ANOMALIES IN THE AIRCRAFT CONTROL SYSTEMS

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Abstract

The anomalies are the deviations in the system parameters initiate the decreasing the prescribed or designed working quality of system but do not generate the failures e.g. break-down of it.

The lecture describes the basic elements of the theory of system anomalies, determines the tasks and shows the recomended model for valuation of system anomalies effects on the dynamics, flight mechanics, controlability, etc.. Some results of application of system anomalies theory to the aircraft control systems are demonstrated in second part of paper.

Introduction

Nowadays the dynamics, the accuracy of aircraft control systems plays the one of the most important role in the synthesis of the several systems like direct lift control, control of the super-maneuverability aircraft, etc.. Therefore the investigation of the internal dynamic processes of the control systems and the studying the nonlinearities, influences of system peculiarities and anomalies on the system characteristics are the actual theoretical and practical task.

System anomalies

The system parameters i.e. real constructional-technical characteristics of aircraft and its systems are scattered to a great extent in the neighborhood of the rated values prescribed in technical documentation. During the operation the deviations mentioned above continue to increase stochastically mostly in a cumulative way as a function of [1]:

- the physical-technical peculiarities of the structural material applied,
- the peculiarities of their design and manufacture,
- the technical and economical condition of operation, and
- the intensity of operation.

The changes in the system parameters naturally involve also the deviation in aerodynamic, flight engineering and flight safety characteristics.

According to our examinations[1,2] these parameter deviations are achievement the 5 - 10 % sometimes even the 25 - 40 % relatively to the nominal values given in technical documentation.

The deviations in parameters can be divided into three parts (Fig.1.):

- the parameter uncertainties, which can be obtained by some specific methods of control, i.e. robust control[3],
- the anomalies, which are greater deviations than uncertainties but do not generate the failures or standstill of systems,
- errors, namely deviations in characteristics coming out of their prescribed tolerance zones and generate the failures and standstills of systems.

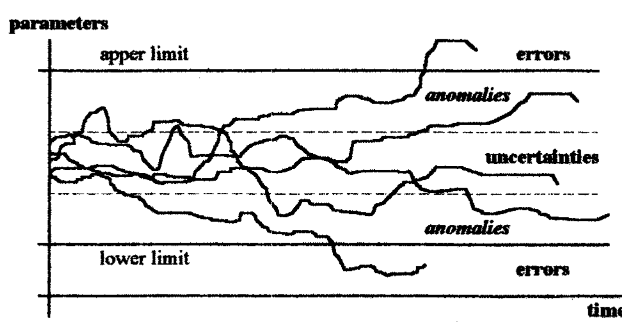

Fig. 1. Parameter deviations and their classification

Generally, the errors are investigated by reliability theory and risk analysis very well. The small disturbance in parameters, e.g. parameter uncertainties, are investigated very well too. The robust control gives possibilities to manage with uncertainties. But the influences of system parameter anomalies on real flight situations, on risk of flight operation have not studied yet on the level needed.

General model

When examining the motion or technical condition of aircraft, it seems to be describable easily for an engineer if the variation of its state vector $\mathbf{x}$ chosen appropriately is expressed as follows

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x},\mathbf{u},t) \quad (1)$$

In fact, the variation of state vector $\mathbf{x}$ is influenced by the variation in the instantaneous values of a number of factors (service conditions, methods of maintenance and repair applied, the realized management, the character istics of the flight, the atmospheric conditions, etc.). These influences can be given in terms of stochastic processes, random variables or random space (turbulence of atmosphere). Moreover, state vector $\mathbf{x}$ can not generally be measured directly. Instead, some output signal vector $\mathbf{y}$ can be measured. Consequently, the controlled motion of the aircraft or their technical conditions, their dynamics can be described only by a much more complicated model than in (1), namely by the following general set of stochastic differential equations[1]:

$$\begin{aligned}
d\mathbf{x} &= f_x\,[\mathbf{x}(t),\mathbf{x}(t-\tau_x),\mathbf{p}(\mathbf{x},\mathbf{z},\omega,\mu,t),\mathbf{z}(\mu,t),\mathbf{u}(t),\omega,\mu,t]dt + \\
&\quad + \sigma_x(\mathbf{x},\mathbf{p},\mathbf{z},\omega,\mu,t)\,d\mathbf{W}, \\
\mathbf{y} &= f_y\,[\mathbf{x}(t),\mathbf{x}(t-\tau_y),\mathbf{p}(\mathbf{x},\mathbf{z},\omega,\mu,t),\mathbf{z}(\mu,t),\mathbf{u}(t),\omega,\mu,t] + \\
&\quad + \sigma_y(\mathbf{x},\mathbf{p},\mathbf{z},\omega,\mu,t)\,\xi, \qquad (2) \\
\mathbf{u}(t) &= f_u\,[\mathbf{x}(t),\mathbf{x}(t-\tau_u),\mathbf{p}(\mathbf{x},\mathbf{y},\omega,\mu,t),\mathbf{z}(\mu,t),\mathbf{u}(t),\omega,\mu,t], \\
\mathbf{x}(t=t_0) &= \mathbf{x}_0(t=t_0,\omega_0,\mu_0), \\
\mathbf{y}(t=t_0) &= \mathbf{y}_0(t=t_0,\omega_0,\mu_0);
\end{aligned}$$

where $\mathbf{x} \in R^n$ is the state vector, $\mathbf{p} \in R^k$ is the parameter vector characterizing the state of the aircraft, $\mathbf{z} \in R^l$ is the vector of environmental characteristics (vector of service conditions), $\mathbf{u} \in R^m$ is the input (control) vector, $\mathbf{y} \in R^r$ is the output (measurable) signal vector $\mathbf{W} \in R^s$ and $\xi \in R^q$ are the noise vector (in simplified case the Wiener and Gaussian noise vectors respectively), σ_x, σ_y are the noise transfer matrices, ω and μ are the random variables assigning the position of vectors $\mathbf{p}$ and $\mathbf{z}$ within admissible space Ω_p Ω_z described by density functions $f_p(\bullet)$, $f_z(\bullet)$, t is the time, and τ_x, τ_y, τ_u, are the time-delay vectors.

In general case, the aim of aircraft operation is to use the aircraft to maximum time with a minimum specific (related to the unit time of operation) life-cost expenditure under the specific service conditions so as to maintain the predetermined level of safety and reliability. It can be seen that the knowledge of the changes in the operational and structural characteristics is indispensable required for controlling the service and operational process of this kind.

The realizing of this kind of aircraft control can be based on the principle shown on Figure 2. The system parameters $\mathbf{p}$ are changing under the real environmental conditions $\mathbf{z}$ and real flight situation and technical works, e.g. control $\mathbf{u}$ realized on aircraft and generate the given realization of state vector $\mathbf{x}$. The state realizations, of course, depend on the system parameters and real environmental conditions too. The measurable input vector $\mathbf{y}$ depends on these system parameter deviations, real environmental conditions and real state change realizations. As it can be understood, the real system parameter, environmental characteristic and state vectors are mapped by solution on the solution space into $S(\mathbf{x},\mathbf{p},\mathbf{z},\mathbf{u})$. From the other hand the system parameters and states can be estimated on basis of measured $\mathbf{y}$. The estimated solution $\acute{S}(\mathbf{x},\mathbf{p})$ should be applied[4] to synthesis of control $\mathbf{u}$ having the operative part (real control on the board) and technical part (technical maintenance and repair include the regulation of system parameters). (The diferents in the solution gaided by real processes and result of identification can generate the systematic anomalies in the construated system.)

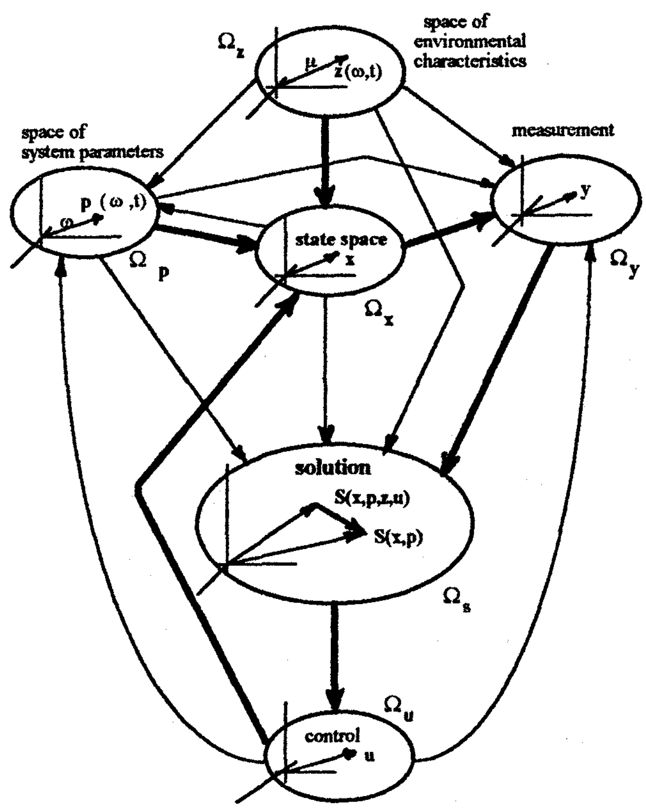

Fig. 2. Aircraft control in general case

Set of equation (2) can be given also in a very simplified time-invariant linerized uncertain system form.

$$\dot{\mathbf{x}}(t) = \mathbf{A}(\omega,t)\mathbf{x}(t) + \mathbf{B}(\omega,t)\mathbf{u}(t) + \mathbf{H}(\mu,t)\mathbf{z}(t) + $$
$$+ \mathbf{A}_{nx}(\mathbf{x}, \mathbf{u},\omega, t) + \mathbf{G}_x(\nu,t)\eta(t) ,$$
$$\mathbf{y}(t) = \mathbf{C}(\omega,t)\mathbf{x}(t) + \mathbf{D}(\omega,t)\mathbf{u}(t) + \mathbf{G}_y(\nu,t)\xi(t) + \qquad (3)$$
$$+ \mathbf{A}_{ny}(\mathbf{x}, \mathbf{u},\omega, t),$$

where **A, B, H, C** and **D** are the state, control, environmental, output and input influence matrices of n x n, n x m, n x l, r x m and r x m dimensions respectively, $\mathbf{G}_x$, $\mathbf{G}_y$ are the noise transfer matrices, η and ξ are the noise vectors, ω and ν are the random values determine the deviations in the matrix elements. The stochastic time-varying vectors $\mathbf{A}_{nx}$, $\mathbf{A}_{ny}$ include the effects of system anomalies depend on the real flight situations initiated by realized control.

In a simple case, for the first approximation the linearized model with system anomalies can be given in following form:

$$\dot{\mathbf{x}}(t) = \mathbf{A}(\omega,t)\mathbf{x}(t) + \mathbf{B}(\omega,t)\mathbf{u}(t) + \mathbf{A}_{nx}(\omega,t) ,$$
$$\mathbf{y}(t) = \mathbf{C}(\omega,t)\mathbf{x}(t) . \qquad (4)$$

Description of the system anomalies effects

The theory of anomalies deals with system anomalies and their effects on the system dynamics.

Generally the deviations in the structural, operational and service characteristics can reach and even exceed the tolerance limits essentially in three different ways (Fig. 3). In first case the system anomalies take place under influence of sudden loads greater than which was taken into account during design. In second case characteristics are changing gradually and reaching the tolerance range in a predictable way. In the third case the tolerance range becomes restricted for some other reason, e.g. by effect of other anomalies or errors, and the excess of the tolerance range can occur even under the influence of otherwise normal design loads.

The system anomalies become by the described way can be called as sudden, gradual (or parametric) and relaxation anomalies. Consequently, the probability of the dwelling of the characteristics within the tolerance range can be given according to the reliability theory with the help of exponential, normal and two-parameter exponential laws.

The system anomalies can be classified as multiplicative (β_1), delay-time (β_2) and additive (β_3) deviations in the parameters and they should be taken into account in the mathematical formalization by following way:

$$\mathbf{p} = (1+ \beta_1)\mathbf{p}_n(t - \beta_2) + \beta_3 , \qquad (5)$$

where $\mathbf{p}_n$ is the initial (nominal) values vector of parameters and the random coefficients β are depend on the realized control and flight situations.

In consideration of these types of anomalies, the general model in simplified case can be rewritten in form of multivariable perturbed linear system with time-delay and additive system anomalies:

$$\dot{\mathbf{x}}(t) = (\mathbf{A} + \Delta\mathbf{A})\mathbf{x}(t) + (\mathbf{A}_d + \Delta\mathbf{A}_d)\mathbf{x}(t - \tau_d) + \mathbf{A}_n +$$
$$+ (\mathbf{B} + \Delta\mathbf{B})\mathbf{u}(t) , \qquad (6)$$
$$\mathbf{y}(t) = (\mathbf{C} + \Delta\mathbf{C})\mathbf{x}(t) ,$$

where the $\Delta\mathbf{A}$, $\Delta\mathbf{A}_d$, $\mathbf{A}_n$, $\Delta\mathbf{B}$ and $\Delta\mathbf{C}$ represent the uncertainties and anomalies.

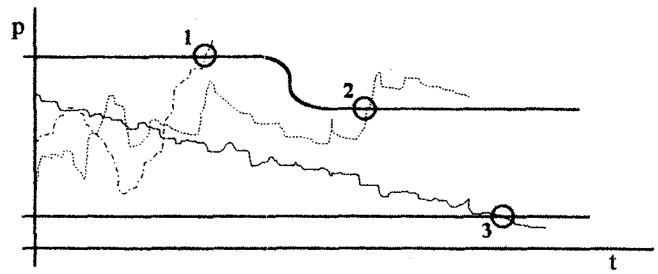

Fig. 3. Typical cases of the characteristic parameters exceeding the tolerance range (p - parameter, t- time, 1.- sudden, 2.- relaxation, 3.- gradual anomalies)

The effects of the system anomalies can be given by the following type of probabilities(1):

$$P_1\{\mathbf{y}(t)\in\Omega_y \mid t_0 \le t \le t_0+\tau,\ \mathbf{x}\in\Omega_x,\ \mathbf{u}\in\Omega_u,\ \mathbf{z}\in\Omega_z,\ \mathbf{p}\in\Omega_p\} ,$$
$$P_2\{\mathbf{u}(t)\in\Omega_u \mid t_0 \le t \le t_0+\tau,\ \mathbf{x}\in\Omega_x,\ \mathbf{z}\in\Omega_z,\ \mathbf{p}\in\Omega_p,\ \mathbf{y}\in\Omega_y\} ; \qquad (7)$$

where the admissible vectorial fields of characteristics are given by Ω.

If joint density function,

$$f_\Sigma = f\,[\mathbf{x}(t), \mathbf{u}(t), \mathbf{z}(t), \mathbf{p}(t), \mathbf{y}(t)] \qquad (8)$$

is known, then the recommended characteristics (7) can be calculated as follows:

$$P_1\{y(t)\in\Omega_y|\ldots\}=\frac{\int\limits_{\Omega_x}\int\limits_{\Omega_u}\int\limits_{\Omega_z}\int\limits_{\Omega_p}\int\limits_{\Omega_y} f_{\Sigma}\,dxdudzdpdy}{\int\limits_{-\infty}^{+\infty}dy\int\limits_{\Omega_x}\int\limits_{\Omega_u}\int\limits_{\Omega_z}\int\limits_{\Omega_p} f_{\Sigma}\,dxdudzdp}, \tag{9}$$

$$P_2\{u(t)\in\Omega_u|\ldots\}=\frac{\int\limits_{\Omega_x}\int\limits_{\Omega_u}\int\limits_{\Omega_z}\int\limits_{\Omega_p}\int\limits_{\Omega_y} f_{\Sigma}\,dxdudzdpdy}{\int\limits_{-\infty}^{+\infty}du\int\limits_{\Omega_x}\int\limits_{\Omega_z}\int\limits_{\Omega_p}\int\limits_{\Omega_y} f_{\Sigma}\,dxdzdpdy}.$$

The tasks of investigation of system anomalies can be defined as follows:

- initial task - investigation of the structural and operational characteristics, signalization of the anomalies and the statistical description of the anomalies,
- direct task - study the effects of system parameter anomalies on the aerodynamics, flight mechanics, controllability and stability,
- inverse task (synthesis) - determining of the bounds for the system parameters from the given bounds (admissible field) of operational characteristics e.g. flight safety, quality of maneuvers, controllability,
- basic task - create the control for the system with anomalies,
- complementary task - determining the basic and additional information for solving the different problems connected with system anomalies, e.g. model-formation, optimal control, identification, etc.

Control system anomalies

We have a long period experience on the investigation of deviations in the structural (e.g. geometrical) characteristics of supersonic fighter and middle-size passenger aircraft[1,2]. For example, the extent and form of permanent deviations in the geometrical characteristics of wings depend on the duty of the airplanes to be carried out, on the flying hours, on the circumstances of operation, on the technique of piloting the airplane (especially on the landing mode of operation), and on man's physiological characteristics. According to our experience the geometrical characteristic deviations of wings generate the changes in the zero-lift angles, relative cambers and asymmetry in the rolling direction.

These types of characteristic deviations generate the deviations in the aerodynamic characteristics and performance data and cause the problem in the flight stabilizing, especially during flight test. Therefore the special study was realized with aim to find the optimal strategy for flight test and adjustment of stabilizing systems. During this work there were investigated the influences of parameter uncertainties and nonlinearities in the control system on the quality of stabilizing.

According to our theme, investigation of system anomalies, there were investigated the different type anomalies on the lateral feedback stabilizing system. The nonlinearities and the time-delays are investigated very well. The nonlinearities should be taken into account only on the flight near the operational limits, for example at high angle of attack[5]. The third type of anomalies, the additive anomalies like rolling moment at zero roll angle caused by asymmetry in wing geometry could be more interesting.

There was investigated a lateral disturbed motion of the middle-size supersonic fighter at high subsonic speed equal to Mach number 0.9 flying on the altitude more then 10 km. The system of equation and the values of matrix-elements were the followings[6,7]:

$$\dot{\mathbf{x}}(t)=\mathbf{A}\mathbf{x}(t)+\mathbf{B}\mathbf{u}(t)+\mathbf{A}_n,$$
$$\mathbf{y}(t)=\mathbf{C}\mathbf{x}(t)+\mathbf{D}\mathbf{u}(t),$$

$$\mathbf{x}=\begin{bmatrix}\beta=\text{slideslip angle}\\ p=\text{roll rate}\\ r=\text{yaw rate}\\ \phi=\text{roll angle}\\ \psi=\text{yaw angle}\end{bmatrix},\qquad \mathbf{u}=-\begin{bmatrix}\delta_a=\text{aileron deflection}\\ \delta_r=\text{rudder deflection}\end{bmatrix},$$

$$\mathbf{A}=\begin{bmatrix}-98 & 0 & -.995 & .035 & 0\\ -18.9 & -1.23 & 1.6 & 0 & 0\\ 2.79 & -.03 & -.263 & 0 & 0\\ 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\end{bmatrix},\quad \mathbf{B}=\begin{bmatrix}0 & .0185\\ -34.7 & 5.07\\ -3.85 & -1.44\\ 0 & 0\\ 0 & 0\end{bmatrix}.$$

The model was used as (6). The control was relized as shown on Figure 4..On this figure anomaly generated in the rolling moment is shown, too. The deviation in the state matrix derivative coefficient demonstrated by decreasing the A(2,2) on 5 %.

The simple feedback was determined by application the optimal linear quadratic problem to the initial system. The another feedback system was designed as the robust feedback controller based on the LQG/LTR algorithm.

There are the some interesting results of investigation are demonstrated on the Figures. The different in the systems and their response on the input shown on Fig.4. in case without and with system anomalies can be checked from Figure 5. The influences of deviation in the state matrix element A(2,2) are represented with Figure 6. The effects of additive system anomalies like rolling moment at zero roll angle are shown on Figure 7. At last on the Figure 8. the interesting effect of additive system anomalies is demonstrated, when the robust control feedback has a greater final error then the simple feedback system. In addition to them the final errors in controlled systems have the different signs.

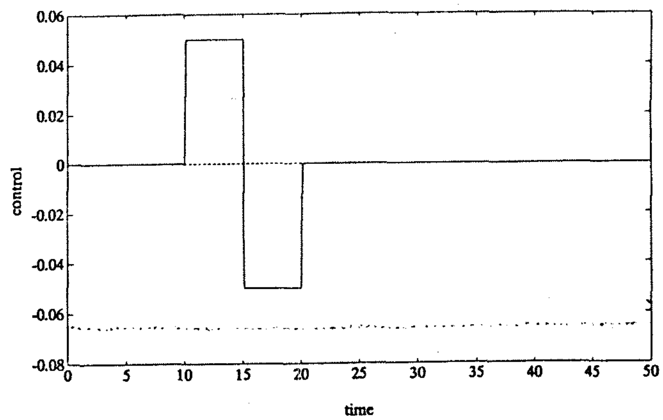

Fig. 4. Aileron deflection input (—) and the anomaly in the rolling moment (...).

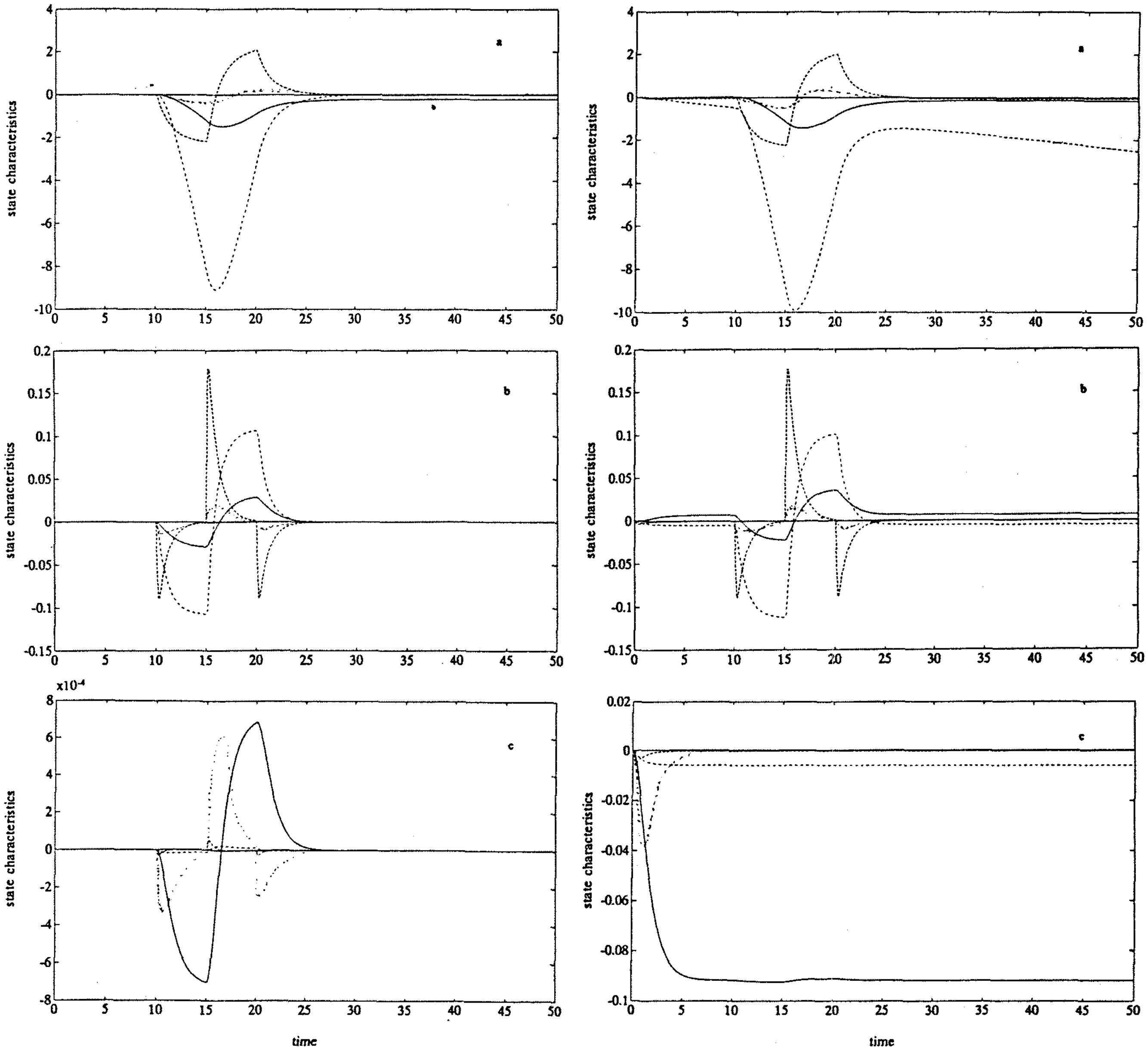

Fig. 5. The response of the initial system (a), system with a simple feedback (b) and the system with the robust feedback controller (c) in case without system anomalies (left) and with anomaly (right) in rolling moment. (—— slideslip angle, ---- roll rate, ... yaw rate, -.-.-.-.-. roll angle, —— yaw angle).

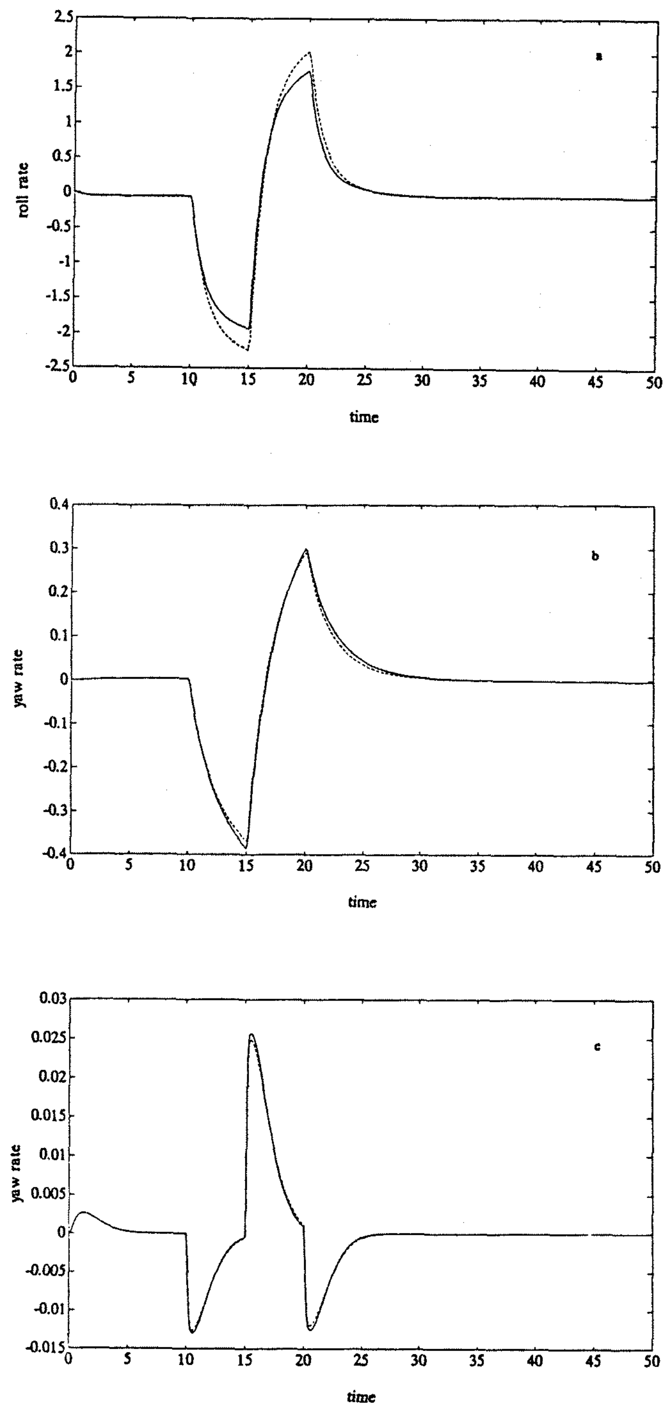

Fig. 6. The effect of decreasing in state matrix element A(2,2) of initial system (a), system with feedback (b), system with robust feedback controller (c).

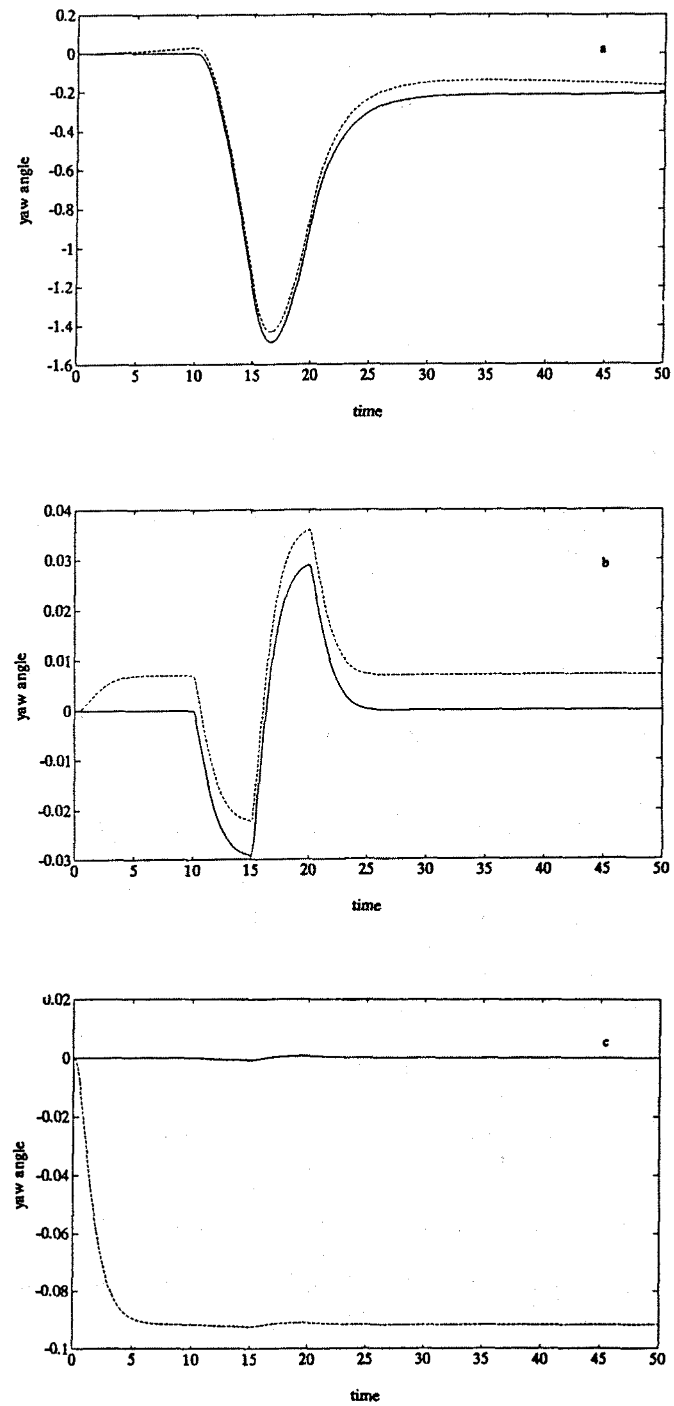

Fig. 7. Effect of anomaly in the rolling moment in case of initial system (a), system with simple optimal feedback (b) and system with robust feedback controller (c).

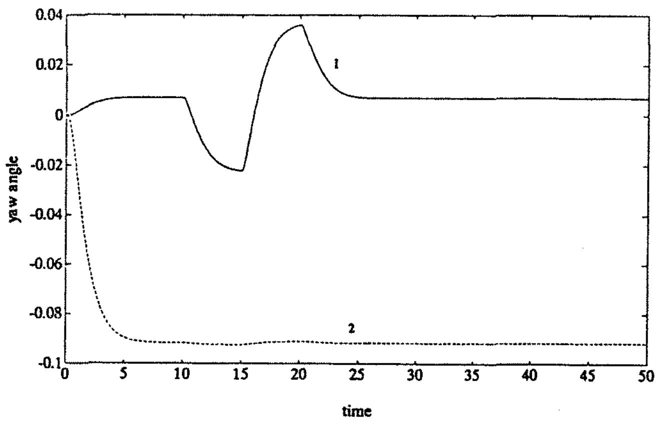

Fig. 8. Yaw angle changes in response of system with simple feedback (1) and system with robust feedback controller (2) in case of system anomaly in rolling moment.

Summery

The aim of this paper was to draw the attention to a new theoretical and practical problem caused by operational life-depended, stochastic changes in the structural and operational characteristics of aircraft systems greater then those could be covered easy by modern methods of control. These deviations in the characteristics as system anomalies play an imported role in the design of operational processes of aircraft include the maintenance, repair of aircraft and their operative, on-board control, e.g. robust control, too.

In our opinion the problem can be investigated in field of theory of system anomalies. The elements of this theory were described and concrete recommendations were offered in this paper for possibly available models for description of system anomalies and their effects on the aerodynamic characteristics and flight data. Some effects of anomalies in the aircraft control system were demonstrated by the results of investigation of stabilizing the lateral disturbed motion of aircraft.

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