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DESIGN, ANALYSIS AND TESTING OF A COMPOSITE INTEGRAL SANDWICH STRUCTURE OF THE OFFSET MIRROR SPACE ANTENNA

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Key words: Spacecraft antenna, Composite sandwich conical shell, Modal analysis, Finite element method, Vibration testing, Thermal cycling testing.

Summary: *Novel design of the space offset antenna is presented in the paper. The antenna body is designed as a composite sandwich conical shell with a cutout on the side surface. The reflector is located at the bottom part of the cone and the antenna feed is placed inside the shell at the top. The validity of the design concept of the composite integral antenna structure is demonstrated based on the results of finite-element modal analysis and vibration and thermal cycling testing of the physical prototype-demonstrator. It is demonstrated that the proposed compact antenna structure has sufficient stiffness characteristics. This ensures efficient applications of such a structure in the designs of space antennas with various ranges of the transmission of radio signals.*

1 INTRODUCTION

In conventional designs of the offset mirror antennas, the antenna body (the supporting structure) is normally located outside the area in which the signal is transmitted from the feed to the reflector and from the reflector to an Earth station [1-5]. This configuration has a number of shortcomings. Firstly, the dimensions of the supporting structure exceed the dimensions of the reflector. So, extra space is required for the installation of the antenna on a spacecraft. Secondly, antennas with the conventional configuration of the supporting structure, example of which is shown in Fig. 1 are normally assembled of many elements with a large number of joints. This leads to the reduced overall rigidity of the structure. The supporting structure (antenna's body) should comply with certain requirements to ensure the prescribed mutual position of the antenna reflector and the feed. Such requirements include strength, stiffness and dimensional thermal stability of the structure. The sufficient strength and stiffness are to be provided to withstand the inertia loads exerted on the antenna body during the launch and injection into orbit. In addition, this structure should possess a geometrical thermal stability in the temperature range typical for the operational conditions of the spacecraft on the orbit. The higher frequency of radio waves the tighter the aforementioned requirements.

In this paper, a novel design of the space offset mirror antenna, in which the transmission area is located inside the supporting structure, is proposed. The supporting structure (antenna's body) is made in the form of a composite sandwich conical shell with a cutout on the side surface. The reflector and the antenna feed horn are located inside the shell, at the bottom and top of the cone, respectively. A signal emitted by the feed is reflected by the reflector and leaves through the side cutout.

The results of the finite-element modal analysis and vibration testing of the physical prototype-demonstrator, using vertical and horizontal vibration tables, are discussed. To assess the dimensional thermal stability, the prototype has also been subjected to the thermal cycling tests carried out in an environmental chamber.

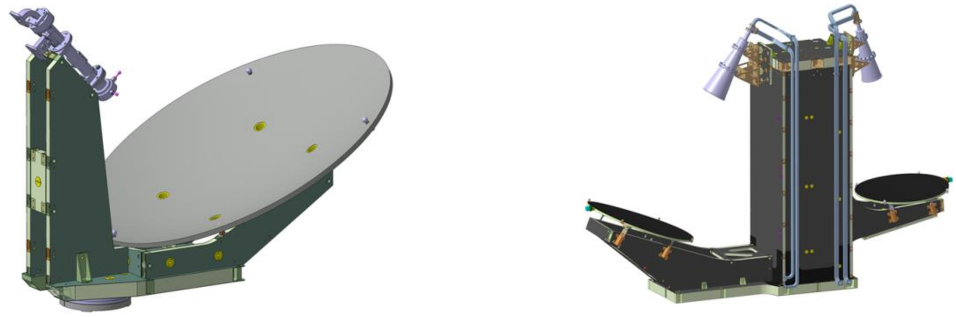
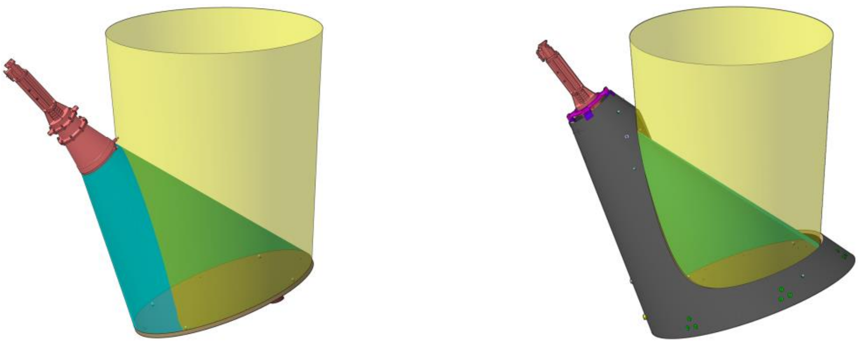


Figure 1: Conventional designs of the offset mirror antennas. (Courtesy of ISS - Reshetnev Company).

2 ANTENNA DESIGN

The shape and geometry of the supporting structure (antenna's body) have been selected considering the area in which the radio wave transmission occurs. It follows from Fig. 2a that this area consists of two intersecting conical radiation zones. One of these zones is created by the antenna feed, whereas another one is generated by the reflector. Considering this, the antenna supporting structure was selected in the form of conical sandwich shell. The shape and dimensions of the shell are selected in such a way that the conical radiation zone of the antenna feed is situated inside of the supporting structure with some small gap between them. The sandwich shell is made of carbon fibre reinforced plastic (CFRP) skins and a honeycomb core. A cutout is made on the side surface of the shell to facilitate the transmission of the signal from the reflector (see Fig. 2b).



(a) (b)

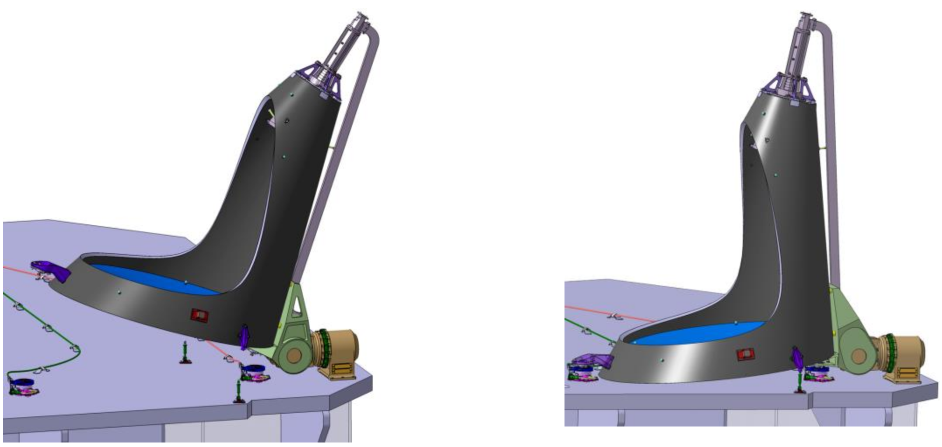
Figure 2: Area of the radio wave transmission (a) and antenna's body covering the transmission area (b).

The top edge of the shell lies in the plane orthogonal to the axis of the feed horn. The bottom end of the cone is located at some distance from the reflector aperture plane. The components of the antenna, i.e. conical body (supporting structure), reflector, feed, waveguide, and set of fastening rings and brackets are shown in Fig. 3a. The reflector is made in the form of parabolic sandwich shell with the CFRP skins. The fastening rings join the reflector and the conical body shell in such a way that the reflector focus is located at the feed phase centre. A longitudinal section of the assembled antenna is shown in Fig. 3b.

(a) (b)

Figure 3: Components of the antenna (a) and a longitudinal section of the antenna (b).

The antenna is attached to one of the body planes of a spacecraft through a pointing drive (see Fig. 4a). This drive enables re-orientation of the antenna if a change in the radio wave radiation direction is required. However, during the launch the antenna should be rigidly fixed. This is achieved through the system of locks shown in Fig. 4b. Once the injection into orbit is complete, the locks are unlocked and the pointing drive puts the antenna in the working position.

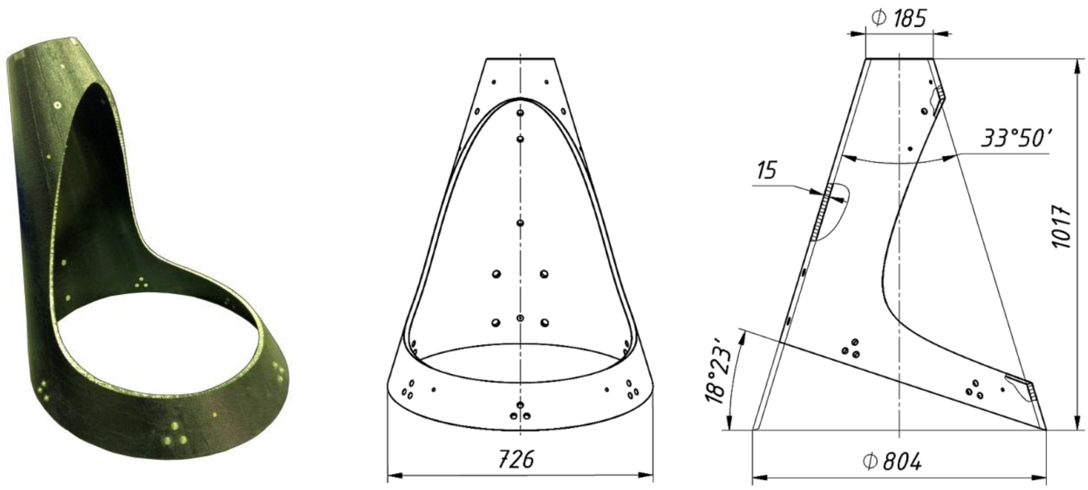


(a) (b)

Figure 4: Antenna with the pointing drive (a) and antenna fastened to a spacecraft (b).

3 ANTENNA PROTOTYPE - DEMONSTRATOR

Physical full-size prototype-demonstrator of the antenna has been built and tested. The sandwich body of the antenna is fabricated by the vacuum bagging using a conical mandrel coated with a release agent. Four layers of a carbon fabric/epoxy prepreg are laid down against the mandrel surface to form the inner skin of the sandwich shell first. Then an adhesive film is placed over the laminate and the layer of an aluminium honeycomb is laid down. The honeycomb layer is covered by the adhesive film and another four layers of the carbon fabric preprpeg are laid. The preforming is completed by applying the standard sequence of release films, bleeder and breather layers. The preform assembly is sealed into the vacuum bag and placed in the oven for curing. The pressure applied to the laminate due to the vacuum drawn is 0.08 MPa. After debugging, the cured sandwich shell has been trimmed to dimensions using high speed milling. The machining involved trimming the edges, cutting off the fragment of the side part of the shell, and drilling the holes as required. The trimmed shell is shown in Fig. 5a with the dimensions presented in Fig. 5b.



(a) (b)

Figure 5: The trimmed sandwich shell (a) and the shell dimensions (b).

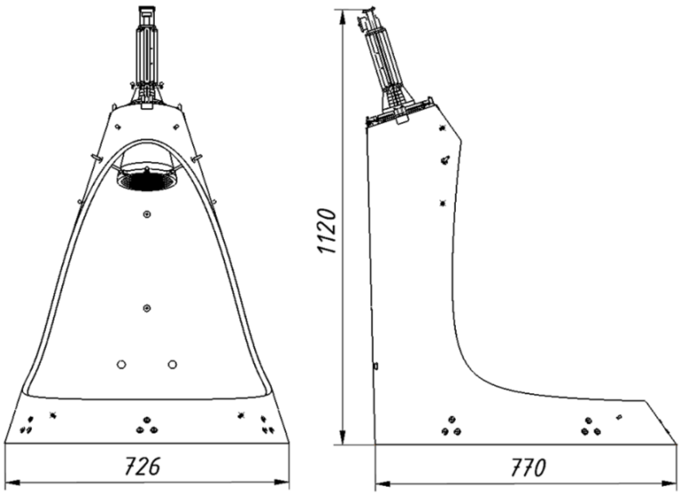
The carbon fabric reinforced material of the sandwich skins has the following characteristics: modulus of elasticity in the warp and weft directions is equal to 70 GPa, the shear modulus is 5 GPa, both Poisson's ratios are equal to 0.31 and density is 1550 kg/m^3. The thickness of each of the skins is 0.5 mm. The layer of the aluminium honeycomb made of the 0.023mm-thick aluminium foil has the thickness of 14 mm. The size of the cell is 2.5 mm. The core material is characterised by two transverse moduli: 150 MPa and 80 MPa, respectively. The density of the honeycomb material is 40 kg/m^3.

The sandwich reflector is made using the same materials and fabrication procedure. The feed components are machined from an aluminium alloy.

The assembled antenna is shown in Fig. 6a with the dimensions given in Fig. 6b.

4 MODAL ANALYSIS

Being attached to the spacecraft, the antenna is subjected to substantial dynamic loads during the launch and injection into orbit. Hence its vibration analysis is important part of the design procedure.



(a) (b)

Figure 6: Assembled antenna (a) and dimensions of the assembled antenna (b).

Finite-element modal analysis of the antenna has been performed using MSC Nastran [6]. The following elements have been employed to model various parts of the structure: BEAM, PLATE, LAMINATE, and MASS. The pins fastening the feed and reflector to the antenna body have been modelled using the BEAM elements. The PLATE elements have been employed to model the fastening rings and the aluminium shell of the horn of the feed. The sandwich body of the antenna and the reflector have been modelled using the LAMINATE elements. The feed is simulated using the MASS element.

The complete finite-element model of the antenna is shown in Fig. 7. The masses of the structural parts are given in Table 1.

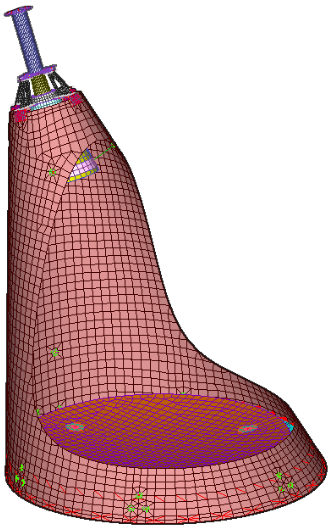


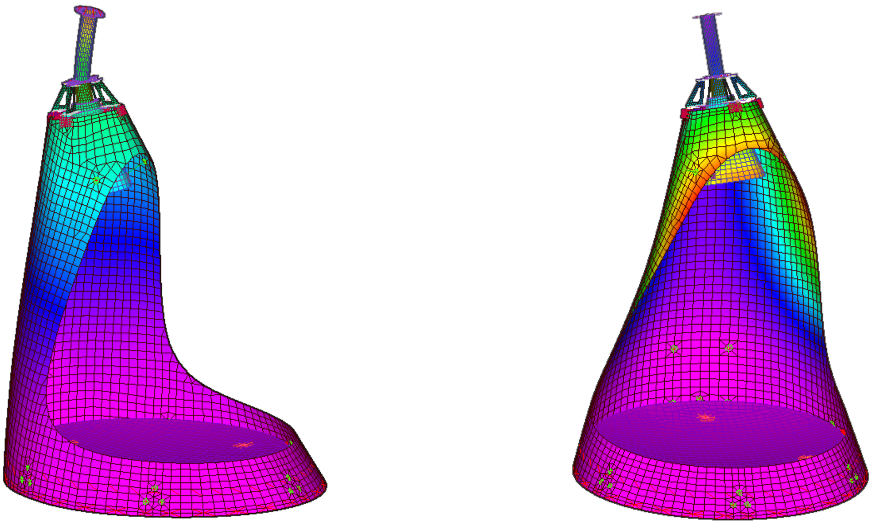
Figure 7: Finite-element model of the antenna.

The conical sandwich body of the antenna is supported at the six points located at the bottom edge of the shell. These boundary conditions reflect the way the structure has been fixed during the vibration tests. The finite-element model is composed of 14289 elements.

Based on the modal analysis, the frequencies and vibration modes of the integral antenna structure have been determined. The first (bending) and the second (torsion) vibration modes are shown in Fig. 8a,b. The corresponding frequencies predicted by the analyses are 92.78 Hz and 113.46 Hz, respectively. It should be noted that the value of the first frequency is often used as an indirect measure of the structural stiffness in aerospace industry. It follows from the results obtained from the finite-element analysis that the structure under consideration has sufficiently high stiffness necessary for the satisfactory technical performance of the antenna.

Structural component	**Mass, kg**
Sandwich body	2.54
Reflector	1.13
Feed	1.27
Fastening rings	0.69
Fasteners	0.53
Overall mass of the antenna	6.16

Table 1: Mass distribution.



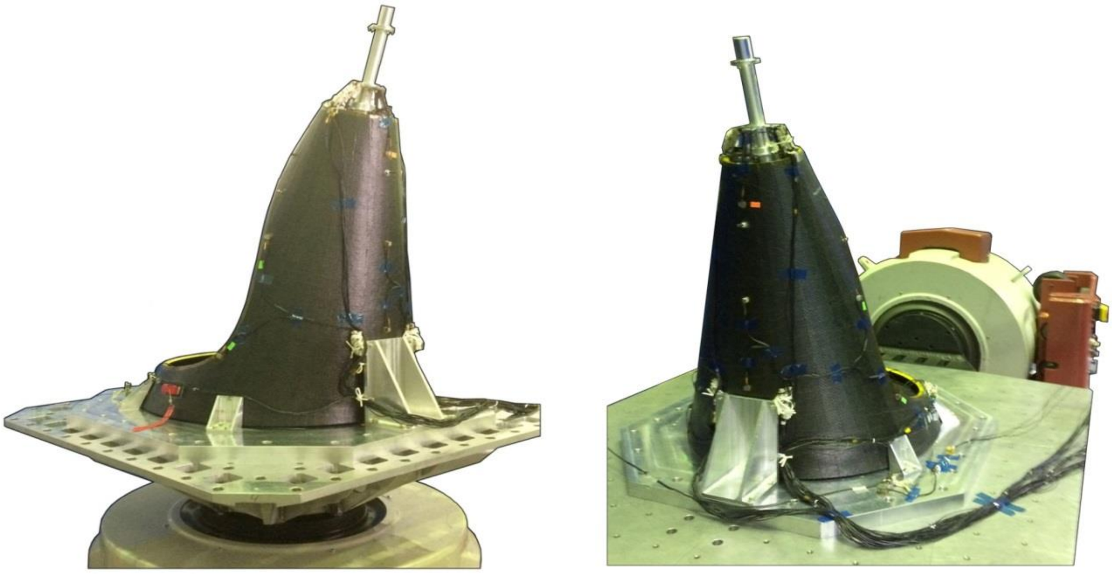
(a) (b)

Figure 8: The first (bending) (a), and the second (torsion) (b) vibration modes.

5 EXPERIMENTAL RESULTS

The design concept of the antenna structure has been verified experimentally using vibration and thermal testing. Before and after each test, the geometry and dimensions of the antenna have been optically measured. The structural parts of the antenna have been marked using polished metal 8-mm-diameter spheres located at certain reference points. Coordinates of these points have been determined before and after testing using laser radar. According to design requirements, deviation of the coordinates of the reference points caused by mechanical and thermal loadings should not exceed 0.2 mm.

Mechanical testing has been performed using a vertical (see Fig. 9a) and horizontal (see Fig. 9b) vibration tables. The antenna is fixed to the table using six brackets. The amplitudes and frequencies of vibrations have been measured by sixteen transducers attached to various parts of the antenna. The acceleration induced by the vibration tables has been controlled using the accelerometers fixed to the supporting platform.



(a) (b)

Figure 9: Antenna on the vertical (a) and horizontal (b) vibration tables.

The antenna has been subjected to a sinusoidal mechanical loading with the frequencies of the table's vibrations ranging from 5 Hz to 200 Hz. The loading has been applied in three stages. At the first stage, the acceleration of 0.1g ($g = 9.81\ \mathrm{m/s^2}$) has been created by the vibration table. The first resonant frequency of vibrations has been determined within the aforementioned frequency range. At the second stage, the table acceleration has been equal to 10g. Under this acceleration, the antenna is subjected to inertia loads typical for the final part of the spacecraft launch. At the third stage of loading program, the acceleration is again lowered to 0.1g and the first resonant frequency is found. Once this is complete, the difference is calculated between the values of the first resonant frequencies determined at the first and third stages of loading. If this difference is less or equal to 5% than it is concluded that no damage causing the stiffness reduction of the structure has been induced.

The response of one of the vibration sensors installed in the vicinity of the top edge of the cone is shown in Fig. 10. The antenna is placed on the horizontal vibration table. The sensor is measuring the vibration parameters in the direction of the loading induced by the vibrating table. The sensor response reflects a relationship between the frequency of vibrations and the acceleration of the controlled point of the structure. The solid and dashed curves of the graph shown in Fig. 10 correspond to the first and third stages of loading, respectively. The resonant frequency of vibrations determined at the stage one is equal to 94 Hz with the acceleration of this point of structure equal to 0.52g. The corresponding resonant frequency at the stage three is equal to 91 Hz and the vibration sensor registered the acceleration of 0.69g. The difference between these values of resonant frequencies is 4%. It should be noted that the results of the vibration tests performed confirm the correctness of the predictions made using the finite-element analysis: the calculated value of the frequency is 92.78 Hz.

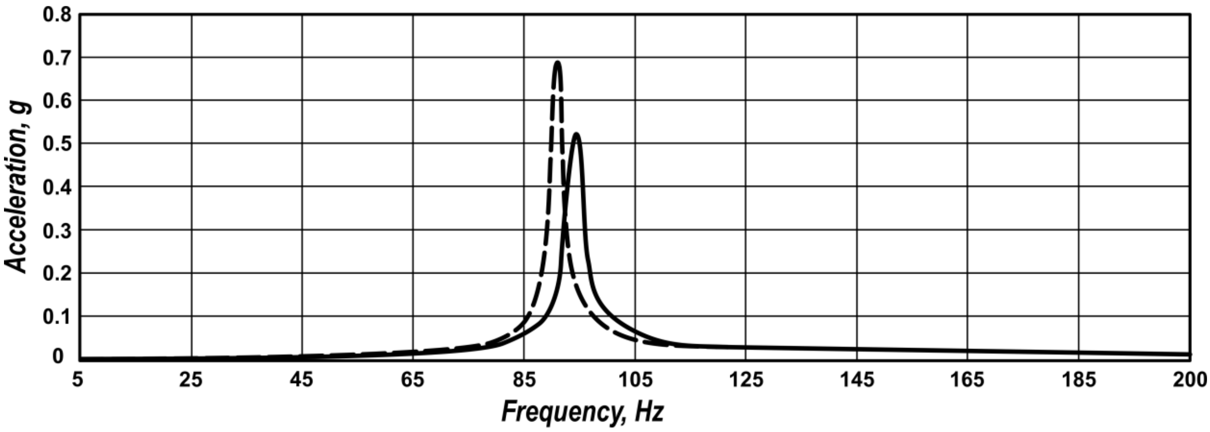


Figure 10: The response of the vibration sensor.

The deviations of the coordinates of reference points measured after vibrations tests did not exceed 0.15mm.

The thermal testing of the antenna has been performed in the environmental chamber. The chamber temperature varied from -135°C to +135°C within 90 minutes and this cycle was repeated three times. Upon completion of the test, the deviations of the coordinates of the reference points have been measured. The maximum deviation registered is equal 0.12 mm. These measurements confirm the geometry and dimensional stability of the structure.

6 CONCLUSIONS

A novel design of an integral structure of the offset mirror spacecraft antenna is proposed in this work. The antenna body is designed in the form of a conical sandwich shell made of composite materials. The radio signal transmission zone fits inside the shell. One of the main advantages of such a structure is in its compact size. The full scale physical prototype was designed, built, analysed, and tested. It was shown, based on the computational (finite-element analysis) and experimental (vibration and thermal testing) results, that the proposed integral structure of the antenna has sufficient stiffness and dimensional stability, and can be successfully implemented in the design of spacecraft antennas with wide ranges of the radio wave transmission. These results provide a proof of design concept and demonstration of its feasibility.

ACKNOWLEDGEMENT

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