IJCTA, 9(35), 2016, pp. 1-22
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Bench and Flight Study of the Airplane System Algorithms to Provide the Crew with the Information and Intellectual Support for Light Aircraft Active Flight Safety

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Abstract : The article deals with the scientific and technical problem of ensuring the safety of light aircraft (AC) carrying out the short-haul operations, and the AC of the general purpose aviation (GPA) using the on-board hardware and software, such as the on-board computer and liquid crystal display located on the dashboard. The system algorithms are described and the basic functionality of the system is studied, providing the crew with the navigation information output on the LCD display. The first experimental results of the system development are demonstrated on a flight bench and flight tests conducted on the IKARUS C42 CJSC "Tehaviakompleks" light aircraft.

Keywords : Flight safety, dangerous situations, onboard display systems, flight data display formats, crew information and intellectual support in critical situations, mathematical and bench modelling, flight study and testing.

1. INTRODUCTION

In the last decade, the Russian light aircraft market segment has been growing significantly; at the same time, regularly performed scheduled air service on local air routes begins to revive and the volume of aviation operations increases, the potential demand for which is very large due to the large Russian spaces, poorly developed road network, increasing purchasing power of the population and the aspiration of its active part for mobility. Light aircraft (AC) are usually piloted by young pilots with little experience of flight operations; at the same time, the majority of light aircraft have a relatively low level of management automation and have little or no protection from dangerous situations and critical modes.

A growing number of private and general aviation aircraft are often operated by private pilots with little flight experience, and hence the low level of flying skills not allowing to ensure a high level of safety.

The existing to the present time approaches to ensuring the flight safety were limited by informing the pilot (crew) that he exceeded a particular limit. However, as the experience shows, when the pilot is in a critical situation, the aircraft exceeds several limitations. The pilot is simply lost in this situation and often acts inappropriately, as it is shown by the accident statistics in the last 20 years [1-3].

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The ICAO has proposed [4] to fundamentally change the preventive work content and change the investigation of rare aviation occurrences for carrying out constant targeted work to identify and eliminate (counteract) the hazards in each component of the aviation system (AS). In other words, the true prevention work must be carried out on the distant approaches to the aviation event, not after it happens. The object of this work is the hazards components of the AS, and the subject is their rapid identification and elimination (regulation, development of protective equipment). The above approach, as it was mentioned, was defined as a “proactive”, that is, predicted event [4].

The analysis of the safety status in the Russian civil aviation shows [3, 5] that the main cause of accidents and incidents to date, is the so-called “human factor” associated with erroneous or inadequate actions of the flight crew when aircraft (AC) piloting or when performing cockpit equipment and airplane system procedure (including failure in performing gear extension before landing). These errors are caused by the crew, as stated in the official documents [5], “due to the insufficient level of training, the inability to properly assess the danger that has arisen in a particular situation and to take timely measures on the localization of the adverse factors”. The main causes of accidents are presented in Table 1.

Table 1
The main reasons for AA

Types of AA	*Aeronautical equipment failures or technical factor (TF)*	*Human factor (HF)*	*Adverse environmental conditions and external factors (EF)*
Crashes	41%	48%	11%
Fatal crashes	6%	84%	10%

The results of the effectiveness evaluation of previously taken measures, based only on the current display settings and not using the aircraft dynamics predictions, showed that today in the modern aircraft operation it is not possible to achieve a high level of safety without taking measures to prevent possible crew error in the process of flight operation. This is determined by the objective reality, which is that it is human to err in one’s operations and that should be considered in the establishment of modern management systems. An effective way to localize the possible crew error is to install on the aircraft board a crew tip system, which warns of pre-made mistakes, and informs on how to proceed in the event of an abnormal situation in flight.

People tend to err by their nature. Thus, along with increasing the level of aeronautical equipment safety and reliability by using aircraft control systems automation, improvement of limit condition systems, an important aspect in enhancing the flight safety and ensuring the crew survival is to account the human factor. Along with the improvement of the skills and training of flight personnel, it is necessary to install on the board such systems, which would promptly and accurately inform the pilot of the aircraft falling in a critical mode or dangerous flight conditions, and also predict the outcome of the further development of the situation.

Thus, the problem associated with the development of the diagnostic algorithms for critical flight modes is very relevant, especially for light aircraft. Integration of these algorithms with the display and control automation algorithms will significantly improve the safety of the current and future aircraft.

2. METHODOLOGY FOR DETERMINING DANGEROUS SITUATIONS

One way out in this situation would be to create a system of the pilot intellectual and informational support that “undertakes” the chore of information collecting and processing, as well as the development of an optimal solution to achieve the target, including the promotion of safety.

The development of the concept of such a system is based on the analysis of the interaction between the student and the instructor.

The student, in terms of a crew member, has the following disadvantages :

- Poor training which can lead to the piloting errors;
- Poor knowledge of aeronautical equipment (especially in difficult or emergency situations), which aggravates the situation;
- Exposure to stress and confusion, which makes the pilot incapacitated;
- Lack of flight experience and, as a result, incorrect or untimely decision making;
- Narrow scope of information perception.

The instructor, having more experience, training and skills, in cases where it becomes necessary in his opinion, interferes in the management process and helps the student. Functionally, the instructor solves the following tasks :

- Collects and processes the information during the flight;
- Helps the student to focus on the individual elements of the incoming information (forms information flow for each of the flight modes);
- Controls the flight mode in the event of a difficult situation, predicts its development;
- Monitors and evaluates the student’s psycho-physiological state, often being aware of his training and skills;
- If necessary, prompts (issues recommendations) to the student, what to do in any given situation;
- In case of improper or erroneous actions of the students, intervenes in the management, and in case of the student’s incapacity fully undertakes the management;
- In the event there is the threat of emergency situation that transfers in the catastrophic one, catapults the crew compulsorily.

An experienced pilot does not need an instructor, but being subject to the influence of the human factor, he can make mistakes or is not able to fully grasp and process the entire volume of incoming information for qualitative decision-making.

In this case, an intellectual support system should play the role of a trainer for the young pilot and partner (assistant) role for the experienced pilot.

The system does not replace the pilot, it “acts” in the role of a more experienced co-pilot, a guard, who is not subject to the piloting errors, stress, fatigue, loss of consciousness and other negative properties of the human factor, also has an enormous database, based on a synthesis of the FP statistics analysis results and the experience of flight practice.

The system also performs the following functions:

- Depending on the flight mode, it generates a flow of information perceived by the pilot during the assignment issued to him by the onboard display systems;
- Diagnoses the flight mode;
- Generates and outputs the information as a hint;
- In the case of improper pilot’s actions, it “intervenes” in the aircraft management;
- In the event of a catastrophic situation, it introduces the rescue system compulsorily [6].

The logic circuit that provides an integral mode of the system functioning is based on two main levels:

- Information collection, processing and analysis of information;
- Forecast of the dangerous flight conditions, including the following:
  - Loss of stability and controllability;
  - Progressive stall;
  - Spin;

  - complex angular position at low altitudes;
  - loss of speed at low altitudes.
- Analysis of the origin and transition of the emergency situation in the catastrophic one, recognition of errors, leading to the trend of the violation of the flight restriction;
- Synthesis of the optimal solutions and hint – giving guidance to the pilot according to the management strategy.

This work is based on a synthesis of the previous experiences and developments [6-10] in the framework of the concept of the crew information and intellectual support, implementation of which has now become possible thanks to the emergence of the onboard computing systems that meet the requirements for speed, memory size and dimensions and weight characteristics, as well as the ability to use colour multifunction displays to display information in any form on the aircraft board.

The purpose of the studies described in this paper is the development of the algorithmic mathematical software (MS) for the crew information and intellectual support system (CIISS) in an emergency flight of light civil aircraft, including general purpose aviation aircraft, as well as the study of the designed CIISS MS on the multifunction bench-simulator complex and in real flight by an aircraft. At the same time, one of the main issues addressed in the work was the choice of algorithms that can be implemented on the aircraft board with the lowest-possible cost in terms of information provision and the CIISS onboard computer capacity, which is very important for light aircraft.

The results can be used in the development of new aircraft safety systems.

2.1. Principles of the CIISS

The diagnostic logics of dangerous situations and the crew information support is built on the knowledge, combining the theoretical understanding of the problem and a set of kinds (types) of special situations, recognition of which is proved by the practice of the subject area in the course of the accident investigation.

The task of forming CIISS algorithms is reduced to the developing of approaches to identify the specific situations that may arise during the flight and timely informing the crew on how to proceed for their localization. Every decision is made based on the initial data representing the flight information. The most important element of the decision is to assess the current situation and the formation of a special crew tips, allowing parrying the situation.

The analysis of the flying accidents statistics shows that the greatest number of accidents occur due to the pilot’s loss of spatial orientation, with the loss of speed, spin stall, dangerously close to the ground, incorrect assessment of the possibility of the initiated mode further implementation.

CIISS is based on two main principles :

- Determination of the special situation caused by the human factor at a very early stage;
- Preventing the further development of the special situation arisen.

2.2. Logics of the CIISS operation

The logic of the OFSS operation is based on the following principles [7] :

(*a*) de jure determination in the phase space of the controllable dynamical system condition (phase state vector is a complete set of motion parameters of the aircraft) of a well-defined area boundaries with existing phase limitations (operational area of de jure flight modes under the terms of the flight safety conditions in accordance with the FCOM);

(*b*) de jure determination in the control area of a dynamic system (control vector is a complete set of deviations of all available controls of the aircraft) of boundaries of a quite well-defined area with existing, interrelated both with the phase state and with each other, restrictions (also de jure in accordance with FCOM);

(c) De jure determination of the logic (rules of execution, sequence and interaction) of all possible procedures, performed by the crew in the cockpit in their respective control area of the dynamic system;

(*d*) De facto continuous analysis of the dynamic system state vector (aircraft motion parameters and parameters of all onboard systems);

(*e*) De facto continuous analysis of the dynamic system control vector (current deviations of controls, procedures performed by the crew);

(*f*) De facto continuous analysis of the controlled object dynamics compliance with the conditions of being in the given operational area de jure and compliance with the reference behavior of the aircraft;

(*g*) De facto continuous comparison of the procedures performed by the crew compliance with the logic determined de jure;

(*h*) Immediate notification of the crew on de facto approximation to the given restrictions both in the phase space and in case of violating the consistency of procedures;

(*i*) Immediately prompting to parry a dangerous situation that has arisen with the output of specific recommendations for control and procedures to the crew;

(*j*) Automatic intervention in the process of parrying the dangerous situation in the absence of the crew's reaction to the prompting and their inaction.

De jure determination of the logic and conditions in case of adoption of a simplified approach to the intellectual system formation is nothing else than the analogue to knowledge base formation. In this case, FCOM is considered as the expert knowledge.

The onboard flight safety system does not replace the existing systems of monitoring and informing the crew, but produces promptings of a higher level, which are formed when the sign of a dangerous situation is triggered. The OFSS has a branched out logic chain to detect the types of dangerous situations, to determine threat signs of arising danger, to notify immediately (display, alarm) and to give appropriate recommendations to the crew. As an example of area boundaries with the existing OFSS phase restrictions in the database by one of the branches of the developing situations chain, associated with the aircraft violating the restrictions on minimum safe altitudes, permissible angle of attack and maximum velocity head. Figure 1 shows the flying operating range de jure.

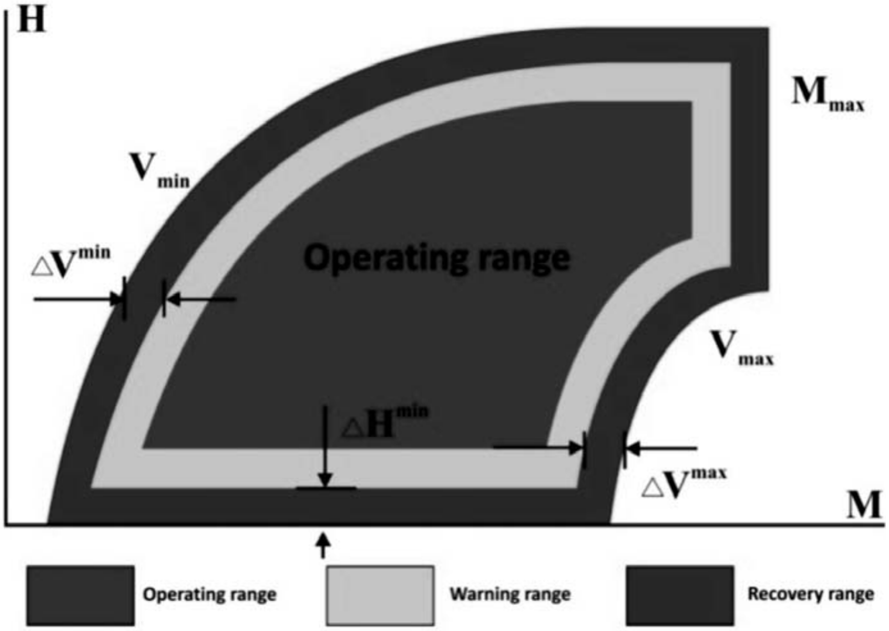


Figure 1: Operational area of the flight modes

3. MAIN OBJECTIVES AND FUNCTIONS OF THE AIRBORNE SYSTEM

3.1. Purpose and functions of the CIISS

The Onboard Crew Information and Intellectual Support (CIISS) and Active Flight Safety System is designed to detect specific flight conditions at a very early stage of their development for timely notifying the crews on their occurrence, for the formation and display of flight information on extreme conditions, to display alarms and director-type commands for the efficient deviation (including automatically if there is the autopilot) from the danger and parrying the identified specific situations in order to prevent their further development.

The system functions were selected on the basis of the statistics of accidents (A) and incidents (I). As the statistical analysis of accidents in CA shows, 70-90% of air crashes are caused by crew errors (HF), less than 10-20% – by the aircraft equipment failures (TF), and about 10% – by other reasons, including external factors (EF).

System algorithms setting was carried out in the process of flight bench development and during the flight tests taking into account the characteristics of the particular C 42 “Icarus” aircraft with a maximum take-off weight (MTOW) of 530 kg and its possible spread, restrictions of the aircraft flight manual (AFM), piloting errors (pilot’s delay, inaccuracy of holding the set values of the control parameters, etc.), errors of the measuring instruments and other random factors.

In each special situation, the system generates the appropriate voice and text messages.

3.2. Problems to be solved by the CIISS

In accordance with the designation, the system provides the detection and parrying of the dangerous consequences of the identified groups of special situations.

The inclusion of the preventive and director-type (including automatic) system modes is based on the risk assessment to consider the flight special situation. The system must ensure the prevention of:

- Entering into a complex angular position at low altitudes;
- Collision with the ground as a result of incorrect implementation of the vertical manoeuvres, loss of spatial orientation while flying over the difficult terrain (especially hilly or mountain) under the conditions of poor visibility, etc.;
- Violations of flight speed limits, including loss of speed at low altitudes;
- Loss of stability and/or handling (stall, spin);
- Collisions with ground objects and other aircraft.

The system should carry out the forecast of altitude and flight speed changes in order to assess that it is safe to continue the current manoeuvre.

4. CIISS BOARD SYSTEM ALGORITHMS

Information processing and analysis in the CIISS is carried out in real time, to recognize the special situation in a timely manner and give the crew the necessary hint about the required action on the localization of the situation.

In the derivation of complex spatial positions, the loss of speed and deviation from the dangerous altitude, the CIISS generates the director-type (information) or command control signals to the advanced process control (APC) to include the roll and pitch trimming mechanisms by the computer of the astatic development of the overload $n_{y\ \mathrm{given}}$ and the given roll γ_{given}. In such a case, management by the A or APC in the longitudinal channel is carried out at the overload n_y.

The signals $\Delta\gamma = \gamma(t) - \gamma_{\mathrm{given}}$ and $\Delta n_y = n_y(t) - n_{y\ \mathrm{given}}$ serve as the basis for the formation of the director-type (information) or command (control) signals for the APC or A.

4.1. Prediction and prevention algorithms

The algorithms for prediction and prevention are used to determine :

- Predicted minimum altitude and speed values (Hpr, Vpr), which can be achieved by performing spatial manoeuvres, as well as the conditions under which these values should be indicated to the crew;
- The value of altitudes and speeds (Hwmin, Vwmin, Vwmax), after which the crew must start the manual deviation from the maximum permissible altitude or speed values.

In this work, four different methods were studied to forecast the aircraft motion parameters that were used in the CIISS system for computing the predicted altitude and speed values: one dynamic and three algebraic forecasts. Method 1 is dynamic, methods 2-4 are algebraic. More information about them is given below.

The paper of Akhrameev and Shulepov [6] proposes to forecast the parameters of the flight restrictions using the parametric dependences obtained with the help of mathematical modelling by full equations of aircraft motion and spatial approximation of the dependences obtained using sufficiently simple formulas. However, preliminary calculations themselves have a very large volume and require precise knowledge of all the aircraft characteristics.

As it was suggested by Dr. Saenko, the system could predict changes of parameters (to calculate the values of phase coordinates X_T, including flight altitude and speed) in order to assess the potential for safe continuation of the current manoeuvre from the point X_0 to the point $X_T = T(X_0)$:

$$X_T = T(X_0),$$

where

$$T(x_0) = x_0 + \int F(x, u_0)\,dt;$$

$$\frac{dx}{dt} = F(x, u) \text{ – equations of FV spatial movement.}$$

When the predicted value of any of the condition vector X_T phase coordinates gets close to the limiting values, warning piloting information must be given to the crew, and if there is the autopilot (AP) or an automatic control system (ACS), the recovery from a dangerous situation can be carried out automatically.

The mathematical model of the aircraft spatial movement, as a rigid body, in a connected system of coordinates is described by quite complex and cumbersome for computing equations:

$$\frac{d\alpha}{dt} = \omega_z - \frac{1}{\cos\beta}\left[\left(\bar{F}_x - \omega_y \sin\beta\right)\sin\alpha + \left(\bar{F}_y - \omega_x \sin\beta\right)\cos\alpha\right];$$

$$\frac{d\beta}{dt} = \bar{F}_z \cos\beta - \left(\bar{F}_x \sin\beta - \omega_y\right)\cos\alpha + \left(\bar{F}_y \sin\beta + \omega_x\right)\sin\alpha;$$

$$\frac{dV}{dt} = V\left[\bar{F}_x \cos\beta\cos\alpha - \bar{F}_y \cos\beta\sin\alpha + \bar{F}_z \sin\beta\right];$$

$$\frac{d\omega_x}{dt} = \frac{\left[M_x - I_{xy}\omega_x\omega_z - \left(I_z - I_y\right)\omega_z\omega_y\right]}{I_x I_y - I_{xy}^2} + \frac{I_{xy}\left[M_y + I_{xy}\omega_z\omega_y - \left(I_x - I_z\right)\omega_z\omega_x\right]}{I_x I_y - I_{xy}^2};$$

$$\frac{d\omega_y}{dt} = \frac{\left[M_y + I_{xy}\omega_y\omega_z + \left(I_z - I_x\right)\omega_z\omega_x\right]}{I_x I_y - I_{xy}^2} + \frac{I_{xy}\left[M_x - I_{xy}\omega_z\omega_x - \left(I_z - I_y\right)\omega_z\omega_y\right]}{I_x I_y - I_{xy}^2};$$

$$\frac{d\omega_z}{dt} = \frac{M_z + I_{xy}\left(\omega_x^2 - \omega_y^2\right) - \left(I_y - I_x\right)\omega_y\omega_x}{I_z}.$$

The Euler's Kinematic Relation System supplements this equation system:

$$\frac{d\gamma}{dt} = \omega_x - \left(\omega_y \cos\gamma - \omega_z \sin\gamma\right) tg$$

$$\frac{d\vartheta}{dt} = \omega_z \cos\gamma + \omega_y \sin\gamma \quad \text{, where}$$

$$\frac{d\psi}{dt} = \frac{1}{\cos}\left(\omega_y \cos\gamma - \omega_z \sin\gamma\right)$$

ϑ – pitch angle;
ψ – azimuth angle;
γ – bank angle;
m – aircraft weight;
g – downward acceleration;
I_x, I_y, I_z – inertia about principal axes, that is, Ox1, Oy1, Oz1;
I_{xy} – inertia off axis moment because of the aircraft asymmetry relative to the plane Oxz.

$\overline{F}_x, \overline{F}_y, \overline{F}_z$, M_x, M_y, M_z – aerodynamic forces and moments in the body axis Ox1y1z1;
ω_x, ω_y, ω_z – body axis angular velocity components.

Aerodynamic force and moment coefficients are functions of the kinematic parameters of control motion and deflection:

$$\overline{F}_x = \frac{\rho(H)VS}{2m}\left(C_x - C_p\right) - \frac{g}{V}\sin\vartheta;$$

P – engine's thrust force;
C_p – thrust force coefficient.

$$M_x = m_x \cdot \frac{\rho \cdot V^2}{2} \cdot S \cdot L$$

$$\overline{F}_y = \frac{\rho(H)VS}{2m} C_y - \frac{g}{V}\cos\vartheta\cos\gamma;$$

$$M_y = m_y \cdot \frac{\rho \cdot V^2}{2} \cdot S \cdot L$$

$$\overline{F}_z = \frac{\rho(H)VS}{2m} C_z + \frac{g}{V}\cos\vartheta\sin\gamma;$$

$$M_z = m_z \cdot \frac{\rho \cdot V^2}{2} \cdot S \cdot b_A$$

Where:
S – wing area;
L – wing span;
ba – mean aerodynamic wing chord;
ρ(H) – air density depending on the barometric altitude;
V – flight air speed;
C_x, C_y, C_z, m_x, m_y, m_z – dimensionless coefficients of aerodynamic forces and moments, which are determined by the formulas:

$$C_\chi = C_\chi(\alpha, \delta_e)\alpha$$

$$C_y = C_y\left(\alpha, \delta_e\right) + C_y^{\dot{\alpha}}\dot{\alpha} + C_y^{\overline{\omega}_z}\overline{\omega}_z$$

where
$$\overline{\omega}_z = \omega_z \frac{b_a}{\mathrm{V}};$$

$$\mathrm{C}_z = \mathrm{C}_z^{\beta}(\alpha)\beta + \mathrm{C}_z^{\delta_r}(\alpha)\,\delta r$$

$$m_x = m_x^{\beta}(\alpha)\beta + m_x^{\overline{\omega}_x}(\alpha)\overline{\omega}_x + m_x^{\overline{\omega}_y}(\alpha)\overline{\omega}_y + m_x^{\delta_a}(\alpha)\delta_a + m_x^{\delta_r}(\alpha)\delta_r;$$

$$m_y = m_y^{\beta}(\alpha)\beta + m_y^{\overline{\omega}_x}(\alpha)\overline{\omega}_x + m_y^{\overline{\omega}_y}(\alpha)\overline{\omega}_y + m_y^{\delta_a}(\alpha)\delta_a + m_y^{\delta_r}(\alpha)\delta_r;$$

$$m_z = m_z(\alpha, \delta_e) + m_z^{\dot{\overline{\alpha}}}(\alpha)\dot{\overline{\alpha}} + m_z^{\overline{\omega}_z}(\alpha)\overline{\omega}_z \text{, where}$$

α – incidence angle;
β – gliding angle;
δr – rudder deflection;
δa – aileron deflection;
dδe – elevator deflection;
H – flight altitude;
δ – control angle in the longitudinal movement (elevator).
δr – control angle the lateral movement (rudder).
δa – roll control angle (aileron).
δech – engine control handle position.

Incidence angle and gliding angle are associated with the aircraft speed V relative to the air:

$$\beta = \arcsin \frac{\mathrm{V}_z}{\mathrm{V}}$$

In order to calculate the aircraft trajectory relative to the fixed inertial reference system related to the Earth's surface, the following equations are used:

$$\frac{d\mathrm{X}_g}{dt} = \mathrm{V}_x \cos\cos\psi - \mathrm{V}_y(\cos\gamma\sin\cos\psi - \sin\gamma\sin\psi) + \mathrm{V}_z(\cos\gamma\sin\psi + \sin\gamma\sin\cos\psi) - \mathrm{W}_x$$

$$\frac{d\mathrm{H}}{dt} = \mathrm{V}_x \sin + \mathrm{V}_y \cos\gamma\cos - \mathrm{V}_z \sin\gamma\cos + \mathrm{W}_y$$

$$\frac{d\mathrm{Z}_g}{dt} = -\mathrm{V}_x \cos\sin\psi + \mathrm{V}_y(\cos\gamma\sin\sin\psi + \sin\gamma\cos\psi) + \mathrm{V}_z(\cos\gamma\cos\psi - \sin\gamma\sin\sin\psi) - \mathrm{W}_z$$

Thus, if the forecast uses the full equations of the aircraft spatial movement, we need to have the following basic data:

- Aircraft aerodynamic characteristics around the achieved range of incidence and gliding angles;
- Propulsion thrust dependence on the speed and altitude;
- Data on the current aircraft configuration and current control deviations;
- Aircraft mass-inertial and geometrical characteristics.

Forecast calculation using full equations gives very good results [7]; however, the main purpose of this work was to choose simple prediction algorithms, which do not require accurate and complete knowledge of all the aircraft characteristics and require the minimum possible amount of the on-board measurements available in a light aircraft.

Four relatively simple, in terms of the implementation in an onboard system, methods were discussed in the work.

4.1.1. Method 1 (the black graph in the figures below)

Forecast using trajectory movement equations:

$$\begin{cases} \dot{\mathrm{V}} = g \cdot \left(n_{xa} - \sin\theta\right) \\ \dot{\theta} = \dfrac{g}{\mathrm{V}} \cdot \left(n_{ya} - \cos\theta\right) \\ \dot{\mathrm{H}} = \mathrm{V}\sin\theta \end{cases}$$

where V. H – trajectory speed, altitude and angle. In solving these equations, the high-speed overload components are used, calculated by the following formulas:

$$n_{xa} = \frac{\mathrm{P}(\alpha_{\mathrm{ECH}}, \mathrm{V}) \cdot \cos\alpha \text{-} c_x(\alpha) \cdot q\mathrm{S}}{\mathrm{mg}}$$

$$n_{ya} = \frac{\mathrm{P}(\alpha_{\mathrm{ECH}}, \mathrm{V}) \cdot \sin\alpha + c_y(\alpha) \cdot q\mathrm{S}}{\mathrm{mg}}$$

where $\mathrm{P}(\alpha_{\mathrm{ECH}}, \mathrm{V})$ $c_x(\alpha)$, $c_y(\alpha)$ – a priori defined thrust and the aerodynamic coefficients dependencies, $q = \dfrac{\rho_0 \mathrm{V}_{fr}^2}{2}$ – speed dialing (approximately), m – aircraft weight, S – wing area.

In the on-board system, which at this stage was investigated in flight by C42 aircraft, this method of forecasting was refused, as at this stage on the aircraft board there are no current control deflections and other necessary for Method 1 on-board measurements, and a simpler version of linear projections was used.

4.1.2. Method 2 (the red graph in the figures below)

The method 2 is a simple time linear forecast based on the measured overloading components.

The projected altitude and speed are calculated by the following formulas:

$$\mathrm{H}(\Delta \mathrm{t}) = \mathrm{H}(0) + \mathrm{V}_{y}, \cdot \Delta t,$$

$$\mathrm{H}(\Delta \mathrm{t}) = \mathrm{V}(0) + (n_{x1} \cos\alpha - n_{y1} \sin\alpha - \sin\theta) \cdot g\Delta t,$$

where H(0), H(Δt)– current and projected altitudes; V(0), V(Δt) – current and projected speeds; n_{x1}, n_{y1} – longitudinal and normal overloads; ϑ – pitch angle; α – incidence angle; $\theta = \vartheta - \alpha$ – flight-path angle; Δt – forecast time.

4.1.3. Method 3 (the green graph in the figures below)

The method 3 (green line) is the simplification of the method 2, in order not use the incidence angle, it is different from the method 2 by the simplified equation for the speed forecast:

$$\mathrm{H}(\Delta t) = \mathrm{H}(0) + \mathrm{V}_y \cdot \Delta t,$$

$$\mathrm{V}(\Delta t) = \mathrm{V}(0) + (n_{x1} - \sin\vartheta) \cdot g\Delta t$$

or

$$\tilde{\mathrm{H}}_{\mathrm{bar}} = \mathrm{H}_{\mathrm{bar}} + \mathrm{V}_y \cdot \Delta t,$$

$$\tilde{\mathrm{V}}_{fr} = \mathrm{V}_{fr} + \left(n_{x1} - \sin\vartheta\right) \cdot \sqrt{\frac{\rho}{\rho_0}} \cdot g\Delta t$$

where $\mathrm{H}_{\mathrm{bar}}$, $\tilde{\mathrm{H}}_{\mathrm{bar}}$ – current and forecast barometric altitudes; $\mathrm{V}_{fr}, \tilde{\mathrm{V}}_{fr}$ – current and forecast air speeds; V_y – vertical speed; n_{x1} – longitudinal overload; ϑ – pitch angle; ρ, ρ_0 – air density at flight altitude, and the current density of the air at the surface; Δt – forecast time. Here, ignoring the insignificance of the incidence angle, the pitch angle ϑ is assumed to be equal to the trajectory angle θ.

4.1.4. Method 4 (the purple graph in the figures below)

The method 4 (purple line) is an attempt to complicate the linear projection by adding quadratic terms. Quadratic forecast for the altitude and separate forecasts for related speed components are such as:

$$
\begin{aligned}
V_x(\Delta t) &= V(0)\cdot\cos\alpha + (n_{x1} - \sin\vartheta)\cdot g\Delta t,\\
V_y(\Delta t) &= -V(0)\cdot\sin\alpha + (n_{y1} - \cos\vartheta)\cdot g\Delta t,\\
V(\Delta t)^2 &= V_x(\Delta t)^2 + V_y(\Delta t)^2,\\
H(\Delta t) &= H(0) + \sin(\vartheta-\alpha)\cdot V(0)\cdot\Delta t + \left(n_{x1}\sin\vartheta + n_{y1}\cos\vartheta - 1\right)\cdot\frac{g\Delta t^2}{2}
\end{aligned}
$$

Figures 2-6 below show the individual graphs on the results of the mathematical modeling of the following flight conditions (in horizontal direction – the time in seconds with an interval of 5-10 *s*; in the vertical direction from the bottom to the top – 5 indicators: altitude, time-to-clime, speed, gliding angle, and incidence angle):

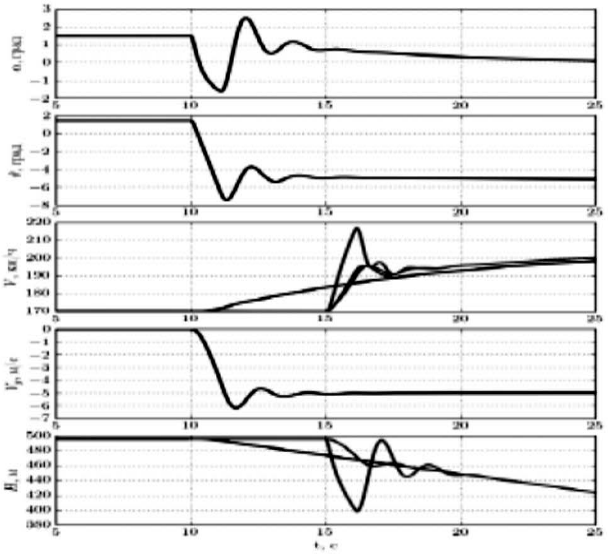


Figure 2: Drifting down from the HF

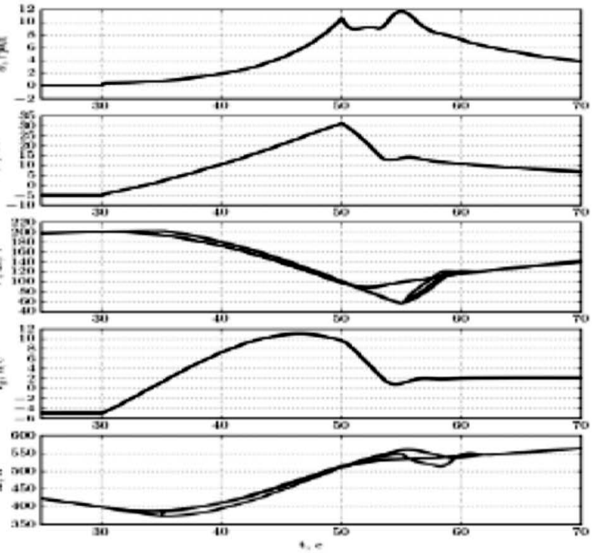


Figure 3: Pitch-up from the drifting down with the subsequent transition in the climb

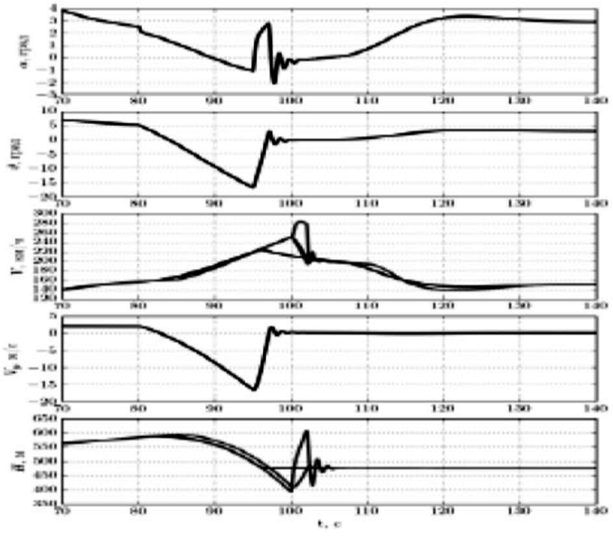


Figure 4: Nosedown from the climb returning to the HF

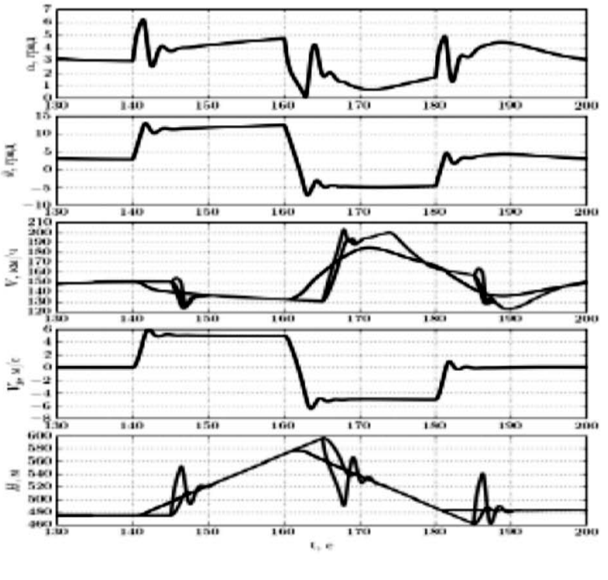


Figure 5: Transition to the climb from the HF with the subsequent drifting down and again to the HF

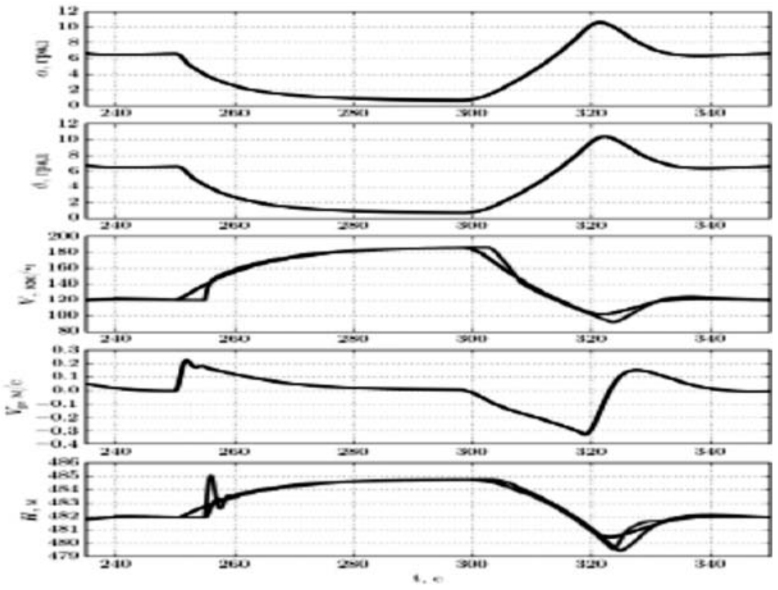


Figure 6: Acceleration and deceleration

The following Figures 7-11 are the graphs comparing the best simple prediction with complex one (trajectory motion equations) (in horizontal direction – time in seconds, with an interval of 5-10 s; in vertical direction from the bottom to the top – 5 indicators: altitude, time-to-clime, speed, gliding angle, and incidence angle):

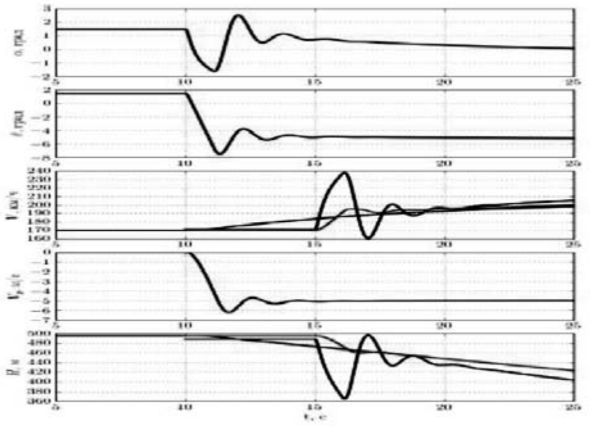


Figure 7: Drifting down from the HF

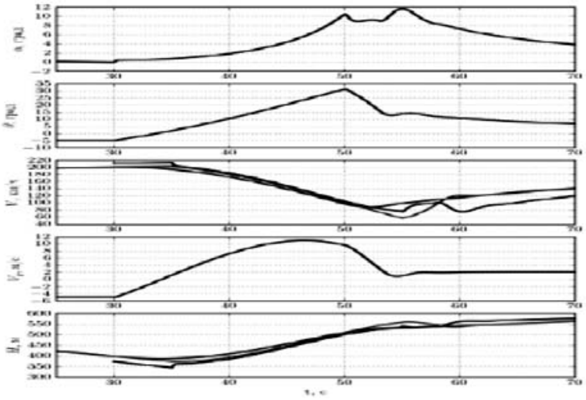


Figure 8: Pitching-up after drifting with the subsequent transition to the climb.

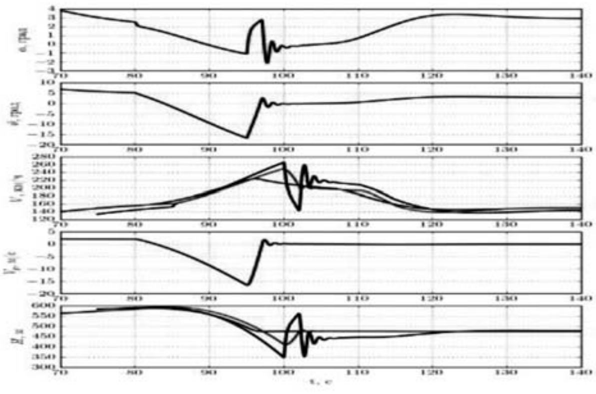


Figure 9: Nose-down after climbing and returning to the HF

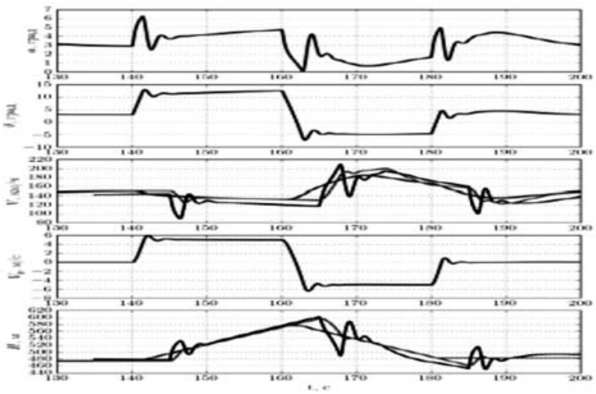


Figure 10: Transition to the climb from the HF with the subsequent drifting down and returning to the HF

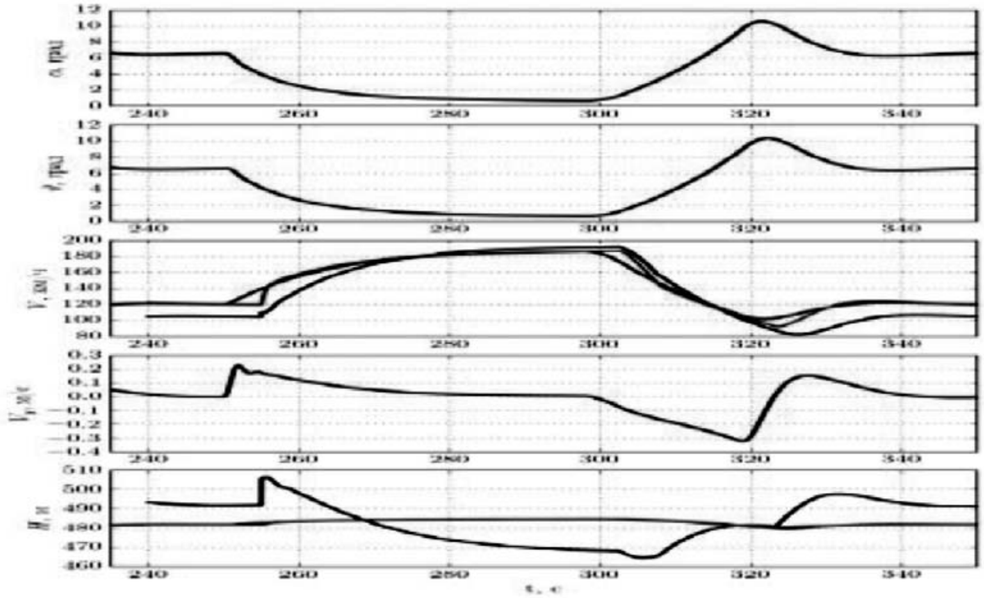


Figure 11: Acceleration and deceleration

Calculation analysis after comparing the different forecasting methods showed that the best option is to stick to the most primitive formulas that have been implemented in the onboard computer, and then verified by the hardware-in-the-loop flight simulation stand and in real aircraft flights.

As studies have shown, when comparing the three methods, the 4th algebraic method is clearly excluded because it is not interesting. The methods 2 and 3 are almost identical, but the method 3 does not use the incidence angle, so it is preferable. All this is shown in the graphs – Figures 2-6.

Further, the method 3 is compared with the method 1 (black line). This is illustrated in the Figures 7-11. Preference should clearly be given to the method 3 that is simple and easily programmable in any modern airborne computer.

4.2. Deviation automated (director-type) algorithms

Deviation automated (director-type) algorithms are used to determine:

- Conditions under which the automated (director-type) deviation from the dangerous altitudes or flying speeds should be initiated;
- Director-type signals, determining the set values of normal overload, roll angle, angular speed ω_x for automatic deviation from the dangerous altitudes or flying speeds.

4.3. Algorithms for the deviation from the stall and spin

The algorithms for the deviation from the stall and spin are used to form :

- Notifications of the aircraft flight operation modes associated with the loss of stability and controllability at the supercritical incidence angles;
- Director-type signals defining the set values of the aircraft and engine control deflection for automated deviation from the critical modes.

The following basic data are needed for the program functioning to deviate from the stall and spin:

- Maximum allowable incidence angle;
- Minimum speed of the horizontal flight;
- Characteristics of the steady spin modes and recommended in FCOM techniques to deviate from the stall and spin according to the flight testing results.

5. FLIGHT INFORMATION DISPLAY FORMATS

An important parameter that characterizes the ability of the pilot to perceive incoming information is the pass-through function or information processing speed. Human pass-through function depends on the degree of memory participation in the information processing and transmitting. The maximum pass-through function does not exceed several tens of bit/s is achieved when memory is not used, which is typical for unconscious reflexes. Well-trained and educated pilot fulfils part of his actions to automatism, that is, he does them without using a memory channel. Pass-through function is approaching the maximum possible value, and is 10-50 bit/s. When using memory, the pass-through function is reduced to 0.5-5 bit/s; if volatile memory is used, the pass-through function is only 0.04-0.2 bit/s.

The human operator pass-through function is also related to the rate at which the information is given to him from the machine. If the rate is too low, the operator's activity falls (the "falling asleep" effect). The high rate of input information flow leads to a sharp increase in making errors and operator's failure to perform the task.

Information reception by the pilot is a process of sensory image formation. The physiological basis of this process is the analyzer work. The analyzers consist of a variety of receptors, nerve pathways and centers in the cerebral cortex. The receptors perceive the impact of the exciter (stimulus) of certain physical nature, carry out the primary information processing and transmit it to the brain. Each analyzer specializes in the perception of certain stimuli. Basic human analyzers are visual, auditory, tactile, gustatory, olfactory, thermal, and vestibular. The pilot uses the information of all the analyzers; however, to transmit the CIISS information to him, only three of them are used – visual, auditory and tactile.

Display methods are classified according to a number of grounds. In relation to the display continuousness, they are divided into:

- Permanent;
- Predictive;
- Event.

5.1. Permanent display

Permanent display is performed during the entire flight. In such a way, the basic flight parameters are indicated – the pitch and roll angles, speed, altitude, vertical speed.

5.2. Predictive information

Figure 12: Prediction of the altitude changes

Predictive information is reported about the possible course of the flight on the basis of the current situation and its development dynamics. The situation prediction allows the pilot to control the aircraft accurately and in a timely manner to avoid the dangers that have not yet occurred, but can occur if not to take corrective actions. To the information projected parameters the authors of this work decided to refer only two ones – the flight speed and altitude after 4 s from the current state based on the current acceleration and vertical speed). An example of projected information display (in this case, altitude) is shown in Figure 12.

5.3. Event display

Event display is carried out if there was an event, information on which should be immediately directed to the pilot, for example, the flight speed or altitude have approached the limits. In these cases, the necessary information is displayed automatically and display lasts as long as it will not be perceived by the pilot or until the event ends.

5.4. CIISS interface

The CIISS uses all three types of display, and two of the three data transfer methods listed above – visual and auditory.

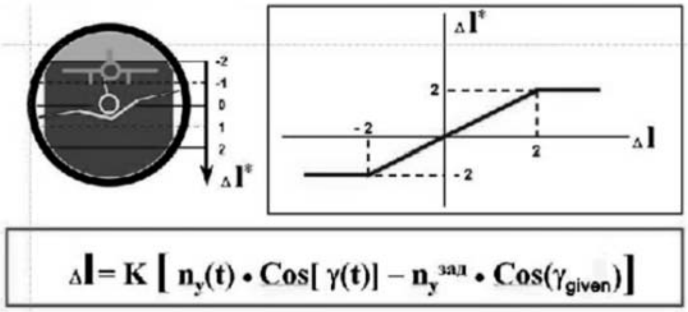
To avoid errors under time pressure and stress crew activities related to piloting and navigation management, the CIISS work logics corresponds to the logics of the business processes. At the same time, this very logic is more intuitive, predictable, and easy for the user. The intuitively understood logics is the one which coincides with the user's (pilot's) mental model – with his understanding of how the system should behave in a given situation. The requirement to the work logics is that it should be as simple as possible, which means that it should be described by a small set of well-defined rules or well-understood graphic symbols. This facilitates the system usage, study, and acquisition by the pilot.

The CISS interface is designed with the emergence of the need to address at the same time more than one task and there should be no conflict, preventing the task solution when another task is solving. At the level of the CISS algorithms program implementation, this means that tasks that may arise at the same time should not require contradictory actions.

Crew working procedure with all systems and objects is normalized; however, each means for displaying information, including the CIISS, has pronounced characteristic features that provide rapid information detection.

Unification also implies that the execution of the same operations should be consistent within the CIISS.

On this basis, for the director-type command Δ*ny* and Δγ display, it was proposed to use the symbol of the so-called "leader" that when a particular situation appears on the LCD display, and is located on the screen with a given roll, and at such a distance ΔI from the centre (the current aircraft position), which corresponds to the difference between the set (for deviation from the special situations) and current overload (Figure 13).



$$\Delta \mathbf{I} = K \left[n_y(t) \cdot \mathrm{Cos}[\gamma(t)] - n_y^{\text{зад}} \cdot \mathrm{Cos}(\gamma_{\text{given}}) \right]$$

Figure 13: Logics for the placement of the director-type "Leader" silhouette on the LCD screen

It should be borne in mind that even a well-designed interface “pilot-aircraft” does not guarantee that pilots will use it correctly; although the misuse refers to the pilot errors, but not to the interface shortcomings.

Prediction, tips and CIISS commands display are issued for all display formats available in the operating modes of the LCD display.

Informational messages generated by the CIISS have the highest priority – in the case of dangerous situation the appropriate information message is displayed in a separate area of the screen on all other pages.

Figures 14-16 below show the CIISS display formats in modes to prevent from the arising of dangerous situation.

Figure 14: CIISS Display when taking the low altitude

Figure 15: CIISS display when taking the minimum speed

Figure 16: CIISS display when taking the maximum speed

Issuance of the sound information by the voice information reporting system (VIRS), duplicating the text messages on the LCD display:

- "Altitude is low, remove the roll, deviate";
- "Speed is low, increase the thrust, diminish the pitch";
- "Speed is high, remove the thrust, increase the pitch";
- "Stall. Push the control stick away";
- "Spin. Push the control stick away. Use the pedals left/right/neutral".

6. RESULTS OF THE EXPERIMENTAL STUDIES

CIISS model testing was carried out at the flight stand (Figure 17) and in flight by a light C42 Ikarus aircraft (Figure 18).

Figure 17: Half-sized modeling flight simulator

Figure 18: C42 Ikarus aircraft

A total of the carried out flights is 12. The purpose of the test :

- Demonstration of the CIISS compliance with the requirements in terms of identifying the flight special conditions at the earliest stage of their development for the early warning of the crew about their appearance, to form and display the flight information on the extreme conditions, to display alarms and director-type commands to parry the arising of the special situation and rational deviation from it in order to prevent the further development;
- Confirmation of the CIISS conformity to the requirements regarding flight altitude and speed change prediction in order to assess that it is safe to continue the current manoeuvre. Confirmation of the warning flight information formation and output to the crew when approaching the safe manoeuvring limit;
- Confirmation of the CIISS conformity to the requirements regarding identifying and countering the dangerous consequences of the emergency situations in flight due to:
  - (*a*) Errors and inadequate actions of the crew;
  - (*b*) Threat of aircraft collision with the ground surface and violation of the flight restrictions.
  - (*c*) Entering a complex spatial position at low altitudes and collision with the ground as a result of the incorrect implementation of the spatial (vertical and horizontal) manoeuvres;
  - (*d*) Loss of stability and/or controllability (stall, spin).

To assess the warning alarm, flights with simulated approaching the critical modes and complex spatial position were performed. There were performed nose-dip modes with the pitch angle greater than 10° to speed Vpr = 180 km/h; pitching with a pitch angle greater than 25°, reducing below the minimum safe altitude of 40 m.

The flight objective was:

- Real flight evaluation of the CIISS algorithms performance implemented in the onboard computer;
- Flight evaluation of the display system and display control methods in all flight phases;
- Flight evaluation of the warning alarm when approaching critical flight modes.

6.1. Evaluation of the CIISS algorithms performance in real flight

CIISS algorithms implemented in the onboard computer, use the value of normal overload $n_y(t)$, which serve as the basis for the formation of the director-type (information) signals, forming the “Leader” position by the $\Delta n_y = n_y(t) - n_{y\ \text{given}}$ value, and the value of the longitudinal overload $n_x(t)$, which is used to predict the speed.

Due to the vibration of the power unit (“Rotax-912ULS” piston engine and propeller), transmitted to the entire aircraft structure, and, consequently, on the board attitude and heading reference system (AHRS) platform, where overload sensing devices $n_y(t)$ and $n_x(t)$ are installed. An additional source of noise is the nature of the microelectromechanical systems (MEMS) used to measure the overload. These noises are in a frequency range of 10 to 80 Hz.

In this connection, there was the task of filtering the airborne overload measurements $n_y(t)$ and $N_x(t)$, available on the aircraft board and used in the CIISS algorithms.

A simple aperiodic filter 1/Tr + 1 was tested. The result of the airborne measurements of normal overload $n_y(t)$ filtration is shown in Figure 19.

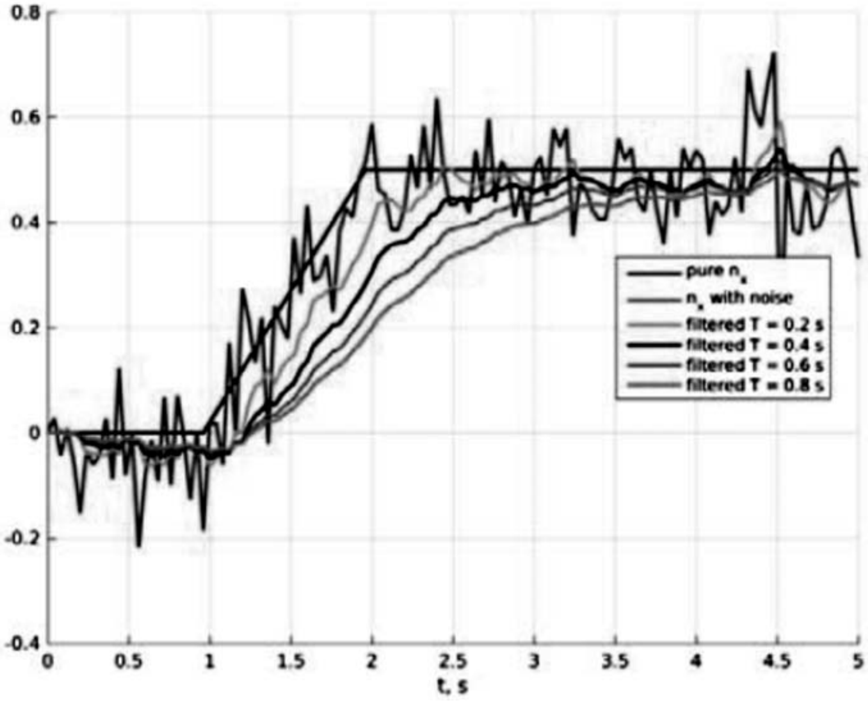


Figure 19: The measurement results *ny*(*t*) using the aperiodic filter

As the results show, a simple aperiodic filter 1/Tr + 1 gives a significant delay. It was therefore decided to try out several options for filtering by a low-pass filter as an infinite response (including the Butterworth’s and Chebyshev’s filters [9-10]), and with a final response (including Parks-McClellan’s and MNC’s filters). Testing these filters with different cut-off frequencies gave not very comforting conclusion. All these algorithms filter well, if you take the higher filter order that is closer to 15-20 Hz. At low frequencies, orders (around 3-5 Hz) in the transition mode, these filters are virtually indistinguishable from the aperiodic filter and to take a high order prevented initially selected low sampling frequency. At a frequency of 25 Hz the delay in filter order of 20 would be about 1 second. Trying to catch them by a sampling frequency of 25 Hz is useless, as the main noise is at frequencies above the Nyquist frequency. Low sampling transposes the noise in the entire release band. In this connection, to solve the problem of filtration the sampling frequency has been increased to 100 Hz, and the Butterworth filter has been selected for the noise reduction. In comparison with the Chebyshev filters of type I and II or elliptical filter, the Butterworth's filter has a more gentle characteristic decline and should therefore have a greater order (which is more difficult to implement) to provide the desired characteristics for the notch frequencies. However, the Butterworth's filter has a more linear phase-frequency characteristic (LPFC) at the bandwidth frequencies (Figure 20).

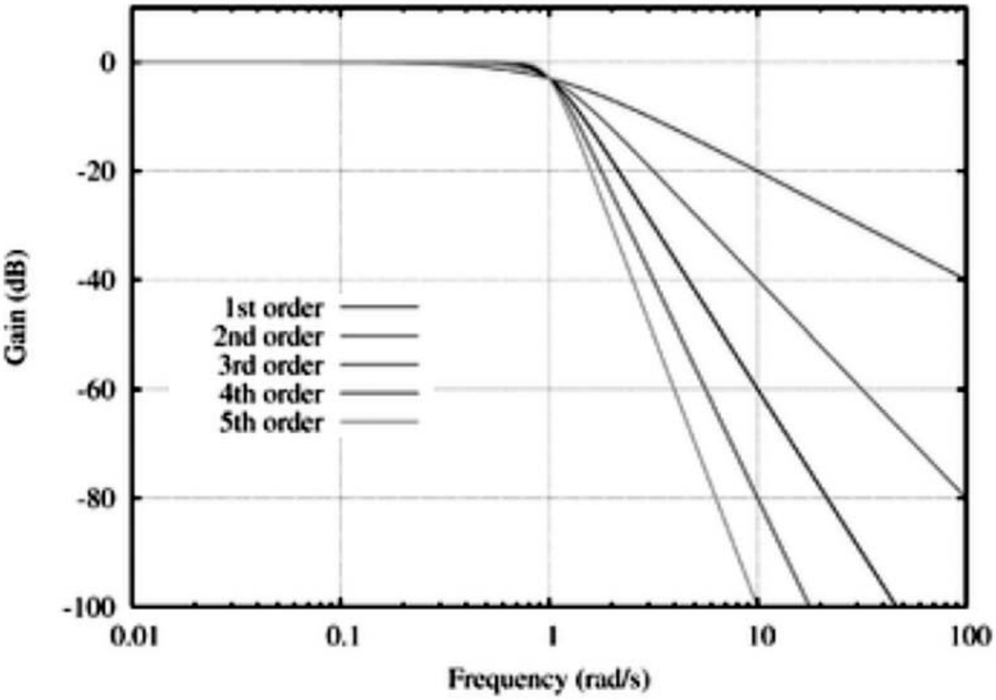


Figure 20: LPFC for the Butterworth's filters of lower order frequencies from 1 to 5

As a result of searching and testing a variety of filters in the CIISS algorithms to suppress the noise in the overload measurement (see Figure 21), the Butterworth's filter of the 5th order with the frequency of 3 Hz has been selected. The amplitude frequency response G(ω) of the Butterworth's filter:

$$G^2(\omega) = |H(j\omega)|^2 = \frac{G_0^2}{1+\left(\frac{\omega}{\omega_c}\right)^{2n}}, \text{ where}$$

n – order of the filter;

ωc – cutoff frequency (the frequency at which the amplitude is equal to –3 dB);

G_0 – amplification factor on the constant component (amplification at a zero frequency).

In the Figure 21(*a*), the transient delay was calculated by the method of maximum cross-correlation of the clear and filtered signals, and the Figure 21(*b*), the graph marks the standard deviations before and after the filtration.

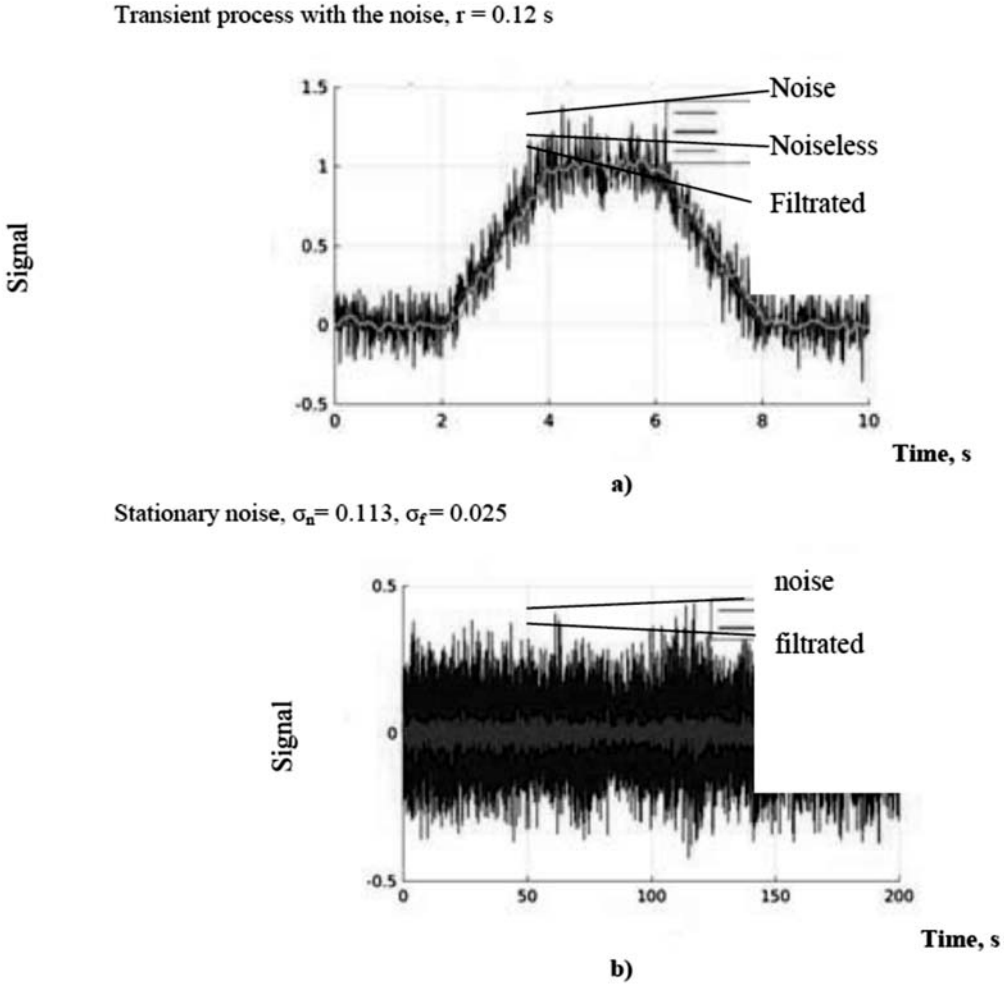


Figure 21: (*a*-*b*). The results of the measurements of $n_y(t)$ using the Butterworth's filter of the 5th order

6.2. Analysis of the flight evaluations

The analysis of the flight display and alarm system evaluations implemented in the CIISS leads to the following conclusions:

The displayed information on the MFI screen corresponds to the adequacy requirements, readability and output of the necessary data to the pilot in accordance with the logics of the selected operating mode.

Implemented reporting algorithms provide security of the maneuvering by informing approaching the dangerous flight conditions, warning of the need for urgent crew actions to prevent the further development of the operating system in accordance with the priorities (emergency, warning, notification alarm);

Implemented algorithms provide commands to parry OS. Display is in the form of visual symbols clearly perceived and attention grabbing.

Ensured consistency of text and voice messages to each other and parametric information on the screen.

Push-button LED display bezel provides optimal display control

Issuance of warning information when approaching the limits of safe manoeuvring and the approach to the flight restrictions are in the form of director-type commands, text messages.

Realized alarm to help low-skilled pilot in identifying the type of dangerous situation and performance of safe deviation from of it without too much burden on the pilot.

Obtained flight evaluation of the information adequacy and readability for the flight crew to provide the crew (pilot) with the necessary data in accordance with the selected operating mode logics.

7. GENERAL CONCLUSIONS

The experimental CIISS sample has been tested at a flight simulator modelling and in flight tests, and the following main tasks have been solved:

- The CIISS algorithms performance and correct warning operation in case of particular situation in the realized warnings list of special situations was shown;
- Tolerance spread in time, distance, altitude deviation at which the CIISS effectively provides the crew a warning about a special situation was assessed;
- The CIISS real-time operation was checked;
- Allowable errors in the input information – raw data and on-board measurements were determined;
- Preliminary assessment of ergonomic data display in the IISPE was carried out.

Introduction into service, including for the GPA aircraft and light aircraft, of on-board systems with the information-analytical and crew intellectual support systems and active flight safety, will significantly reduce (virtually eliminate) the effect of the “human factor” on the flight safety.

The dynamic prediction potential has still not been achieved. A more detailed study of its features is needed. Probably the start shall be in solving the longitudinal motion equations (drawn up in such a way that the trajectory equations have been separated). Moreover, after the gradual reduction of these equations, constantly comparing with the model, to come to the simplest form. This approach will more fully show the features that you want to capture in the equation solution.

8. CONCLUSION

The results given herein were obtained during the execution of applied research, which is sponsored by the Ministry of Education and Science of Russia under the Agreement No. 14.579.21.0051 on September 16, 2014. A unique identifier of the applied scientific research is RFMEFI57914X0051.

Of course, the development, improvement and implementation of the on board crew information and intellectual support systems is one of the key elements in the system to ensure safety, “slacking up” in the weakest link today, that is, the man. And the mass introduction of these systems will significantly reduce (virtually eliminate) the effect of the “human factor” on the safety flights, which today, as the analysis of the condition of the safety in Russian civil aviation shows, is the main (almost 90%) cause of accidents and incidents.

At the time when the aircraft is a highly reliable automated system, the human remains the weakest link in the flight safety circuit. A human’s reaction to a suddenly arisen complicated situation is not always sufficient to timely correct the assessment of the current event dynamics and its prognosis, and make the right decision.

Thus, we can conclude that the presented publication on the development of the information and intellectual support system for the crew is extremely relevant today and actually feasible.

The market aspects and the assessment of the competitiveness of the information and intellectual support for the crew system are with no doubt due to the lack of such systems in the complexes offered for small aircraft in the market today.

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