig. 3). Here become actual processes of regeneration, restoring quality, utilization and recycling [28, 29].

Classics of systematic approach indicates that the solution of any problem is characterized by the following elements:

1) Someone (or some group) should be put into the front of the problem, i.e. requires the existence of decision-making;

2) The purpose, desire of decision-making aimed at solving a problem situation that is its purpose and the basis for formulation of the problem and to achieve this goal

3) Decision-making should have a choice among alternative actions that lead to achieving the goal.

These arguments allow us to assert that Chemmotology system "engine-fuel-lubricants-technical liquid" is a management task, in which apply prescriptive and descriptive methods. Here we can trace Chemmotology coherence with cybernetics (which depicted connections in the upper part of Fig 3). At each stage of engine creation (the right side of Fig. 3), operation and application of SCL it's also demonstrates the need for decision-making (the left side of Fig. 3), which eventually is embodied in the synergetic result: to ensure efficient, ecological, reliable and economical operation of equipment.

4. Conclusion

Consequently, the fundamentality of Chemmotology science is the manifestation of the system of methodological characteristics for solving modern engineering problems, improving of technology and development of energy sources for motor vehicles simultaneously. Applying Chemmotology and acting its knowledge is possible to achieve significant results of scientific and technical progress in the technique. The concept of Chemmotology is the systematic integration of knowledge of engineering, chemical, oil-refining and petrochemical spheres of scientific and practical activities to achieve synergistic results in ensuring reliability, safety, durability and efficiency of equipment.

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Бойченко. С.В.

Феноменологічна концепція хіммотології

Національний авіаційний університет, м. Київ, просп. Комарова 1, 03058, Україна
E-mail: chemmotology@ukr.net

Мета цієї статті полягає у розгляді цілей та завдань науки хіммотології. У роботі представлено сучасне трактування науки, її роль для розвитку техніки і суспільства в цілому. **Методи**, що використовувалися при підготовці даної роботи включають системний аналіз, системологію, формалізацію, гіпотетичні та абстрактно-логічні методи. **Результати:** Показано, що з розвитком асортименту сучасних паливо-мастильних матеріалів, розробкою і популяризацією альтернативних палив, розгляд проблем хіммотології є неможливим без системного підходу. Крім теоретичної складової науки хіммотології, невід'ємною є і прикладна складова, завданням якої є забезпечення енергетичної та екологічної безпеки економіки країни, раціональне застосування традиційних і альтернативних паливо-мастильних матеріалів при експлуатації сучасної і перспективної техніки. **Обговорення:** У статті акцентується увага на тому, що в останні роки однією з найважливіших є екологічна сутність хіммотології, яка полягає у максимально можливій мінімізації негативного впливу паливно-мастильних матеріалів і технічних рідин на екосистеми. Крім того стають актуальними процеси регенерації, відновлення якості, утилізації і рециклінгу паливо-мастильних матеріалів. На закінчення даної роботи показано, що фундаментальність науки хіммотології полягає в прояві системних методологічних властивостей під час вирішення сучасних інженерних задач вдосконалення техніки і розвитку джерел енергії для двигунів транспортних засобів.

Ключові слова: експлуатація; паливно-мастильні матеріали; системний підхід; техніка; хіммотологія; якість.

Бойченко С.В.

Феноменологическая концепция химмотологии,

Национальный авиационный университет, г. Киев, просп. Комарова 1, 03058, Украина
E-mail: chemmotology@ukr.net

Целью данной статьи является рассмотрение целей и задач науки химмотологии. В работе представлено современное трактование науки, ее роль для развития техники и общества в целом. **Методы**, которые использовались при подготовке данной работы включают системный анализ, системологию, формализацию, гипотетические и абстрактно-логические методы. **Результаты:** показано, что с развитием ассортимента современных топливо-смазочных материалов, разработкой и популяризацией альтернативних топлив, рассмотрение проблем химмотологии невозможно вне системного похода. Помимо теоретической составляющей науки химмотологии, неотъемлимой является и прикладная составляющая, задачей которой является обеспечение энергетической и экологической безопасности экономики страны, рациональное применение традиционных и альтернативных топливо-смазочных материалов при эксплуатации современной и перспективной техники. **Обсуждение:** в статье акцентируется внимание на том, что в последние годы одной из важнейших является экологическая сущность химмотологии, которая состоит в максимально возможной минимизации негативного влияния топливо-смазочных материалов и технических жидкостей на экосистемы. Кроме того становятся актуальными процессы регенерации, восстановления качества, утилизации и рециклинга топливо-смазочных материалов. В заключение данной работы показано, что фундаментальность науки химмотологии состоит в проявлении системных методологических свойств при решении современных инженерных задач совершенствования техники и развития источников энергии для двигателей транспортных средств.

Ключевые слова: качество; системный поход; техника; топливо-смазочные материалы; химмотология; эксплуатация.

Boichenko Sergii (1968). Doctor of Sciences, Professor
Head of the department of ecology of the Education and research institute of Environmental safety, National Aviation University
Education: Kyiv Institute of Civil Aviation Engineers, Kyiv, Ukraine, 1992
Research area: Effective and rational use of fuels, lubricants and technical liquids, environmental protection
Publications: 250.
E-mail: chemmotology@ukr.net

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Oleksandr Davydenko[1]
Volodymyr Ledovskykh[2]

CARBOXYLIC ACIDS ELECTROOXIDATION ON SHUNGITE ELECTRODE

[1,2]National Aviation University
Kosmonavta Komarova avenue 1, 03680, Kyiv, Ukraine
E-mails: [1]dom237@ukr.net; [2]uchneftexim@bigmir.net

Abstract

Purpose: *This article discusses the electrochemical method of directional conversion of carboxylic acids, which are the most aggressive hydrocarbons oxidation products back into the corresponding hydrocarbons. Existing methods for the regeneration of waste petroleum oils have significant drawbacks, which include the formation of new hard-reclaimed waste and loss of a significant part of the oil during regeneration.* ***Methods:*** *Electrooxidation processes of carboxylic acid on various electrode materials: platinum, graphite and shungite anodes were studied.* ***Results:*** *Potentiostatic polarization curves with simultaneous measurement of near-electrode solution pH showed differences in the process on these anode materials: dimer yield for Kolbe is decreased under the transition from platinum to shungite. At potentials higher than 2.0 v, carboxylic acid has a higher adsorbability compared to water. Therefore Faraday's side-process of water oxidation doesn't almost occur, which contributes to high yield of expected product according to current. Electrolysis of carboxylic acids solutions under controlled potential (2.0 and 2.4 V) and chromatographic analysis of the formed products showed that along with the dimeric structures formation for Kolbe reaction, the occurrence of a hydrocarbons mixture takes place, which may be the result of disproportionation of hydrocarbon radicals (alkane and alkene) and hydrocarbons of isomeric structure, by further oxidation of the hydrocarbon radical to carbocation and its subsequent transformation into the corresponding saturated and unsaturated isomers. Such statement is not supported by conception of the process of one- and two-electron carboxylic acid oxidation.* ***Discussion:*** *General carboxylic acid oxidation scheme according to one-electron mechanism (dimerization and disproportionation of the radical) and two-electron mechanism (formation and carbocation rearrangement) is proposed. The formation of hydrocarbons under carboxylic acid electrooxidation of waste oils during their regeneration can promote the increase of oil yield without formation of dangerous by-products.*

Keywords: electro-oxidation; carboxylic acid; regeneration; shungite; waste oils.

1. Introduction.

The annual world usage of petroleum oils became widespread. In 2014, annual production reached 38.6 million tones. It is predicted that in 2019 the needs in oil will increase up to 42.8 million tones, which corresponds to 2.1% increase. Mineral oils make up 90% of total world production, while the synthetic oils – only 10%. At the same time the market of synthetic oils is developing more actively. Automotive oils make up 56.0% of the total oil production, industrial oils – 26.2%, processing oils – 9.4%, cutting oils – 5.3%, and grease – 3.1% [1].

Use of oils is accompanied by triggering of additives, accumulation of wear products, water, solids, and the progress of hydrocarbons oxidation. Hydrocarbons oxidation occurs according to radical chain mechanism through the stages of hydro- and dehydroperoxide formation, aldehydes and ketones are some of the degradation products. The last in their turn experiences further oxidation with the formation of carboxylic acids the content of which can be up to 1% by oil weight. They negatively affect the quality of oil and significantly increase its corrosivity. Due to mentioned above transformations oils no longer satisfy quality characteristics, especially such as the kinematic viscosity, acid number, flash point, base number, lubricating ability and require replacement, leading to formation of large quantities of hazardous waste – waste oils. [2]

There are several ways of disposing of waste oils the most promising one is the regeneration. Most of regeneration methods are based on oils adsorption and oils cleaning processes with sulfuric acid. These methods are rather effective but cause the formation of new and high difficultly recyclable waste [3]. Therefore the development of new methods for waste oils regeneration is a promising and topical task.

This work is dedicated to the research of electrochemical methods of carboxylic acid waste oils regeneration by means of electrochemical anodic oxidation up to hydrocarbons and to search for new effective electrode materials.

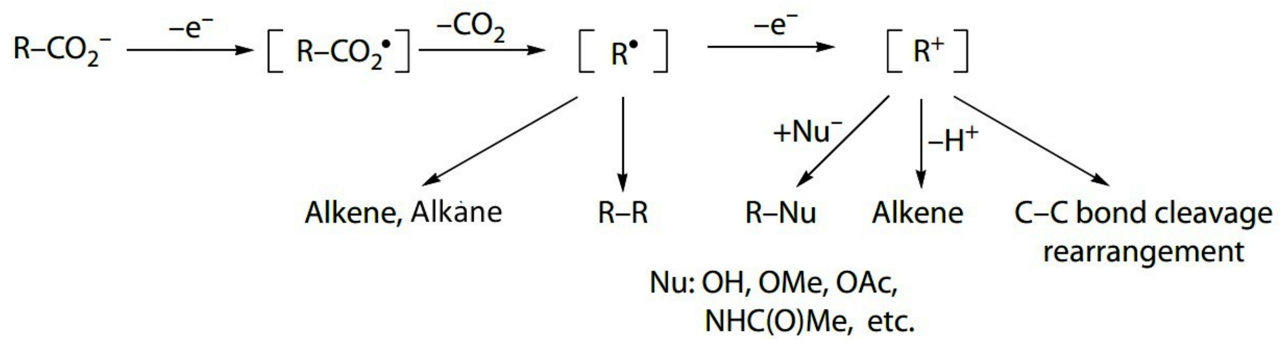
2. Analysis of the latest research

Kolbe reaction or anodic condensation process includes the electrochemical oxidation of carboxylic acids up to hydrocarbons which contain twice the number of carbon atoms relative to the initial acid. Kolbe electro-synthesis example is the formation of ethane and carbon dioxide by the electrolysis of acetate aqueous solutions [4].

$$2CH_3COO^- - 2e^- \longrightarrow 2CH_3COO\bullet \longrightarrow$$

$$2CH_3\bullet + 2CO_2 \longrightarrow CH_3CH_3$$

The reaction mechanism of the anode decarboxylation of carboxylic acids includes the step of forming a carboxylate radical which in its turn can be oxidized further to carbocation that depending on the conditions of the electrolysis process and an anode material leads to the following products [5]:



A typical anode, on which many of the researches are performed, is smooth platinum. But the use of platinum in industry is extremely expensive and is accompanied by a gradual removal of metal from an electrode. Therefore, the search for new electrode materials for anodic oxidation of the carboxyl compounds is an important scientific and technical challenge.

There are directions [4] for the implementation of Kolbe reaction on graphite anodes and at the same time yields in these cases are much lower than for platinum. Use of platinum is caused by having high overvoltage of water oxidation and corrosion resistance even at high positive potentials. For example, under electro-oxidation of sodium acetate aqueous solution, current output of dimeric product has made up: for a smooth Pt - 89%; for platinized Pt - 3%; for Au, Ni, PbO_2 - 0%; for retort coal - 21%; for graphite - 4.0%. One of the byproducts of the anode reaction are alcohols, although in some cases they are in fact the only product of the conversion, it is observed in alkaline media where the probability of encountering a hydrocarbon radical with hydroxide radical is significantly higher than with the hydrocarbon radical to form the dimeric structure of hydrocarbons. [4] In addition, in [4 - 6] works the optimum conditions for increasing the yields of products are not determined, namely the influence of the medium pH on the product nature and the ratio of their yields under electrolysis, and the possibility of reaction spreading from the alkali metal acetates to carboxylic acids of higher molecular weight.

A disadvantage of graphite anodes is large porosity and low mechanical resistance, due to that during electrolysis, electrode material is partially destroyed [7]. This thing prompted us to search for alternative electrode materials on which the process of anodic decarboxylation (Kolbe reaction) would pass satisfactorily and it would have high mechanical resistance. Our choice was focused on a natural mineral - shungite. Shungite is the final stage of natural graphite formation. It has high electrical conductivity and mechanical stability (Table. 1), making it perspective for use as a new electrode material.

3. Purpose

The focus of this paper is given to comparative research of course mechanisms of carboxylic acid electro-oxidation on various materials – platinum, graphite, shungite, to determine the possibility of applying for such processes shungite anodes and search for conditions of their performance in the transformation direction of the carboxyl compounds back into hydrocarbons, i.e. in the direction opposite to petroleum oil oxidation processes under their operation.

4. Experimental

Major world deposits of shungite are in the Republic of Karelia (Russia), and total about 1 billion tons. Main shungite mining is produced on Shungskom, Maksovo, Zazhoginskom, Nigozerskom, Myagrozerskom and Turastamozerskom deposits. There are known deposits on Kamchatka too. Mining is also underway on Koksuyskom deposit (49 million tons) in Kazakhstan. Small deposits of shungite are known in Austria, India and the Democratic Republic of Congo [8].

Comparison of the physical properties of natural graphite and shungite is shown in Table 1. [9-10].

Table 1

Physical properties of natural graphite and shungite

Index	Graphite	Shungite
Density, g/cm^3	1,9 - 2,6	2,1 – 2,4
Electric current resistivity, Ohm•m	5-30$\cdot 10^{-6}$	32,9 – 3,53$\cdot 10^{-3}$
Thermal conductivity, W/m•K	3,55	3,8
Thermal conductivity coefficient, W/m•K	10,87	5
Melting point (at P = 0.9 - 1 atm), °C	3845 - 3890	—
Boiling point, °C	4200	—
Combustion heat, kJ/kg	32769 - 32869	31380
Magnetic properties	diamagnetic	diamagnetic
Specific heat capacity (298,15 K), kJ/(kg•K)	0,79-0,81	0,98
Ultimate tensile strength, MPa	9,8 - 14,7	17534,6
Flexural strength, MPa	6,9 – 100	13062,2
Compressive strength, MPa	20 – 200	10054,75
Hardness according to Mohs scale	1 - 2	3 – 4
Porosity, %	30 - 32	0,5 - 5
Elasticity modulus (E), MPa	8 – 15$\cdot 10^3$	31 $\cdot 10^3$
Conductivity, S/m	125 $\cdot 10^6$	(1 - 3) $\cdot 10^3$
Average temperature coefficient of thermal expansion, 1/°C	1,2 – 8,2$\cdot 10^{-6}$	12$\cdot 10^{-6}$

From Table 1it is seen that shungite is an electrically conductive material but in comparison with the graphite it has a higher resistivity and lower electric current conductivity. At the same time, it has much less porous and substantially higher ultimate tensile strength, bending and compression. These shungite properties indicate the possibility of its use as an anode material instead of mechanically less stable graphite and especially expensive platinum.

Differences of graphite from shungite are explained by their nature and origin conditions and element characteristics and chemical composition (Tables 2 and 3). Unlike of graphite it has considerably lower carbon content, but contains more silicon, which is in the form of polymeric oxide SiO_2, and oxides of many metals that provide high mechanical stability [11].

Table 2

The main element composition of shungite and natural graphite

Element	Content, % (wt.)	
	graphite	shungite
F*	0,03060	—
Cl*	0,00200	—
Na*	0,00300	0,27000
Mg*	0,01980	0,34000
Al*	0,02060	1,46000
Si*	0,13000	17,01000
P*	0,00040	0,02000
S*	0,07270	0,37000
K*	0,00170	0,51000
Ca*	0,02130	0,09000
Ti*	0,00080	0,14000
V	0,00030	0,01500
Cr	0,00010	0,00720
Mn	0,00060	0,09000
Fe	0,09360	0,91000
Co	0,00010	0,00014
Ni	0,00140	0,00850
Cu	0,00350	0,00370
Mo	0,00080	0,00310
Ba	0,00090	0,32000
As	0,00001	0,00035
Pb	0,00010	0,02250
Zn	0,00020	0,00670

C	matrix	26,26000

* for these elements in shungite, content is calculated on the basis of their oxide contents

Table 3

Averaged chemical composition of oxides in shungite

Components	Content, % (wt.)
SiO_2	18,793
TiO_2	0,457
Al_2O_3	4,287
Fe_2O_3	3,67
FeO	0,34
MnO	0,006
MgO	1,193
CaO	0,293
Na_2O	0,14
K_2O	1,723
(H_2O)	2,05
P_2O_5	0,07
Cr_2O_3	0,02
V_2O_5	0,256
CoO	0,002
NiO	0,021
CuO	0,007
ZnO	0,01
$S_{зar}$.	2,833
Wastes under decrepitation	68,4

For experimental researches of carboxylic acid electro-oxidation, we used natural shungite, the chemical content of which was determined by X-ray spectroscopy (Table 4). The carbon content in the graphite anode, which was used for comparative electrochemical measurement was 91.5% (Table 5).

Table 4

The chemical composition of natural shungite used as an electrode material for electrochemical measurements in this paper.

Components	Content, % (wt.)
SiO_2	51,6
TiO_2	0,18
Al_2O_3	3,04
Fe_2O_3	1,07
MnO	-
MgO	0,6
CaO	0,66
Na_2O	-
K_2O	1,27
P_2O_5	0,87
Cr_2O_3	-
V_2O_5	0,019
Co_3O_4	-
NiO	0,028
CuO	-
ZnO	0,012
SO_3	5,4
BaO	0,026
Au	0,011
ZrO_2	0,012
Cl	0,2
C	35
Lanthanides	0,004

Table 5

Physical and chemical properties of natural graphite used for experimental researches

Index	Value
Specific electric resistance, Ohm·mm^2/m, more	150
Flexural strength, MPa Compressive strength, MPa	200 500
Rockwell hardness under a load of 60 kg, HRB	50-75

As a model substance which contains a carboxyl group we used chemically pure hexanoic acid: $CH_3CH_2CH_2CH_2CH_2COOH$, M = 116.16 g/mole, t_{mel} = - 3.4°C, t_{boil} = 202°C. Solution neutral pH of output media was put with NaOH.

Polarization measurements were performed on a potentiostat P-5827M, where we used three electrode thermostated chamber (10 °C) with a working electrode made of natural shungite, graphite and platinum, a platinum wire separated from the working electrode with a porous glass septum was an auxiliary electrode, potentials were measured against a silver chloride electrode, and enumerated according to a normal hydrogen scale. At the same time pre-anode layer pH (pH-meter pH-150MI) was measured during the measuring of anodic polarization.

Preparative electrolysis of hexanoic acid solution under concentration of 0.5 mol/L we carried out under controlled potential (potentiostat) of shungite, graphite and platinum electrodes (E_{work} = 2.0 - 2.4 V (HBE)), the current of the electrochemical process was measured by milli-ammeter M2020 with a scale of 1 micron uA.

To determine the products of electrooxidation carboxylic acid – the analyte – was subjected to isooctane extraction followed by chromatographic analysis (gas chromatograph Crystal 5000.2 with capillary columns and temperature programming device). To identify the peaks we used standard samples of substances.

5. Results discussion

Fig. 1 shows the potentiostatic polarization curves of shungite, graphite and platinum in the background solution and Fig. 2 shows the corresponding curves of pH dependence on potential during measuring of potentiostatic polarization curves.

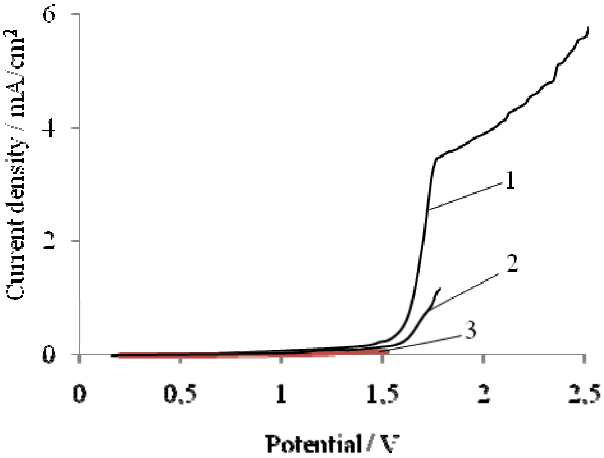


Fig. 1 Potentiostatic polarization curves of various anodes in the aqueous neutral background solution: 1– platinum; 2 – shungite; 3 – graphite.

According to potentiostatic polarization curves (Fig 1.) we can see areas of water oxidation, which exist under potentials higher than 1.23 V in neutral solutions according to an electrode reaction, which causes acidification of analyte (Fig. 2):

$$2H_2O = O_2 + 4H^+ + 4e^-$$

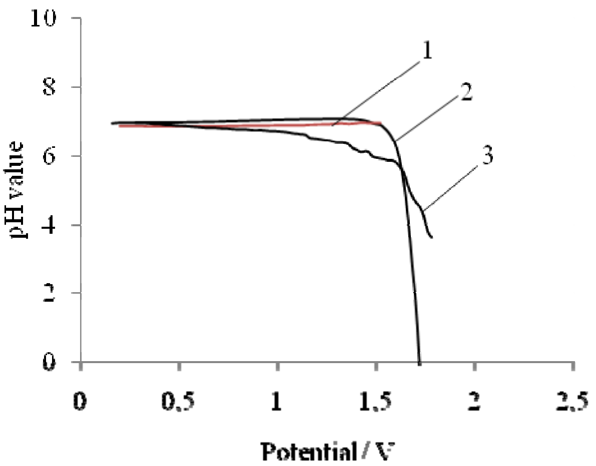


Fig. 2. The pH value dependence on potential during measuring potentiostatic polarization curves in the aqueous background solution at various anodes: 1 – graphite; 2 – platinum; 3 – shungite.

Fig. 3, 4 show potentiostatic polarization curves of shungite, graphite and platinum correspondingly in 0.5 mol/l hexanoic acid solution and the analyte pH change when receiving the curves.

Only one area of the limiting current can be seen on the polarization curves, which corresponds to the process of hexanoic acid oxidation:

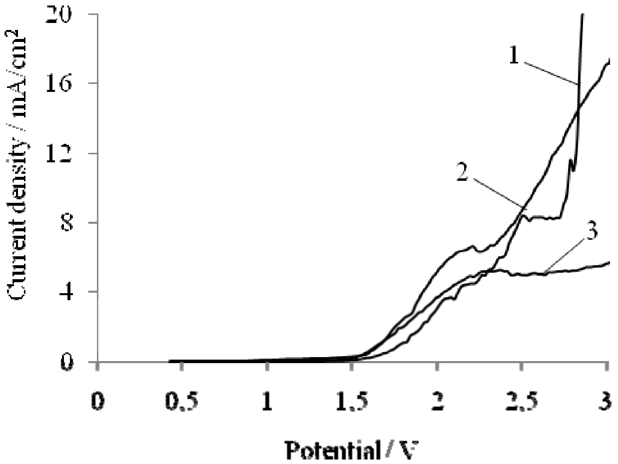


Fig. 3 Potentiostatic polarization curves of various anodes in 0.5 mol/l hexanoic acid solution: 1 – platinum; 2 – shungite; 3 – graphite.

$$RCOO^- \xrightarrow{-e^-} R^\bullet + CO_2$$

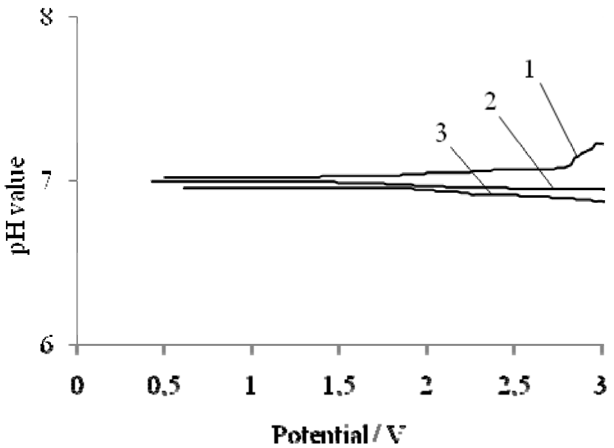


Fig. 4 Dependence of pH value of 0.5 mol/l hexanoic acid aqueous solutions on the potentials of various anodes while receiving potentiostatic polarization curves: 1 – platinum; 2 – graphite; 3 – shungite.

Fig. 4 shows that when reaching potentials of water oxidation the process of its oxidation on the anode does not proceed and curves pH – E are linear and there is no acidification of the solution, that indicates organic acid adsorption and the course of its only oxidation process.

To evaluate the electrooxidation velocity of carboxylic acid solutions we carried out preparative electrolysis of its solution under controlled potentials of 2.0 V and 2.4 V (HBE). Fig. 5 shows the current fall of hexanoic acid electrooxidation according to time at carrying out electrolysis under the potential of 2.0 V on various anode materials. The current decreases regularly in the process of electrolysis, which indicates a decrease of the explored organic acid concentration at the expense of its oxidation process, and this reaction occurs quickly enough.

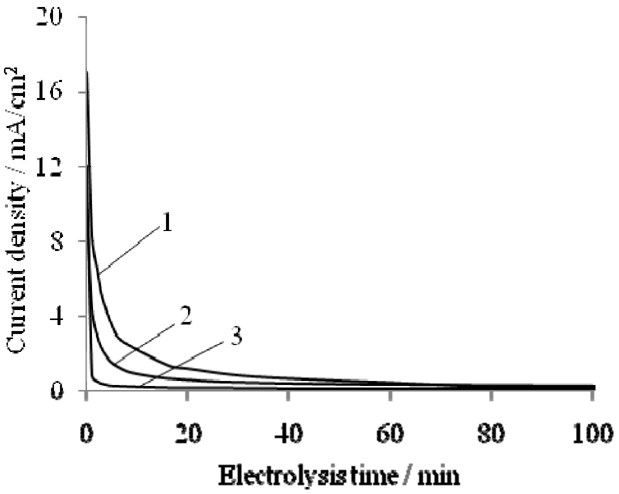


Fig. 5 Dependence of electrooxidation current of hexanoic acid on different anodes according to time under the potential of 2.0 V (pH=7): 1 – graphite; 2 – shungite; 3 – platinum.

During the electrolysis of hexanoic acid solution, adsorption and correspondingly water electrooxidation process on the anodes does not nearly occur, as evidenced by the almost constant pH (Fig. 6).

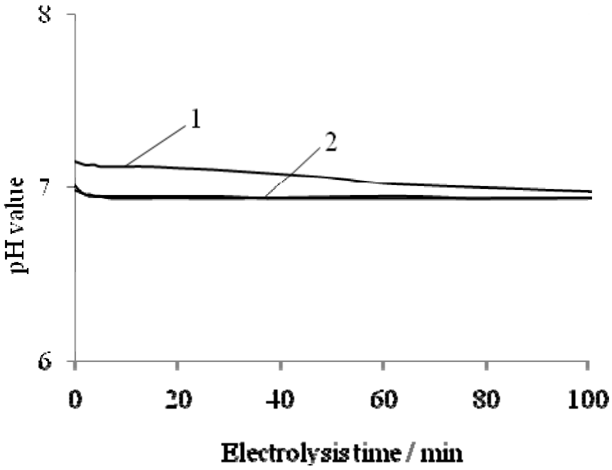


Fig. 6 The dependence of pH on electrolysis carrying out time of 0.5 mol/l hexanoic acid solution on the anodes: 1 – platinum; 2 – graphite and shungite.

Chromatographic analysis of the reaction mass after the electrolysis (Fig. 7) showed that the product of hexanoic acid electrooxidation in aqueous neutral solution on shungite anode is a mixture of hydrocarbons. Similar results were obtained with extracts chromatography after hexanoic acid solution electrolysis on the graphite and platinum anodes.

Formation of products obtained by acid electrooxidation conforms to the reaction course mechanism, proposed for process on a platinum anode [12-19].

According to the one-electron mechanism (dimerization and disproportionation of hydrocarbon radical) these representations are reflected by the scheme 1.

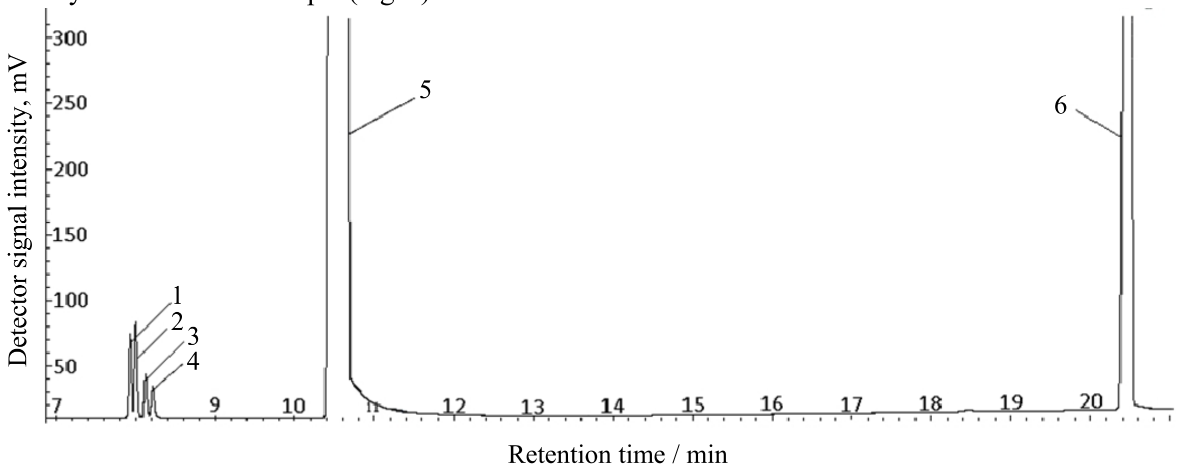
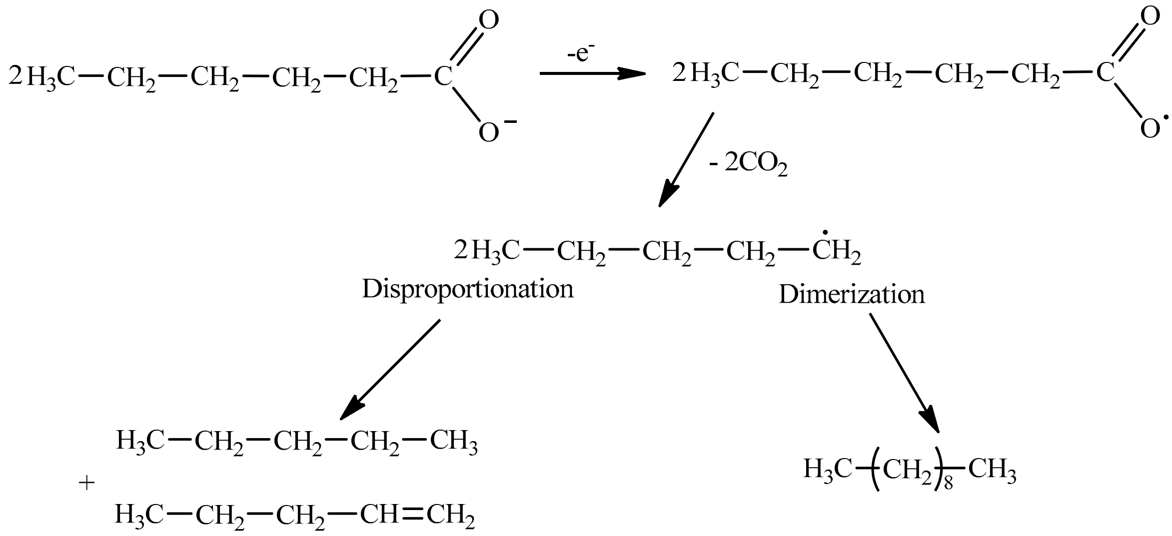


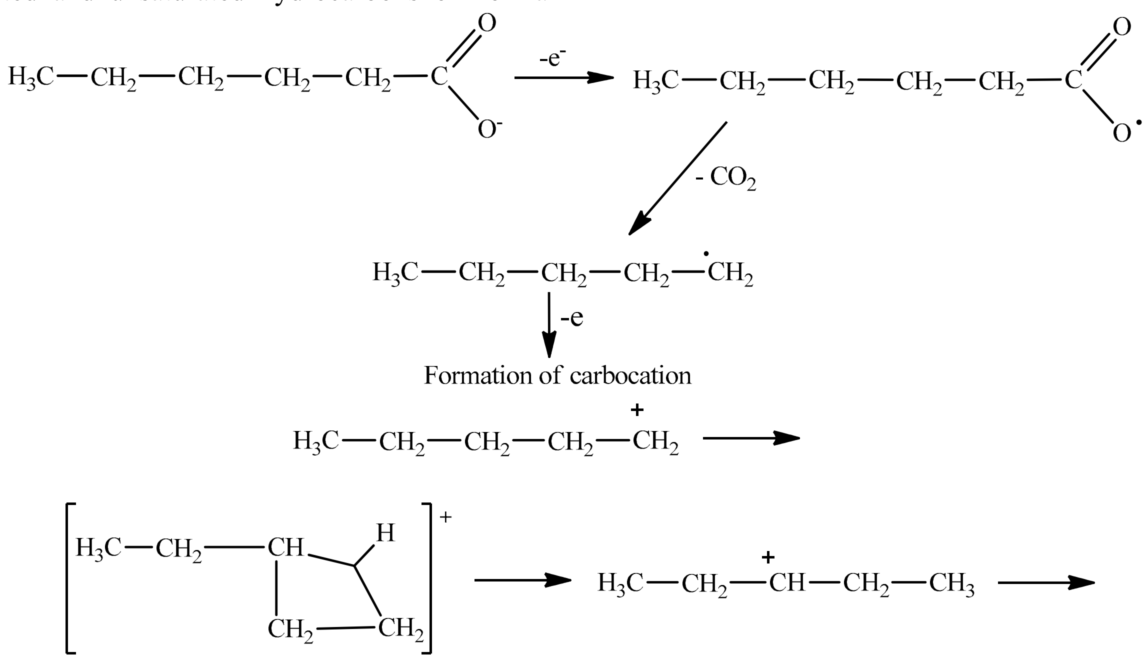
Fig. 7 Chromatogram of products extract of 0.5 mol/l hexanoic acid electrooxidation on shungite electrode under 2.4 V: 1 – n-pentane; 2 – pentene; 3 – isopentane; 4 – 2-methyl-2-butene; 5 – iso-octane (solvent-extractant); 6 – n-decane.

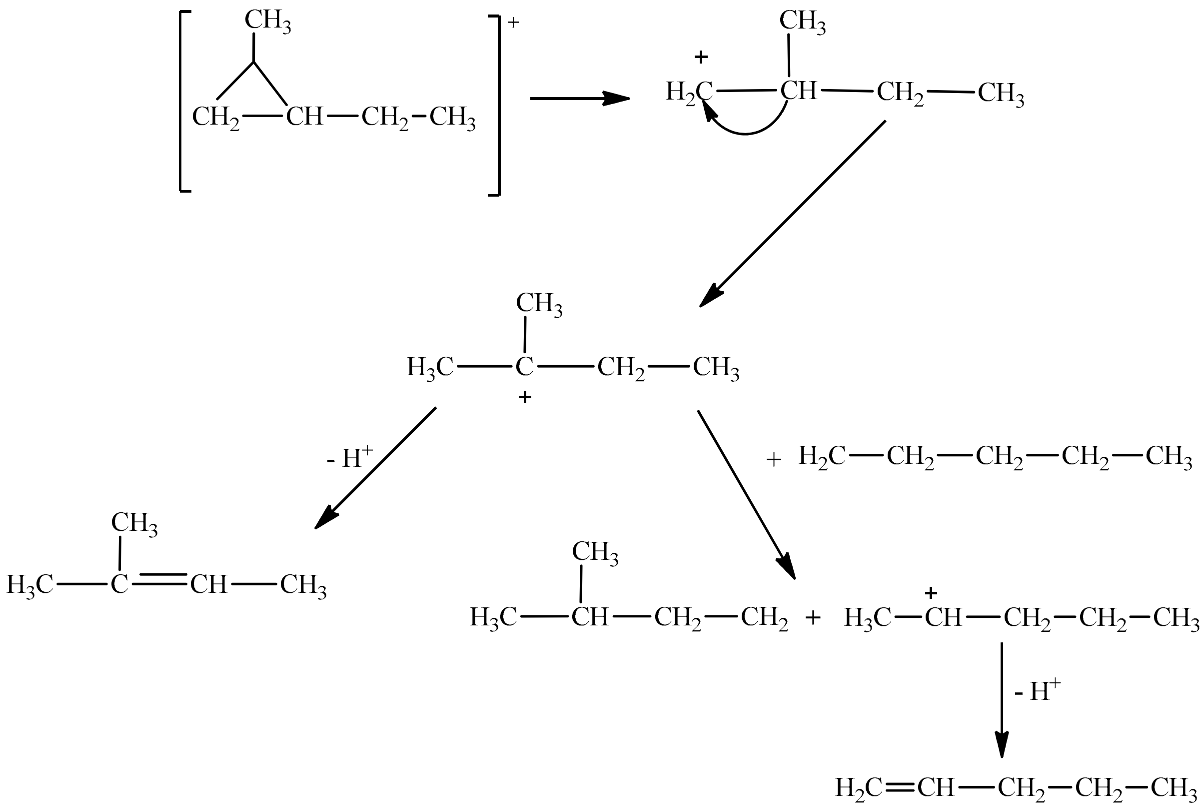


Scheme 1. One-electron oxidation mechanism hexanoic acid.

This scheme does not fully reflect all electrochemical processes occurring on the anode in aqueous solutions of carboxylic acids under pH close to neutral. The totality of electrolysis products defined in this paper can be explained on the basis of representation of two-electronic circuit, which provides electrochemical oxidation of the initially generated alkyl radical into carbocation, and its subsequent transformation into the corresponding saturated and unsaturated hydrocarbons of normal and isomeric structure. This point of view corresponds to the general concepts of organic chemistry in relation to the rearrangement of hyper-coordinated carbon atom in thermo-catalytic processes [12].

The general mechanism of carboxylic acids electro conversion under their anodic oxidation in close to neutral media can be submitted by the following scheme 2.





Scheme 2. Two-electron oxidation mechanism hexanoic acid

The proposed mechanism explains the formation together with the products of one-electron anode reaction also the substances emergence which can be explained by two-electron mechanism of the process course involving carbocations.

Fig. 8 shows a percentage ratio between the mentioned above substances in electrolysis products of 0.5 mol/l hexanoic acid solution under the potential of 2.4 V on various electrode materials.

Fig. 8 shows that the ratio of product yield under the same anodic potential (2.4 V) depends on an electrode material, that is the evidence of their electro-catalytic effect. The formation of products of carboxylic acid anodic oxidation (pentane, pentene and decane) on the selected anodes can be explained by one-electron acid anion oxidation course, and isopentane and 2-methyl-2-butene is explained by two-electron oxidation course.

The main product of the anodic hexanoic acid oxidation is a dimer (n-decane) – a product of Kolbe reaction. On platinum which is a typical anode material for Kolbe process, products formation through the stage of forming carbocation did not practically observed.

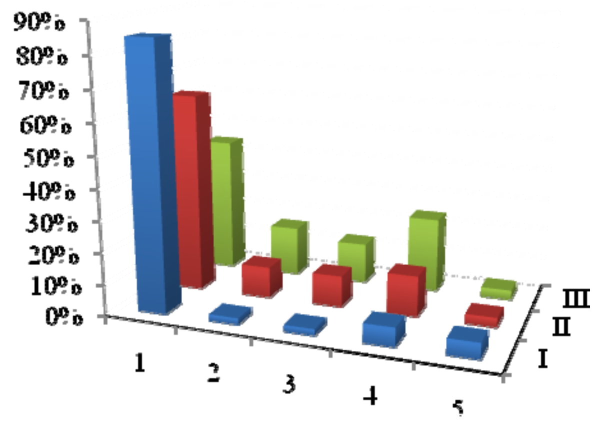


Fig.8 Product yields ratio during electrooxidation process of 0.5 mol/l hexanoic acid solution (pH = 7) on platinum (I), graphite (II), shungite (III) anodes under the potential of 2.4 V: 1 – decane (dimer); 2 – 2-methyl-2-butene; 3 – isopentane; 4 – pentene; 5 – pentane.

6. Conclusions

Based on the comparison of the physicochemical properties of natural shungite with graphite and platinum, we show that the application of a shungite electrode material in technology of electrochemical carboxylic acids oxidation into hydrocarbons is perspective for oxidized hydrocarbons regenerating, including waste petroleum oils. We show that shungite allows satisfactorily and with a high yield to oxidize carboxylic acids up to a mixture of hydrocarbons, the main of which is a dimer formed by Kolbe reaction. Anode material reveals electro-catalytic effect causing a comparative decrease in dimer yield under the transition from platinum to shungite.

According to one-electron mechanism of an anode reaction decarboxylation of carboxylic acid occurs, followed by disproportionation of hydrocarbon radical into saturated and unsaturated hydrocarbons.

Electrooxidation of carboxylic acids under high anodic potentials we explain by conceptions of the intermediate forms formation – hydrocarbon radical and subsequent carbocation.

To explain this mechanism we propose the general scheme, which allows the formation and rearrangement of hyper-coordinate carbon atom, resulting in the formation from hexanoic acid, besides the product of Kolbe condensation, also saturated and unsaturated hydrocarbons of pentane series.

Due to the high adsorption of carboxylic acid on the anode under operating potentials of 2.0 V or even higher, the Faraday by-product water oxidation process is not almost observed, which contributes to high yield of expected product according to current.

Comparative evaluation of anode materials including shungite showed the possibility of application of different electrode materials to perform process of carboxylic acids electro-oxidation.

The formation of hydrocarbons during carboxylic acid electrooxidation is aimed at improving existing technologies of waste oils regeneration and increasing their yield.

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О. М. Давиденко[1], В. М. Ледовських[2]

Електроокиснення карбонових кислот на шунгітовому електроді

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, Україна, 03680
E-mails: [1]dom237@ukr.net; [2]uchneftexim@bigmir.net

Мета: Стаття розглядає електрохімічний метод спрямованого перетворення карбонових кислот, як найагресивніших продуктів окиснення вуглеводнів, назад у відповідні вуглеводні. Існуючі методи регенерації відпрацьованих нафтових олив мають суттєві недоліки, до яких належить утворення нових важкоутилізованих відходів та втрата значної частини оливи під час регенерації. **Методи:** Дослідженні процеси електроокиснення карбонової кислоти на різних електродних матеріалах: платиновому, графітовому та шунгітовому анодах. **Результати:** Потенціостатичні поляризаційні криві з одночасним вимірюванням pH приелектродного розчину показали відмінності перебігу процесу на даних анодних матеріалах: вихід димеру за реакцією Кольбе зменшується при переході від платини до шунгіту. За потенціалів, вищих за 2,0 В, карбонова кислота має більш високу адсорбційну здатність порівняно з водою. Тому побічного фарадеївського процесу окиснення води майже не спостерігається, що сприяє високому виходу за струмом цільового продукту. Електролізом розчинів карбонових кислот при контрольованому потенціалі (2,0 та 2,4 В) та хроматографічним аналізом утворених продуктів показано, що разом з утворенням димерних структур за реакцією Кольбе, спостерігається виникнення суміші вуглеводнів, які можуть бути результатом диспропорціонування вуглеводневого радикалу (алкан та алкен), та вуглеводнів ізомерної структури, за рахунок подальшого окиснення вуглеводневого радикалу до карбкатіону і його подальші трансформації у відповідні насичені та ненасичені ізомери. Таке твердження не підтверджується уявленням про перебіг одно- та двох-електронного окиснення карбонової кислоти. **Обговорення:** Запропонована загальна схема окиснення карбонової кислоти за одно-електронним механізмом (димеризація та диспропорціонування радикалу) і двох-електронним механізмом (утворення та перегрупування карбкатіону). Утворення вуглеводнів при електроокисненні карбонових кислот відпрацьованих олив при їх регенерації, може сприяти збільшенню виходу оливи без утворення побічних небезпечних продуктів.

Ключові слова: відпрацьована олива; електроокиснення; карбонова кислота; регенерація; шунгіт.

А. Н. Давыденко[1], В. М. Ледовских[2]

Электроокисления карбоновых кислот на шунгитовом электроде

Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, Украина, 03680
E-mails: [1]dom237@ukr.net; [2]uchneftexim@bigmir.net

Цель: Данная статья рассматривает электрохимический метод направленного преобразования карбоновых кислот, как агрессивных продуктов окисления углеводородов, обратно в соответствующие углеводороды. Существующие методы регенерации отработанных нефтяных масел имеют существенные недостатки, к которым относится образование новых тяжело утилизированных отходов и потеря значительной части масла при регенерации. **Методы:** Исследовании процессы электроокисления карбоновой кислоты на различных электродных материалах: платиновом, графитовом и шунгитовом анодах. **Результаты:** потенциостатические поляризационные кривые с одновременным измерением pH приелектродного раствора показали различия течения процесса на данных анодных материалах: выход димера за реакцией Кольбе уменьшается при переходе от платины до шунгита. При потенциалах, превышающих 2,0 В, карбоновая кислота имеет более высокую адсорбционную способность по сравнению с водой. Поэтому побочного фарадеивського процесса окисления воды почти не наблюдается, что способствует высокому выходу по току целевого продукта. Электролизом растворов карбоновых кислот при контролируемом потенциале (2,0 и 2,4 В) и хроматографическим анализом образованных продуктов показано, что вместе с образованием димерних структур за реакцией Кольбе, наблюдается возникновение смеси углеводородов, которые могут быть результатом диспропорционирования углеводородного радикала (алкан и алкен) и углеводородов изомерной структуры, за счет дальнейшего окисления углеводородного радикала в карбкатион и его дальнейшие трансформации в соответствующие насыщенные и ненасыщенные изомеры. Такое утверждение не подтверждается представлением о ходе одно- и двух-электронного окисления карбоновой кислоты. **Обсуждение:** Предложенная общая схема окисления карбоновой кислоты с одно- электронным механизмом (димеризация и диспропорционирования радикала) и двух-электронным механизмом (образование и перегруппировки карбкатиона). Образование углеводородов при электроокислении карбоновых кислот отработанных масел при их регенерации, может способствовать увеличению выхода масла без образования побочных опасных продуктов.

Ключевые слова: карбоновая кислота; отработанное масло; регенерация; шунгит; электроокисление.

Davydenko Oleksandr. Graduate student.
Department of Chemistry and Chemical Technology, National Aviation University, Kyiv, Ukraine.
Education: National Aviation University, Kyiv, Ukraine (2013).
Research area: processes of electrochemical regeneration of used oils.
Publications: 10.
E-mail: dom237@ukr.net

Ledovskykh Volodymyr. Doctor of chemical sciences. Professor.
Chemistry and chemical technology Department, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Polytechnic Institute, Kyiv, Ukraine (1962).
Research area: corrosion and defence of metals, purposeful development of PAIRS for retrofitting of oil and oil products, processes of electrochemical regeneration of oxidation of hydrocarbons and general chemistry.
Publications: 157.
E-mail: uchneftexim@bigmir.net

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