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Valerii Azarskov[1]
Grygorii Rudyuk[2]

METHODOLOGY AND RESULTS OF PILOT MODEL IDENTIFICATION IN SEMIAUTOMATIC FLIGHT CONTROL

[1]National Aviation University
Kosmonavta Komarova avenue 1, 03680, Kyiv, Ukraine
[2]ANTONOV Company
1, Tupolev Str., Kiev, 03062,Ukraine
E-mails: [1]azarskov@nau.edu.ua; [2]rudyuk@antonov.com

Abstract. *The article reviews statement of identification stage of pilot action models in the control loop, methodology, algorithms and certain results of its performance on flight simulator. New approach is offered for identification of operator dynamic models in moving object control loop. Distinctions are mainly related to multichannel expansion of traditional models that allows considering to a great extent the biological features of the operator.*

Keywords: dynamic model; dynamic object; flight simulator; stabilization object; stochastic data; structural identification

1. Introduction

In order to solve different tasks of dynamic object controlling, it is necessary to know real dynamic characteristics of signals, impacts and disturbance in control system, set subsystem, for example the stabilization object. It is also necessary to evaluate the object state (output reaction vector) in operation or in conditions close to operational.

The aircraft and the pilot (operator) fulfilling the tasks set for specific real continuous stabilizable flight is constantly affected by many stochastic random disturbing factors causing certain rather evident changes in expected control mode. These are “minor” factors mainly which do not cause critical changes in controlled modes. But real behavior of the pilot reflects to a considerable extent the influence of stated disturbing factors. Peculiarities of “disturbed” behavior of the pilot at stated control can be characterized with “disturbed” models of its dynamics. Such models are those which can be adequately objective in reflecting the peculiarities of real control of the object motion in above-stated modes.

Main difficulties in compiling similar models have problematic nature. This is first of all connected with that the composition, peculiarities, mechanisms of impact of “minor” influences, its variability due to specific conditions of addressed flight, etc. are not explored enough till now. In other words, at the present time there is no clear conception of influence of stated disturbances on the pilot, reaction for it of specific person in specific flight, biological and psychophysical abilities of the person under such conditions. Secondly, rather complicated and expensive means of motion simulation, specified if possible, are required to get comprehensive and reliable enough conception of the pilot behavior in prescribed conditions. Thirdly, new methods and algorithms of structural identification of requested pilot dynamics models, adequate physical and mathematical statements of identification tasks and its solution methods leading to needed results are necessary. Fourthly, knowledge of behavior peculiarities of the pilot as biological dynamic object.

A reservation should be made that acute need for identification of “disturbed” models of pilot activities has emerged due to the engineering progress and stronger competition on the market of “flying” products when the requirements to flight control quality (accuracy) have increased.

So-called “standard” models were enough not so long ago. Knowledge of “disturbed” models of pilot (operator) activity in flight control loop is necessary for both optimizing the control process itself and searching for ways and means of facilitation of pilot professional activity on board of the moving object.

Thus, as a complicated self-organizing dynamic system, the pilot (operator) reacts to many stochastic environmental factors in the process of his production activities. For example, he feels the motion through his direct perception by motoric, optic, auditory and other channels. Each perception channel is subject to quantitative estimation in specific operating flight conditions. The most important part of estimation is identification of “disturbed” dynamics models of each perception channel. The aggregate of such pilot (operator) models forms the model of his professional activity of flight controlling in continuous and responsible stabilizable mode.

While "standard" features of the operator in closed control system in standard semiautomatic mode are explored enough, though perception by the pilot of disturbed stochastic motion close to requested real by certain criteria is practically not estimated. The models of disturbed behavior of the pilot in flight control conditions close to full-scale are explored insufficiently.

2. General statement of assumed research

Thereby, the need is ripe for statement and effective execution of problematic nature work cycles, each of which includes several stages (by the number of requested navigation data perception channels) and a set of work steps for any intended stage. The main goal of each cycle is to draw up "disturbed" models which reflect, full enough for practical goals, actions of the pilot (operator) stabilizing specific moving object in specific mode and in conditions close to full-scale. Stated models shall be applicable for synthesis of future optimum control system of involuntary structure object (for example, [2–4]).

Below is brief description of typical mandatory work steps in each intended stage of researching.

- Statement of the task of identification of pilot action model required channel in controlling the object in specific operation mode and service conditions. As a rule, such statement of the task shall be done jointly with research supervisors of the entire cycle and specific work step.
- Preparation for using the requested object specific motion simulator additionally equipped with the simulator of other "strong" disturbing factors. The simulator also includes stimulating signal generators, filtering systems and converters of simulated navigation signals, data recorders, and proximity evaluation systems for simulating and simulated signals. The simulator shall be dynamically certified [4] for simulation process quality.
- Preparation of mathematical support and software for implementation of stages of structural identification of complicated dynamic object models and vectors of disturbing signals generated by the pilot (operator) in the process of work as results of errors in his perception of valuable information. Mathematical support is based on acceptable developed procedures and algorithms of structural identification (for example, [2,4]) and primary processing of multidimensional stochastic data.
- Direct experimental research of the behavior of surveyed person (pilot), operator on above-stated test complex with synchronous input and output data logging during testing.
- Primary and secondary processing of test input and output data, preparation of dynamic characteristics of vectors of input and output stochastic signals, dynamic characteristics of researched channel of the pilot (operator) behavior model in conditions of assigned test.
- Iteration of conducted tests and above-stated test result processing for other assigned test conditions.
- Formation of the model channel of "real" navigation data perception by the pilot and the vector of disturbing signals emerging due to errors of the pilot in perception of input data, performance analysis of suggested models.

The content and peculiarities of works are illustrated with certain results [5] of conducting the identification stage of the pilot dynamics models and pilot-induced remnant on the simulator of flight dynamic factors.

3. Statement of research in one of the stages

The task of experimental definition of quasi-linear model of motoric perception by the pilot of the aircraft random disturbed angular motion and received data transmission to controls will be stated as follows. Let the task consist in defining by the array of "input-output" signals the transfer function of the pilot (operator) "seat motion – controls motion", and also spectral density of the remnant concomitant to data perception process. It is assumed to define the seat motion as a stationary random process with frequency band exceeding frequency range of probable reactions of the operator, at that spectral density of simulating motion shall be close to the same characteristic of simulated motion. To solve the task we use standard procedure of primary processing of "input-output" signals (procedure of definition of spectral and reciprocal densities of signals) and particular case of the algorithm of structural identification of multidimensional stationary object dynamics and affecting uncontrolled disturbance [2], and also special package of application software for computer-aided solving of structural identification tasks.

It is also assumed that inputs to the operator model are not only the base motion signals, but also simultaneously the signals of velocity and acceleration of this motion, that shall enhance the model and increase the rate of its adequacy to the motion perception process. Expediency and efficiency of such three-channel model shall also be estimated, as well as its content and capabilities, and also identification algorithm efficiency. The results are based on the data obtained by exploring one operator only. If applying mentioned approach to identification of models of several pilots of each qualification group and averaging obtained results, the average pilot (operator) models can be estimated.

4. Algorithm of structural identification of dynamic system model

The essence of applicable algorithm of structural identification is as follows. Let the experiment define arrays of input (u) and output (x) signals of multidimensional object under consideration (fig. 1), which motion is defined by the system of simple differential equations with constant factors as

$$Px = Mu + \psi \quad (1)$$

where u and x are vectors of the object output and input signals accordingly, ψ is vector of uncontrolled disturbance signals being random stationary process uncorrelated with input u; P and M are matrices which elements are polynomials of argument $s = j\omega$, matrix determinant P submitted to Gurvits condition.

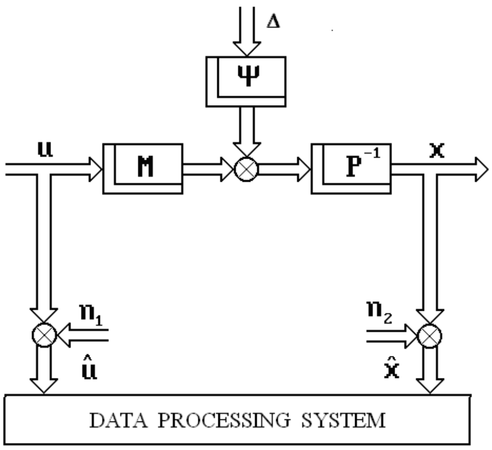

Fig. 1. Flow chart of dynamic object identification

As a result of signal primary processing there are defined [2] matrices of spectral and reciprocal spectral densities $S_{uu}(s)$, $S_{xx}(s)$, $S_{xu}(s)$, $S_{ux}(s)$. By introducing the designation $\psi = \Psi\Delta$ where Ψ is matrix of transfer functions of the filter formed from the vector of "white" noise $\Delta(s)$ vector $\psi(s)$ (Fourier transform of disturbing signals). Equation (1) to be rewritten as

$$x = P^{-1}Mu + P^{-1}\Psi\Delta . \quad (2)$$

Assuming that measurements of signals u and x are "perfect", we make algorithm of structural identification as

$$P^{-1}M = S'_{ux}\left(S'_{uu}\right)^{-1} ; \quad (3)$$

$$P^{-1}\Psi\left(S'_{\Delta\Delta}\right)^{-1}\Psi_* P_*^{-1} = S'_{xx} - S'_{ux}\left(S'_{uu}\right)^{-1}S'_{xu} ; \quad (4)$$

$$P^{-1}\Psi = \left[S'_{xx} - S'_{ux}\left(S'_{uu}\right)^{-1}S'_{xu}\right]^{+} , \quad (5)$$

where " ′ " is transposition sign, index "+" upward is factorization operation sign, symbol "*" is hermitian conjugate sign.

From expressions (2) and (4) by inserting thereto primary processing results of measured signals we define required matrices of transfer functions of control and disturbance model. Matrix of disturbance spectral densities (remnant) is defined by expression (3).

5. Methodology and some results of estimation of pilot motoric perception model of cockpit disturbed angular motion

Testing was done using movable seat in flight simulator cabin. The seat was moving in horizontal plane with standard actuators by "white" noise generator signals passing through ramp unit. Input signals were random stationary processes close to disturbed angular motions of the aircraft on the course. The pilot was forming model output by simulating perceptible motions with control handle. Data arrays of input and output signals were sent to standard primary processing which resulted in receiving relevant spectral and reciprocal spectral densities. Spectral and reciprocal spectral densities of input u and output x signals in described version are given on figures 2 and 3.

Therein SPUU is input u spectral density, SPXX is input x spectral density, SPXU is reciprocal spectral density of signals u and x, AMP is operator logarithmic amplitude frequency response, FAZA is operator logarithmic phase frequency response, VOZM is remnant spectral density. Simultaneously, velocity and acceleration data arrays are obtained by means of differentiation using input signal special programs. Primary processing of these arrays is also done, spectral and reciprocal spectral densities of the model input and output signal velocity are shown on fig. 3. Then, using the package of applied programs which realize structural identification algorithm (2), (3), (4), there is done sequential solution of scalar tasks of identification of the pilot model where input are the signals of angular motion, velocity and acceleration, and output is fixed array of motions of the control.

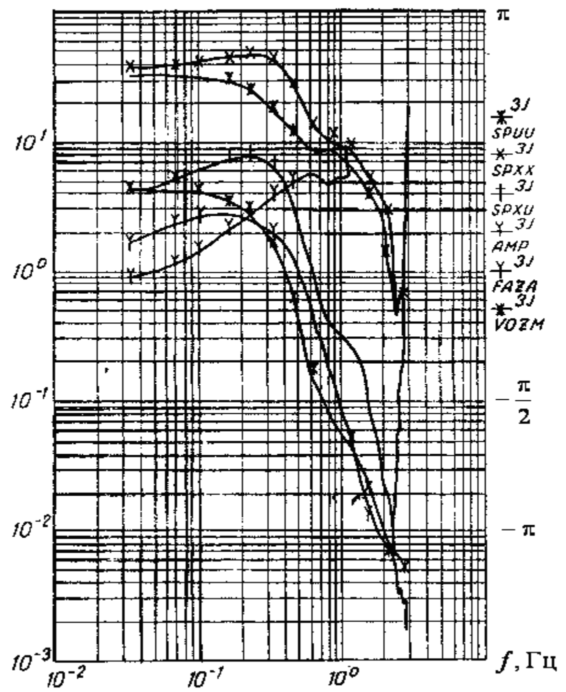

Fig. 2. Results of operator model identification (angular position input)

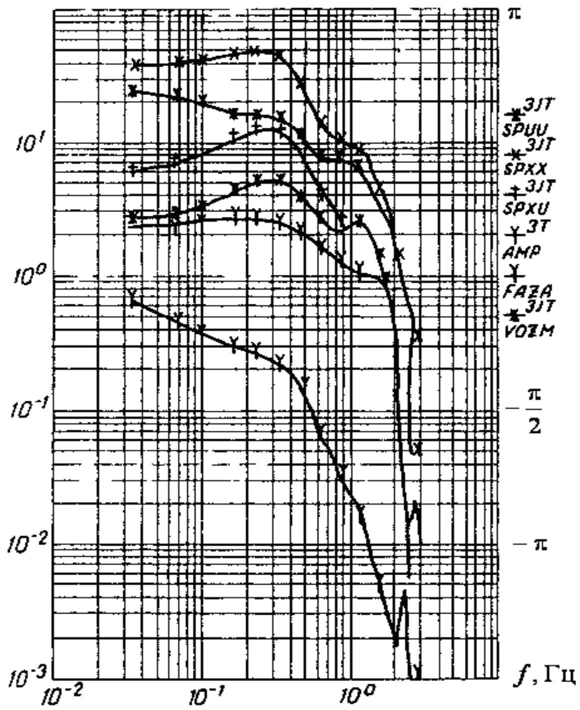

Fig. 3. Results of operator model identification (angular velocity input)

Figure 2 shows logarithmic amplitude and phase frequency responses (LAFR and LPFR accordingly) of the operator model where input is base angular motion signal u, and output is control handle motion x. Figure 3 shows LAFR and LPFR of the link where input is base velocity signal u, output is signal x. By analogy, the same characteristics of the link are made where input is base acceleration signal, output is signal x. LAFR and LPFR of the links are actually defined by the features of reciprocal spectral densities of appropriate input and output of the link.

The charts of spectral and reciprocal spectral densities of the signals, LAFR and LPFR of the links were subject to approximation by analytic expression and analysis. Approximation of stated spectral characteristics was done by method of generalized logarithmic frequency responses.

6. Models of perception by the pilot of seat disturbed motion information

Using the example of making stated model of pilot dynamics received for one of operators, we will consider suggested procedure of defining the models of pilot information model channels.

As stipulated, in the result of identification there are obtained (see fig. 2) graphic representations of spectral densities of pilot model input and output, pilot LAFR and LPFR, remnant spectral density. Having approximated them by the method of logarithmic frequency characteristics, we obtain estimations of transfer function of explored pilot model channel and spectral densities of the signals marked in indexes of characteristics in the following form:

$$S_{uu}(s)=\frac{(3{,}72)^2}{\pi}\left|\frac{(0{,}2s+1)}{(0{,}58^2s^2+2\cdot 0{,}7\cdot 0{,}58s+1)(0{,}16^2s^2+2\cdot 0{,}6\cdot 0{,}16s+1)}\right|^2,\ \text{[seat grad.}^2\cdot\text{s.]};\qquad(6)$$

$$S_{xx}(s)=\frac{(10{,}8)^2}{\pi}\left|\frac{(0{,}18^2s^2+2\cdot 0{,}65\cdot 0{,}18s+1)}{(0{,}27^2s^2+2\cdot 0{,}5\cdot 0{,}27s+1)a(s)b(s)}\right|^2\ \text{[grad.}^2\cdot\text{s.]};\qquad(7)$$

$$W_x^u(s)=\frac{0{,}83(2{,}5s+1)}{(0{,}44s+1)b(s)},\ \text{[grad./seat grad.]};\qquad(8)$$

$$S_{rr}(s)=\frac{(10{,}2)^2}{\pi}\left|\frac{(0{,}18^2 s^2+2\cdot 0{,}65\cdot 0{,}18s+1)}{(0{,}58s+1)a(s)b(s)}\right|^2,\ \text{[grad.}^2\text{·s.]};\qquad (9)$$

where $a(s)=0{,}13^2 s^2+2\cdot 0{,}3\cdot 0{,}13s+1,\ b(s)=0{,}1^2 s^2+2\cdot 0{,}6\cdot 0{,}1s+1.$

Expressions of reciprocal spectral densities S_{ux} and S_{xu} are not reduced.

From (9) and known integral table [6] or using the package of application software, the remnant dispersion is defined:

$$<r_u^2>=\frac{1}{j}\int_{-j\infty}^{j\infty}S_{rr}(s)ds=\frac{1}{j}\int_{-j\infty}^{j\infty}\left|\frac{(0{,}18^2 s^2+2\cdot 0{,}65\cdot 0{,}18s+1)}{(0{,}58s+1)a(s)b(s)}\right|^2 ds=1{,}865(10{,}2)^2,\cdot\ \text{[grad.}^2\text{]}.\qquad (10)$$

For the cases of single and double differentiation of input signal after carrying out actions analogous to those described at pilot model identification by angular motion signal, there are defined estimations of spectral densities of cockpit acceleration and velocity signals, reciprocal spectral densities of these signals with output signal, LAFR and LPFR of explored links.

Having approximated LAFR and LPFR obtained by above-described means, we make models of perception by the pilot of the signals correlated with seat acceleration and velocity, in the following form

$$W_x^{\dot u}(s)=\frac{2{,}1(2{,}5s+1)}{(1{,}87s+1)(0{,}44s+1)b(s)},$$

[grad. s./seat grad.]; (11)

$$W_x^{\ddot u}(s)=\frac{-0{,}8(12{,}2s+1)(2{,}5s+1)c(s)}{(5{,}5s+1)(1{,}87s+1)(0{,}57s+1)b(s)},$$

[grad.·s.^{2}/seat grad.]. (12)

Using information of the formula (6)÷(12) obtained at identification of operator features by seat motion acceleration and velocity data, we make expanded (equivalent) model of explored (motoric) channel of pilot model. At that we assume that when perceiving angular motion, besides main perception tract (seat motion), the operator perceives to certain extent the velocity and acceleration of this motion. Supplementary tracts of the model can output in full or in part only those signals which are not accounted in the main tract. Thus, the model output for velocity tract is only velocity perception signal which is not accounted in the motion tract. Acceleration tract creates addition to the output signal which is not accounted in velocity and motion tracts. The share of supplementary signals is defined by choosing coefficient τ with possible rate range 0-1 s. Besides, it is necessary that the obtained sum of correlated and noise parts of the model output signal (remnant) does not exceed the model real output. For such rating it is necessary to introduce factor β to the model.Quantitative criterion of higher efficiency of enhanced model comparing to the model accounting motion only, can be remnant dispersion rate. Willing to certify the explored pilot activity in the best way, we consider more efficient to be the model where remnant has less intensity. Selection of introduced parameters τ and β of the enhanced model allows redefining the introduced model. Considering the rules of structural transformation of the tracts we define estimation of equivalent transfer function of the explored operator model channel. According to the structure (fig. 4), equivalent transfer function of the operator is written as follows

$$W_o(s)=\beta\left[W_x^u+s(W_x^{\dot u}-\tau W_x^u)+s^2(W_x^{\ddot u}-\tau W_x^{\dot u})\right].\qquad (13)$$

By inserting to the expression (13) requested functions (8), (11), (12) defined in the process of identification, we obtain the following

$$W(s)=\beta\left\{\frac{0{,}83(2{,}5s+1)}{(0{,}44s+1)b(s)}+s\left[\frac{2{,}1(2{,}5s+1)}{(1{,}87s+1)(0{,}44s+1)b^2(s)}-\frac{0{,}83\tau(2{,}5s+1)}{(0{,}44s+1)(0{,}44s+1)b^2(s)}\right]-s^2\left[\frac{0{,}8(12{,}2s+1)(2{,}5s+1)c(s)}{(5{,}5s+1)(1{,}87s+1)(0{,}57s+1)b^2(s)}+\frac{2{,}1\tau(2{,}5s+1)}{(1{,}87s+1)(0{,}44s+1)b^2(s)}\right]\right\}=$$

$$=\frac{0{,}83\beta(v_1 s+1)(v_2 s+1)(v_3 s+1)(T^2 s^2+2\xi Ts+1)}{(5{,}5s+1)(1{,}87s+1)(0{,}44s+1)b^2(s)}\beta,$$

[grad./seat grad.], (14)

where parameters v_1, v_2, v_3, T and ξ depend to known extent on coefficient τ. By limiting with mean values of parameters v_1, v_2, v_3, T, ξ and value β= 0,413, and by inserting them into formula (14), we obtain the expression of equivalent transfer function of the operator reproducing angular motion of the base in the following form

$$W(s) = \frac{0{,}343(9{,}5s+1)(3{,}7s+1)(2{,}5s+1)}{(5{,}5s+1)(1{,}87s+1)(0{,}1^2 s^2 + 2\cdot 0{,}6\cdot 0{,}1s+1)}, \text{ [grad./seat grad.]}, \qquad (15)$$

Table

Coefficient τ, s.	Parameters				
	ν_1, s.	ν_2, s.	ν_3, s.	T, s.	ξ
0	10	2,78	0,43	0,13	0,45
0,3	9,5	3,16	0,54	0,10	0,36
0,7	9,2	4,06	0,77	0,08	0,30
1,0	8,9	4,70	0,88	0,07	0,26

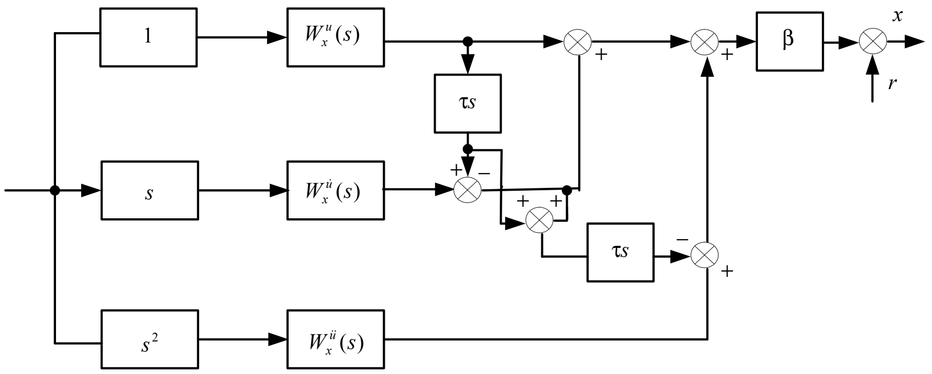

Fig. 4. Flow chart of operator enhanced model

Knowing the equivalent model of the operator (15) and the function (6) we define spectral density of the part of output signal correlated with input as follows

$$S_{xx_1}(s) = |W(s)|^2 S_{uu} = \frac{(1{,}27)^2}{\pi}\times \left|\frac{(9{,}5s+1)(3{,}7s+1)}{(5{,}5s+1)(1{,}87s+1)(0{,}58^2 s^2+2\cdot 0{,}7\cdot 0{,}58s+1)}\times \frac{(2{,}5s+1)(0{,}2s+1)}{(0{,}13^2 s^2 + 2\cdot 0{,}5\cdot 0{,}13s+1)(0{,}1^2 s^2 + 2\cdot 0{,}6\cdot 0{,}1s+1)}\right|^2,$$

[grad.^{2}·s.]. (16)

Using the expressions (7) and (16), by the equation (4) we obtain estimation of remnant spectral density in the following form

$$S_{rr}(s) = \frac{(10{,}2)^2}{\pi}\times\left|\frac{0{,}48s^2+0{,}264s+1}{(0{,}76^2 s^2+2\cdot 0{,}65\cdot 0{,}76s+1)(0{,}22^2 s^2 + 2\cdot 0{,}6\cdot 0{,}22s+1)}\right|^2, \text{ [grad.}^2\text{·s.]}; \qquad (17)$$

By inserting (17) to the integral (10), we calculate remnant dispersion in case of accounting the operator enhanced model as $\langle r^2\rangle = (10{,}2)^2 \cdot 0{,}507$, grad.^{2}.

7. Conclusion

Thereby, when using the operator enhanced model, remnant dispersion has reduced by 3,57 times compared with the same one in case of accounting only angular motion in the model. The suggested model appears substantially more effective.

The important point in suggested methodology of defining model channels is the fact that using the dispersion value of remnant signal we can quantitatively and promptly estimate the extent of efficiency of specific pilot actions in controlling the aircraft in stochastic disturbed flight.

References

[1] The modern theory of control systems / Ed. K.T. Leondesa. – M.: Mir, 1970. – 511 p. (In Russian).

[2] *Blokhin L.N.* Optimal stabilization systems. – K.: "Technika", 1982. – 143 p. (In Russian).

[3] *Blokhin L.N.* Synthesis of optimal robust systems in problems of ergonomics and stochastic stabilization // Cybernetics and Computer Science, 2000 – Vol. 122, – P. 28-50. (In Russian).

[4] *Azarskov V.N., Blokhin L.N., Zhiteckii L.S.* Methodology of designing optimal stochastic stabilization systems. Monografiya. K.: NAU – 2006. – 432 p. (In Russian).

[5] *Azarskov V.N., Blokhin L.N., Burdin B.V.* Pilot perception model of perturbed angular cabin motion as a part of his information model. – M.: "Space Biology" – 1991. – Vol. 6. – P. 14-17. (In Russian).

[6] *Newton J.K., Gould L.A., Kayser. J. F.* The theory of linear servo systems. – M.: FM, 1961. – 407 p. (In Russian).

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В. М. Азарсков[1], Г. І. Рудюк[2]. Методика і результати ідентифікації моделі пілота при напівавтоматичному керуванні польотом

[1]Національний авіаційний університет, проспект Космонавта Комарова, 1, Київ, 03680, Україна
[2]ДП «Антонов», вул. Туполєва, 1, Київ, 03062, Україна
E-mails: [1]azarskov@nau.edu.ua; [2]rudyuk@antonov.com

Розглядається постановка етапу ідентифікації моделей дій пілота в контурі управління, методика, алгоритми й деякі результати його проведення на комплексі імітації польоту. Запропоновано новий підхід до ідентифікації моделей динаміки оператора в контурі управління рухомим об'єктом. Відмінності в основному пов'язані з багатоканальним розширенням традиційних моделей, що дозволяє значно більше враховувати саме біологічні властивості оператора.

Ключові слова: динамічний об'єкт; імітатор польоту; модель динаміки; об'єкт стабілізації; стохастична інформація; структурна ідентифікація

В. Н. Азарсков[1], Г. И. Рудюк[2]. Методика и результаты идентификации модели пилота при полуавтоматическом управлении полетом

[1]Национальный авиационный университет, проспект Космонавта Комарова, 1, Киев, Украина, 03680
[2]ГП «Антонов» ул. Туполева, 1, г. Киев, 03062, Украина
E-mails: [1]azarskov@nau.edu.ua; [2]rudyuk@antonov.com

Рассматривается постановка этапа идентификации моделей действий пилота в контуре управления, методика, алгоритмы и некоторые результаты его проведения на комплексе имитации полета. Предложен новый подход к идентификации моделей динамики оператора в контуре управления подвижным объектом. Отличия в основном связаны с многоканальным расширением традиционных моделей, что позволяет в большей мере учитывать именно биологические свойства оператора.

Ключевые слова: динамический объект; имитатор полета; модель динамики; объект стабилизации; стохастическая информация; структурная идентификация.

Azarskov Valerii. Doctor of Engineering. Professor.
Aerospace Control Systems Department, National Aviation University, Kyiv, Ukraine.
Education: Kyiv Civil Aviation Engineers Institute, Kyiv, Ukraine (1968).
Research area: system identification, aircraft control systems, aviation and flight simulators and devices.
Publications: 250.
E-mail: azarskov@nau.edu.ua

Rudyuk Gryhoriy. Candidate of Engineering. Chief Designer.
Aeronautical Scientific / Technical Complex Antonov, Kyiv, Ukraine.
Education: Kyiv Civil Aviation Engineers Institute, Kyiv, Ukraine (1981).
Research area: aircraft control systems, flight simulators, design of perspective aviation equipment.
Publications: 15.
E-mail: rudyuk@antonov.com