DEVELOPMENT DESIGN PRINCIPLES OF LARGE PRECISION SPACE REFLECTOR ANTENNAS CONTAINING ACTUATORS OF SMART MATERIALS

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Abstract
This document is the layout template to be used for the 5 th European Conference for Aeronautics and Space Sciences which will take place in Munich, Germany, on July 1–5, 2013. The paper presents the formulation of the optimization problem the position, the number and the value of active force factors by which management is unwanted deformations of the intelligent structure.

1. INTRODUCTION

Development of space and astronautical associated with the creation of space satellite with large precision structures on the board, which observe the Earth's surface, a global communications and positioning, as well as the research of near and far space.

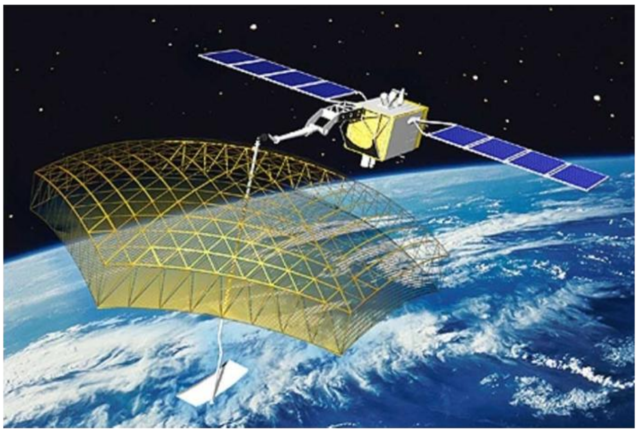

Figure 1 Large space precision reflector antennas

In satellite communications, space observatories and satellites - repeaters are used reflector antennas (Fig.1). Such antennas are now in operation in the frequency range of *4 - 6 GHz* and *11 - 14 GHz*. Begin to master a range of *20 - 30 GHz*. There are plans to increase the carrier frequency up to *60 GHz*. The increase in carrier frequency requires a large precision reflector antennas that have to meet stringent requirements on the stability of the shape and size of working surfaces ("mirror").

When creating precision structures important are the composite materials (CM) that provide a wide range strength, stiffness, thermal and other properties. CM have the high specific mechanical properties (high specific strength and stiffness), low coefficient of linear thermal expansion (CTE) compared with metals, the ability to adjust the physical and mechanical characteristics depending on the structural organization of the CM, as well as high corrosion resistance, and low conductivity. In precision designs often use the CM on the basis the continuous fibers and a polymer binder. This is due to high values of strength and stiffness, low CTE value in the reinforcement direction and the possibility to adjust the properties of materials due to the volume content and fiber orientation in certain directions.

In flight and ground exploitation in design open to many external factors that influence the shape and size of the design of work surfaces and also on the strength and functional properties of the material. The main external factors include: heat, vibration loads, as well as gravity, radiation, electromagnetic and aerodynamic load.

The impact of external factors results to deformation of precision of work surfaces of reflectors antennas. According to the theory Ruse value ΔW of power losses at a deviation from the ideal reflecting surface is determined from the following relationship:

$$\Delta W = 1 - \exp\left(\frac{4\pi\sigma}{\lambda}\right)$$

where σ – standard deviation of the reflecting surface from the ideal;;
λ – wavelength of operation.

The permissible value of the ratio of the standard deviation to the wavelength be in range of 0.02 - 0.03. Accordingly, the power losses will be less than 13%. Increasing the size of working mirrors antennas can increase the power and frequency of the transmitted / received signal and increase the deformations of the working surfaces of the antennas.

With an increase the size of the antenna structures of space technology is an acute problem of stability shape and size of work surfaces antennas. The mechanisms to control the shape and size of the working surface of the antenna structures of space technology can be roughly divided into active and passive mechanisms. In the present scientific research active control mechanisms we have in mind the mechanisms that are part of the control system have the active elements of monitoring (sensors) and control (actuators) deformations of work surfaces. Accordingly, passive mechanisms do not have such active elements. In the future, will be discussed only on the active controls, i.e. of actuators.

Perspective direction of creating large precision structures of space technology is the creation of "smart structures". "Intelligent structures" is structures, which are capable of monitor and control the shape and size of work surfaces in real time in response to an external influence. As of today the development of design principles and the creation of large intelligent space structures is the primary task for the development of the space industry.

The design stage of any space structure is responsible and difficult stage of creation, comprising the steps of mathematical modeling and full-scale tests. The creation of conditions similar outer space (for full-scale ground tests) is required costly installation. Therefore mathematical experiment that uses the mechanical structure model with the identified parameters is an alternative to determine the functional suitability and reliability of structures. For the mathematical modeling of large space structures are frequently used numerical methods such as finite element method.

The design stage is much complicated when the it comes to designing of smart structures containing elements of monitoring and active control of deformities of work surfaces structures (i.e., sensors and actuators). The complexity of designing of this type structures is due to the design of structures simultaneously with the design of the active elements of the monitoring and management of deformities and their relationship to intellectual structure, as well as the design of control algorithms for active elements. Design of actuators and sensors with precision structure requires special design techniques, which take into account peculiarities of functioning of the active elements and their interaction with the material of structure, as well as allowing you to select the optimum position, the number and power of the active elements for the most effective control strains. This is only a small part of the functional and geometric parameters of the active elements that need to be considered when designing the intellectual structure, but even these parameters make development of common design principles creating of intelligent design is very complicated.

One of the key characteristics of the actuators is their weight and size characteristics. Motivated by dissatisfaction with rocket - launcher, a necessary condition imposed on the actuators - is the optimal ratio of the power actuator to it's the mass and size. Small (in size and weight), but powerful actuators are embedded in the structure of material allow to manage the stability of shape and size intelligent structures. Such actuators are the actuators on the basis the continuous or short the piezoelectric fibers, the wires of shape memory alloys, actuators out of dielectric elastomer, magnetostrictive films, etc. The most promising of these actuators are the piezoelectric actuators on the basis of fibers, which have the high specific energy and functionality characteristics. In the present scientific research treated just such actuators.

Are being actively developing different methods of design and creating intelligent structures. Analysis of open print sources shows the limitations of the proposed methods of designing and creating large-precision space structures containing actuators of smart materials. One of the identified shortcomings is the fact that the design and creation of structures choice of material and type of actuators carried in the initial stages of the project. Changing the type and material of the actuator requires a return to the initial stage designing and revision of its basic characteristics. For example, a technique of designing structures with piezoelectric actuators and actuators of a shape memory material differ from each other on all stages of the design project. For different types of actuators of smart materials required to modify or even completely change the itself as the method designing, as and the mathematical models underlying.

In the present scientific research attempted to combine some stages of designing of intelligent structures, regardless of the type of actuator and its material. In a scientific research done on the aktsent determining the optimal position, the number and value of the active force of actuators, regardless of the type of actuator and the structure of its material, that will become the main base for the design techniques of precision antenna structures.

The mathematical basis of the scientific research is the finite element method, which is used for the implementation of the program complex ANSYS. The paper presents the formulation of the problem optimize the position, quantity and value of the active efforts of actuators for compensate for undesired deformations of the working surfaces of precision space structures.

In determining the optimal position, number and capacity of actuators is offered at the first stage to replace the specific functional (power) characteristics of the actuator (which are linked to a specific type actuator (such as the activation voltage of the electric or magnetic fields, etc.)) on the mechanical the force factors (forces and moments) that transmit efforts from the actuator to the intelligent structure, i.e., to move from designing characteristics actuator to designing communication performance «intelligent structures – actuator». The aims of the first stage is formulated as follows: to determine the optimal position, the number and value of force factors necessary to compensate for unwanted strain construction and preservation of stability shape and sizes of its working surfaces. In the second stage the optimal position, the number and value of power factor is replaced by a specific type of actuators with the necessary functional and geometric characteristics. The aim of the second stage formulated as follows: create a mathematical tool for replacing defined at the first stage, the optimal positions, the number and value of power factors on specific functional and geometric characteristics of real actuators. Based on the results of the two stages is proposed to develop design principles of precision structures of space technology comprising out of smart material actuators that preserve the stability of the shape and size of work surfaces in response to an external influence.

The described scientific research in the initial stage, therefore this article covers only the statement of the problem in the first stage.

2. SELECTED SUBJECTS FOR RESEARCH AND MATHEMATICAL MODELS

The article suggests formulation of the problem of determining the optimal position, number and power of actuators for controlling undesirable deformation of the structure and maintains the stability of the shape and size of work surfaces of smart structures.

As object of research is selected thin multilayer structures made of composite material consisting from the matrix and reinforcing fibers with different angular orientation of layers in the package. As an actuators is selected out of piezoelectric actuators made of fibers embedded in the structure of the CM of intelligent structures as separate layers and / or linings.

The basis of the numerical modeling the behavior research subjects is the finite element method, for which is applicable the theory of anisotropic laminated thin plates and shells based on the conditions of small deformations under external influence.

The solution of optimization problems based on the use of indirect methods of optimizing a necessary condition for optimality Kuhn - Tucker. The algorithms are based on an iterative approximation to the optimal solution.

3. FORMULATION OF THE PROBLEM OF OPTIMIZATION POSITION, THE NUMBER AND VALUE OF ACTIVE POWER FACTOR

In determining the optimal position, number and capacity of actuators is proposed to replace the specific functional (power) characteristics of the actuator (which are linked to a specific type actuator (such as the activation voltage of the electric or magnetic fields, etc.)) on the mechanical the force factors (forces and moments) that transmit efforts from the actuator to the intelligent structure.
Design parameters are the position, the number and the value of active force factors (concentrated forces and moments). The conditions restrictions are superimposed on the values of nodal displacement finite - element model, which must not exceed the permissible value. As the main functional being minimized is selected functional of functional of the total energy of the system, which depends on the conditions of the design parameters and limitations. For the case of a stationary load the total energy functional can be written:

$$\begin{gathered}\mathbf{J}(\mathbf{F_a},\boldsymbol{\alpha}) = \boldsymbol{\Pi}(\mathbf{F_a},\boldsymbol{\alpha}) + \mathbf{A}(\mathbf{F_a},\boldsymbol{\alpha}) \\ \mathbf{J}_{*}(\mathbf{F_a},\boldsymbol{\alpha}) = \min_{\mathbf{F_a},\boldsymbol{\alpha}} \mathbf{J}(\mathbf{F_a},\boldsymbol{\alpha}) = \min_{\mathbf{F_a},\boldsymbol{\alpha}} \left(\boldsymbol{\Pi}(\mathbf{F_a},\boldsymbol{\alpha}) + \mathbf{A}(\mathbf{F_a},\boldsymbol{\alpha})\right)\end{gathered} \tag{1}$$

where $\boldsymbol{\Pi}\ (\mathbf{F_a}, \boldsymbol{\alpha})$ – potential energy of the system;
$\mathbf{A}\ (\mathbf{F_a}, \boldsymbol{\alpha})$ – work of external forces;
$\mathbf{F_a}$ – vector - column design parameters of active force factors;
$\boldsymbol{\alpha}$ – matrix, which determines the position of the active force factors.

Column vector of active force factor is

$$\begin{aligned}\mathbf{F_a} = \{&F_{ax1}, F_{ay1}, F_{az1}, M_{ax1}, M_{ay1}, M_{az1}, F_{ax2}, F_{ay2}, F_{az2}, M_{ax2}, M_{ay2}, M_{az2}, \dots \\ &\dots, F_{axN_{nodes}}, F_{ayN_{nodes}}, F_{azN_{nodes}}, M_{axN_{nodes}}, M_{ayN_{nodes}}, M_{azN_{nodes}}\}^T\end{aligned} \tag{2}$$

where N_{nodes} – the number of nodes in the finite - element model;
F_{axi}, F_{ayi}, F_{azi}, M_{axi}, M_{ayi}, M_{azi} – concentrated forces and moments in the direction of x, y and z, respectively;

By the term active force factor are understood the concentrated forces and moments applied to the nodes of finite - element model of the object of the research. The matrix $\boldsymbol{\alpha}$ is a binary matrix, whose components have a value of 1 or 0. If a node with a given degree of freedom comprises the active force factor, then the value of the component is equal to 1, otherwise 0.
The problem of optimizing is to minimize of the functional (1):

$$\mathbf{J}(\mathbf{F_a}, \mathbf{U}_{\max}(\mathbf{F_a})) \to \min \tag{3}$$

Under the condition that the values of the nodal displacements and active force factor change in the permissible range:

$$\begin{aligned}|\mathbf{U}| &\le |U_d| \qquad \text{or} \qquad -U_d \le \mathbf{U} \le U_d \\ |\mathbf{F_a}| &\le |F_{ad}| \qquad\qquad -F_{ad} \le \mathbf{F_a} \le F_{ad}\end{aligned} \tag{4}$$

We expand the functionality of the equation greater detail:

$$\Pi(\mathbf{F_a},\boldsymbol{\alpha})=\frac{1}{2}\left(\mathbf{U}(\mathbf{F_a},\boldsymbol{\alpha})\right)^T\left(\mathbf{K}(\mathbf{F_a},\boldsymbol{\alpha})\right)\left(\mathbf{U}(\mathbf{F_a},\boldsymbol{\alpha})\right)$$
$$\mathrm{A}(\mathbf{F_a},\boldsymbol{\alpha})=\left(\mathbf{U}(\mathbf{F_a},\boldsymbol{\alpha})\right)^T\left(\mathbf{P}(\mathbf{F_a},\boldsymbol{\alpha})\right) \tag{5}$$
$$\mathbf{J}(\mathbf{F_a},\boldsymbol{\alpha})=\frac{1}{2}\left(\mathbf{U}(\mathbf{F_a},\boldsymbol{\alpha})\right)^T\left(\mathbf{K}(\mathbf{F_a},\boldsymbol{\alpha})\right)\left(\mathbf{U}(\mathbf{F_a},\boldsymbol{\alpha})\right)+\left(\mathbf{U}(\mathbf{F_a},\boldsymbol{\alpha})\right)^T\left(\mathbf{P}(\mathbf{F_a},\boldsymbol{\alpha})\right)$$

where **К ($\mathbf{F_a}$, α)** – global nodal stiffness matrix;
U ($\mathbf{F_a}$, α) – vector - column global nodal displacements from external influence;
P ($\mathbf{F_a}$, α) – vector - column of global nodal forces;

Vector - Column global nodal displacement is

$$\mathbf{U}=\{U_{x1},U_{y1},U_{z1},\gamma_{x1},\gamma_{y1},\gamma_{z1},U_{x2},U_{y2},U_{z2},\gamma_{x2},\gamma_{y2},\gamma_{z2},\ldots$$
$$\ldots,U_{xN_{nodes}},U_{yN_{nodes}},U_{zN_{nodes}},\gamma_{xN_{nodes}},\gamma_{yN_{nodes}},\gamma_{zN_{nodes}}\}^T \tag{6}$$

where U_{xi}, U_{yi}, U_{zi}, γ_{xi}, γ_{yi}, γ_{zi} – nodal values of displacements and the angles of rotation in the direction of *x*, *y* and *z*, respectively;

Let us write the withdrawal the necessary optimality conditions of the Kuhn - Tucker in general terms. There is a point $h^0 \epsilon \Omega$ called a regular point of the set Ω, if the function $J(h^0)$ is differentiable for $h = h^0$ and if linear - independent all the gradients $\nabla\phi_i\left(h^0\right)$, for which $\phi_i\left(h^0\right)=0$, $i = 1, 2, \ldots, \kappa$.
For the optimization problem with differentiable functions $J(h)$ and $\phi_i(h)$ for the point of relative minimum h^0 a regular in the set Ω there are Lagrange multipliers at λ_i, $i = 1, \ldots, k$ such that [1]:

$$\begin{cases} \lambda_i \ge 0, & i=1,\ldots,k \quad (7)\\ \lambda_i\phi_i(h^0)=0, & i=1,\ldots,k \quad (8)\\ \nabla J(h^0)+\sum\limits_{i=1}^{k}\lambda_i\nabla\phi_i(h^0)=0 & \quad (9)\end{cases}$$

where h^0 – design parameters;
λ_i – Lagrange multipliers;
ϕ_i – limiter function.

We will assume that the equations (7) – (9) are applicable to the problem of optimization stated above (3) – (4), i.e. function $J(F_a, \alpha)$ is differentiable at $F_a = F_a{}^0$ and linear - independent all the gradients $\nabla u_i\left(F_a{}^0\right)$, for which $u_i\left(F_a{}^0\right)=0$, $i = 1, 2, \ldots, \kappa$. Then the equations (7) - (9) are transformed as follows:

$$
\begin{cases}
\lambda_i \geq 0, & i = 1,\dots,k \\
\left[\begin{array}{l} \text{if} \quad u_i(F_a{}^0) \geq 0 \quad \text{then} \quad \lambda_i\left(u_i(F_a{}^0) - u_d\right) = 0, \\ \text{else} \quad \lambda_i\left(-u_i(F_a{}^0) - u_d\right) = 0 \end{array}\right. & i = 1,\dots,r \\
\left[\begin{array}{l} \text{if} \quad F_{ai} \geq 0 \quad \text{then} \quad \lambda_i\left(F_{ai} - F_{ad}\right) = 0, \\ \text{else} \quad \lambda_i\left(-F_{ai} - F_{ad}\right) = 0 \end{array}\right. & i = r+1,\dots,k \\
\nabla J\left(F_{ai}{}^0, \alpha\right) + \sum\limits_{i=1}^{r} \lambda_i \nabla u_i\left(F_{ai}{}^0, \alpha\right) + \sum\limits_{i=r+1}^{k} \lambda_i = 0
\end{cases}
\tag{10}
$$

On the basis of equations (10) is proposed to develop a program to optimize embedded in a complex ANSYS to determine the optimal position, the number and value of compensation force factors $\mathbf{F_a}$.

4. CONCLUSION

The paper presents the formulation of the optimization problem position, number and value of compensation force factors (concentrated forces and moments). On the basis of the obtained equations is proposed to develop a program of optimization embedded in a complex ANSYS.

After solving the optimization problem position, number and value of active force factor needs to shift from force factor to a particular type of actuators. For this purpose, the active force factors relate to the possible types of actuators are able to transfer the active forces of a specific value and position. The transition from mechanical forces and moments to the characteristics of the actuator requires the development of appropriate mathematical models, and in this paper is not provided. Results of the development of such models to be presented in the following publications. The result proposed to develop design principles of precision construction of space technology comprising of smart material actuators that preserve the stability of the shape and size of working surfaces of mirrors in response to negative external influences.

References

[1] Banichuk N.V. - "Introduction to optimization of structures", Moscow, 1986 (In Russian)