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Investigation of free oscillations for reasoning constructive decisions of mirror segments of parabolic antenna

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Abstract. The paper deals with studying qualitative and quantitative relationships between constructive decisions of mirror segments of parabolic antenna and dynamic characteristics for both individual segments and ready-assembled reflector. It is shown the influence stressed state induced by thermal deformation to natural modes and frequencies of free oscillations of mirror segments. There are justified constructive decisions of the mirror to ensure low sensitivity of dynamic characteristics to service temperature conditions.

1. Introduction
Dynamic characteristics (natural modes and frequencies of free oscillations) of large-size mirror antennas for ground stations of satellite communication have a great effect on antennas productivity. Such is the case of just dynamic characteristics generate structural response to effect of wind flow, acoustic noise and sinusoidal vibrations. Regardless of the fact that the dynamics of antenna system is predominantly determined by configuration of bearing skeleton, the great practical interest is to analyze dynamic behavior of mirror segments. This analysis allows to predict and to prevent development of functional failure of antennas essentially because of vibration of mirror segments despite high dynamic characteristics of skeleton. One of the intelligent design mission is to search constructive decisions to provide overshot of lower natural frequencies of free oscillations for segments of the same for bearing skeleton. The feature of this mission is close connection of constructive decisions for bearing skeleton and mirror because of necessity of guaranteeing their assemblability and associativity as parts of mechanical system. This fact brings to the impossibility of permanent modification of structural parameters for both skeleton and mirror segments. On the contrary, one has to choice of short amount of possible alternative variants of mechanical system consisting of agreed constructive decisions for mirror segments and skeleton.

This paper deals with qualitative and quantitative relationships between constructive decisions of parabolic antenna and their natural modes and frequencies of free oscillations. Deep understanding of these relationships is the basis for intelligent design of mirror segments of parabolic antenna taking into account restraints on its dynamic characteristics.

2. Problem definition
The objects of research are $Q/K_a$-band parabolic reflector antennas for ground stations of satellite communication. Reflector diameter is in the range 9 to 12 m, and ratio of focal length to diameter is between 0.3 to 0.5. Two alternative variants of mirror organization are considered. The first variant
consists of six partitions, each of them contains one segment of form factor 1 (segment 1), two segments of form factor 2 (segment 2), and two segments of form factor 3 (segment 3) (figure 1, a). Each segment rests on skeleton by means of five adjusting bays (red spots in fig. 1). The second variant of mirror organization consists of fifteen partitions, each of them contains one segment of form factor 4 (segment 4), and two segments of form factor 5 (segment 5) (figure 1, b). Segments 4 rest on skeleton by means of seven adjusting bays, while segments 5 are connected to eight adjusting bays. Segments 4 and segments 5 are reinforced by radially extended 100 mm high stiffening plates made of 1.4 mm thickness carbon fiber composite. Segments of all five form factors have the same cross-section structure: external layers of 0.6 mm thickness carbon fiber composite, internal layer of 40 mm thickness plastic foam. The fundamentally important fact is that each segment, regardless of others, rests on skeleton by means of adjusting bays; there are no mechanical connections between neighboring segments.

In accordance with regulations the antennas functioning is permitted on condition that ambient air temperature is within the range of minus 50 to plus 55 Celsius degree. Reflector thermal state is developed under the impact of integrated density of Solar flux $Q_{sol}$ in conditions of radiation-convective heat exchange between the mirror and its surrounding.

The research task involves determination and comparative analysis of natural modes and frequencies of free oscillations for mirror segments of five form factors, both taking and without taking their stressed states induced by thermal deformation into account. Result of such comparative analysis is one of the factors for selection preferable variant of parabolic antenna mirror organization.

![Figure 1. Partition configuration and connections (red spots) between segments and bearing skeleton.](image)

Problem definitions similar by applied-physics implication are also known. The problem definitions involve numerical [1-6] and experimental [1] studies of dynamic behavior of ground-based [1] and space deployable [2-6] reflector antennas. In certain cases the dynamic analysis was performed over wide temperature range: from minus 200 to 180 °C [3], from minus 70 to 120 °C [5]. Natural modes and frequencies were analyzed in connection with prestressed state [2] and some structural features [4] of reflectors.

3. Mathematical formulation of the problem

To execute analysis of free oscillations, it is necessary to develop discrete (finite-element) models of structures and solve following constitutive equations. Natural frequencies $\omega_i$ for $i$-th natural mode can be determined by numerical solving equation

$$\left(K - \omega_i^2 M\right) u_{\cos \omega_i t} = 0,$$

where $M$ – mass matrix; $K$ – stiffness matrix; $u$ – displacement vector; $t$ – time.

The $i$-th natural mode is determined by eigenvector
To fulfill modal analysis of prestressed structures the stiffness matrix $K$ must be superseded by matrix $K_c = K + K_g$, where $K_g$ – tangent stiffness matrix. Calculation of $K_g$ is based on prestress tensor jointly with nonlinear part of strain tensor.

4. Numerical modeling and results
There are realized three series of computing experiments. The first one is devoted to analysis of natural modes and frequencies of mirror segments 1, 2, and 3 (figure 1, a). The second series is subsidiary and aimed to modal analysis of segments 4, 5 (figure 1, b) without stiffening plates. Natural modes and frequencies of segments 4, 5 with radially extended stiffening plates are investigated during the third experiment series.

Let us consider the main tendencies founded in the first experiment series by the example of the first natural mode of free oscillations (table 1).

| Segment | Without prestressing | The prestressed state at ambient temperature, °C |
|---------|----------------------|-----------------------------------------------|
|         |                      | −50  | −35  | −20  | −5   | 10   | 25   | 40   | 55   |
| 1       | 44.0                 | 46.4 | 46.2 | 46.0 | 45.7 | 44.5 | 42.4 | 39.3 | 34.1 |
| 2       | 45.7                 | 49.3 | 48.9 | 48.5 | 47.8 | 46.8 | 44.0 | 37.8 | 16.0 |
| 3       | 32.6                 | 37.3 | 36.6 | 35.8 | 34.7 | 33.1 | 30.2 | 21.8 | 35.2 |

A comparison between the lowest frequencies of the mirror segments (table 1) and bearing skeleton (in the order of 37 Hz) makes it clear that the natural frequency of mirror segment 3 is less than the same for the skeleton, that won’t pass.

One can see tendencies of the lowest frequency toward lowering while increasing ambient air temperature. At the same time temperature dependencies for segments 2 and 3 involve some features. On case of increasing ambient air temperature from 40 to 55 Celsius degree the lowest natural frequency of the segment 2 decreases drastically (greater than two), but the same of the segment 3, on the contrary, increases. The last fact breaks general tendency towards decreasing frequency. This is because of qualitative changing nature of the first mode in this temperature range (figure 2).

![Figure 2. The first natural mode of free oscillation of segment 2 (a, b) and segment 3 (c, d) at the temperature 40 (a, c) and 55 (b, d) Celsius degree.](image-url)
Similar patterns may be observed at the least for six lower frequencies of free oscillations. One can see sufficiently large scattering of the first frequency at examined temperature interval. Another feature is big difference in natural frequencies for six lower modes (44.0...144.0 Hz, 45.7...160.2 Hz, 32.6...98.1 Hz for segments 1, 2, and 3 without prestressing accordingly).

At the initial stage of the second series of computing experiments it was detected the availability of numerous natural forms of free oscillations having their origin in oscillations of single mirror segments or groups of segments in various combinations (figure 3). The most obvious reason of the obtained result is following fact. Radial and circumferential dimensions of segments 1, 2, and 3 are great and similar. This circumstance makes possible positive effects of high stiffness of double curved shell. Segments 4 and 5 may be characterized by increasing radial dimensions and decreasing circumferential dimensions. This results in drastic increasing double curvature and stiffness of segments.

**Figure 3.** The three lowest natural modes of three oscillations of ready-assembled reflector.

The next step of investigation lies in insertion of structural connections between neighboring mirror segments. Hypothetically, such connections must activate double curvature effect and make possible co-operative motion of segments during free oscillations.

To proof effectiveness of this decision there were formulated and solved some model problems. The object of research was group of three neighboring mirror segments connected with each other with various numbers of connections.

**Model problem 1** – segments are not connected in circumferential direction. In this case each segment oscillates transversely to its surface with frequency about 17 Hz, independently of other segments.

**Model problem 2** – segments in pairs are rigidly connected along all the adjacent sides. In this case connected segments form very rigid body with only oscillation of unsupported sides with frequency about 23 Hz. As can be seen, rigid connection between segments excludes their independent oscillations. But rigid connection is not technologically feasible, only limited number of connections in the form of mechanical locks may be realized.

**Model problem 3** – segments in pairs are connected by means of single mechanical lock in the middle of common side. In this case one can see both collective and independent modes of segments oscillation with frequencies 17.8, 18.0, 18.4 Hz.

Segments with common sides connected by means of three, seven and fifteen mechanical locks are analyzed in model problems 4, 5 and 6 (figure 4). Obtained results show gradual rise of lower frequencies (table 2) and gradual convergence (as the number of locks rises) of natural modes of oscillations towards the same for the variant with rigidly connected segments. But all the variants failed to escape from oscillations of unsupported sides of mirror segments.
Figure 4. Connected segments (a) and three lowest natural modes of oscillation for three segments united with fifteen connections between each other (b).

Table 2. The lower frequencies of oscillations of a group of three segments with different number of connections between them.

| Connections between segments | No | One connection | Three connections | Seven connections | Fifteen connections | Rigid along the entire length |
|------------------------------|----|----------------|-------------------|-------------------|--------------------|-------------------------------|
| 1 frequency                  | 16.97 | 17.83 | 17.87 | 18.01 | 18.23 | 22.81 |
| 2 frequency                  | 17.98 | 18.05 | 18.44 | 18.89 | 19.97 | 22.97 |
| 3 frequency                  | 17.02 | 18.38 | 19.76 | 21.37 | 21.92 | 23.44 |

On the basis of obtained results, it was recommended to reinforce segments with stiffening plates in radial direction, and to enlarge number of connections between segments and bearing skeleton.
The third series of computing experiments is devoted to studying segments 4 and 5 rested on skeleton which lowest natural frequency of free oscillation is about 47 Hz. Calculated frequencies of segments free oscillation for six lower natural modes (table 3) at all interval of ambient air temperature and stress state are much more than the lowest frequency of free oscillations for bearing skeleton.

Table 3. The natural frequencies of the first six modes of oscillation, Hz.

| Mode | Without prestressing | The prestressed state at ambient temperature, °C |
|------|----------------------|---------------------------------------------|
|      |                      | – 50  | – 35  | – 20  | – 5   | 10    | 25    | 40    | 55    |
| 1    | 133.2                | 133.3 | 133.3 | 133.3 | 133.3 | 133.2 | 133.1 | 132.9 |
| 2    | 133.7                | 133.8 | 133.8 | 133.7 | 133.7 | 133.7 | 133.7 |
| 3    | 134.8                | 134.7 | 134.8 | 134.8 | 134.8 | 134.8 | 134.7 |
| 4    | 135.0                | 135.0 | 135.0 | 135.0 | 135.0 | 135.0 |
| 5    | 135.3                | 135.3 | 135.3 | 135.3 | 135.3 | 135.4 |
| 6    | 137.4                | 137.3 | 137.4 | 137.4 | 137.4 | 137.2 |

Segment 4

| Mode | Without prestressing | The prestressed state at ambient temperature, °C |
|------|----------------------|---------------------------------------------|
| 1    | 125.1                | 126.2 | 126.0 | 125.7 | 125.5 | 125.3 | 125.0 | 124.7 | 124.5 |
| 2    | 137.1                | 137.2 | 137.1 | 137.1 | 137.1 | 137.0 | 137.0 |
| 3    | 138.9                | 139.5 | 139.4 | 139.4 | 139.2 | 139.0 | 38.8  |
| 4    | 140.7                | 140.4 | 140.5 | 140.6 | 140.7 | 140.7 | 140.7 |
| 5    | 141.1                | 141.7 | 141.7 | 141.6 | 141.4 | 141.2 | 141.1 |
| 6    | 141.7                | 142.2 | 142.0 | 141.9 | 141.9 | 141.8 | 141.7 |

Segment 5

It is essential to make a note of high constancy of frequencies values: they are almost independent of ambient air temperature and prestressed state. This is because of very high stiffness of three-layered composite shell reinforced by stiffening plates. Finally exactly the segments 4 and 5 are recommended for manufacturing.

5. Conclusion

On the basis of multivariant numerical analysis of mirror segments of parabolic antenna there are determined qualitative and quantitative relationships between structural forms of mirror segments and their dynamic characteristics (natural modes and frequencies of free oscillations) in wide range of temperature conditions. These results are used for substantiation for efficient constructive decisions of the mirror and appropriate skeleton configuration.

It is desirable that dynamic analysis of structures under development involves their natural modes and frequencies of free oscillations in connection with stress state because of thermal deforming in exploitation range of temperatures. Structural variants with low sensitivity of dynamic characteristics to temperature conditions should be considered as preferable.

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