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SYNTHESIS OF KINEMATIC CONTROL OF AN AIRCRAFT IN "BIG"

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Abstract. *In the article the application reconfiguration technology for the decision of a problem of difficult nonlinear object control in the greatest possible area of its states is shown.*

Keywords: aircraft; autonomy; bifurcation; invariance; nonlinear object; reconfiguration technology.

1. Problem statement

Now, essential increase of intensity of dynamic processes occurs in modern conditions. Also the problems solved at control of mobile objects become more and more difficult and various.

Synthesis of reliable algorithms of control of difficult mobile objects and difficult dynamic nonlinear processes is an actual problem of the present. Real systems are so difficult, that the general method of creation of the controlling systems guaranteeing necessary quality and efficiency of their functioning in modern conditions does not exist today. It causes importance of the given problem.

Creation of civil aircraft control systems is based on the concept of creation of CNS/ATM Systems (Communication, Navigation, Surveillance and air traffic management system) and the concept of transition from Managed Airspace to zones of free flight accepted by the International Civil Aviation Organization.

2. Analysis of researches and publications

The difficult nonlinear systems dynamically controlled in "big" are a new class investigated in the dynamic systems and processes control theory [10, 11]. Natural tendencies of complication make active new requirements of maximum use of all potential control possibilities of purposeful systems, including extremely possible on dynamics and on the states space size.

In the control theories such type processes occurring on the verge of possible and providing control of an object state in maximum big area of its states are called marginal or control processes in "big".

Heart of the problem is absence of a regular complex system research method of difficult nonlinear systems. Today it means, that researches and synthesis in "big" each concrete system are necessarily carried out by combination theory methods, methods of the theory of linear differential systems with constant factors [1, 2, 6, 15], heuristic methods, that for considered type systems are not effectively.

Practical insistency of control of processes in "big" demands the decision of the given problem.

The analysis of scientific publications and researches (on materials of 10th IFAC International Symposium on Dynamics and Control of Process Systems, December 18-20, 2013, IIT Bombay, Mumbai, India; 9th IFAC Symposium on Nonlinear Control Systems, September 4-6, 2013, Toulouse, France; 19th IFAC Symposium on Automatic Control in Aerospace, September 2-6, 2013, University of Würzburg, Würzburg, Germany) has shown the absence of the works devoted to analytical methods of the analysis of all possible process states as close, and far from simple, special and critical points and system manifold and also devoted to synthesis of controlling functions for expedient change of evolution and a process state.

3. The object of paper

Article purpose is the solution of a problem of difficult nonlinear object control in the greatest possible its states area at complex use of all possibilities of an aircraft design.

4. Problem solving

The reconfiguration technology based on a method of absolute invariance and autonomy of essentially nonlinear multidimensional systems, V.V.Pavlov's Functional Homeostasis law [9] and McR&C&D law [3, 7] is offered.

These laws meet the optimum ergatic systems requirements and define a choice of virtual object and its property.

This technology for automatic and piloted modes of aircraft control uses homeostatic strategy of synthesis of algorithms and structures of functioning of system “pilot – control system – aircraft”.

That is especially important at such unusual control modes as flight on modes: subcritical, critical and supercritical.

In article the kinematic equations of spatial aircraft motion relative to the flat earth in semi-stability coordinate frame at neglect centrifugal Coriolis forces are considered [4, 5, 8, 13, 14]:

$$\begin{aligned}
&m\frac{dV}{dt} = P_f\cos(\alpha+\varphi_x)\cos\beta - X_a - G\sin\theta;\\
&Vm\frac{d\theta}{dt} = P_f(\sin(\alpha+\varphi_x)\cos\gamma_c +\\
&+\cos(\alpha+\varphi_x)\sin\beta\sin\gamma_c) + Y_a\cos\gamma_c -\\
&-Z_a\sin\gamma_c - G\cos\theta; \qquad (1)\\
&-Vm\cos\theta\frac{d\Psi}{dt} =\\
&= P_f\left(\sin(\alpha+\varphi_x)\sin\gamma_c - \cos(\alpha+\varphi_x)\sin\beta\cos\gamma_c\right)+\\
&+Y_a\sin\gamma_c + Z_a\cos\gamma_c;
\end{aligned}$$

$$\begin{aligned}
&\frac{dX}{dt} = V\cos\theta\cos\Psi;\\
&\frac{dH}{dt} = V\sin\theta; \qquad (2)\\
&\frac{dZ}{dt} = -V\cos\theta\sin\Psi
\end{aligned}$$

where m – the aircraft mass;

V – the speed of mass center;

P_f – the engine force;

α – the angle of attack;

φ_x – the angle of engine setting;

β – the sideslip angle;

X_a, Y_a, Z_a – the projections of complete aerodynamic force R to the axes OX, OY, OZ;

G – the gravity force;

θ – the flight path angle;

γ_c – the stability roll angle;

Ψ – the track angle;

X – the flight range;

H – the flight altitude;

Z – the lateral displacement.

The forces are given by

$$P_f = \delta_g P_0(\delta_g, \alpha, \varphi_x, H, M);$$

$$X_a = C_x qS;$$

$$Y_a = C_y qS;$$

$$Z_a = C_z qS,$$

where δ_g – the sector of thrust;

P_0 - the altitude-speed characteristic of the engine;

M – the Mach number;

S – the wing area;

q – the aerodynamic force parameter;

C_x, C_y, C_z – the aerodynamic coefficients of similarity.

The general model of aerodynamic coefficients of similarity in the form of modified Newton polar [4, 5, 8, 13, 14] is used most aerobatics,emergency, for the generalized research problem on modes: normal, critical:

$$\begin{cases} C_x = C_x(M) + B_\alpha(M)C_y^2,\\ B_\alpha \approx \left(\dfrac{1}{\pi\lambda}+0{,}01\right)(C_y^\alpha)^2, \end{cases}$$

at $0 < M < 5\ldots7$;

$$\begin{cases} C_x = C_{x_0}(M) + C_{x_\alpha}^i(M)|\sin^3\alpha| +\\ +C_x^i(M)|\sin^3\beta|,\\ C_y = \frac{1}{2}C_{y_0}^\alpha(M)\sin\alpha\cos\alpha|\sin\alpha|, \end{cases}$$

at $M > 5\ldots7$; (3)

$$C_z = \tfrac{1}{2}C_{z_0}^\beta(M)\sin\beta\cos\beta|\sin\beta|.$$

Reliability domain of model:

$$\begin{aligned}
&Q_x: \{M = (0{,}10); \theta = (0°,360°);.\\
&\psi = (0°,360°); H = (0{,}15000\text{m})\}; \qquad (4)\\
&U\ : \{\alpha = (0°;360°); \beta = (0°;360°)\};\\
&\gamma_c = (0^o;360°); \varphi_g = (0°;360°); \delta_g = (0;1)\}, \qquad (5)
\end{aligned}$$

where Q_x - the set of object state parameters,

U – the set of object control parameters.

Use of modified Newton polar (3) allows to carry out researches in the expanded range of speeds without boundary conditions on an angle of attack α. It is supposed that the aircraft aerodynamic scheme allows to create thrust on any angles of attack α.

The problem is solved in two stages.

At the first stage the direct problem is solved. It is necessary to synthesize virtual object with the independent organization of controls, its virtual area of states $Q_i^{\square}$ and virtual area of controls $P_i^{\square}$ on real object (1) – (5):

$$\begin{aligned}
&\frac{dV}{dt} = p_1; \qquad (V,\theta,H) \in Q_i^{\square},\\
&\frac{d\theta}{dt} = p_2; \qquad (p_1,p_2,p_3) \in P_i^{\square},\\
&\frac{d\Psi}{dt} = p_3;\\
&\frac{dX}{dt} = V\cos\theta\cos\Psi;\\
&\frac{dH}{dt} = V\sin\theta;\\
&\frac{dZ}{dt} = -V\cos\theta\sin\Psi.
\end{aligned} \qquad (6)$$

At the second stage the inverse problem is solved. It is necessary to synthesize the real controls $\alpha(t)$, $\delta_g(t)$ and $\gamma(t)$ of real object (1) – (5) on virtual object (6) and virtual controls $p_1(t)$, $p_2(t)$ and $p_3(t)$.

Solvers of direct and inverse problems taking into account conditions of the problem correctness are based on the functional equations of absolute invariance:

$$\begin{aligned}
&\{P_f(H,M,\theta,\delta_g)\cos(\alpha+\varphi_x)\cos\beta -\\
&- X_a(H,M,\theta,\alpha) - G\sin\theta\} = mp_1;\\
&\{P_f(H,M,\theta,\delta_g)(\sin(\alpha+\varphi_x)\cos\gamma_c +\\
&+\cos(\alpha+\varphi_x)\sin\beta\sin\gamma_c) + Y_a(H,M,\theta,\alpha)\cos\gamma_c -\\
&+\cos(\alpha+\varphi_x)\sin\beta\sin\gamma_c) + Y_a(H,M,\theta,\alpha)\cos\gamma_c -\\
&- Z_a(H,M,\theta,\gamma)\sin\gamma_c - G\cos\theta\} = mVp_2;\\
&\{P_f(H,M,\theta,\delta_g)(\sin(\alpha+\varphi_x)\sin\gamma_c -\\
&-\cos(\alpha+\varphi_x)\sin\beta\cos\gamma_c) + Y_a(H,M,\theta,\alpha)\sin\gamma_c +\\
&+ Z_a(H,M,\theta,\gamma)\cos\gamma_c\} = -Vm\cos\theta p_3.
\end{aligned}$$

These absolute invariance equations in a direct problem are the mapping operator of the space of real controls $(\alpha,\delta_g,\gamma_c) \in (\mathrm{A},\mathrm{B},\Gamma)$ in the space of virtual controls $P(p_1,p_2,p_3)$ over the space of real object states $(V,\theta,H) \in Q_x$ and in a inverse problem are the mapping operator of area of virtual object controls $(p_1,p_2,p_3) \in P_i^{\square}$ in area of real object controls $(\alpha,\delta_g,\gamma_c)$ over space of virtual object states $(V,\theta,H) \in Q_i^{\square}$.

The purpose of virtual object synthesis consists in a finding of such rectangular area $Q^{\square} \times P^{\square}$ where

$$Q^{\square} = (\Delta V \times \Delta\theta \times \Delta H),$$

$$P^{\square} = = (\Delta p_1, \Delta p_2, \Delta p_3),$$

that for it point $(p_1 = 0; p_2 = 0;\ p_3 = 0)$ is internal point $P^{\square}$.

Then, if the decision of the given problem exists, the virtual object exists in states space $Q^{\square}$

$$\begin{aligned}
&\frac{dV}{dt} = p_1, \qquad p_1 \in \Delta p_1;\\
&\frac{d\theta}{dt} = p_2, \qquad p_2 \in \Delta p_2;\\
&\frac{d\Psi}{dt} = p_3, \qquad p_3 \in \Delta p_3.
\end{aligned}$$

and the corresponding real object (1) – (5) exists with real controls $(\alpha,\delta_g,\gamma_c)$.

The complete structure of the closed system is shown on Fig. 1.

Results of modeling of algorithm of aircraft kinematics control in "big" by means of given reconfiguration technology are shown on Figs 2-5.

Figs 2–5 show that the object (1) – (5) is controlled at any definition (generator) of virtual controls in the expanded control area. System coordinates change according to virtual programs $p_1(t)$, $p_2(t)$ and $p_3(t)$ without features. The object is controlled in all area $Q^{\square}$, in a wide values range of Mach numbers and in values of angles of attack outside of usual boundary conditions. The bifurcation property of object (1) – (5) shows that virtual single-valued controls (p_1, p_2, p_3) generate bifurcation of values of real controlling variables α, δ_g and γ_c on two sets $(\alpha^1,\delta_g^1,\gamma_c^1)$ and $(\alpha^2,\delta_g^2,\gamma_c^2)$ [12].

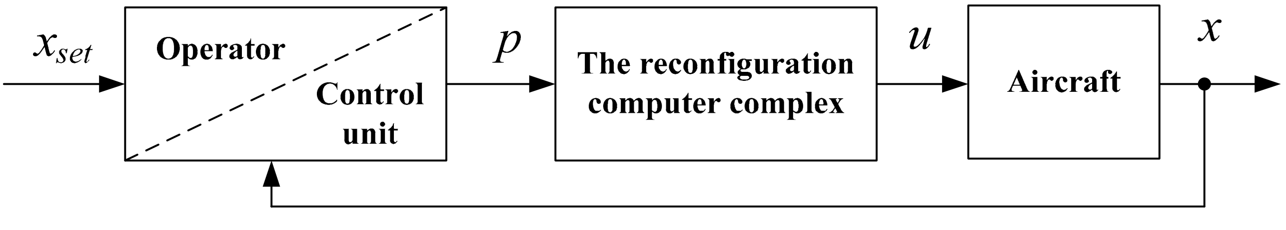
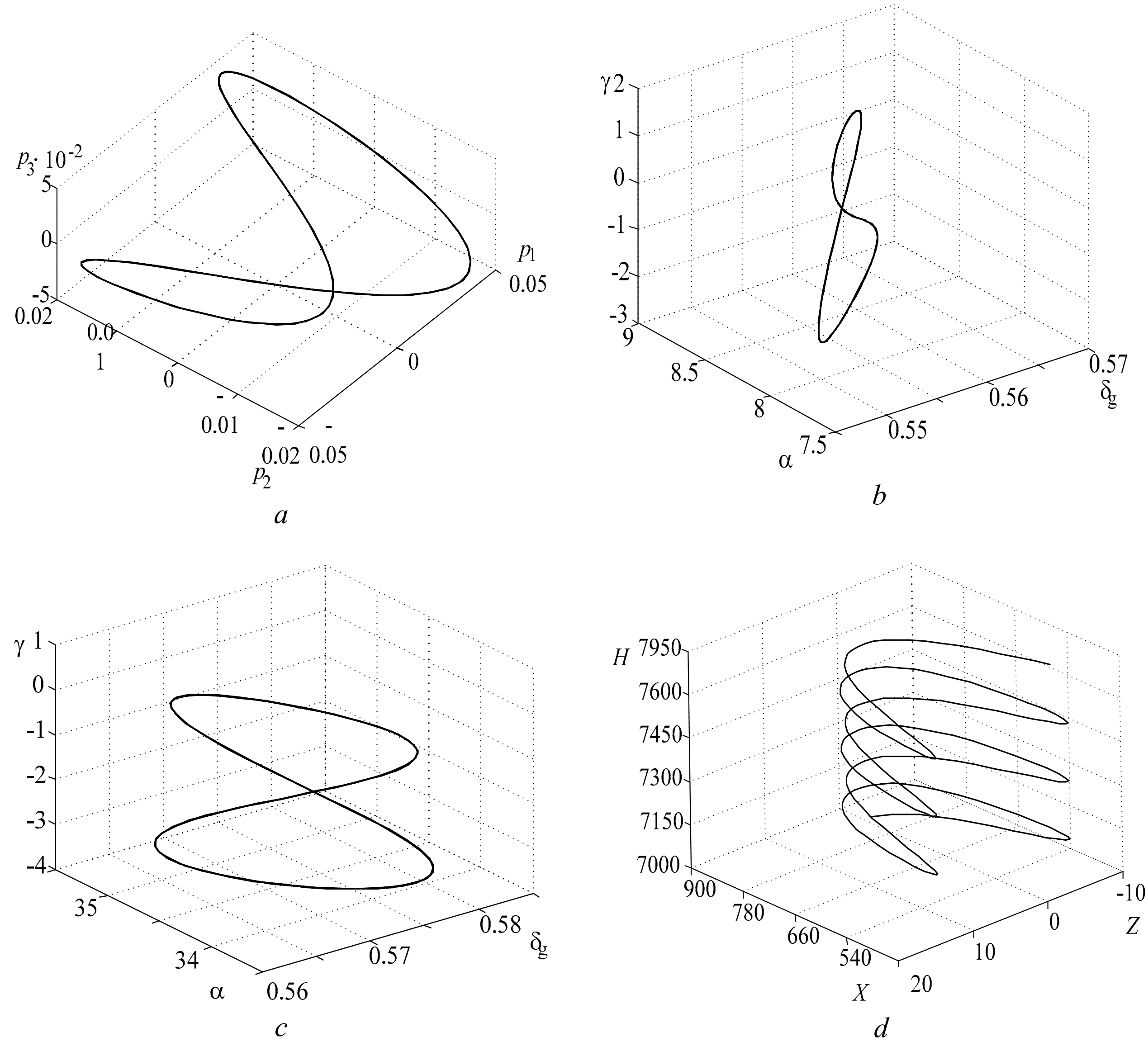


Fig. 1. Integrated structure ergatic multidimensional reconfiguration systems



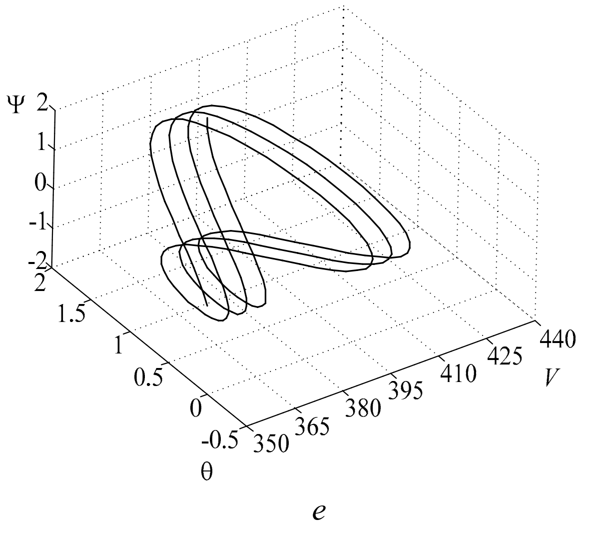


Fig. 2. Modeling of algorithm of aircraft kinematics control in “big” by means of given reconfiguration technology ainitial conditions $H_0 = 7000$ m; $\theta_0 = 0^{\circ}$; $V_0 = 350$ m/s:

a – the definition of virtual controls (p_1, p_2, p_3);

b – the received first set of real controls $(\alpha, \delta_g, \gamma_c)_1$;

c – the received second set of real controls $(\alpha, \delta_g, \gamma_c)_2$;

d – the parameters of aircraft state (X, H, Z);

e – the parameters of aircraft state

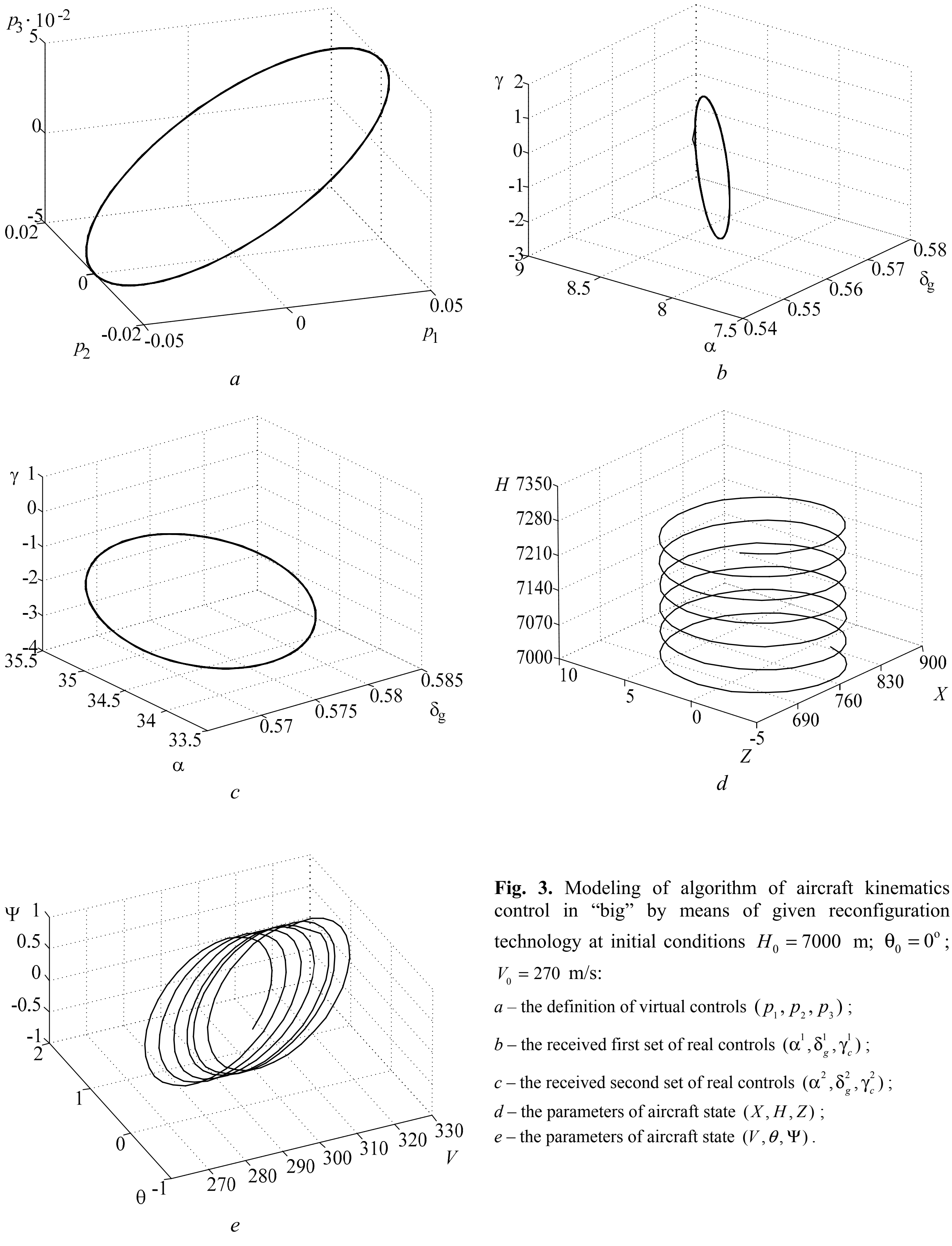


Fig. 3. Modeling of algorithm of aircraft kinematics control in "big" by means of given reconfiguration technology at initial conditions $H_0 = 7000$ m; $\theta_0 = 0^{\circ}$; $V_0 = 270$ m/s:

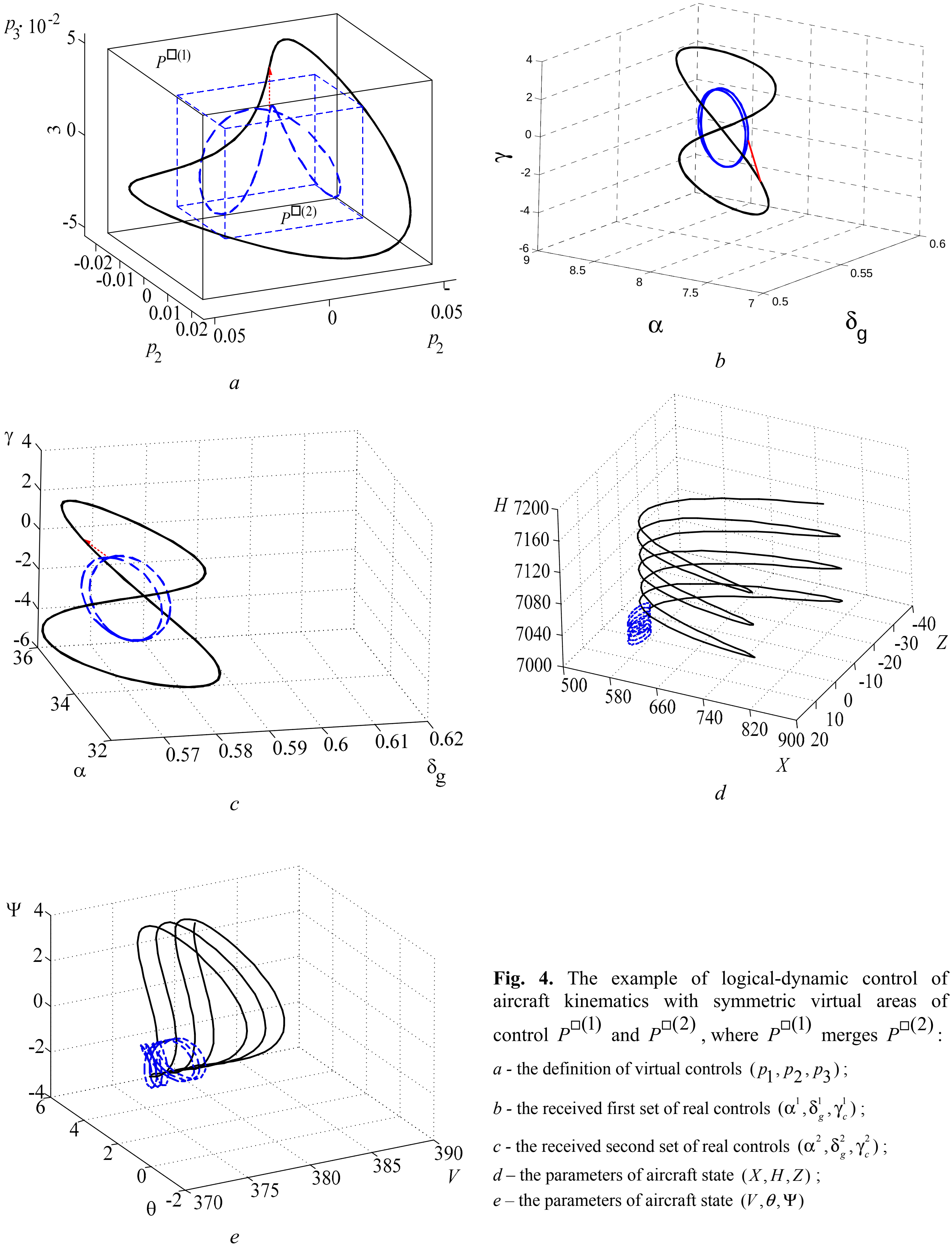
a – the definition of virtual controls (p_1, p_2, p_3);

b – the received first set of real controls $(\alpha^1, \delta_g^1, \gamma_c^1)$;

c – the received second set of real controls $(\alpha^2, \delta_g^2, \gamma_c^2)$;

d – the parameters of aircraft state (X, H, Z);

e – the parameters of aircraft state (V, θ, Ψ).



a

b

c

d

e

Fig. 4. The example of logical-dynamic control of aircraft kinematics with symmetric virtual areas of control $P^{\square(1)}$ and $P^{\square(2)}$, where $P^{\square(1)}$ merges $P^{\square(2)}$:

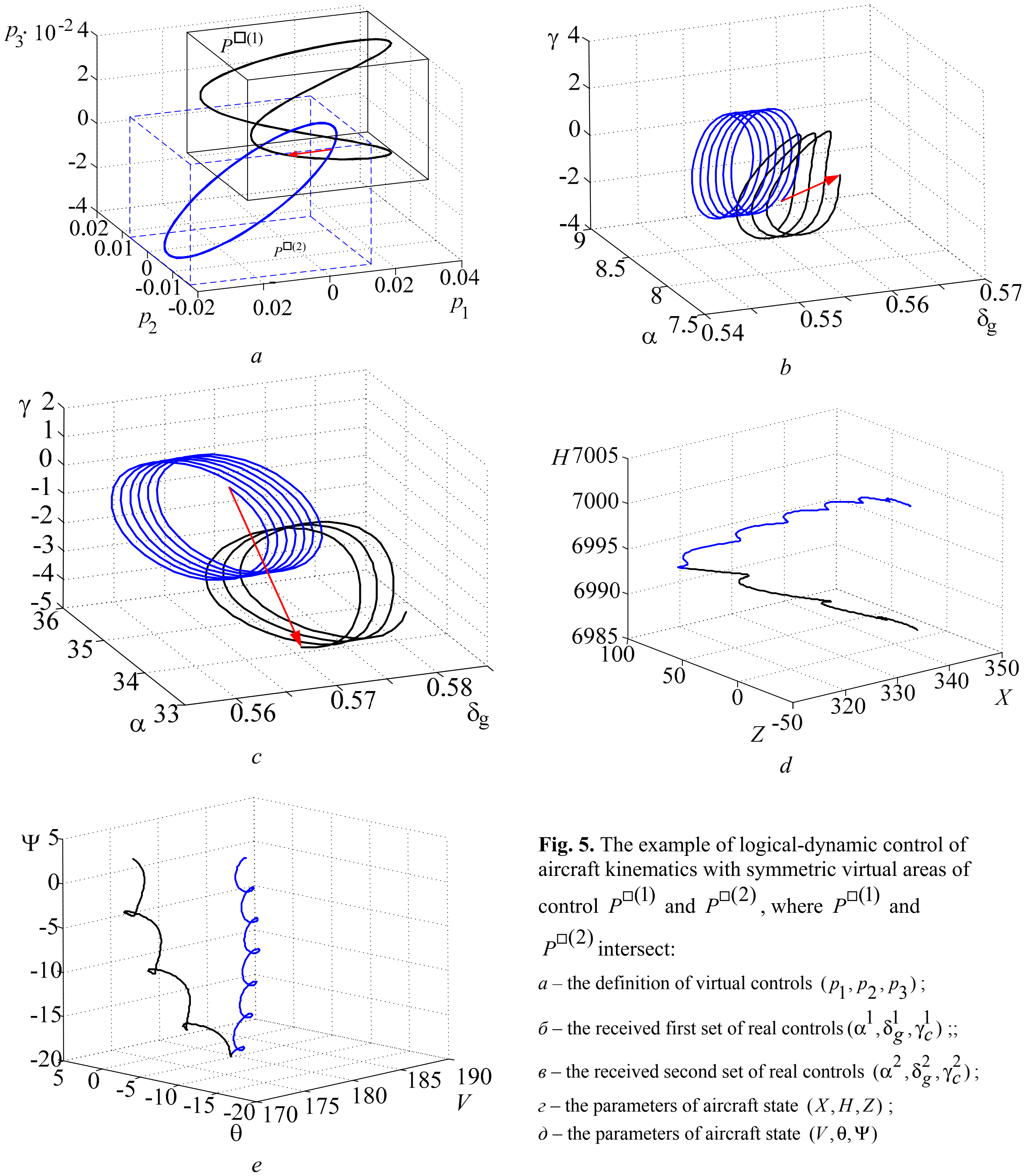
a - the definition of virtual controls (p_1, p_2, p_3);

b - the received first set of real controls $(\alpha^1, \delta_g^1, \gamma_c^1)$;

c - the received second set of real controls $(\alpha^2, \delta_g^2, \gamma_c^2)$;

d – the parameters of aircraft state (X, H, Z);

e – the parameters of aircraft state (V, θ, Ψ)



a *b* *c* *d* *e*

Fig. 5. The example of logical-dynamic control of aircraft kinematics with symmetric virtual areas of control $P^{□(1)}$ and $P^{□(2)}$, where $P^{□(1)}$ and $P^{□(2)}$ intersect:

a – the definition of virtual controls (p_1, p_2, p_3);

б – the received first set of real controls $(\alpha^1, \delta_g^1, \gamma_c^1)$;;

в – the received second set of real controls $(\alpha^2, \delta_g^2, \gamma_c^2)$;

г – the parameters of aircraft state (X, H, Z);

д – the parameters of aircraft state (V, θ, Ψ)

Controls are constructed in the form of Lissajous figures in phase spaces (p_1, p_2, p_3) and $(\alpha, \delta_g, \gamma_c)$ visually to see bifurcation effect.

Figs 2–5 show that two sets of controls $(\alpha^1, \delta_g^1, \gamma_c^1)$ and $(\alpha^2, \delta_g^2, \gamma_c^2)$, two figures in phase space of real controls correspond to one set of the controlling forces (p_1, p_2, p_3), one figure in phase space of virtual controls. Both sets of real controls are equivalent in sense of maintenance of a uniform dynamic behavior image of controlled object (1) – (5). They use one or other part of object characteristics. State parameters of controlled object are shown on figures in phase spaces (X, H, Z) and (V, θ, Ψ). On Figs. 4–5 transition from one set of virtual controls $(p_1, p_2, p_3)_1$ to other set of virtual controls $(p_1, p_2, p_3)_2$ is shown. The two sets of real controls correspond to each of these sets.

Figs 2–5 illustrate that the virtual object meets requirements of the V.V. Pavlov's Functional Homeostasis law [9] in the form of the properties defined by McR&C&D law [3, 7]. It allows instead of the definition generator for p_1, p_2 and p_3 to use the operator or the computer.

5. Conclusions

The bifurcation property of object results in bifurcation controlling variables $(\alpha, \delta_g, \gamma_c) \to (\alpha^i, \delta_g^i, \gamma_c^i)$, $i = 1{,}2$ with two sets of controlling forces equivalent action on dynamic behavior of object. It is important that the object is controlled without any features in all area $\Delta Q_x^{\square}$ despite a critical point.

The application reconfiguration technology for the decision of a problem of difficult nonlinear object control in the greatest possible area of its states will allow to use as much as possible the technological resource which has been put in pawn in its design.

This technology contains direct and inverse problems.

These problems solution is searched by a computer method. The algorithm of these problems solution is search recurrent procedure of all solutions of essentially nonlinear algebraic equations system for each time moment.

The analysis has shown that the number of solutions providing set virtual controls $P(p_1, p_2, p_3)$ of nonlinear object (aircraft) has at least two sets of solutions (for unimodal characteristics of aerodynamic coefficients) $(\alpha^1, \delta_g^1, \gamma_c^1)$ and $(\alpha^2, \delta_g^2, \gamma_c^2)$, and in case of n-modal is equaled -2^n.

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С.В. Павлова. Синтез керування кінематикою повітряного корабля у «великому»

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Розглянуто актуальну проблему сучасності – синтез надійних алгоритмів керування складними рухливими об’єктами та складними динамічними нелінійними процесами. Показано, що застосування реконфігуруючої технології для вирішення завдання керування складним нелінійним об’єктом у максимально можливій області його станів дозволить максимально використовувати технологічний ресурс, закладений у його конструкцію. Описано пряме завдання, коли відповідно до моделі реального об’єкта синтезується віртуальний об’єкт з автономною організацією керувань, його віртуальна область станів і віртуальна область керувань та зворотне завдання, коли відповідно до віртуального об’єкту та віртуальних керувань синтезуються реальні керування реальним об’єктом (літальним апаратом). Наведено вирішення прямого та зворотного завдань, які з урахуванням умов коректності завдання базуються на функціональних рівняннях абсолютної інваріантності та шукаються комп’ютерним методом. Зазначено, що алгоритм вирішення даних завдань є рекурентною процедурою пошуку всіх розв’язків системи істотно нелінійних алгебраїчних рівнянь для кожного моменту часу.

Ключові слова: автономність; біфуркація; інваріантність; літальний апарат; нелінійний об’єкт; реконфигуруюча технологія.

С.В. Павлова. Синтез управления кинематикой воздушного судна в «большом»

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Рассмотрена актуальная проблема современности – синтез надежных алгоритмов управления сложными подвижными объектами и сложными динамическими нелинейными процессами. Показано, что применение реконфигурирующей технологии для решения задачи управления сложным нелинейным объектом в максимально возможной области его состояний позволит максимально использовать технологический ресурс, заложенный в его конструкцию. Описаны прямая задача, когда по модели реального объекта синтезируется виртуальный объект с автономной организацией управлений, его виртуальная область состояний и виртуальная область управлений, и обратная задача, когда по виртуальному объекту и виртуальным управлениям синтезируются реальные управления реальным объектом (летательным аппаратом). Приведены решения прямой и обратной задач, которые с учетом условий корректности задачи базируются на функциональных уравнениях абсолютной инвариантности и ищутся компьютерным методом. Отмечено, что алгоритм решения данных задач представляет собой рекуррентную процедуру поиска всех решений системы существенно нелинейных алгебраических уравнений для каждого момента времени.

Ключевые слова: автономность; бифуркация; инвариантность; летательный аппарат; нелинейный объект; реконфигурирующая технология.

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