Adaptive Control Systems of Large Space Structures with Variable Parameters

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Abstract: The paper discusses the problems of control by large space structure (LSS). The mathematical technique to solve the task of computer-based derivation and transformations of the current motion equations of the LSS is proposed. Some problems in the LSS control in the course of its assembly and possible ways and means to overcome them are considered. The task of an optimal trajectory choice of the LSS in-orbit assembly is proposed. Possibility of using the “portrait” of the construction dynamics for analysis and design of the dynamic characteristics of the LSS is discussed. Three strategies of the LSS adaptive control were considered. This paper is a survey of the researches that were carried out in the Trapeznikov Institute of Control Sciences.

Keywords: spacecraft, large space structure, attitude control system, adaptive control

1. INTRODUCTION

Development of some global projects for the next stage of mastering the space has started in the mid-1980s. It was required design of a new type of spacecraft that was called as the large space structure (LSS) (Nurre et al., 1984) (or discretely evolving structure). The scale of these projects may be illustrated by well-known examples. For instance, in order to replace the decreasing resources of energy carriers, it is planned to construct in the near-earth space the large solar power stations provided with solar cell panels of size running up to that of the football ground. There exists also a project of using the large orbiting reflectors to illuminate by solar light the northern regions during the polar nights in order to promote development of these under populated territories. The most important direction in development of astronomy lies in design and deployment of large radio-telescopes in the near-earth orbit.

It is clear that realization of such projects requires insertion into orbits or in-orbit assembly of large structures and control of their angular position. At the same time, the specific properties of this new class of objects such as the infra-low (of the order of 0,01÷0,1 Hz) structural vibrations approaching the control frequencies of the LSS "rigid" motion, impossibility of carrying out the ground-based checkout tests and, as the result, very poor definiteness not only of the object model coefficients but its structure as well, almost complete lack of external and internal damping of the elastic oscillations, and large number of the LSS degrees of freedom suggested the following conclusion which appeared in the USA Government-owned journal (Nurre et al., 1984): "…All solutions of the problems of control of the elastic satellites that were by now established by the international scientific community only superficially touched upon the specificity that properly manifests itself only in the problems of controlling the large space structures, a new class of the space objects of the near future. Therefore, new efforts of the experts are required to solve these problems which are important for the entire mankind".

Such objects as LSS can not be inserted into orbit because of their desirable size. So it is necessary to realize step-by-step in-orbit LSS assembly. In the course of the assembly LSS passes three qualitatively different periods of its existence.

1. The initial period is the rigid carrying body.
2. Once the first construction flexible element and some other flexible elements are attached to the assembled object begins to exhibit the properties of a flexible mechanical system, which is characterized by the presence of one or several comparatively high-frequency (~1÷10 Hz) vibration modes. Such type of the object usually is called as flexible spacecraft.
3. As the number of the flexible elements increases, the assembled object turns into a hard-to-control system. Such system is distinguished by a big inertia moment and many low elastic modes frequencies (<0.1 Hz). These frequencies close with the fundamental frequency of the "rigid" motion of the object. Such space object is LSS.

Hence LSS in the course of its in-orbit assembly is discretely evolving structure (DES). As the control object it is multi-frequency oscillating system with discretely time-varying parameters and number of freedom degrees.

It should be mentioned that despite the efforts of the scientists of many countries (Putz, 1999; Khang et al., 1976; Woerkom, 1993; Rutkovsky and Sukhanov, 1996), the problem of creating on a near-Earth orbit a large space structure suitable for solving the aforementioned and some other important problems of the new stage of space development (Putz, 1999; Buyakas, 1990; Bekey, 1999) in fact remains still unsolved.

Only in single paper (Nakasuka et al., 2007) the authors describe the results of deploying large "Furoshiki" net in space. But this object is not the LSS. It is in-orbit deploying object of small sizes. Nevertheless we can consider it as a predecessor of the DES.

In this work it is adduced the survey of the papers that are due to DES control and that were performed in the Institute of Control Sciences, Russian Academy of Sciences (Moscow). Mathematical models of DES, principles of step-by-step in-orbit their assembly and methods of design of the control systems for such space structures are considered.

2. MATHEMATICAL MODEL OF DES

A DES of a sufficiently simple form, which can be represented by umbrella-type structure (Zemlyakov et al., 2007; Glumov et al., 2003; Glumov et al., 2005) is considered. In such DES, the passive bodies, the rods that form the required frame surface, are sequentially attached to the carrying body and to each other. Although the rods are supposed to be rigid bodies, we take into account the link elasticity at their attachment points (it is possible to consider the rods as a weightless elastic ones, which are attached to carrying body and to each other rigidly).

In Zemlyakov et al. (2007) the mathematical technique to support the on-line computer-based derivation of the current mathematical model of the three-dimensional motion of the umbrella-type DES is developed.

In the course of designing the DES, assembling it in orbit, or while it is functioning, the necessity may arise to obtain the mathematical model of motion for the case when some of the generalized coordinates take constant values and become the parameters of the model. For instance, for one reason or other, some attached rods lose their degree of freedom. The common method of designing the control system of the spacecraft based on the mathematical model of its two-dimensional motion can be another example. The computer-based method of deriving the mathematical model of the DES motion have taken into account all special cases.

As the result it was developed:

1. Mathematical technique for computer-based derivation of the three-dimensional motion equations for the DES of complete structure (LSS).
2. Mathematical technique for computer-based derivation of the three-dimensional motion equations for the DES of any intermediate structure and structure with extra constraints imposed.
3. Computer-based linearization of the mathematical model for all special cases.
4. Computer-based reducing the linearized mathematical model of the DES motion to the main (normal) coordinates.
5. Computer-based construction of mathematical models of partial motions with respect to each of the controlled coordinates.
6. Computer-based constructing modal-physical models of partial motions.

Obtained results are constructive and can be used for getting all types of the DES mathematical models in symbolic (Maple) and in numerical (Matlab) forms.

As an example in Glumov et al. (2003) it was considered two-dimensional motion of the structure (Fig. 1) which consists of a central (carrying) body of mass m_0 and inertia moment J_0. The radial rod elements of the frames of the first, second, and subsequent levels are attached in a certain sequence to the carrying body. Each element is regarded as a weightless elastic rod of flexural rigidity B_{ij}, length r_{ij}, and mass m_{ij} lumped at the free end and taking into account the reduced mass of the rod and fitting mounting. We agree to call one or more serially connected elementary units of a given kind the i-th ($i = \overline{1, n_i}$) frame branch. At that, $\{r_{0i}, \alpha_i\}$ are the polar coordinates of the points o_i where the i-th frame branch is attached to the central body. The totality of all elements of the DES frame that are like (in the number of place on the branch) but are not connected to each other will be called the j-th frame level, where $j = \overline{1, n_j}$ is the level number. The frame elements are rigidly connected to the body and each other.

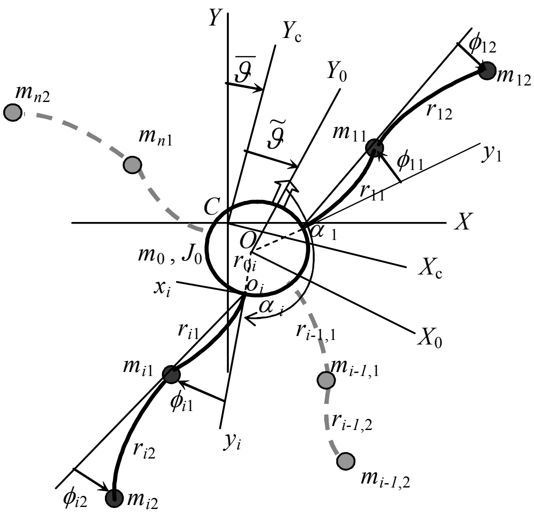

Fig. 1. Generalized umbrella-type structure

The number of the assembly stage is denoted by $n = \overline{0, N}$, where N is the total number of the attached elements, $N = \sum_{j=1}^{n_j} s_j$, were s_j is the total number of the elements in the j-th level.. The intermediate DES structure obtained at the n-th stage and remaining unchanged (fixed) until attachment of the next element is denoted here by F_n. Positioning of the central DES body at the initial point of assembly corresponds to the structure F_0. The final structure F_N defines the completed form of LSS.

Further procedure of forming the package of DES models will be considered using for simplicity structure of an umbrella-type having at the final stage two levels of development ($n_j = 2$) of which the first level has $s_1 = n_1$ elementary frame elements, and the second level has $s_2 \le n_1$ elements.

Using the results of the paper (Zemlyakov et al., 2007) by computer-based derivation and transformations of DES motion equations and taking into account the aforementioned parameters of the DES the required mathematical model in the symbol form was obtained as follows:

$$
\begin{aligned}
&J_n\ddot{\vartheta}+\sum_{i=1}^{n}[a_{i\vartheta}r_{i1}+a_{i\phi_2}L_i-\frac{1}{m_n}a_{i\phi_1}\sum_{k=1}^{n}a_{k\vartheta}\cos(\alpha_i-\alpha_k)]\ddot{\phi}_{i1}+\\
&+\sum_{i=1}^{n}a_{i\phi_2}[L_i-\frac{1}{m_n}\sum_{k=1}^{n}a_{k\vartheta}\cos(\alpha_i-\alpha_k)]\ddot{\phi}_{i2}=Q_{\vartheta},\\
&[a_{i\vartheta}r_{i1}+a_{i\phi_2}L_i-\frac{1}{m_n}a_{i\phi_1}\sum_{k=1}^{n}a_{k\vartheta}\cos(\alpha_i-\alpha_k)]\ddot{\vartheta}+(a_{i\vartheta}r_{i1}+a_{i\phi_2}L_i-a_{i\phi_1}r_{0i})\ddot{\phi}_{i1}+a_{i\phi_2}l_i\ddot{\phi}_{i2}-\\
&-\frac{1}{m_n}a_{i\phi_1}\sum_{k=1}^{n}(a_{k\phi_1}\ddot{\phi}_{k1}+a_{k\phi_2}\ddot{\phi}_{k2})\cos(\alpha_i-\alpha_k)+c_{\phi_1\phi_1}\phi_{i1}+c_{\phi_1\phi_2}\phi_{i2}=Q_{\phi_{i1}},\ i=\overline{1,n}, \qquad (1)\\
&a_{i\phi_2}\{[L_i-\frac{1}{m_n}\sum_{k=1}^{n}a_{k\vartheta}\cos(\alpha_i-\alpha_k)]\ddot{\vartheta}+l_i\ddot{\phi}_{i1}+r_i\ddot{\phi}_{i2}-\\
&-\frac{1}{m_n}\sum_{k=1}^{n}(a_{k\phi_1}\ddot{\phi}_{k1}+a_{k\phi_2}\ddot{\phi}_{k2})\cos(\alpha_i-\alpha_k)\}+c_{\phi_2\phi_1}\phi_{i1}+c_{\phi_2\phi_2}\phi_{i2}=Q_{\phi_{i2}},\ i=\overline{1,n}.
\end{aligned}
$$

where $m_n = m_0 + \sum_{i,j=1}^{n,2} m_{ij}$ the total mass of the DES F_n-structure; $a_{i\vartheta} = m_{i2}L_i + m_{i1}l_{0i}$, $a_{i\phi_1} = m_{i2}l_i + m_{i1}r_{i1}$, $a_{i\phi_2} = m_{i2}r_{i2}$; $L_i = r_{0i} + r_{i1} + r_{i2}$, $l_i = r_{i1} + r_{i2}$, $l_{0i} = r_{0i} + r_{i1}$; $c_{\phi_{ij}\phi_{ij}} = c_{ij}(B_{i1}, B_{i2})$, are the coefficients depending on the flexural rigidities B_{i1}, B_{i2} of the elastic elements of DES; $J_n = J_0 + \sum_{i=1}^{n}(m_{i2}L_i^2 + m_{i1}l_{0i}^2) - m_\Sigma r_{c_0}^2$ is the main axial moment of inertia of the "equivalent" rigid DES F_n-structure; $r_{c_0}^2 = m_n^{-2}\sum_{i,k=1}^{n} a_{i\vartheta}a_{k\vartheta}\cos(\alpha_i - \alpha_k)$ is the squared distance between the center of mass of the entire system and the center of mass of the main body.

The generalized forces in the right-hand sides of the equation system (1), which depend on the means of creating the control forces and on the form of perturbations, are determined by a well-known procedure. If the control moment $M(u)$ is lumped and applied to the main body, then in (1) we get $Q_\vartheta = M(u),\ Q_{\phi_{i1}} = Q_{\phi_{i2}} = 0$.

The angular deviation of the axes of the carrying body from the axes of the basic coordinate system (ϑ) is the main coordinate controlled to orientate the DES. If there is no need to control the form of DES surface in the course of the assembly, then the model (1), which describes not only the controlled coordinate ϑ, but also the coordinates of the form of surface $[\alpha_{ij}, r_{ij}, \phi_{ij}]$, is redundant. In this case, it is more convenient to describe dynamics of such elastic objects by the modal-physical model (MPM).

$$
\begin{aligned}
&\ddot{\bar{x}}_n = m_n(u);\quad \ddot{\tilde{x}}_{in} + \tilde{\omega}_{in}^2\tilde{x}_{in} = \tilde{k}_{in}m_n(u),\quad i=\overline{1,n},\ n\in(0,N);\\
&x_n = \bar{x}_n + \tilde{x}_n,\qquad \tilde{x}_n = \sum_{i=1}^{n}\tilde{x}_{in};\qquad m_n(u) = M(u)/I_n,
\end{aligned} \qquad (2)
$$

where $x \doteq \vartheta \in q$ is the controlled coordinate of the carrying body; $\bar{x}$ is the coordinate of the transfer (rigid) motion; $\tilde{x}$ is the additional motion of the carrying body due to the influence of the flexible elements; $\tilde{\omega}_{in}, \tilde{k}_{in}$ are the fundamental frequencies and the excitability coefficients of the elastic modes; n is the number of the flexible carried elements at the n-th stage of the assembly; N is the total number of attached elements; $M(u)$ is the control action; u is the control law (the input signal of the orientation system actuator device); $I_n = I_c(n)$ is the inertia moment of the construction at the n-th stage of the assembly, F_n, ($n = 0,1,2,\ldots,N$) defines MPM of the object at the n-th stage of its assembly in the orbit. Index $n = 0$ identifies the MPM of the carrying body:

$$F_0:\ \ddot{\bar{x}} = m_0(u),\quad m_0(u) = M(u)/I_0\,. \qquad (3)$$

At this stage, carrying body is set up, oriented and stabilized with the accuracy, which is need for the next assembly stages.

From system (2) we get the set of transfer functions:

$$W_n(\tilde{\lambda}_n, p) = \frac{L\{x\}}{L\{M(u)\}} = \frac{1}{J_n p^2} + \sum_{i=1}^{n}\frac{\tilde{k}_{in}}{p^2 + \tilde{\omega}_{in}^2}\,, \qquad (4)$$

where $n \in (0, N)$, $\tilde{\lambda}_n = \{\tilde{k}_{in}, \tilde{\omega}_{in}, J_n^{-1}\}$, $i = \overline{1,n}$.

3. APPARENT PROBLEMS OF LSS CONTROL IN THE COURSE OF ITS ASSEMBLY AND POSSIBLE WAYS AND MEANS TO OVERCOME THEM

Large space structure is the third and the main period of the DES existence.

Multiple problems of orientation control of the LSS's defined as time-invariable mechanical systems are discussed in numerous publications of which a hundred was analyzed in (Nurre et al., 1984). Nevertheless, the interest in this problem does not abate seemingly because of the lack of service-tested methods and algorithms to control this class of objects (Kirk, Ed.,1990, 1993, 1996, 1999, 2002, 2005; Woerkom,1993; Rutkovsky and Sukhanov, 1996; Rutkovsky et al., 2005a). At the same time, new problems involved in the in-orbit LSS assembly (Putz, 1999; Buyakas, 1990; Bekey, 1999; Glumov et al., 2005a) and the methods of control of the structure varying discretely in the course of assembly (Glumov et al., 2004; Frolov et al., 2000) are appearing. Their study is now at the initial stage and needs special attention because the in-orbit realization of the new class objects of the space technology, large space structures intended for various purposes, eventually depends namely on solution of these problems. The main difficulties arising at the design of the control systems for the objects like DES's are the same as in the case of LSS's and include the following.

(A) Problem of large model dimensionality growing with the developing structure. The arising difficulties of controller design are overcome by model reduction. However, the modes "lost" at that in model (2) are excited in the course of control and result in "over-control" and "excessive observations" (Nurre et al., 1984) not only causing lower precision but sometimes even loss of system stability (Woerkom,1993; Rutkovsky and Sukhanov, 1996). The requirements on the designed DES control system that are necessary to solve this problem lie in providing stability and control performance in the conditions of varying parameters and the form of the model itself, that is, in designing algorithms that meet the conditions for robust control of the object over its entire life time.

(B) Problem of poor definiteness of the LSS models due to the infeasibility of the ground-based testing of the completely assembled structure with the aim of specifying the model coefficients. Its solution is traditionally based on using various methods of identification (Nurre et al., 1984; Rutkovsky and Sukhanov, 1992; Banichuk, 1993; Kharchenkov and Shubin, 1998; Ermilova et al., 2004) and correcting the imprecisely defined parameters of the LSS model from the results of the in-orbit experiments. Using the experimental results of DES parameter identification at subsequent stages of DES development, it is possible to adjust the controller and thus realize one or another method of adaptive control (Nurre et al., 1984; Kabganian, and Shahravi, 2004; Dodds, 1999; Rutkovsky et al., 2005a; Frolov et al., 2000; Silaev and Sukhanov, 2002), which often makes the system robust (Rutkovsky et al., 2005b).

(C) Problem of insufficient information support of the LSS control system arises because of limitedness of the measurement complex traditionally used to control the spacecraft in the case of extremely high number of the degrees of LSS freedom, that is, high dimensionality of the vector of controllable coordinates. This contradiction provokes uncontrollable growth of some elastic components $\tilde{x}_i \in \tilde{x}$ and accounts for system instability (Nurre et al., 1984; Rutkovsky and Sukhanov, 1996). Possible ways out of this situation seem to lie in using one or another method of estimation of the nonmeasurable coordinates (Rutkovsky and Sukhanov, 1992; Banichuk, 1993; Kharchenkov and Shubin, 1998; Ermilova et al., 2004; Silaev and Sukhanov, 2002), facilities of intelligent diagnostics and prediction to compensate the informational inefficiency at control (Rutkovsky et al., 2005a; Rutkovsky et al., 2005b).

(D) A specific problem arising at design of the control system of a variable space structure lies in the need for stability and the desired control performance at all stages of assembly, that is, for the entire sequence of discretely varying DES models (Glumov et al., 2005a), provided that at all stages the same actuator devices are used. Although the study of this problem has just started (Frolov et al., 2000; Rutkovsky et al., 2003), nevertheless the advisability of using computer-aided methods of on-line derivation of the motion equations of the elastic object (Glumov et al., 2005) [26] with the aim of generating a sequence of DES models by means of on-board computers was already established. This approach simplifies control of DES orientation at in-orbit assembly.

One may assume that the aforementioned problems of controlling the in-orbit assembled LSS and the outlined approaches to them can lead to realization of a complicated controller meeting all requirements on stable and highly precise control of elastic space structures with the parameters and structure varying substantially in the course of operation. Unfortunately, it is insufficient to solve the problem at hand on the whole because the desired LSS's usually cannot be injected into orbit in the finally assembled form (Putz, 1999; Buyakas, 1990; Bekey, 1999) and their assembly in the outer space is the only acceptable variant. At that, depending on the type and destination of the assembled structure, one of the three existing methods of assembly can be used. In particular, the automatic docking-based block assembly (Frolov et al., 2000), which was successfully used for a long time for automatic approach and docking of two spacecraft, is suitable for the in-orbit assembly of a spacecraft meant for distant missions to the planets of the solar system. Minor assembly works in the immediate vicinity of the manned orbiting station can be done by the astronauts (Buyakas, 1990). Finally, the method of automatic assembly by the space free-flying robotic modules (Putz, 1999; Khang et al., 1976; Lampariello and Hirzinger, 2000) is advisable for step-by-step assembly of the large-scale grid structures meant for various purposes. This method of LSS assembly relieves the man of the dangerous work in the open space.

In this case the task of the choice of the LSS assembly sequence (trajectory of the assembly) is very important.

4. OPTIMAL TRAJECTORY OF IN-ORBIT ASSEMBLY OF THE DES

The problem of in-orbit assembly of DES is of current importance. However, as far as the present authors know, the problem of the optimal sequence of the in-orbit DES assembly was not developed either by Russian scientists or scientists from other countries or at the international symposia.

The distinctive feature of the DES as a complex dynamic plant permanently subjected to control lies in the multiplicity of its successively changing structural states defined by the models F_n each of which one can assign a certain F_n-structure with the parameters $\tilde{k}_{in}$ and $\tilde{\omega}_{in}^2$ ($i = \overline{1,n}$) depending both on the characteristics of the F_{n-1}-th DES models and on the type of the currently attached element and the point of its attachment. It is quite clear that the final goal of these operations (creation of the desired final LSS form) can be reached in various ways differing in the sequence of the assembly the set of elements. These physically realizable sequences of the DES assembly were called as trajectories (Glumov et al., 2005a).

We introduce $\mathrm{Tr}_k \in \mathrm{T}$ ($k = 1, 2, ..., \Upsilon$) as the k-th trajectory belonging to the trajectory set T. Since to each trajectory Tr_k corresponds a proper series of intermediate F_n-structures differing in their dynamic characteristics from the identical structures arising along other assembly trajectories, it is advisable to consider the problem of choice from the set $\mathrm{Tr}_k \in \mathrm{T}$ of an optimal trajectory meeting, for example, the criterion for minimal excitation of the elastic oscillations generated by the stabilization system of the DES angular position in the course of its assembly.

It is possible to indicate two causes of occurrence and growth of the DES elastic oscillations during its in-orbit assembly. First, the shock disturbances which act on the elastic structure at the instants of attaching the elements to the existing DES and may be taken into account in the dynamic as the initial conditions at the *n*-th stage of assembly. Second and the main, in the course of stabilizing the DES angular position at each life stage of the F_n-structure, the amplitude of elastic oscillations can grow under the action of the control pulses.

Owing to the need for highly reliable and efficient operation of the control system and the use of on-board computers, the problem of stabilizing the spacecraft axes is traditionally solved in the class of discrete systems with discontinuous controls. For flexible-structure objects, this kind of control amplifies the degree of perturbing action of the controller on the elastic oscillations, thus substantially complicating the task of the DES stabilizing (Rutkovsky and Sukhanov, 1996).

In Glumov et al. (2005a) it was obtained that the correlation

$$\sigma_k = \sum_{j=1}^{N(k)} \sum_{i=1}^{n} (\mu_i)_k^j \tag{5}$$

can be considered as the integral characteristic (criterion) of the controller impact on the DES elastic oscillations. Here $N(k)$ is the total number on controller switching on the k-th assembly trajectory, $(\mu_i)_n^j$ is the maximum increment of the amplitude of the *i*-th elastic mode which is possible at the given *j*-th switching of the controller for the *n*-th number of the assembly stage.

By comparing estimates (5) for different sequences of the models of F_n-structures, one can extract the trajectory $\mathrm{Tr}_{\mathrm{opt}\,\sigma}$ such that for it the condition $\sigma_{k\,\mathrm{opt}} = \min$ is met, which defines the optimal sequence of the DES assembly.

Another criterion suitable for the design of the optimal DES assembly trajectory is represented by the size of the MPM kernel (Glumov et al., 2005a) of the DES F_n-structure that defines the least possible number of accountable modes of elastic oscillations of the multifrequency object.

This criterion enables one to specify a sequence with the minimum total number of modes involved in generation of the models F_n which makes it possible to use simpler algorithms of the DES stabilization on the set of assembly stages.

One may use (Glumov et al., 2005a)

$$R_k = \sum_{n=1}^{N} (r_n)_k \tag{6}$$

as the minimized function defining the total number of elastic modes in the kernels of models of all F_n-structures on one or another DES assembly trajectory. Here $(r_n)_\nu$ is the number of essential elastic modes at *n*-th stage of the object assembly.

It is clear that the smaller R_k, the lower sizes of individual models F_n and, consequently, the simpler control of the developing DES. Therefore, solution of the problem

$$[R = R_k] \to R_{\min} \tag{7}$$

based on the computer-aided comparison of the set of sequences of the F_n-structure MPM's allows one to determine the corresponding trajectory which is optimal $\mathrm{Tr}_{\mathrm{opt}\,R}$ in the above sense.

The proposed one-criterion approaches to choosing the optimal assembly trajectory by minimizing functions (5) or (6) can be contradictory because of the difficulty of meeting the consistency condition $\mathrm{Tr}_{\mathrm{opt}\,\sigma} \equiv \mathrm{Tr}_{\mathrm{opt}\,R}$ for two optimal trajectories. To resolve the contradiction, one may employ the methods of vector optimization using by way of the objective function the expression

$$I_k = c_R R_k + c_\sigma \sigma_k , \tag{8}$$

where c_R and c_σ are the weight preference coefficients for the criteria (5) and (6).

Analytical solution of the task about assembly optimal trajectory is not obtained because of complexity of its mathematical description. So for solving this task it was suggested computer method.

For the assembly trajectory to be perceptive by the computer aided design system as a suitable object, it is required to formalize the notion of the assembly trajectory. To define this notion in the computer terms, it is convenient to use matrices in the computer procedures.

Toward this end we assign the (2×*n*) matrix S_k to some k-th assembly trajectory. According to the chosen assembly sequence, the first row of the matrix indicates the numbers $p = \overline{1, p_k}$ coinciding with those of the points number of attachment of the branch base to the DES carrying body.

Under the entries of the first row, the second row shows the numbers $l = \overline{1, l_m}$ of the frame levels to which the attached elements belong. The so-constructed matrix S_k is called the assembly trajectory matrix.

To explain the introduced matrix, we return to the framed structure of the hypothetical DES (Fig. 2).

The notations like $p^l \to n$ at the named (p^l) attaching elements indicate the ordinal number (*n*) of attaching the p^l-th element to the already assembled part of the DES.

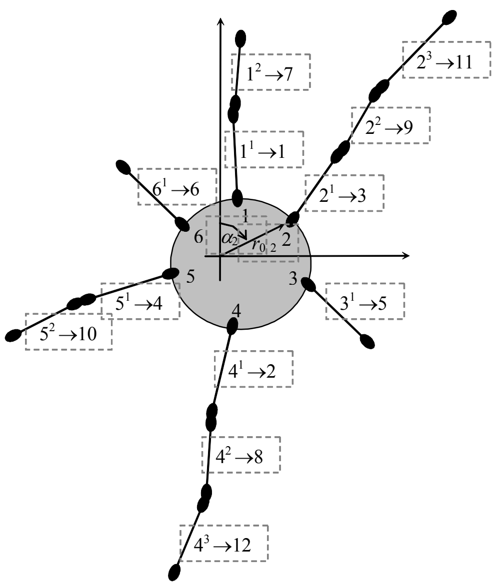

Fig. 2. Scheme of the DES assembly

For example, "$1^2 \to 7$" suggests that an element of the second level of the first "branch" of the DES frame is installed at its place at the seventh assembly stage. Analyses of the entire totality of the explanatory tables enables one to specify the DES assembly sequence realized in the example and set it down informally as $0 \to^1 1^1 \to^2 4^1 \to^3 2^1 \to^4 5^1 \to^5 3^1 \to^6 \ldots \to^{12} 4^3$. A formalized representation by the matrix S_v that corresponds to the given assembly trajectory is as follows:

$$S_v = \begin{pmatrix} 0 & 1 & 4 & 2 & 5 & 3 & 6 & 1 & 4 & 2 & 5 & 2 & 4 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 & 2 & 2 & 2 & 2 & 3 & 3 \end{pmatrix}.$$

The first column of the matrix corresponds to the stage of injecting to the given point the DES carrying body.

The task of generating the set of DES assembly trajectories having the desired frame structure comes to calculating the set of matrices $S = \{S_k\}$ ($k = \overline{1, \Upsilon}$), where Υ is the total number of feasible assembly trajectories.

5. USING THE "PORTRAIT" OF THE STRUCTURE DYNAMICS FOR ANALYSIS AND DESIGN OF THE DINAMIC CHARACTERISTICS OF DES AS THE OBJECT OF CONTROL

For design of the control systems of complex objects, an important part is played by the choice of constructive parameters of the controlled object with regard for the possibility of subsequent use of the simplest control algorithms (Kulebakin, 1955). As applied to the objects like DES's, this idea of V.S. Kulebakin can be rather easily realized by the method of constructing on the basis of the modal-physical model (2) the portrait of the object structure dynamics (Rutkovsky et al., 1996) which reflects numerous characteristics of the elastic object dynamics and allows one to make well-grounded decisions for the orientation control system design. The "portrait" also enables one to optimize the parameters of all $F_n, n = \overline{1, N}$, structures with the aim of improving its dynamic characteristics already at the early stage of spacecraft design. For the methods of solving this problem, determination of the optimality criteria, and some results of using the proposed approach the reader is referred to (Rutkovsky and Sukhanov, 1997; Rutkovsky et al., 1997).

As was shown in Rutkovsky et al. (1996), being certain functions of the object physical parameters $\Lambda = (\lambda_c, \lambda_v)$ part of which (λ_c) is regarded as constant and the other part (λ_v) can be varied to a certain extent, the coefficients of the DES Lagrangian equations allow one to determine the dependences of the coefficients of MPM (2) on the parameters λ_v: $\tilde{\omega}_{in} = \tilde{\omega}_{in}(\lambda_v)$, $\tilde{k}_{in} = \tilde{k}_{in}(\lambda_v)$. Together with the vector μ which depends on the coefficients $\tilde{\omega}_{in}$ and $\tilde{k}_{in}$ and has elements that are essentially the unit degrees of excitability [32] $\mu_{in} = \tilde{k}_{in}\omega_{in}^{-2}$, the totality of these characteristics defining the dynamics of the structure of an elastic object was called in Rutkovsky et al. (1996) as the "portrait" of DES structure dynamics:

$$\tilde{\omega}_{in} = \tilde{\omega}_{in}(\lambda_v),\ \tilde{k}_{in} = \tilde{k}_{in}(\lambda_v),\ \mu_{in} = \mu_{in}(\lambda_v),\ i = \overline{1, n};\ n = \overline{1, N}. \quad (9)$$

Now, the problem of studying the dynamics of the DES structure can be formulated as that of analysis of behavior of the coefficients (9) of MPM (2) in the space of permissible variations of the parameters λ_v. The "portrait" of structure dynamics constructed by computer-aided methods plays an important role in improving the characteristics of DES as the controlled object. In particular, analysis of the "portrait" can reveal latent useful features of the elastic multi-frequency object that can be realized by permissible variations of the parameter λ_v.

For example, the zeros of the functions $\tilde{k}_{in}(\lambda_v) = 0$ indicate on the important fact that at these points of the structure parameter space the external forces exert no disturbing action on the corresponding elastic modes. Analysis of the mutual position of the graphs of the functions $\mu_{in}(\lambda_v)$ allows one to identify the domains where the higher modes are more excitable than the lower ones. Existence of such modes prevents model reduction just by simple rejection of some higher modes. At analysis of "portrait" (9), these domains are identified by the intersection points of the graphs $\mu_{jn}(\lambda_v) = \mu_{kn}(\lambda_v)$. Assuming that the contribution of the *i*-th mode to the total component of the elastic motion $\tilde{x}(t)$ is defined by the excitability degree μ_i of this mode, then the elastic modes can be ranked in terms of the index μ_i. Indeed, any mode $\tilde{x}_{in}(t)$ whose excitability degree satisfies some established smallness condition ($\mu_{in}\mu_{dn}^{-1} \le \varepsilon_{\mu n}$) as compared with the dominant mode $\tilde{x}_{dn}$ having $\mu_{dn} = \max$ can be regarded as inessential for DES dynamics. This enables substantiated reduction of the elastic object model and identification of the MPM kernel comprising the equation of the "rigid" DES motion and a finite set of equations of the elastic modes remaining after elimination of the inessential group of modes that are regarded as the residue of the MPM.

In the general case, decomposition, of the original high-order model into a simplified (suitable for designing the control system) and full (for test checks) models is an exceptionally important task for the objects like DES's. A vast literature devoted to it was analyzed in Nurre et al. (1984). Determination of the decomposition criterion presents a special difficulty. In this sense, the method of analysis of the "portrait" of structure dynamics (Rutkovsky et al., 1996) offers one of the possible criteria for reduction of the DES model.

6. ADAPTIVE ATTITUDE CONTROL OF THE DES

As mentioned above the DES has three periods (or phases) of its existence. The simplest period for the control is the first one when the DES is the rigid carrying body. There are many papers and books in which the problem of control of rigid spacecrafts is considered. At the present time two qualitatively different groups of the control algorithms are well known.

The first one is the relay control law $u_0(x,t)$ (base algorithm) with hysteresis and dead zone. There are many types of such algorithms (Raushenbakh, and Tokar, 1974). One of them is relay-logical algorithm (Rutkovsky and Sukhanov 2007):

$$u_0(x,t)=\begin{cases} +m_\varepsilon \forall |x|<\varepsilon \vee t<t_0; \\ -m_u \forall x \geq \varepsilon \vee t\in[t_0,t_1),\ \varphi(t_1)=\varepsilon-\gamma, t_1-t_0=\tau_1; \\ +m_u \forall x\leq \varepsilon-\gamma \vee t\in[t_1,t_2), t_2-t_1=\tau_2=k_t\tau_1,\ k_t<1; \\ +m_\varepsilon \forall |x|<\varepsilon-\gamma \vee t\geq t_2. \end{cases} \quad (10)$$

Here m_u and m_ε are two levels of relay control action.

Their values are chosen according to the requirements to the control system; ε, γ are the dead zone and hysteresis of the relay link; k_t is the coefficient of reversing.

It defines the time interval of reverse control action that is applied to the carrying body after the completion of the "right" control action. Stable limit cycle that is realized by base algorithm (10) is shown in Fig. 3, where $\tau_\Gamma=\tau_a+\tau_\varepsilon$ is the limit cycle period, $\tau_a=\tau_1+\tau_2$, $\tau_1,\tau_2,\tau_\varepsilon$ are the time intervals, when $m(u)$ is equal $-m_u, m_u, m_\varepsilon$ respectively. This cycle should be in compliance with the requirements to the accuracy ($|\bar{x}|\leq \bar{x}_{\max}$) and economics ($\chi=\tau_a/\tau_\Gamma\leq\chi^*$) of the control, $\bar{x}_{\max}$ and χ^* are desired indexes of the control quality. This limit cycle Γ is chosen as a reference motion. Other attitude motions throughout the lifetime of the DES are to tend to this one and elastic oscillation component $\tilde{x}$ must be small. The discrete analogies of the PD algorithms form the second group of the carrying body control algorithms:

$$u_0(t_k)=-k_0[k_1\hat{x}(t_k)+k_2\Delta\hat{x}(t_k)],\quad k=0,1,2,... \quad (11)$$

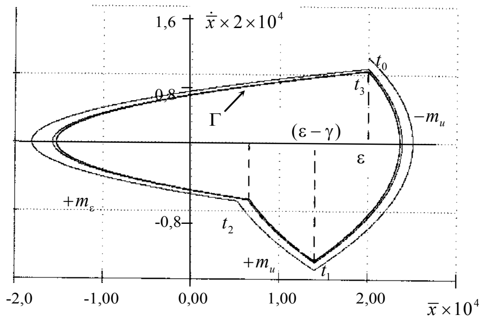

Fig. 3. Stable limit cycle of the DES for condition of the rigid body

In (11) k_0,k_1,k_2 are constant coefficients of the first period of the DES existence. Coordinate $\hat{x}(t_k)$ is the estimation of the measured one $x(t_k)$. For calculation of this estimation it is used s values of the coordinate $x(t_k),\ t_k=\overline{1,s}$, during the discreteness period T_0 of the control action. The value $\Delta\hat{x}(t_k)$ is calculated as the first difference of the coordinate $\hat{x}(t_k)$. As the system is discrete the control action $m(u)$ is discontinuous and it is constant during the discreteness period T_0. It is necessary to stress that in both cases as the stationary process is auto-oscillations.

After attaching of the first element and the following ones to the carrying body the DES transforms into flexible structure or flexible spacecraft. In this case control actions that correspond to any control algorithm including (10) and (11) lead to appearance of the object elastic oscillations. These oscillations deform limit cycle Γ and decrease the orientation accuracy. Without control strategy change the oscillations can lead to instability of the system motion.

Other control problem is the increase of the inertia moment in the course of the object assembly. This fact at constant level of the control actions leads to the control effectiveness decrease and of the dynamic error increase. And at last the main problem in the DES control system design is the increase of the model (2) order in the process of the object assembly. This is followed by step-like variations of the model (2) coefficients and decrease of the lower boundary of the elastic oscillations frequencies spectrum. And it should be particularly emphasized that the parameters of all elastic modes (frequencies and coefficients of excitability) are changed at each new stage of the object assembly.

An inaccuracy of the assignment in advance of the object construction parameters and the values of the elastic modes parameters together with aforementioned problems require to have the control strategy as an using adaptive one.

Because of this for the second and the third periods of the DES life-time it was suggested three types of the adaptive control strategies, namely, tuning of the base algorithm:
1) using intelligent diagnostics of the elastic modes condition (Rutkovsky and Sukhanov 2007; Glumov et al., 2007),
2) using the idea of phase control (Rutkovsky et al., 2007; Rutkovsky and Sukhanov, 1973),
3) idea of fuzzy logic (Glumov et al., 2004).

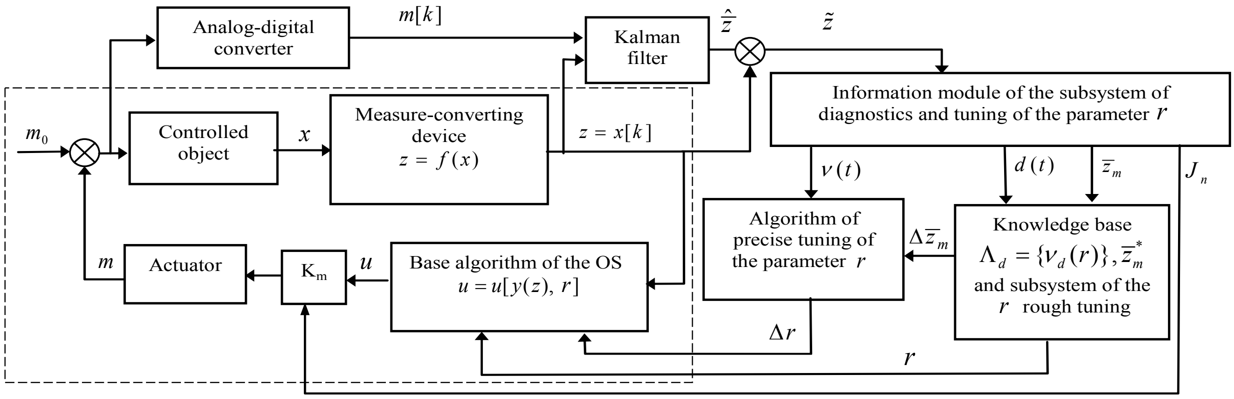

Fig. 5. Block diagram of the adaptive control system

The use of one or other strategy depends on the concrete construction of the object, its dimensions, dimensions of the at-
Let us consider the first strategy. Intensity of the elastic oscillations that is defined essentially by the dominant mode $\tilde{x}_d$ (other modes are usually much less then $\tilde{x}_d$) can be as a signal of the control system functioning quality. This signal is used for the diagnostics of the system and for tuning of the base algorithm $u_0(x,\dot{x},r)$ parameter *r*. The influence of the base algorithm on the character of the component motion $\tilde{x}$ can be evaluated by quasi-envelope $\rho(t,r) = \mathrm{Env}[\tilde{x}(u(\bullet,r),t)]$ of the transient process $\tilde{x}(t) = \tilde{x}_d(t) + \sum \tilde{x}_i(t)\big|_{i \neq d}$ (Glumov et al., 2007). This envelope after two-stage approximation can be represented by the exponential curve $\rho_d(t,\nu_d(r)) \approx ae^{\nu_d(r)t}$. The value $|\nu_d(r)|$ defines the rate of the component $\tilde{x}_d$ amplitude varying. The sign $\nu_d(r)$ defines the type of the dominant mode $\tilde{x}_d$ (convergent, divergent, with constant amplitude). Thus for any fixed value $r_* \in [r_{\min}, r_{\max}]$ where $[r_{\min}, r_{\max}]$ is the range of the parameter r admissible values the regulator influence on the component $\tilde{x}(t)$ can be defined by the single number $\nu_* = \nu(r_*)$. Varying parameter r and calculating the index $\nu(r)$ it is possible to get "influence function" $\nu_d = \nu_d(r)$. Each such function for *d* = *i*, $i = \overline{1,n}$, has many local extreme and global minimum, see Fig. 4.

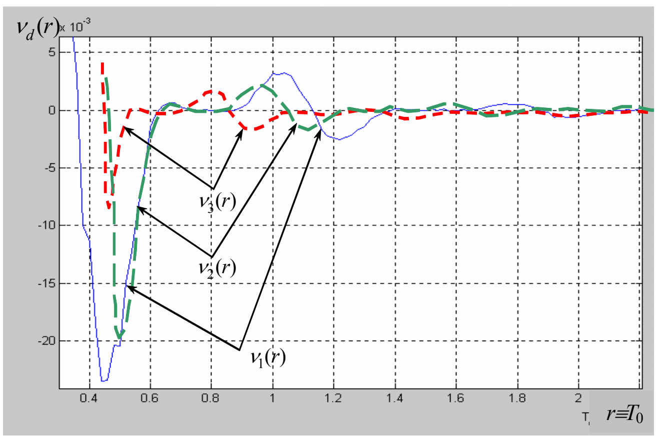

Fig. 4. Functions of basic control on elastic oscillations

tached elements, their parameters and so on.

Totality of the influence functions $\Upsilon_d = \{\nu_d(r)\}$, $(d \in i = \overline{1,n})$ is used for diagnostics of the component $\tilde{x}(t)$ current condition and for following base algorithm adaptive correction with the goal of the component $\tilde{x}(t)$ amplitude decreasing (if it is close with the critical value). In order to have high effective control of the DES at every stage of the assembly it is necessary to solve on-line three tasks (if $\nu(r) > 0$): 1) to determine the number *d* of the dominant mode using the identified frequency ω_d, $d \in i = \overline{1,n}$; 2) using the number *d* it is required to determine new value $r_1 \in [r_{1\min}, r_{1\max}]$ under which $\nu(r_1) < 0$; 3) usually designed influence functions $\nu_d(r)$ do not coincide with actual functions $\hat{\nu}_d(r)$.
Therefore it is required to seek additionally a point $r_2 \in [r_{1\min}, r_{1\max}]$, where $\hat{\nu}_d(r_2)$ =min min, which provides maximal speed of the dominant mode $\tilde{x}_d$ damping.

A solution of these tasks [35] realizes the procedure of the base algorithm tuning. It is significant that damping of the dominant mode is achieved without an additional consumption of the energy for control. Block scheme of the control system is shown in Fig. 5. It has the base loop and the loops of the elastic component $\tilde{x}$ diagnostics and tuning rough and precise of the base algorithm parameter *r*. Here the coefficient $K_m(n)$ is varied according to the information about the moment of inertia I_n. It solves the task to have constant value of the control effectiveness at all stages of the assembly.

Information module of the subsystem of the base algorithm rough tuning using the set Z_m produces the signal $\nu(r)$ on the basis of the method of quasi-envelope $\rho(t) \approx ae^{\nu(r)t}$ calculation. The device of the dominant mode frequency identification uses the set Z_m also. The set Z_m consists of the maximal values $z_m[l]$ that are the amplitudes at $k = l$ of the rectified signal $z_a[k]$. In addition to the set Z_m the one $T_m = \{t_m[l]\}$ is used in the last device. In the regime of dominant mode the differences $\Delta t_m[j] = \{t_m[l] - t_m[l-1]\} \approx 0{,}5\tilde{\tau}_{jd}$ between two adjacent elements of the set T_m that have maximal amplitudes coincide with the half-period $0{,}5\tilde{\tau}_{jd}$ of the oscillating component. After average operation: $\tilde{\tau}_d = 2(L-1)^{-1}\sum_{j=1}^{L-1}\Delta t_m[j]$, ($L = \dim T_m$) with the help of formula $\omega_d = 2\pi\tilde{\tau}_d^{-1}$ the frequency of the dominant mode can be calculated. For identification of the dominant mode number d the differences $\Delta\omega_i = \left|\omega_i - \omega_d\right|_{(i=\overline{1,n})}$ are considered. It is accepted $d = i$ from the condition $\Delta\omega_i = \left|\omega_i - \omega_d\right| = \min_i$.

The information module outputs ν, d and average value $\bar{z}_m$ of the set Z_m elements are the inputs of the subsystem of the parameter r rough tuning. The value $\bar{z}_m^*$ is the admissible level of the vibrating process intensity.
For the parameter r tuning it is required to take from the totality $\Lambda_d = \{\nu_d(r)\}$ the influence function $\nu_d(r)$ corresponding to the determined number d and employ it to the supply the varied parameter r with a new value r_1 for which $\nu_d(r_1) = \min < 0$. This allows to reduce the amplitude of the dominant mode at the subsequent intervals of active control ($m(u) \neq 0$).

To eliminate the inaccuracy of the parameter r rough tuning the contour of precise tuning is introduced into the system. The aim of this contour lies in determining a value $r_2 \doteq r_{\mathrm{opt}}$ such that it ensures $\hat{\nu}_d(r_2) = \min\min < 0$. In this case we will have the maximum possible speed of damping the dominant mode. The process of precise tuning can be realized by search algorithms in the class of extremal control [38].
By the action of the new control $m[u(\bullet, r_2)]$ dominant mode is damped by optimal way. But if one of the other elastic modes begins to diverge then from the certain moment it will be as the dominant one and the process of the parameter r tuning must be repeated. Hence if it is not possible to choose the constant values of the base algorithm parameters which guarantee convergence of all elastic modes the process of the algorithm tuning will be recurred during the whole active lifetime of the DES. The adaptive control system of a LSS was reproduced in the MATLAB 6.5-Simulink system. The LSS obeying the model (2) at n = 6 with discrete analog of the PD algorithm (15) was considered as the controlled object. The discreteness period $T_0 \doteq r$ was used as the tuning parameter. For the considered object it was not possible to choose the value T_0 in its admissible range ($T_{\min} \le T_0 \le T_{\max}$) at which all six elastic modes would be stable. One from three first modes (d = 1, 2, 3) diverges at any value of $T_{\min} \le T_0 \le T_{\max}$ but others (d = 4, 5, 6) converge. On simulation the parameters of the elastic modes were set up with errors (20 % with respect to their nominal values). The period of the limit cycle was ≈150 s, $T_{00} = T_0(t_0) = 1{,}0\,s$. Some results of simulation are shown in Fig. 6.

2. As the strategy of the DES control can be used also the one that was suggested in [37, 39]. In this type of control it is used the estimations of the dominant mode phases β in the instants t_j of the control action switching.

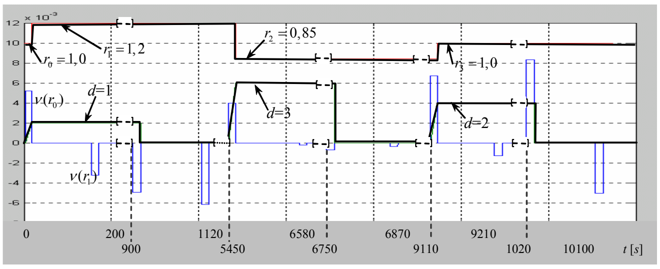

Fig. 6. Stabilization dynamics as estimated from the output of the information unit.

The time-delay τ_β for control action switching is introduced until the instant $t_j^* = t_j + \tau_\beta$ when the aforementioned phase will be as optimal. This time-delay can be introduced only in a part of switching points of the limit cycle.

Optimal phase β_j is the phase at which the dominant mode's amplitude after the switching will be the smallest from all possible ones. It depends on the direction of the control action switching. The optimal phase is defined as follows [39]:

$$\beta_j = \begin{cases} 2\pi k & \forall\ \mathrm{sign}\,\dot{m}_j = +1, \\ \pi(2k+1) & \forall\ \mathrm{sign}\,\dot{m}_j = -1, \quad k = 0,1,2,\ldots \end{cases} \tag{12}$$

For example the minimum value of the time-delay τ_β in the switching point that is characterized by the condition $x(t_0) = \varepsilon$, $\mathrm{sign}\,\dot{m}(t_0) = -1$ (ε is the dead zone) will be as follows:

$$\tau_\beta = \begin{cases} [\pi - \beta_d(t_0)]\tilde{\omega}_d^{-1}\ \forall\ 0 \le \beta_{d0} \le \pi, \\ [3\pi - \beta_d(t_0)]\tilde{\omega}_d^{-1}\ \forall\ \pi < \beta_{d0} \le 2\pi, \end{cases} \tag{13}$$

where $\beta_{d0} = \beta_d(t_0)$ is the dominant mode phase at the instant when $x(t_0) = \varepsilon$.

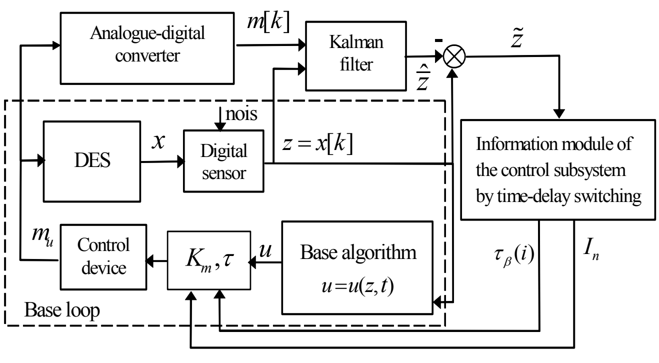

Fig. 7. Block-scheme of control system with estimation of the dominant mode phase

In [39] it was shown that for the system movement stability optimal phase of switching must be at least at the one-half of the switching points that occur at each period of the limit cycle. Block scheme of such type control system is shown in Fig. 7. The main loop of the control system is depicted by a dot line. This loop includes an additional link with two tuning

parameters K_m, τ. The first parameter K_m is the tuning amplification coefficient that is needed for the maintenance of the constant level of the control action $m_u = M_u K_m I_n^{-1}$ of the assembled object with the variable mass-inertia properties.
The second tuning coefficient τ implements the control by the time-delay of the control action, which switches with respect to the base algorithm requirements. The estimation of current phase of the dominant mode is obtained with the help of Kalman filter [22].

The example of computer simulation of the suggested system for the 6-th stage of the object assembly is shown in Fig. 8. As the object corresponding to equations (2) at $n = 6$ it was chosen the large space structure with the inertia moment $I_n = 10^4 kg \cdot m^2$. Other parameters are given in the table.

Table 1. Some parameters of the LSS

$i = \overline{1,6}$	1	2	3	4	5	6
$\tilde{f}_i = \tilde{\omega}_i / 2\pi$	0,07	0,1	0,15	0,5	2,8	5,2
$\tilde{k}_i$	0,17	0,03	0,015	0,01	0,004	0,002
$\tilde{x}_i(0)$	5×10^{-4}	$1{,}5\times10^{-4}$	10^{-4}	10^{-5}	5×10^{-5}	3×10^{-5}

As the dominant mode at the initial moment of control was $\tilde{x}_1$. This mode is subjected to the control action influence the most strongly because of its degree of excitability $\mu_1^{(1)} = \tilde{k}_1 \tilde{\omega}_1^{-2} = 0,88$ is the most high.

At the initial interval of the simulation ($t \le t_1 = 220c$) the loop of time-delay of the control action switching was not operated. In this case the control action $m(u_0)$ causes the increase of the elastic mode amplitude to the value $\tilde{A}_d \approx 1,2 \cdot 10^{-3}\, rad$ that is close to the critical one.

In order to prevent the capture of the regulator by elastic oscillations and instability of the system movement at $t_1 = 220c$ the algorithm with time-delay for control action switching $u(\bullet,\ \beta)$ was applied. The intervals of the time-delay are shaded (see oscillogram 2). As the result the dominant mode amplitude was decreased very quickly.

3. The third strategy is based on the idea of fuzzy logic [40].

In [17] the DES adaptive control system with control law (15) and the tuning parameter $r \doteq T_0$ was considered again. It was introduced for each stage of the DES assembly n, $n = \overline{1,N}$, state diagram where the horizontal axis of the base algorithm tuning parameter r is decomposed into the domains $L_{in}^-, L_{in}^+, L_{in}^0, i = \overline{1,n}$, corresponding to stable ($\tilde{x}_{in}^-$), unstable ($\tilde{x}_{in}^+$) and neutral ($\tilde{x}_{in}^0$) behavior of the isolated ($\tilde{x}_{jn}(t) = 0$ at $j \ne i$) mode $\tilde{x}_{in}(t)$. The mode $\tilde{x}_{in}(t)$ is characterized by the parameter $\tilde{\omega}_{in}$ indicated on the vertical axis of the diagram. At this $\tilde{x}_{in}(t) \in \tilde{x}_{in}^-$, provided that its envelope $\rho_{in}(r,t)$ is a decreasing function, $\tilde{x}_{in}(t) \in \tilde{x}_{in}^+$ provided that $\rho_{in}(r,t)$ is an increasing function. And finally, $\tilde{x}_{in}(t) \in \tilde{x}_{in}^0$ provided that $\rho_{in}(r,t)$ is a weakly time-varying function.

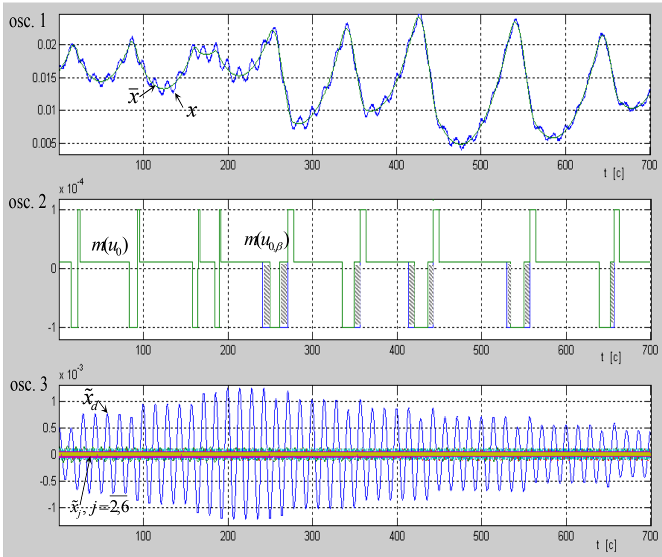

Fig. 8. Processes in a regime of stabilization

State diagrams for isolated modes differ from the real diagrams because of we do not know the object's parameters with the high accuracy and we can not take into account all elastic modes. As a result it is not possible to use directly aforementioned state diagrams for tuning parameter $r \doteq T_0$ and it is appropriate to use these diagrams in combination with the results of the fuzzy logic theory.

According to [17], for given initial values of $T_0 = T_{00}$, the discrete system of control by the parameter T_0 is represent able by a fuzzy model with input ΔT and outputs $\nu_{nk}(t)$ and $y_{nk}(t)$, where $\nu_{nk}(t)$ and $y_{nk}(t)$ define the envelope of the process $\tilde{x}_n(t)$ and the local speed of its variation in time. It was introduce the linguistic variables ΔT, V, Y, and TO that correspond to the aforementioned variables and are defined by the intervals where the particular values of the initial variables lie. It is further assumed that the linguistic variables ΔT, V. Y, and TO can have values defined by the term-set like Q_W = {*NB, NM, NS, ZE, PS, PM, PB*}, where N stands for the negative values, P for positive values, B, M, and S stand for large, medium, and small values, respectively, ZE defines the zero value, and W is a linguistic variable which can be any of the variables T, V, Y, or TO.

Now the fuzzy model of the adaptation algorithm can be represented by the following fuzzy functions [40]:

$$F_R : Q_V \times Q_{\Delta T} \to R_A, \quad F_T : \nu_{nk} \times R_A \to T_0,$$

where the function F_R defines the dependence of the elements of the set of fuzzy rules of the adaptation algorithm R_A on the linguistic variables $V \in Q_V$ and $\Delta T \in Q_{\Delta T}$, the function F_T determines the neat output coordinate of the algorithm of adaptation of T_0 using the neat value of the output variable of the system v_{nk} and the corresponding fuzzy rules from the set R_A.

The task of designing the adaptation algorithm lies in determining the fuzzy functions that must correspond to characteristics of the T_0 tuning loop defined in the general case by the fuzzy functions

$$f_y : Q_{TO} \to Q_Y,\ f_v : Q_{TO} \to Q_V.$$

For the system under study, the fuzzy function f_y corresponds to a sequence of smoothed envelopes of the processes of variation of the flexible component $\tilde{y}_n(t), n = \overline{1, N}$, containing the flexible modes $\tilde{x}_{in}(t), i = \overline{1, n}$. The fuzzy function f_v corresponds to the set of characteristics $v_{in}(T_0)$ for all modes.

To solve the problem of designing the algorithm of adaptation of T_0, one needs to determine a set of rules R_A realizing the desired functions, provided that the processes $\tilde{y}_n(t), n = \overline{1, N}$, damp so fast that at the end of each assembly stage $Y \in PS$. The condition $V \in (NM, NB)$ should be satisfied at that.

In [17] it was obtained fuzzy rules for the procedure of the parameter T_0 tuning.

Operation of the fuzzy adaptation algorithm was studied by digital simulation using the model (2) of the DES for $N = 8$ with the base control algorithm (15) and the adaptation algorithm R_A (see [17]). Digital simulation corroborated the high effectiveness of suggested control system.

9. CONCLUSIONS

The large space structures assembling in orbit are the objects of the immediate future. At the present time the control theory of such kind objects is poorly developed. In this paper some new problems of this theory are formulated and certain of them are discussed. They are graph-models of feasible assembly trajectory and object's dynamics, optimal assembly trajectory. Three strategies of adaptive control were suggested. But of course these results are only the first steps or infancy in the control theory by large space structures.

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