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Technology of Quality and Reliability of Complex Technical Systems Characteristics Stage-By-Stage Improvement on Examples of Rocket-Space Technology Objects

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Abstract: The principles of the evolutionary process of creating complex technical systems are formulated. The possibility of using the technology of stage-by-stage manufacturing of each specific sample of the system is considered. In the process of stage-by-stage manufacturing, the system improves its properties and characteristics, moving from relatively simple versions to more complex and effective versions. Based on the results of the control, the system adapts to the real operating conditions.

Keywords: reliability, improvement of quality characteristics, rocket and space technology, complex technical system

1. INTRODUCTION

When improving the quality and reliability characteristics of complex technical systems (CTS), which include modern objects of rocket and technical equipment (RTE), problems have arisen that affect the conceptual basis of technology of their creation [1].

These systems are characterized by a multi-level hierarchical structure, a variety of "behaviors", a high dimension of the state space and a large number of elements, the ability to interact with the environment (adapt to and effect on the environment).

For such objects, the incompleteness of physico-chemical processes knowledge underlying in the basis of their functioning, manufacturing technology and application conditions is characteristic. For the method of manufacture based on the decomposition of the product into the simplest elements, and production - on the sequence of the simplest technological operations, these factors serve as the causes of design errors, production defects and violations in the operational procedures.

In connection with the mentioned factors, the creation of complex systems is not a one-stage act of manufacturing the finally chosen variants according to previously known technologies, but occurs through trial and error on simpler product prototypes [1, 2].

By experimental development of each new version, the missing information is filled and the correctness of design, technological and other innovations is confirmed.

Improvement of the technical characteristics of each new version of the system involves the use of new more effective principles of the system elements operation and a deeper understanding of the physical processes that underlie its functioning. As a result of a number

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of iterations, the system approaches a certain limiting level of quality characteristics achievable within the product of this type.

An example is the on-board control systems of launcher rockets, which in their development went from the forms of construction based on disintegration to the simplest subsystems and the use of the element base in the 1950s. to modern integrated control systems [3, 4], which include high-performance on-board computational facilities.

Let us stop on the fundamental principles of the stage-by-stage technology of creating CTS:

- at all stages CTS should retain the basic properties inherent in products of this type;
- transition to a new, more sophisticated product modification is associated with innovations;
- new CTS maintains continuity with old, prior product samples;
- new product is created on the basis of a workable, reliable prototype;
- each product with innovations passes the stage of development test.

The principles of stage-by-stage (additive) manufacturing are the basis of the Additive Manufacturing technology. This technology is associated with the use of three-dimensional printing and is considered by several authors as one of the important directions of the unfolding new production revolution.

The most obvious possibility is the technology of stage-by-stage manufacturing in the production of dynamic systems and software (control algorithms) for these systems.

Elements of formalization of this technology within the life cycle of a dynamic system were considered in [5]. The improvement of the characteristics of the system was linked to the possibility of implementing a wider range of movements [6].

The existing technology of creating a system's software (control algorithm) resembles the assembly of a technical product from individual parts. With respect to the algorithm, the assembling elements are computational operations and the data of aprior and current information used in them. All the disadvantages of this method of manufacturing indicated above are also present in this case.

A new, additive technology involves a stage-by-stage improvement of the properties and capabilities of the algorithm due to the sequential complication of the synthesis problem.

The experiment in this case is simulation modeling.

2. FORMULATION OF A STEADY-STATE CONTROL PROBLEM

Let us consider the problem of complex multiply connected objects controlling, which include liquid-propellant launcher rockets and booster blocks.

The control object is described by a differential equation of the form:

$$\dot{x} = f(x(t), w(t), t),\ x(t) \in X \subset E^k,\ w \in E^{\nu},\ u(t) \in U \subset E^r,\ \nu < r, \tag{2.1}$$

$$t \in [t_0, T],\ x(t_0) = x_0 \in X_0.$$

There $x(t)$ - is the combined vector of the state coordinates of the object and the equations of the perturbation factors model; $x(t_0)$ - extended vector of unknown initial conditions; f - known vector function, differentiable with respect to the set of its arguments; $w(t)$ - control, which is a known vector function of time t; T - the moment of achievement of the required final state (terminal time moment).

For the final state of the object, boundary conditions are designated:

$$\phi^{\ell}(x(T), T) = \phi_3^{\ell},\ \ell = \overline{1, L},\ L \le k,\ r = L. \tag{2.2}$$

The value of the terminal time moment can be specified in advance. In general case, its magnitude is unknown in advance, and a certain degree of freedom in the assignment of the moment T is allowed. Under perturbed conditions, the terminal time moment can be considered as a control parameter, chosen together with the parameters *u* from condition (2.2). For equation (2.1), we shall assume that the existence conditions and the uniqueness of the solution conditions are fulfilled.

Taking into account the possibility of control errors in solving problem (2.1)÷(2.2), we introduce the notion of boundary conditions discrepancies and reformulate the goal of control (2.2):

$$z = \left\{ z^{\ell} = \phi^{\ell}(x(T),T) - \phi_3^{\ell},\ \ell = \overline{1,L},\ L \le k \right\},\ z \in \delta, \tag{2.3}$$

where δ - the set of admissible values of the vector of discrepancies, characterizing the accuracy of the solution of the problem (2.1)÷(2.2).

In addition to the terminal conditions (2.3), we also consider indicators of integral type:

$$I_n = \int_{t_0}^{T} g_n(x,\mu,w,\tau)d\tau,\ n = 1,2,\ldots,N, \tag{2.4}$$

where g_n - known function of fixed sign, the physical content of which can compose the cost of energy resource, time, loss due to control.

To control the object, $x(t)$ process measurements are made, defined by equation (2.1).

The measuring devices are usually represented by static links. In the general case, the equation of the measuring part of the system for the control object (2.1) is written in the form:

$$y(t) = \chi_t(x(t),h(t)), \tag{2.5}$$

where $y(t)$ – dimension measurement vector p, $h(t)$ - measurement error random vector.

Equations (2.1) describe the processes of various physical nature occurring on a rocket carrier: the mechanics of rigid body motion, fluid hydrodynamics, heat exchange and thermodynamic processes, etc.

The boundary conditions (2.1) and the discrepancies (2.3) are determined by the problems of launching the spacecraft and the conditions for the safe shutdown of the engine. Criterion (2.4) is formed, based on the constant need to improve the energy characteristics of launching missile systems.

The control problem formulated above should be solved taking into account the probabilistic nature of the perturbing factors, the relationship between the coordinates of the equations of various physical processes in the object, the diversity of the launching problems and the modes of operation of the control system.

Due to the complexity of the overall task, the object management is decomposed into specific tasks: navigation, guidance and stabilization, fuel consumption, tank pressurization, engine control. The mathematical support of each subsystem is formed from separate functional blocks and computational operations. At the same time, the understanding of the unity of the management of the object is lost, and the interconnections are not properly taken into account. When upgrading and improving the characteristics of the control system, developers constantly faced with the difficulties of making changes to the existing, proven technology of forming the software of the system.

3. DECOMPOSITION OF THE SYNTHESIS PROBLEM BY THE DEGREE OF USE OF APRIOR AND CURRENT INFORMATION AND DEFINITION OF THE MAIN CLASSES OF TERMINAL CONTROL

It is advisable to consider the possibility of building a new technology based on the procedure for the stage-by-stage solution of partial problems of synthesis and continuity of these solutions.

In this connection, let us consider possible ways of decomposition of the above terminal control problem into a sequence of simpler synthesis problems. As a result of solution of these problems, various classes of terminal control can be formed.

By the nature and efficiency of aprior information and current information in the formation of physically realizable control, there are four main classes of terminal control:

1. Program control (or open-loop control), where the formation of the control completely ignores the current information about the measured coordinates and realized controls.

The program control is formed as a function of the time $w_{пр}(t)$ for the undisturbed motion of the object under given initial conditions and the terminal time T . Under these conditions, the nominal (undisturbed) trajectory of the object $x_{н}(t)$ is realized. For the formation of software control, aprior information about the equations of the object and the specified boundary conditions for the nominal operating mode of the system is used.

As a rule, optimal control is chosen as program control, which ensures the maximization of criterion (2.4), for example, on the basis of the maximum principle [7].

In accordance with this principle, a Hamiltonian is constructed, which is the scalar multiplication of the vector of the right-hand sides of the equations of the object by the coordinate vector of the conjugate system. As a result of maximization, the control is defined as the vector function $\Delta w(u,t)$ of the parameters u and the current time. Parameters u are determined as a result of the solution of the main and conjugate system under given initial conditions. The initial conditions for the conjugate system must be linked to the terminal conditions of the terminal problem.

As an example of a control program, it is possible to give an optimal law of variation of the pitch angle θ at given boundary conditions with respect to the position and velocity of the rocket's motion in a homogeneous plane-parallel gravitational field: $\mathrm{tg}\theta = u_1 + u_2 t$.

The law in the form $\Delta w(u,t)$ turns out to be convenient for control with feedback.

2. Control with feedback on the full vector of coordinates. When forming the control, the data of the current information arriving via the feedback loop is used. In the synthesis of control, a deterministic aprior description of the system is used.

In this case, a considerably idealized formulation of the synthesis problem for an undisturbed object is considered. The deviations of the coordinates from the nominal trajectory and the discrepancy of the boundary conditions are caused by variable initial conditions, previously unknown before the time of measurement. The discrepancies are predicted for boundary conditions under a known vector of the current values of the object coordinates and given, for example, program control.

The synthesis problem is to choose control with feedback in the form $\Delta w(u,t)$. In the previous section, this vector-function was determined when solving the optimal control problem.

The dynamics of the control process is characterized by a change in the vector of discrepancies of the boundary conditions. On that basis, it is advisable to choose a control from the Lyapunov stability condition of the object's motion in the part of the vanishing of the predicted value of the residual vector at $t \to T$.

Stability of motion can be considered from the linear approximation of the object for deviations from the nominal trajectory:

$$\dot{x} = A(t)x(t) + B(t)\Delta w(t),\ t \in [t_0, T],$$

(3.6)

$$\dot{z}_x(t) = \Phi(T,t)B(t)\Delta w(t),\ z_x(t) = \Phi(T,t)x(t) - x_3,$$

where $A(t)$, $B(t)$ – matrix of order $k\times k$, $k\times \nu$, $\Phi(T,t)=X(T)X^{-1}(t)$, $X(t)$ – fundamental system of solutions.

For the quadratic Lyapunov function, the asymptotically stable motion and the condition $z_x(T)=0$ are provided by the control of the following form:

$$\Delta w(t) = -B^{\mathrm{T}}(t)\Phi^{\mathrm{T}}(T,t)u(t)\,,\ u(t) = C^{-1}(t)z_X(t)\,,\ C(t) = \int_t^T D(\tau)d\tau\,,$$

$$D(t) = \Phi(T,t)B(t)B^{\mathrm{T}}(t)\Phi^{\mathrm{T}}(T,t)\,.$$

Consider the case when the dimension of the control vector $\Delta w(t)$ coincides with the dimension of the coordinate vector of the state $x(t)$ ($\nu=K$), and the matrix $B(t)$ is such that the components of the control vector $\Delta w(t)$ directly affect the derivatives of all coordinates of the state vector.

As a rule, restrictions are imposed on the deviations of coordinates. In connection with this, for such deviations, it is possible to determine the values that are minimally needed for the solution of the terminal problem.

The minimum required deviations are provided for a pulsed control action $\Delta w(\tau)$ on a small time interval ε in the t surroundings, for the remaining time interval $\Delta w(\tau)=0$: $\Delta w(\tau)=\Delta w(t)$, $t\le\tau\le t+\varepsilon$, $\Delta w(\tau)=0$, $\tau>t+\varepsilon$. Here $\varepsilon>0$ - is a small value in comparison with T.

Impulse control action on the object (3.6) from the condition $\hat{z}_X(t_1)=0$ for all t_1: $T\ge t_1>t+\varepsilon$, is defined as follows:

$$\Delta w(t) = -\Phi_B^{-1}(T,t)z_X(t)/\varepsilon\,,\ \Phi_B(T,t) = \Phi(T,t)B(t)\,.$$

Such control is used in fuel consumption control systems for liquid-propellant launcher rockets.

3. Deterministic control with feedback on the incomplete vector of object coordinates measurements.

When measuring $y(t)=Hx(t)$, H – is a constant matrix of order $n\times k$, $k>n$, to recover $x(t)$ let's use the values of $y(\tau)$n a limited interval of prehistory $\tau\in[t-\Delta T,t]$. As a criterion for the quality of recovery $x(t)$ we take a definite-positive scalar function of the form:

$$s(t) = \int_{t-\Delta T}^{t} 0{,}5(y(\tau)-\hat{y}(\tau))^{\mathrm{T}}Q(\tau)(y(\tau)-\hat{y}(\tau))d\tau\,,$$

where $Q(\tau)$ - diagonal matrix of positive coefficients.

Let $x(t-\Delta T)=x_0(t)$. At this $x(t)=\Phi(t,t-\Delta T)x_0(t)$. For $\hat{x}_0(t)$ equation is specified:

$$\dot{\hat{x}}_0 = A(t-\Delta T)\hat{x}_0(t) + B(t-\Delta T)\Delta w(t-\Delta T) + u_0(t)\,,\ t\in[t_0,T]\,,\ u_0(t)\in E^k\,, \quad (3.7)$$

$$u_0(t) = -K_1(t)\frac{\partial s(t)}{\partial \hat{x}_0(t)}\,,\ \frac{\partial s(t)}{\partial \hat{x}_0(t)} = -\int_{t-\Delta T}^{t}\Phi^{\mathrm{T}}(\tau,t-\Delta T)H^{\mathrm{T}}Q(\tau)(y(\tau)-\hat{y}(\tau))d\tau\,,$$

where $K_1(t)$ - diagonal matrix of algorithm parameters of order $k\times k$.

Algorithm (3.7) provides an asymptotically stable process of convergence $\hat{x}_0(t)$ to $x_0(t)$.

4. Stochastic control with feedback by a disturbed object.

Probability distribution laws and interference are assumed to be known. To solve the synthesis problem, the terminal quality control criterion is represented as a conditional mathematical expectation of the loss function, which depends on the discrepancies of the boundary conditions. For a wide class of problems, the synthesis of stochastic control is divided into independent estimation and control problems by estimating the extended coordinate vector of the object, including the parameters of disturbance models. To solve the estimation problem it is convenient to use the discrete analogue of the control object and the measurement channel in the form:

$$x_i = A_i x_{i-1} + B_i \Delta w_i\,,$$

$$i=0,1,2,\ldots,I+1,$$

$$y_i = Hx_i .$$

As a result of solving a discrete equation, a linear function of the following form can be obtained:

$$x_j = \varphi_j(x_{i-r}, \vec{w}_{i-r,\,j-1}),$$

$$\vec{w}_{i-r,\,j-1} = (w_{i-r},\ldots,w_{j-1}),$$

$$j = i - r + 1,\ldots,i,\; r \ge k .$$

The estimation algorithm is presented in the following form:

$$\hat{x}_{i-r/i} = A_{i-r+1}\hat{x}_{i-r/i-1} + L_i\vec{y}'_{i-r+1,i}, \tag{3.8}$$

$$\vec{y}'_{i-r+1,i} = (y'_{i-r+1},\ldots,y'_i),$$

$$y'_j = y_j - H\varphi_j(\hat{x}_{i-r/i-1}, \vec{w}_{i-r,\,j-1}),$$

$$j = i - r + 1,\ldots,i .$$

The resulting estimation algorithm is a discrete analogue of the algorithm for reconstructing the full vector of state coordinates. In the case of an excessive number of measurements ($r>k$) with an appropriate choice of weighting matrix L_i in the algorithm (3.8) measurements error filtering is performed.

CONCLUSION

In conclusion, we note the following. Based on the analysis of a number of known, more complicated problems of synthesis, continuity of solutions has been revealed - from program control to stochastic control with feedback. In the process of stage-by-stage improvement, approaching the real conditions of functioning, the possibilities of control are expanding, it acquires new useful properties. The carried out analysis can be used at creation of additive technology of control synthesis in complex technical systems.

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