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An Approach to Developing Mathematical Software of On-Board Helicopter Flight Simulator Decision Support System

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Abstract: The work explores methods and develops aids to improve a pilot flight training level using Full Flight Simulators. It examines their didactic advantages over real helicopters by implementing on-board intelligent decision support systems (IDSS). These simulation programs monitor actions of learner, find the best ways to correct errors and generate appropriate instructions. The training is carried out by reference point methods while the helicopter flight dynamics model simulates a flight and helps an instructor in parallel. Sufficiently simple and accurate model of helicopter flight dynamics was selected and tested to assess the proposed methods and aids. Our analysis introduces a functional structure of IDSS as an adaptive control system with a reference model. We further conducted a study on developing models, methods and means of automatic analysis, forecasting, optimization and correction of actions. Combining single-criteria conditional and vector optimization methods, we found out optimal flight parameters. The research findings revealed that the chosen optimization method requires too many system resources for the optimal solution to be found in a short time. The study thereby comes up with applying ANNs to solve this problem.

Keywords: Pilot training, flight simulators didactic features, on-board decision support system, mathematical modeling of pilot actions, automatic synthesis of instructions

1. Introduction

Helicopters are widely used to solve various transport and combat tasks. However, these heavy machines are incredibly expensive and difficult to control. Accordingly, flight training is a long, complex and expensive process. Thanks to the rapid development of information technologies, flight simulators have reached a high level of perfection, allowing pilots to perform most flight tasks without costly helicopters. Apart from the economical aspect, the advantages of the simulator include greater safety, whereas the encountered disadvantages were incomplete adequacy of the flight information model compared to a real helicopter. An immediate problem to tackle is improving the quality of pilot professional training at simulators by introducing ia process called "electronic instructors" [1] - on-board intelligent decision support systems (IDSS). This method involves automatically analyzing pilot's actions, predicting their results and generating real-time instructions for optimal and safe error correction. The submitted study seeks to create models and devise methods and means of automatic analysis, forecasting, optimization and correction of pilot's actions in the process of training at a flight simulator. The Mi-8MTV helicopter simulator, produced by "Avia" Ltd (Ukraine), was chosen as a platform for IDSS development for various reasons, including a software-hardware complex of qualification evaluation [2], which makes the task much easier.

2. Data and Methods

The simulator is the helicopter information model comprising a local computer network that controls the virtual reality peripherals. This electronic facility sufficiently and accurately displays the information received by the pilot in the real flight [3]. It should be noted that modern methods of flight simulating are not much different from training in a real helicopter. The techniques involveverbal instructions and visual demonstrations of the pilot instructor. However, the didactic capabilities of the simulator are significantly different from a real helicopter, as they requirespecific adjustment of teaching methods and aids [4].

To make a full use of simulator didactic capabilities the model should involve IDSS, in case the pilot instructor needs help or must be completely replaced. [5-12]. The main simulator component includes a mathematical model of helicopter flight dynamics., so thatIDSS may predict the results of the real-time control, find the optimal actions for error correction and generate appropriate instructions.

The real mathematical model of helicopter flight dynamics consists of dozens of nonlinear differential and algebraic equations. In our case, there is no need to use such a complex model, because the task is to select and to pre-study the adequacy of mathematical methods and tools for automatic analysis of piloting errors and generation of instructions for their correction. Therefore,

this paper is based on a simple model of helicopter dynamics as a material point for a rough analysis of helicopter maneuverability [13].

The description of the helicopter movement is performed in the following coordinate systems [14] (Fig. 1). All systems are Cartesian, right-handed, with origin in helicopter center of mass (CM):

1. Body system (helicopter-bound) OXYZ. The normal Y axis coincides with the axis of the main rotor shaft and directed to helicopter top. The longitudinal X axis is perpendicular to Y axis and directed to helicopter front.

2. Velocity system (airflow-bound) $OX_aY_aZ_a$. The velocity axis X_a coincides with the helicopter speed V relative to the air. The angle α between the axes X_a and X is called the angle of attack. It determines the helicopter position in the airflow and aerodynamic forces acting onto it.

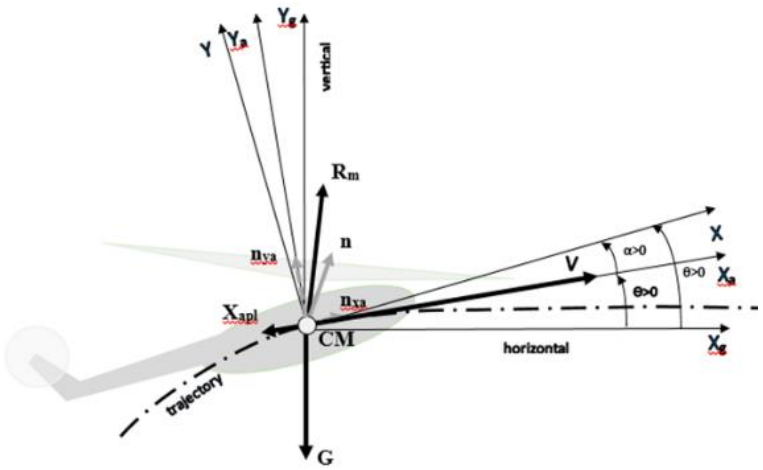


Fig. 1 Coordinate systems describing a helicopter movement, acting forces, load factor and kinematic parameters (for maneuvering in the vertical plane). Source: authors

3. Normal system (earth-bound) $OX_gY_gZ_g$. The Y_g axis is directed upward along the local vertical. The angle Θ between the axes X_g and X_a is called the angle of trajectory inclination. The angle θ between the axes X_g and X is called the pitch angle of helicopter.

The reason of movement - the forces acting onto the helicopter. In our case, there are three main ones:

1. The resultant aerodynamic force (thrust) of the main rotor R_m. The pilot, using control levers (collective pitch lever and cyclic stick), changes the magnitude and direction of thrust, forcing the helicopter to accelerate in the desired direction (collective pitch lever up - thrust increases, down - decreases, cyclic stick forward - thrust tilts forward, back - back). Thrust depends on the pitch angle of main rotor blades, helicopter airspeed and angle of attack;

2. X_{apl} helicopter air resistance;

3. Gravity force G.

The vector n, of which the direction coincides with the direction of helicopter acceleration a, caused by active external forces R_m and X_{apl}, and the magnitude, shows how many times a > g (where g is the acceleration of free fall), is called load factor. The pilot feels the load factor as his body acceleration in the opposite direction. The components of n along the axes of the velocity coordinate system n_{xa} and n_{ya} are called tangential (changes the value of speed) and normal velocity (changes the direction of speed) load factors, respectively.

The equations of motion represent Newton's second law (a = dV/dt = F/m, where F - the force acting onto the body, m - mass of the body, t - time) in the projection on the axis of the velocity coordinate system [13].

$$\frac{d}{dt}V = \sum F_{xa} = g\left(n_{xa} - sin(\Theta)\right), \quad [-] \qquad (1)$$

$$\frac{d}{dt}\Theta = \sum F_{ya} = \frac{g}{V}\left(n_{ya} - \cos(\Theta)\right), \quad [-]$$

It is assumed that piloting techniques training is performed by a method of "reference points" - points at the flight path, where the control over achievement of the previous goal and the transition to achieve the next takes place. At the reference point, the pilot evaluates the flight information, makes a decision and begins its implementation. Each point is characterized by a certain spatial position of the helicopter, instrument readings and specific non-instrumental signals that form information image of the reference point [1].

DSS based on artificial intelligence [12] and the method of reference points should have an access to a parallel use of the simulator mathematical flight dynamics model, a description of the maneuvers to perform in the form of reference points sequence, values of flight parameters and limits and a reference model of the control in the form of control levers (aerodynamic forces) and deviations depending on time.

The following generalized cyclic algorithm of IDSS operation involves the program monitoring learner’s actions and forecasting their results for a certain time interval, which is different for each maneuver and is determined in advance by expert evaluation. It also involves exceeding established parameter limits will trigger calculation of the optimal corrective measures and instructions for corrective measures are generated and provided to the learner in an acceptable form.

We consider a straight acceleration at constant altitude without roll and sideslip from speed V_0 to speed V_1 within the range of permissible speeds as a specific maneuver. The description of the maneuver will contain only two reference points - the beginning (p. 0) and the end of acceleration (p. 1). As an exemplary piloting technique, we will take a real record of flight parameters by an on-board registrator of Mi-8MTV-1 helicopter provided by "Avia" Ltd, Kremenchuk, Ukraine (Fig.2).

Noisy data can be satisfactorily approximated by linear and quadratic regression dependencies. Deviations of parameters from the standard are given in table 1 [15]. Other possible approaches to the evaluation are described in [16].

Table 1 Flight parameters deviations. Source: [15]

Speed maneuvering	Standards of deviations on a scores		
	perfectly	good	satisfactory
Maximum speed, km/h	-5	-10	-15
Minimum speed, km/h	+5	+10	+15
Altitude, m	+/- 20	+/- 30	+/- 50

3. Results

Since the adopted model the helicopter is regarded as a material point (the body-bound coordinate system loses sense), the real angles of deviation of controls and forces cannot be calculated. Therefore, the model includes the angle δ of thrust R_m inclination relative to Y_a axis, which is positive when the thrust tilts forward. Although the model is built on idealized principles, it will work well towards achieving the prescribed goals.

The following control inputs are needed to realize acceleration (Fig.2). The control stick (force R_m) must tilt forward to increase the X_{am} component (speed increases). However, this reduces the component Y_{am} (helicopter loses altitude). Therefore, simultaneously, the collective pitch lever rises upwards (R_m and, accordingly, Y_{am} increases).

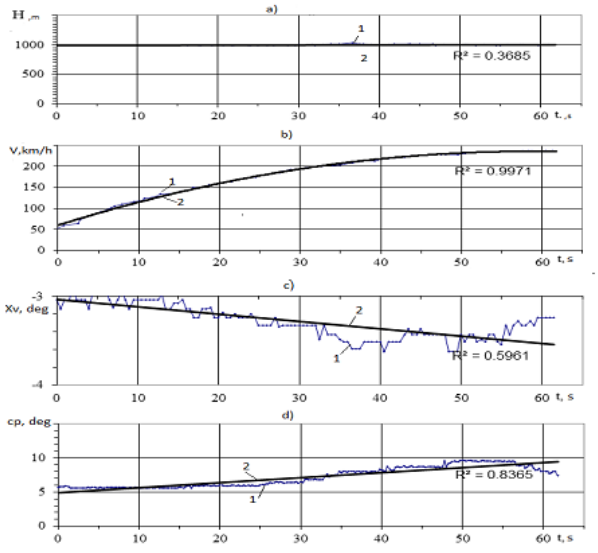


Fig. 2 Records of flight parameters during acceleration at constant altitude (1) and their polynomial approximation or reference control model (2): a) H - altitude; b) V - airspeed; c) xv - longitudinal control stick inclination; d) cp - collective pitch. Source: authors

The load factors in equations (1) are determined by formulas

$$n_{xa} = \frac{R_m \cdot \sin(\delta) - X_{apl}}{G} \quad (2)$$

and

$$n_{ya} = \frac{R_m \cdot \cos(\delta)}{G}, \quad (3)$$

where

$$X_{apl} = C_{xa} \cdot \frac{\rho \cdot V^2}{2} \cdot F_m \quad (4)$$

means X_{apl} aerodynamic drag force of the helicopter body, C_{xa} - drag coefficient which depends on the body shape, the state of its surface and position in the airflow (angle of attack), ρ - air density, V - airspeed, F_m - the main rotor area.

The availability of real flight parameter records makes it possible to identify the model.

In our case, the barometric altitude H = 1000 m, ρ = 1.11 kg/m^3, at point 0 speed V_0 = 60 km/h = 16.7 m/s, at point 1 speed V_1 = 240 km/h = 66,7 m/s, F_m = 356 m^2. The angle of attack α within the accepted model is not determined, but it is known that the real helicopter is designed in such a way that it differs from zero by no more than a few degrees at cruising speed (220 km/h) α ≈ 0 and in the range of speedsunder consideration The dependence of $C_{xa}(\alpha)$ looks like at Fig. 3 [13]. Therefore, we will further assume that C_{xa} (α) = C_{xa} (0) = const and find the dependence $X_{apl}(t)$.

Having the time dependence of velocity (regression line equation, Fig.2b)

$$V(t) = -0.051t2 + 5.987t + 60.338 \quad (5)$$

We can find the first derivative (time dependence of acceleration) and the acceleration of the helicopter a_{x0} at point 0, the components of thrust

$$X_{am0} = X_{apl0} + ma_{x0}, \quad Y_{am0} = G \quad (6),$$

total thrust

$$R_{m0} = \sqrt{{X_{am0}}^2 + {Y_{am0}}^2} \quad (7) \text{ and angle } \delta_0 = \text{tg}^{-1}\frac{X_{am0}}{Y_{am0}} \quad (8).$$

Similarly, given that a_{x1} = 0 we find X_{am1}, Y_{am0}, R_{m0} and δ_0.

The control laws $R_m(t)$ and δ(t) for the whole time interval $[t_0,t_1]$ are found by linear interpolation.

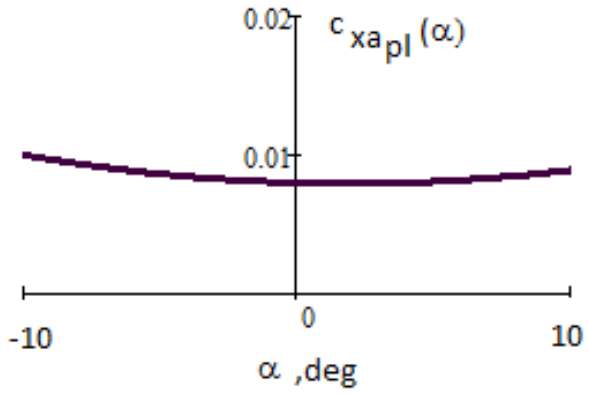


Fig. 3 Dependence $Cxa_{pl}(\alpha)$. Source [13]

Thus, we finally get a complete system of equations of the flight dynamics model, which also includes equations for calculating the altitude h(t) and flight range L(t)

$$\frac{d}{dt}V(t) = g \cdot \left[\frac{R_m(t) \cdot sin\big(\delta(t)\big) - X_{apl}(t)}{G} - \sin\left(\Theta(t)\right)\right]$$

$$\frac{d}{dt}\Theta(t) = \frac{g}{V(t)} \cdot \left[\frac{R_m(t) \cdot cos\big(\delta(t)\big)}{G} - cos(\Theta(t))\right] \quad (9)$$

$$\frac{d}{dt}h(t) = V(t) \cdot cos(\Theta(t))$$

$$\frac{d}{dt}L(t) = V(t) \cdot \sin\big(\Theta(t)\big)$$

by integrating them under initial conditions V(0) = 16.67 m/s, Θ(0) = 0 rad., H (0) = 1000 m, L (0) = 0 m we obtain the following results (see Fig. 4).

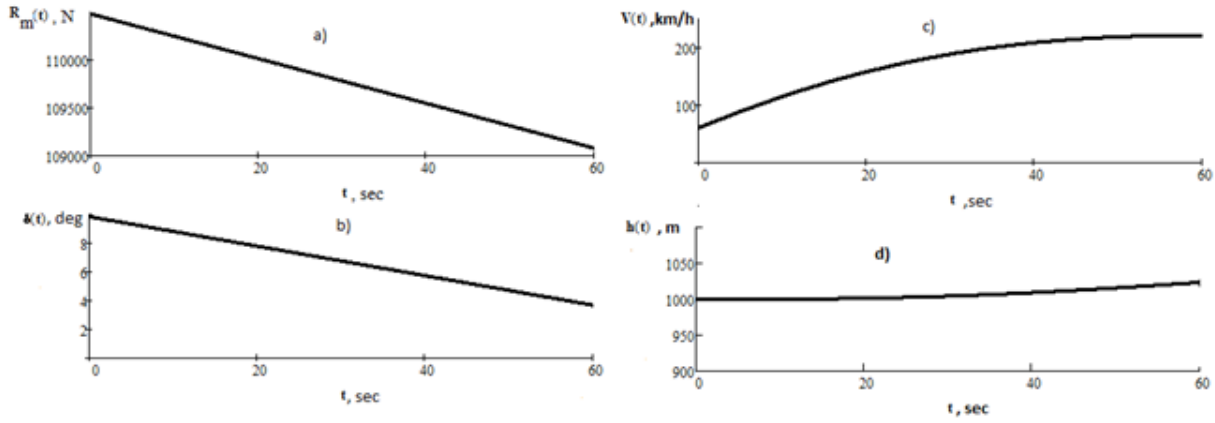


Fig. 4 The results of the adopted model of flight dynamics. Source: authors

The synthesis of corrective instructions is performed at the basis of formalized flight task, which, in turn, is a sequence of reference points with the phase coordinates specified in each of them and can be formulated as an adaptive control task with a reference model [17]: a transition between the previous and next reference points with the forecast of discrepancies within the reference model at the time of the planned achievement.

The use of decision support systems in aviation in order to improve the reliability and safety of flights is relevant and promising.

The analysis of modern works in this area [5-12] allows using IDSS to solve flight control problems, pilot training, optimization of aircraft movement parameters, etc.

The general structure of IDSS [7,8] is shown in Fig. 5. The proposed system includes X(t) as the vector of input influence parameters (control signals $R_m(t)$, δ (t)). Y(t) is the vector of the output parameters of the controlled object. According to the helicopter motion model Y(t) = (V(t), Θ(t), h(t), L(t)). The object of control is a helicopter and the dynamics of movement is set by the system (10). Controls - control levers that affect the change of system parameters according to the model (9). The unit for forming the objective function contains a formalized description of the optimality criteria based on the output parameters of the system Y(t). The unit for organizing the optimal values of the

input parameter search provides the formation of the optimal vector of input values based on the formed optimum of the objective function q(t). The block of comparison of the current actions at each step with optimum ones allows defining a vector of deviations of the actions from optimum, received by applying optimization criteria and objective function q(t). The unit for making recommendations to the learner generates verbal instructions to adjust the parameters of input signals received by the controls. The system parameter prediction unit allows predicting the values of system parameters for a given number of subsequent steps based on the selected prediction model. The predicted parameter display unit provides the pilot with information about predicted behavior of the system in a convenient way (graphically or verbally).

The implementation of the proposed system assumes that there is a state space of the system X = (x1,x2,...,xn), which is the domain of the given quality function or objective function J(x_1,x_2,..., x_n). From the states x it is necessary to choose certain states $H_i = h_i$ (x_1, x_2, ..., x_n) where i = 1,2, ..., m, at which the extreme value of the quality function J (x_1, x_2, ... , x_n) is provided [17].

The objective function formation unit sets the optimization function at each estimated time. Since the problem of finding the optimal value of the speed functional under constant altitude conditions is solved, it is necessary to minimize the deviation of the flight speed and decrease the modulus of the altitude derivative.

The rules of the helicopter operation impose restrictions on the range of possible control values: $R_{m_bmin} \leq R_{m_t} \leq R_{m_bmax}$; $\delta_{bmin} \leq \delta_t \leq \delta_{bmax}$, where R_{m_t}, δ_t are the current values of the parameters and R_m and δ, R_{m_b}, δ_b are the limit values determined by the type of the helicopter.

In this case, the optimization problem [18] can be represented as:

$$(R_{m_opt}, \delta_{opt}) : J \rightarrow opt, \tag{10}$$

where:
$$J: \begin{pmatrix} abs(V(t) - Vetalon(t)) \rightarrow min \\ \frac{dh}{dt} = f\big(V(t), \Theta(t)\big) \rightarrow 0 \end{pmatrix};$$

$$R_{m_bmin} \leq R_{m_t} \leq R_{m_bmax}; \ \delta_{bmin} \leq \delta_t \leq \delta_{bmax} \tag{11}$$

means *F* is optimality criterion, R_{m_opt}, δ_{opt} is optimal values of parameters R_m and δ, $V(t)$ is current value of speed, $V_{etalon}(t)$ is reference (optimal) value of speed $V(t)$ at time moment *t*, $\Theta(t)$is current value of trajectory inclination angle.

Since the optimality criterion J is represented by a vector of functions, multicriteria (vector) optimization methods [18,19] were used to find the optimal control parameters.

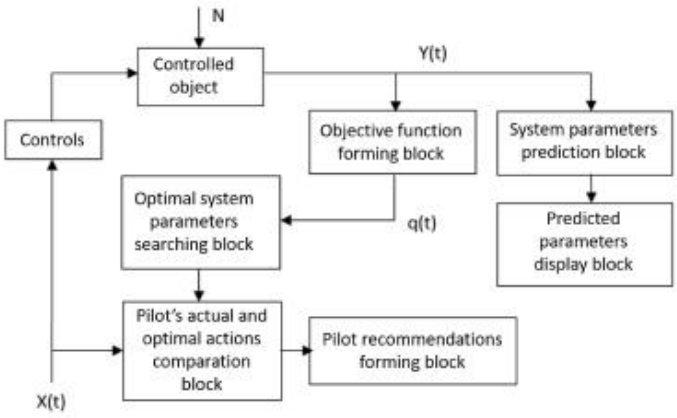


Fig. 5 The general structure of IDSS. Source: authors

To optimize the input parameters, the trajectory shown in Fig. 4 with corresponding control input signals ($R_m(t)$, $\delta(t)$) was chosen as a reference model of the speed at the stage of acceleration.

Simulation of the pilot's actions during the training flight is represented by distorted input values ($R_{mk}(t)$, $\delta_k(t)$), presented in Fig. 6, under the preserved parameters of the helicopter motion model (10). This leads to a significant deviation of the flight speed $V_k(t)$ and altitude $h_k(t)$ from the reference trajectory, exceeding the allowable limits. Fig. 6 shows Rm(t), $\delta(t)$ - optimal values of input parameters, $R_{mk}(t)$, $\delta_k(t)$ - modified, non-optimal values of input parameters, respectively, V(t), h(t) - optimal values of the system output parameters, $V_k(t)$, $h_k(t)$ - respectively, non-optimal values of the system output parameters. V_{max} - boundary, maximum allowable value of flight speed, h(t)+50, h(t)-50 - boundary values of flight altitude change.

The optimization procedure [19] of input control parameters allows obtaining the optimal vector of the input influence ($R_{m_opt}(t)$, $\delta_{opt}(t)$) at each step.

The following input parameter constraints were used for modeling:

$$0 \leq R_{m_t} \leq 13*10^5;\ -2*\pi/180 \leq \delta_t \leq 2*\pi/180. \quad (12)$$

The following graphs (Fig.6) compare the reference values of the system output parameters and the parameters obtained by applying the input parameters optimization unit, starting from the 30-th second.

The presented graphs indicate V(t) - the reference value of speed, $V_k(t)$ - the speed obtained under influence of input parameters uncontrolled values ($R_{mk}(t)$, $\delta_k(t)$), $V_r(t)$, $h_r(t)$ - speed and altitude obtained by controlling the input parameters.

These graphs make us conclude that desired movement parameters can be achieved by a proper regulation. The defined limits are fairly acceptable, but different from the prescribed reference values. Thus, to get closer to the reference speed rates and altitude, we have to adjust the system input parameters as soon as possible.

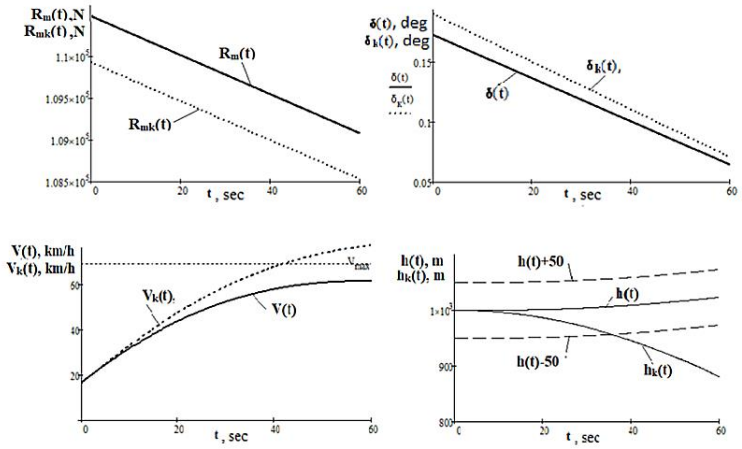


Fig. 6 Reference and distorted values of input and output flight parameters. Source: authors

Upon applying optimized input influence parameters at the interval 060s, we achieved desired speed and altitude values, fully complying with the reference. It should be noted that the corresponding results can be obtained if the sampling rate is 0.01 s, which requires using substantial computer resources.

The helicopter motion parameters should be set to the following: vector $Z_{progn} = (V_{progn}, \Theta_{progn}, h_{progn})^T$ over time t based on the statistical matrix of control parameters $||X= (R_{m\ prev}, \delta_{prev})||$ obtained in the previous steps.

We used Bjorg's method [20] for forecasting, which calculates autocorrelation coefficients for last m points in vector v, to predict the value at (m+1) point. This procedure is repeated in the sliding window. The algorithm is very useful for smoothed and oscillating data, not necessarily periodic.

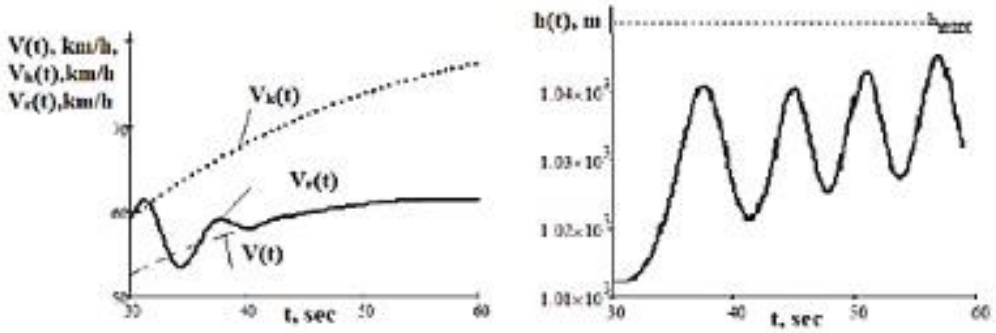


Fig. 7 The system output parametrs obtained by the optimization unit. Source: authors

The built forecasting procedure is included into system general cycle and allows at each step, based on current control signals, current speed value and speed reference value, to generate a forecast for a given time interval and notify the pilot in advance in case of predicted speed parameters exit beyond normal limits.

4. Discussion

In modern conditions, professional training of pilots is largely takes place at simulators. But the simulator, as a didactic tool, differs significantly from the real helicopter, which requires a corresponding change of training methods and implementation on-board IDSS, which would use the existing model of flight dynamics in parallel to simulate the flight and automate instructor functions.

The paper shows that such a possibility really exists.

5. Conclusion

The paper proposes an approach to developing mathematical support and software for on-board decision support system of a flight simulator to automate instructor functions involving the simulator flight dynamics model. A simple model of helicopter flight dynamics is adapted for the specific needs and tested at real flight parameter records. Established flight parameter restictions and flight control laws observe normative documents on helicopter operation. We also formalized optimal control parameters, considering alternative approaches to resolving the optimization problem.

The study further proposes the functional structure of IDSS as an adaptive control system including a reference model. We also suggested procedures for finding optimal parameters by a combined method of single-criteria conditional and vector optimization techniques. The model experiment determined the optimal value of the parity criterion in the adaptive folding method of the optimality criterion vector.

Numerical real-time methods accurately measured the pilot-controlled helicopter movement, how it deviates from the ideal one and calculated a dynamic forecast of the deviation based on Brown model. Our experimental findings proved that a reliable prediction can be successfully made involving Brown’s model linear or nearly-linear control laws. The study also identified values of the model parametersby means of carefully developed software.

Acknowledgments

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