Movement control of nonrigid mechanical systems with a changing vector of parameters and number of freedom degrees

V.Yu. Rutkovsky, V.M. Sukhanov, V.M. Glumov

Abstract. The paper discusses the peculiarities of the controlled movement dynamics of flexible mechanical systems with time-varying number of freedom degrees. The strategies sequence of such kind nonstationary objects control is stated. These strategies guarantee the high accuracy of the control and damping of the elastic oscillations. Block schemes of the control system are suggested that realize these control strategies at different stages of the object.

I. INTRODUCTION AND STATEMENT OF A TASK[1]

Many different types of moving mechanical objects that clearly exhibit the properties of flexible multi-frequency oscillating systems with discretely time-varying number of freedom degrees are well known. Typical examples of such mechanical systems (MS) are the orbit-assembled large space structures (LSS) [1]. Space and underwater robotic modules that change their structure during the operation and have long flexible manipulator links or flexible payloads can be considered as such kind objects. Similar dynamics exhibit exotic multistory buildings that are constructed on moving basement with active stability systems [2]. These objects are created in earthquake-prone zones.

A principal feature of such MS is a rigid carrier body (main body) and attached to it throughout the assembly some flexible elements (carried bodies).

Such construction makes it possible to solve the control problems of discretely evolving structure (DES) with the use of equations that are shaped as a sequence of model-physical models (MPM) [3]

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

where $x^{\Sigma} \doteq \vartheta \in q$ is the controlled coordinate of the carrier body; $\bar{x}$ is the coordinate of the transfer (rigid) motion; $\tilde{x}$ is the additional motion of the carrier 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, $\mathfrak{M}_n$, ($n = 0,1,2,...,N$) defines MPM of the object at the n-th stage of its assembly in the orbit. Index $n = 0$ identifies the MPM of the carrier body:

$$\mathfrak{M}_0: \quad \ddot{\bar{x}} = m_0(u), \quad m_0(u) = M(u)/I_0. \tag{2}$$

At this stage, carrier body is set up, oriented and stabilized with the accuracy, which is need for the next assembly stages. With increasing the value of n, the model (1) becomes more complicated since the number of freedom degrees and the inertia moment also increase. According to the general Rayleigh's theorem, an increment of the inertia moment leads to decreased frequencies $\tilde{\omega}_i$. They close with the frequency of the "rigid" controlled motion. It is well known that, as a result, a quality control becomes problematic and motion instability may arise. This instability can be caused by the "capture" of the regulator by elastic oscillations.

At $n = N$ equations (1) defines completely assembled construction.

The above discussion suggests that, when designing the control system, the following three qualitatively different types of the controlled object condition should be distinguished.

1. The initial type ($n = 0$) involves the carrier body orientation with respect to the required direction and its stabilization with accuracy that is necessary for the further assembly.
2. Once the first construction flexible element ($n = 1$) and some other flexible elements ($n \le n^*$) are attached to the assembled object that begins exhibit the properties of a flexible MS, which is characterized by the presence of one or several comparatively high-frequency (~1÷10 Hz) vibration modes.
3. As the number of the flexible elements increases ($n^* < n \le N$), the assembled construction turns into a hard-to-control system. Such system is distinguished by a big inertia moment of the attached bodies and low elastic modes frequencies (< 0,1 Hz). These frequencies close with the fundamental frequency of the "rigid" motion of the object.

In the paper the following tasks are solved:

– the transformation of dynamical properties of a discretely evolving structure that is being changed in accordance with prescribed construction assembly sequence;

– determination of the transformation boundaries Between the boundaries the assembled construction retains the properties that correspond to one of three aforementioned types of the system condition: a) rigid body, b) flexible object with insignificantly affected system dynamics of the construction elastic oscillations, c) flexible multi-frequency construction that requires an extension of the observation

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vector, so that the desired controlled dynamics can be achieved;
– the control system design of discretely evolving flexible object with the use of the sequence of algorithms that correspond to the object condition and implement a stable control of the main body with regards to elastic oscillations and provide a high accuracy on all stages of the assembly.

II. TRANSFORMATION OF THE DES DYNAMICAL PROPERTIES

For brevity as the control object it will be considered the construction of "umbrella" type [3] that is shown in Fig. 1. This construction is suitable for describing such objects as

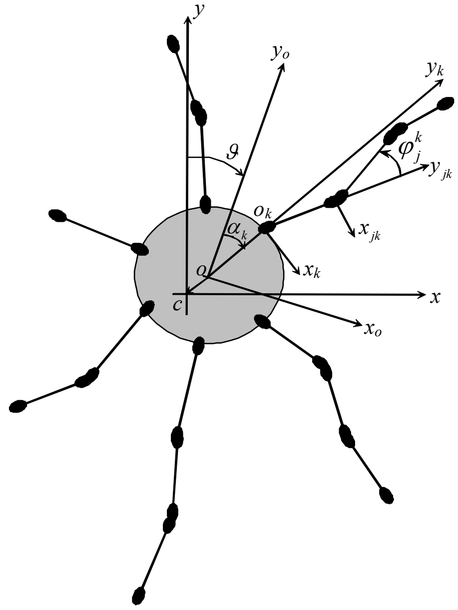

Fig.1.Current structure of the DES.

the big space radio-telescopes and space solar-reflectors [1,2]. As the MS it is the totality of rigid bodies one of them is the carrier body (m_0, I_0). Others (carried bodies, m_j, I_j) are the elements that are attached to the carrier body in one or another order. At the attaching points of the elements there are the springs that imitate the flexibility of the carried bodies and restrict their displacements. Further plane-parallel motion of all bodies is considered.

For definiteness the regular structure is considered (for example big compound reflector [1]). Radially (Fig. 1) K chains are attached to the carrier body at the points o_k (α_k, $r_0^k = \overline{oo_k}$, $k = \overline{1,K}$). Each the k-th chain has s_k connected in tandem rigid elements of a pivot type. The parameters of the elements are: m_j^k, I_j^k, l_j^k, r_j^k (mass, moment of inertia, length and the distance from the point o_{jk} to its center of mass, $j = 1, 2, ..., j_k, ..., s_k$, is the number of the element in the k-th chain, $j_k \le s_k$ is the number of the last element when the chain is not completely assembled yet). Chain deformations is defined by the elasticity coefficients b_j^k of the aforementioned springs. $N = \sum_{k=1}^{K} s_k$ is the total number of the construction elements.

Transformation of the dynamical properties of the DES intermediate structures can be reflected by the MPM (1) coefficients $\tilde{\omega}_{in}, \tilde{k}_{in}, I_c(n)$, $i = \overline{1,n}$; $n = \overline{0,N}$. Calculation of these coefficients at big values of the number n requires much time. For solving of the task that is defined the transformation of the DES dynamical properties throughout the assembly it is convenient to use the package of programs [3] for computer derivation of the DES mathematical graph-model. As the output product of this package, moreover of computer visualization the graph-model, we have two triangular matrices $\tilde{\omega} = \begin{vmatrix} \tilde{\omega}_{11} & 0 & 0 \\ \tilde{\omega}_{12} & \tilde{\omega}_{22} & 0 \\ \tilde{\omega}_{1j} & \tilde{\omega}_{2j} & \tilde{\omega}_{jj} \end{vmatrix}$, $\tilde{k} = \begin{vmatrix} \tilde{k}_{11} & 0 & 0 \\ \tilde{k}_{12} & \tilde{k}_{22} & 0 \\ \tilde{k}_{1j} & \tilde{k}_{2j} & \tilde{k}_{jj} \end{vmatrix}$ and row matrix $(I_n)^{-1} = \begin{vmatrix} \frac{1}{I_0} & \frac{1}{I_1} & \frac{1}{I_2} & ... & \frac{1}{I_n} \end{vmatrix}$, $n = \overline{0,N}$.

In Fig. 2 it is shown the example of this package use for the "spiral" type of the object assembly (Fig. 3) with the parameters: K=12, $j_k = \overline{1, s_k}$, $(s_k = 5)$, $k = \overline{1,K}$, $m_j^k = 20 kg$ $m_0 = 500 kg$, $I_0 = 50 kg \cdot m^2$, $r_0 = 0{,}5 m$;, $l_j^k = 2 m$, $n = \overline{1,60}$ (all elements are the same).

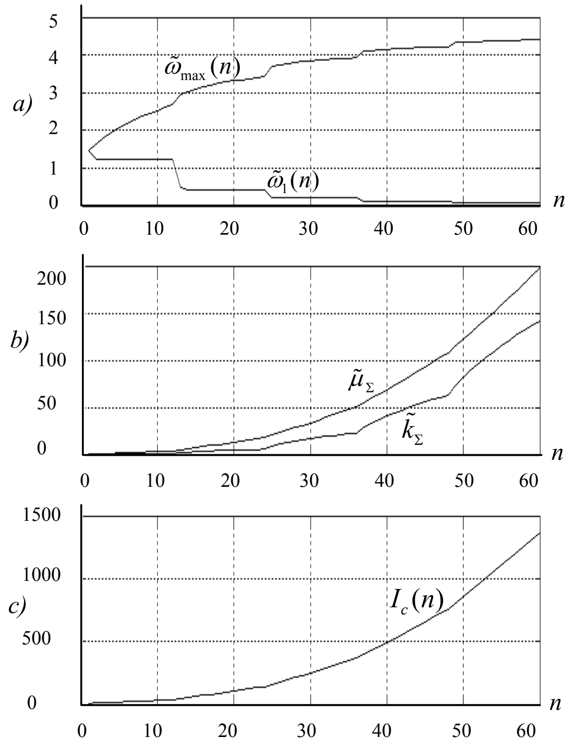

Fig. 2. Changing of the MPM coefficients throughout the object assembly.

Fig. 2a shows that the fundamental frequencies range of the elastic oscillations widen as the number n increases. At this the lowest frequency $\tilde{\omega}_1(n) \equiv \tilde{\omega}_{1n}$ decreases that leads to coming together the frequency $\tilde{\omega}_{1n}$ with the frequency $\bar{\omega}(n) \equiv \bar{\omega}_n$ of rigid motion.

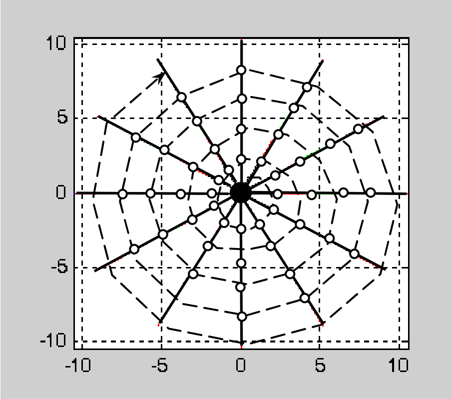

Fig. 3. The "spiral" type of the object asse

Summary coefficient of elastic oscillations excitability $\tilde{k}_\Sigma(n) = [(I_c(n)/I_0) - 1]$ and the degree of excitability $\tilde{\mu}_\Sigma(n) = \sum_{i=1}^{n} \tilde{k}_i \tilde{\omega}_i^{-2}$ with at the increment of the number n increase also. This fact indicates that disturbing influence of the elastic oscillations on the control quality grows, the construction turns into the hard-to-control system and it is required to have more perfect control algorithm.

Let us consider the process of coming together of the lowest frequency $\tilde{\omega}_{1n}$ and the frequency of the rigid motion $\bar{\omega}_n$ (rigid object with the moment of inertia $I_c(n)$) at *PD* control algorithm.

In this case $m_n(u) = M(u) I_c^{-1}(n) = -(k_1 \bar{x} + k_2 \dot{\bar{x}})$. The frequency $\bar{\omega}_n$ is defined by characteristic equation $p^2 + I_c(n)(k_1 + k_2 p) = 0$, $p = j\bar{\omega}$. Obtained with the help of computer the graph $\Delta_\omega(n) = \tilde{\omega}_1(n) - \bar{\omega}(n)$ of coming together the frequencies $\tilde{\omega}_{1n}$ and $\bar{\omega}_n$ is shown in Fig. 4.

It is obvious that at the assembly of the first row elements ($k = \overline{1,12}$, $j_k = 1$) the frequencies $\tilde{\omega}_{1n}$ and $\bar{\omega}_n$ come together slowly ($\Delta_\omega(n) \approx 1,2$). This is explained by small increment of the summary moment of inertia. At the attaching the first element of the second row ($n = 13$) the moment of inertia I_{13} increases significantly (proportionally to square of the distance of the attached mass from the center of inertia of the system). This leads to step-wise coming together frequencies $\tilde{\omega}_{1n}$ and $\bar{\omega}_n$ ($\Delta_\omega \approx 0,4$).

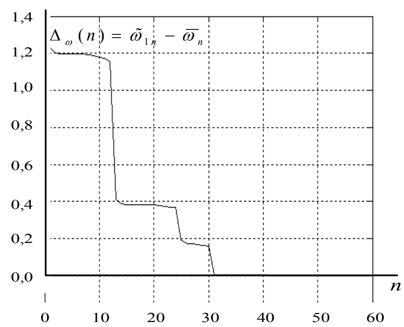

Fig. 4. The graph of frequencies $\tilde{\omega}_{1n}$ and $\bar{\omega}_n$ coming together.

This coming together of aforementioned frequencies occurs also for more general case of *PD* control of multi-frequency objects. In Fig. 5 it is shown the example of computer constructed of the trajectory hodograph of the characteristic equation roots in the space of three dimensions ($\alpha, j\omega, n$). Along the third axis that completes the plane of complex variable to orthogonal trihedron the number of attached element *n* is put aside. Such approach to the analysis

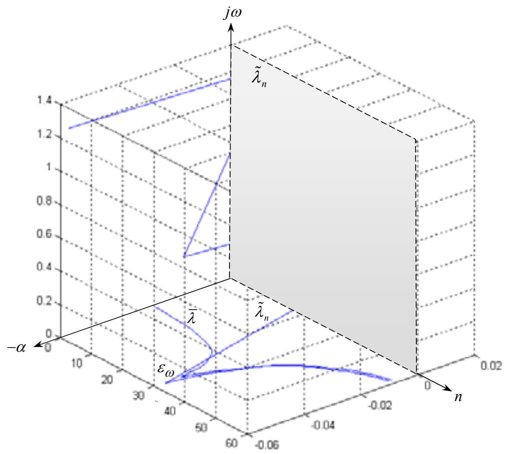

Fig. 5. The roots trajectory throughout DES assembly.

of the system dynamical properties makes it possible to connect the configuration of the roots distribution with the current value of the number *n*.

Fig. 5 illustrates the general example of the trajectory behavior of the system (1) characteristic equation roots $\bar{\lambda}(n) = \bar{\alpha}_n \pm j\bar{\omega}_n$ and roots $\tilde{\lambda}_1(n) = \tilde{\alpha}_n \pm j\tilde{\omega}_{1n}$ with linear *PD* control algorithm at $n = \overline{1,60}$.

The big distance between of the trajectory initial points of the roots $\bar{\lambda}(n_{\min})$ and $\tilde{\lambda}(n_{\min})$ along the axis $j\omega$ shows unessential influence of the dominant mode $\tilde{x}_1(t)$ on the rigid body movement $\bar{x}(t)$. At increasing of the number *n* aforementioned property is remained valid only at low *n*. At passage from one row of the assembly to the next row it is occurred jump-like character of the coming together the frequencies $\tilde{\omega}_{1n}$ and $\bar{\omega}_n$. The distance Δ_ω decreases and from an value of the number n^* (in our example $n^* = 36$) the distance between the roots becomes too little ($\Delta_\omega \le \varepsilon_\omega$) in order to guarantee desired dynamics of the controlled DES and it is necessary to use more complicated control algorithm.

III. CONTROL STRATEGY TRANSFORMATION THROUGHOUT THE DES ASSEMBLY

Above it was determined the presence of three types of the controlled object condition throughout its assembly: rigid body $\rightarrow$ elastic MS $\rightarrow$ essentially flexible MS. For each type of the object condition it is required particular approach to the control algorithm design.

A. The strategy of the DES control in the initial stage of its condition

For realization of the required quality of the object control first of all the base control algorithm $u_0(x,\dot{x},t)$ is synthesized. At least this algorithm must guarantee desired dynamics during the first phase of the DES existence as the rigid body. Mathematical model of the rigid object corresponds to equation (2). For the concreteness of the investigation and taking into account that almost all control systems use the on-board computer discrete analog of PD algorithm is chosen as base one

$$u(t_k) = -k_0[k_1\hat{x}(t_k) + k_2\Delta\hat{x}(t_k)], \ \ k = 0, \ 1, \ 2, \ldots, . \quad (3)$$

The use of this discrete algorithm leads very often to the excitation of the construction elastic oscillations. In (3) $\hat{x}(t_k)$ the estimation of the measured coordinate. For the process of estimation it is used s values of the coordinate $x(t), t=\overline{1,s}$, during the discreteness period T_0. 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.

Throughout regime of the object stabilization that is the main one dead zones and hysteresis in the actuator device characteristics lead to the auto-oscillations. Today there arte many well-known algorithms that guarantee desired dynamics of the stabilization processes ($|\overline{x}| \le \overline{x}_{\max}$, $\chi = \tau_a / \tau_\Gamma \le \chi^*$, τ_a is the part of the stable limit cycle period τ when $m(u) \ne 0$, τ_Γ is the one when $m(u) = 0$, χ^* is the admissible value of the coefficient of the limit cycle quality). The movement that corresponds to this limit cycle can be considered as the reference one. Since it is required that the influence of the elastic oscillations on the system dynamics will be negligible

$$|\tilde{x}| = |x - \overline{x}| \le \varepsilon_x , \quad (4)$$

all transient processes throughout the object assembly must tend to the reference movement.

B. The strategy of the DES control in the stage of the elastic MS

Once the first flexible element ($n=1$) and some other ones ($n \ge 1$) are attached to the carrier body the object turns into elastic MS. Usually at this case discrete base control excites elastic oscillations of the construction that deform the stable limit cycle and, as the result, condition (4) is broken. The control accuracy decreases. Without transformation of the control strategy the high amplitude of the elastic oscillations can be as a course of the system instability [5]. The other problem for the elastic MS control is increase of the DES inertia moment (Fig. 2, c) that leads to decrease of the control action effectiveness and to increase of the dynamic errors. At last the main problem in the control algorithm synthesis for this stage of the object condition is increasing throughout the assembly dimension of model (1), jump-like changing all its coefficients and decrease of the $\tilde{\omega}_{1n}$.

Inaccuracy of the DES mechanical parameters calculation in the system designing (and consequently of model (1) coefficients) and the same for the initial values of the new elastic modes that occur at each next stage of the object assembly require not only transformation of the control strategy but the use of adaptive control.

At the small values of the number n the fundamental frequencies of the elastic oscillations are comparatively high and far away from the frequency of the "rigid" motion (Fig. 5). In this case it is convenient to apply as a control strategy the approach with the use of intelligent diagnostic [6]. This approach intends the tuning of the base algorithm that guarantees both the "rigid" motion stabilization and the elastic oscillations damping.

The essence of this approach is following. It is well-known [5] that the excitation of the elastic oscillations occurs at each switching of the discrete control action. Intensity of the oscillations $\rho(t) = |\tilde{x}(t)|$, when it exceeds some critical level ρ_{cr}, leads to instability of the control system (mainly at the expense of the dominant mode $\tilde{x}_d$ increasing). Consequently, the value $\rho(t)$ and the inequality $\rho(t) < \rho_{\text{cr}}$ can be used both for diagnostics of the system condition and as the control signal $u_a = f(\rho_{\text{cr}} - \rho(t))$ in the loop of the base algorithm $u_0(x,\dot{x},t,\lambda)$ parameter λ tuning (adaptation). At this the base algorithm influence on the oscillating component $\tilde{x} = \tilde{x}_d + \sum \tilde{x}_i \big|_{i \ne d}$ of the model (1) can be estimated by quasienvelope $\widehat{\rho}(t,\lambda) = \text{Env}[\tilde{x}(u(\bullet,\lambda),t)]$ in an interval that is equal to several periods of the limit cycle. This quasienvelope after two-stage approximation can be presented by exponential curve $\widehat{\rho}(t,\lambda) = \text{Env}[\tilde{x}(u(\bullet,\lambda),t)]$. The value of exponential curve index $|\nu(\lambda)|$ defines the rate of the dominant mode amplitude changing. The $\operatorname{sign}\nu(\lambda)$ defines the character of this changing. At $\operatorname{sign}\nu = -1$ the dominant mode converges, at $\operatorname{sign}\nu = +1$ it diverges.

Thus, for any fixed value $\lambda_* \in [\lambda_{\min}, \lambda_{\max}]$, ($[\lambda_{\min}, \lambda_{\max}]$ is admissible range of the parameter λ tuning) the regulator influence on the elastic component $\tilde{x}(t)$ can be defined by the single number $\nu_* = \nu(\lambda_*)$. Changing the value λ and calculating the index $\nu(\lambda)$ we obtain "model" function $\nu_d = \nu_d(\lambda)$ can be obtained. This function estimates the base algorithm influence on the object of the elastic oscillations. Totality of the "model" functions $\Upsilon_d = \{\nu_d(\lambda)\}$, ($d = \overline{1,j}$; $j \le n^*$), each of that has some local extremis (including global minimum), is used as an informational software for the intelligent diagnostics subsystem of the oscillation component $\tilde{x}(t)$ current condition and for tuning of the base algorithm parameter λ. In [6] it was shown that for designing of the DES control system at each stage of the object assembly it is necessary to solve the next two tasks: 1) to define the number d of the dominant mode using the identified value of its frequency $\tilde{\omega}_d$; 2) to choose from the totality $\Upsilon_d = \{\nu_d(\lambda)\}$, that is kept in the computer as the knowledge base, the corresponding to number d "model" function $\nu_d(\lambda)$ and to choose new value of the parameter $\lambda_1 \in [\lambda_{\min}, \lambda_{\max}]$ that guarantees the fulfillment of two conditions $\mathrm{sign}[\nu(\lambda_1)] = -1$ and $\nu(\lambda_1) = \nu_{\min}$. At this case the new control action $m[u_1(\bullet, \lambda_1)]$ remains good quality of the control of the object rigid movement and at the same time realizes maximal rate of the dominant mode $\tilde{x}_d$ damping.

Block scheme of the stabilization system of the DES as the flexible MS that has additional loop of the oscillating component diagnostics and adaptive correction of the base algorithm is shown in Fig. 6.

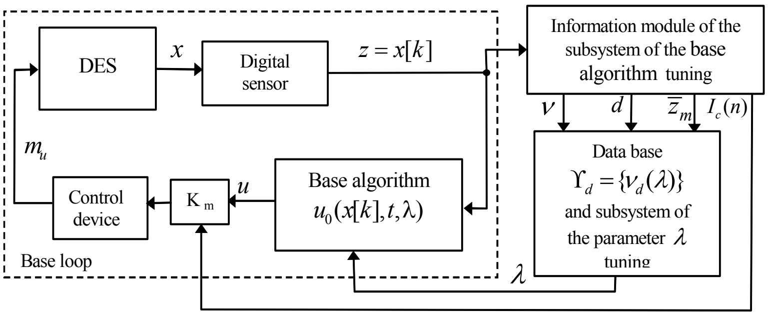

Fig. 6. Block scheme of the adaptive stabilization system of the DES as the flexible MS.

Here the amplification coefficient $K_{\mathrm{m}}(n)$ of the control device is tuning according to the value of the inertia moment $I_c(n)$ that is calculated in advance. This tuning realizes constancy of the control action effectiveness $m_u(n) = \mathrm{const}\ \forall\, n \in \overline{0, N}$ throughout all stages of the object's assembly. Aforementioned procedure of the quasienvelope $\breve{\rho}(t) \approx a e^{\nu(\lambda)t}$ estimation is realized in the information module of the subsystem of the base algorithm tuning. This module has identification device of the dominant mode frequency and the device of the index $\nu(t, \lambda)$ calculation. As the input signal it is used the date base Z_m that consists of the base data $z_m[l]$ (amplitudes of the rectified signal $z, l \in k$) and the date base $T_m = \{t_m[l]\}$. In the regime of the dominant mode the differences $\Delta t_m[l] = \{t_m[l] - t_m[l-1]\} \approx 0{,}5\tilde{\tau}_{jd}$ of the adjacent elements of the base data $T_m = \{t_m[l]\}$ coincide with the semiperiod $0{,}5\tilde{\tau}_{jd}$ of the oscillation component that has maximal amplitude. After the average operation $\tilde{\tau}_d = \dfrac{2}{L-1}\sum_{j=1}^{L-1} \Delta t_m[l]$, ($L = \dim T_m$) the dominant mode frequency $\omega_d = 2\pi\tilde{\tau}_d^{-1}$ can be calculated. For the determination of the dominant mode number d the differences $\Delta\omega_j = \left|\omega_j - \omega_d\right|_{(j=\overline{1,n})}$ are analyzed and it is assumed $d = j$ for $\Delta\omega_j = \left|\omega_j - \omega_d\right| = \min\limits_j$.

Corrected control action $m[u_1(\bullet, \lambda_1)]$ damps dominant mode by optimal way. At the same time other elastic modes can be increased and one of them will be as new dominant mode. Then the process of the parameter λ tuning is repeated.

Described processes of sequential damping of the dominant modes take place throughout the object assembly and do not require additional consumption energy for control.

C. The strategy of the DES control in the stage of the essentially flexible MS

The main deficiency of the previous strategy of control in this stage of the object's presence is impossibility to estimate the quesienvelope $\breve{\rho}(t)$ during the observation interval T_{sur} that is acceptable for control. This is the result of coming together the lowest frequency of the elastic oscillations with the frequency of the "rigid" movement (Fig. 5). At this case resonance processes can occur and the system becomes unstable.

As the base of the strategy of control for the essentially flexible MS can be used the one that was suggested in [7]. 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. 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.

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 β_j is defined as follows [7]:

$$\beta_j = \begin{cases} 2\pi k & \forall\ \mathrm{sign}\,\dot{m}_j = +1, \\ \pi(2k+1) & \forall\ \mathrm{sign}\,\dot{m}_j = -1, \quad k = 0, 1, 2, \ldots \end{cases} \tag{5}$$

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

$$\tau_\beta = \begin{cases} [\pi - \beta_d(t_0)]\tilde{\omega}_d^{-1}\ \forall\ 0 \le \beta_{d0} \le \pi, \\ [3\pi - \beta_d(t_0)]\tilde{\omega}_d^{-1}\ \forall\ \pi < \beta_{d0} \le 2\pi, \end{cases} \tag{6}$$

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

In [7] 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 $m_u = M_u K_m I_c^{-1}(n)$ with the variable mass-inertia properties of the assembled object.

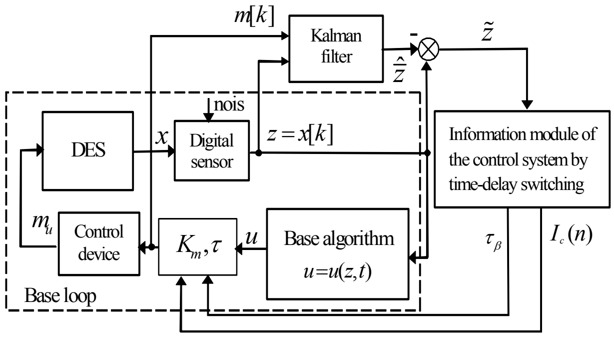

Fig. 7. Block-scheme of control system for DES as the …

The second tuning coefficient τ implements the control by the time-delay of the relay 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 [8].

The example of computer simulation of the suggested system for one stage of the object assembly is shown in Fig. 8. As the object corresponding to equations (1) at $n=6$ it was chosen the large space structure with the inertia moment $I_c(n=6)=10^4 kg\cdot m^2$. Other parameters are given in the table.

$i=\overline{1,6}$	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
$\tilde{x}_i(0)$	0,0005	0,00015	0,0001	0,00001	0,00005	0,00003

As the dominant mode at the initial stage of the control was $\tilde{x}_1$. This mode is subjected to the control action influ-

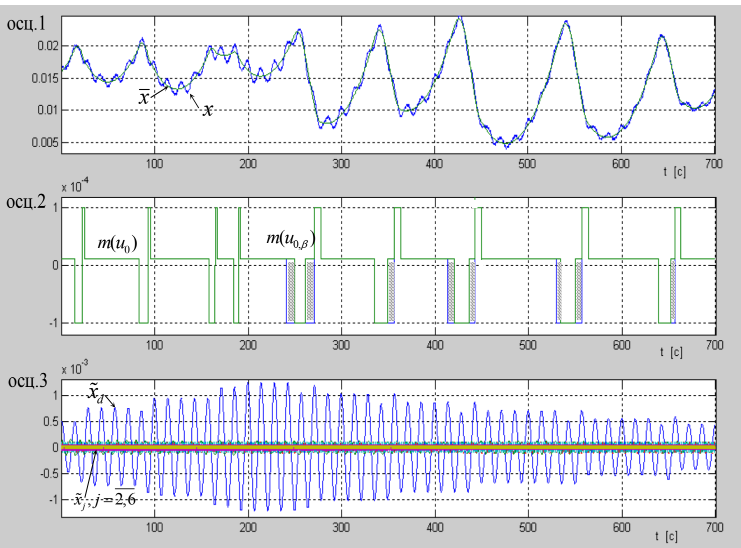

Fig. 8. Processes in a regime of stabilization DES at phase control for a case $d=1$.

ence the most strongly because its degree of excitability $\mu_1^{(1)} = \tilde{k}_1\tilde{\omega}_1^{-2} = 0,88$ in the most high.

At 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 of phase control $m[u(\bullet,\beta_t,t)]$ was applied. The intervals of the time-delay of the control action switching are shaded (see oscillogram 2). As the result the dominant mode amplitude was decreased very quickly.

IV. CONCLUSION

Suggested approaches that realize adaptive correction of the base algorithm with using the elements of intelligent diagnostics and the method of phase control guarantee damping of elastic oscillations without increasing consumption of the energy for control.

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