MODEL OF DEPLOYABLE COMPOSITE RIM OF LARGE SPACE ANTENNA

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Abstract

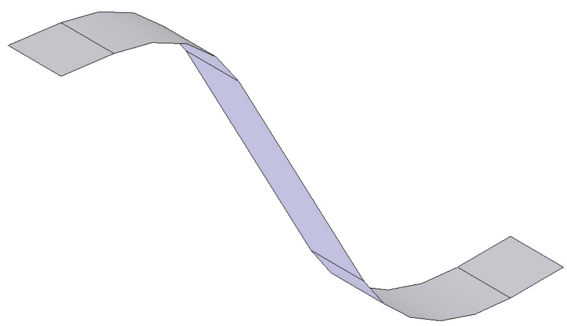
The new model of a deployable composite rim of the large space antenna is considered in the present paper. The basic element of the rim is the curved composite strip. Deployed antenna rim consists of two circles of the carbon-epoxy curved strips and carbon-epoxy tubes connecting them. In the folded configuration the curved strips are straightened and reserve the energy owing to structural deformation. Opening of the antenna on the orbit is accounted for by the release of the reserved energy. The equations describing nonlinear deformation of a composite strip during transformation of the antenna rim are received. The solution of these equations will allow to define the optimum form of the curved strip and to estimate the reserved energy. The finite element modeling of stresses arising in the composite strip at its deformation from the curved state to the rectilinear state has been performed. The modal analysis of the antenna rim has been executed.

1 Introduction

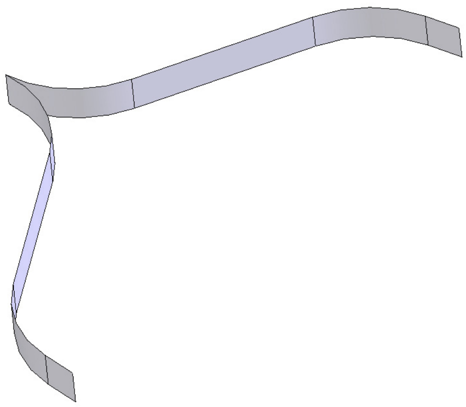
At present the large deployable antennas are being used increasingly for modern space vehicles. Space antennas have the sizeable diameter in the operating configuration. At the same time the internal volume of carrier rocket fairing is limited. Therefore, the essential features required of any large antennas are that the antenna should be compactly packed to place in space vehicle and reliably deployed on orbit. Several structural concepts of deployable space antennas can be found in the literature [1]-[5]. One of such concepts is the antenna consisting of a rim and attached to them of a thin radioreflecting membrane. The rim deployment on the orbit can be carried out in several ways. The most promising way is such that the rim deployment is accounted for by the deformation energy of its elastic elements. The application of composite materials in the design of such rim is the most effective. The new model of a deployable composite rim of the large space antenna is considered in the present paper. The equations describing nonlinear deformation of a composite strip during transformation of the antenna rim are received. For the purposes of design the inverse problem has been solved. In this problem the stresses and the displacements arising in the strip at its deformation from the rectilinear state to the curved state have been investigated. The received analytical solution will allow to define the optimum form of the curved strip and to estimate the reserved energy. These results enable to design of the basic elastic elements of the antenna rim. The finite element modeling of stresses and displacements arising in the composite strip at its deformation from the curved state to the rectilinear state has been performed. In addition to the stress analysis the modal analysis of the antenna rim has been executed.

2 Design of deployable composite rim

The basic element of the rim is the curved composite strip, which in unloaded state has the form shown in Fig. 1a.



(a)



(b)

Fig. 1. The curved strip (a) and elastic element (b)

Such curved strip can be received by forming on the mold, repeating its contour. Two curved strips form the elastic basic element of the rim as shown in Fig. 1b. Referring to Fig. 2, the deployed antenna rim consists of two circles of the carbon-epoxy curved strips and carbon-epoxy tubes connecting them.

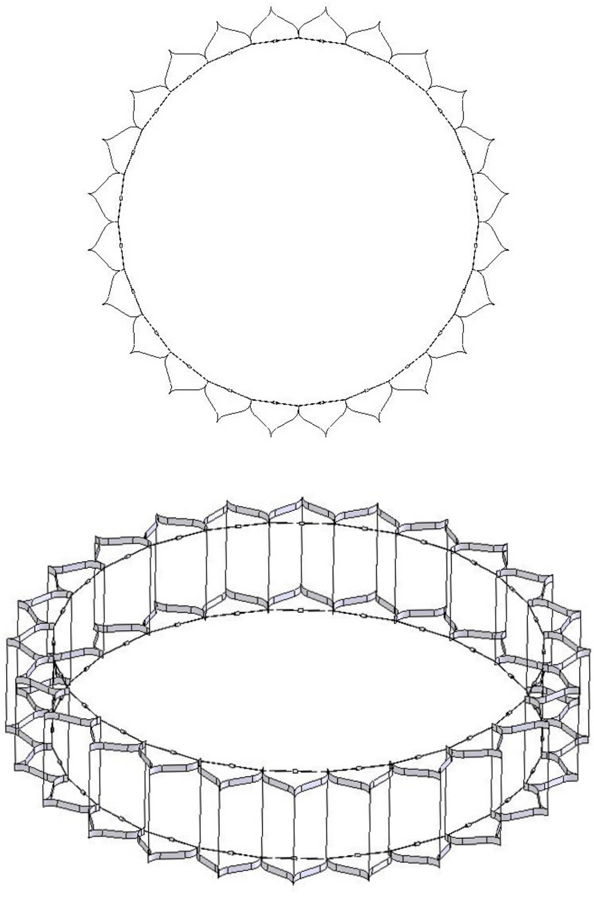


Fig. 2. The deployed antenna rim

Through strips on an internal circle the flexible cables are passed. The cables stretch before placing of the antenna on the space vehicle. The connection points of the curved strips move on radius to the antenna center as in Fig. 3.

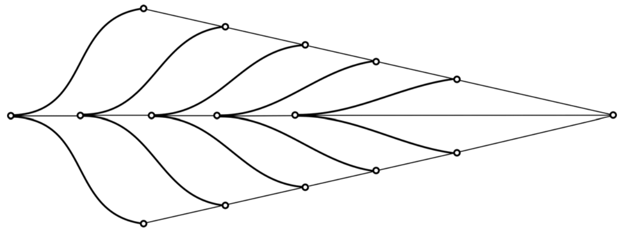


Fig. 3. The deformation of the strips during transformation of the antenna rim

In the folded configuration the curved strips are straightened and reserve the energy owing to structural deformation. The antenna in the folded configuration is shown in Fig. 4.

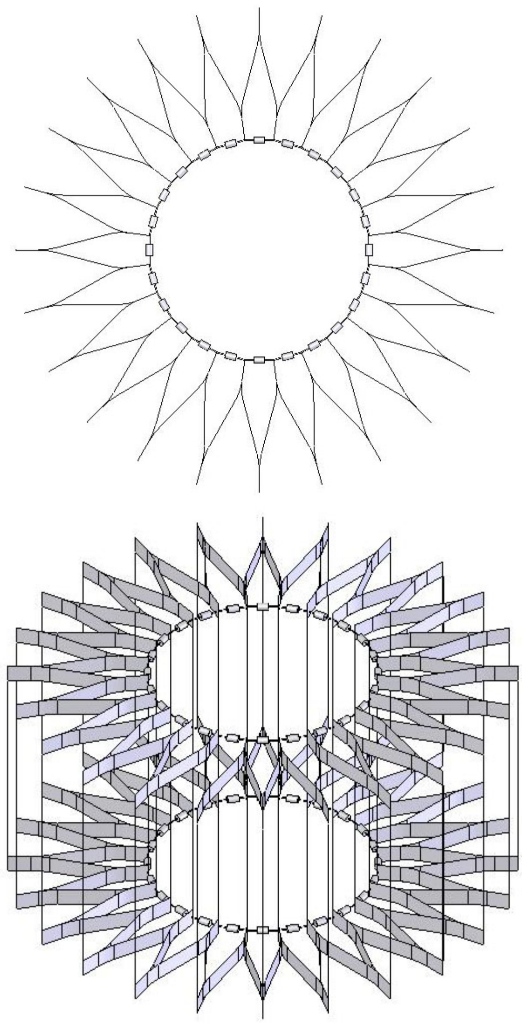


Fig. 4. The folded antenna rim

Opening of the antenna on the orbit is accounted for by the release of the reserved energy. The cable is unreeled and the elastic elements move on radius from the antenna center to the external circle as in Fig. 3. The deployable antenna with attached net system is shown in Fig. 5.

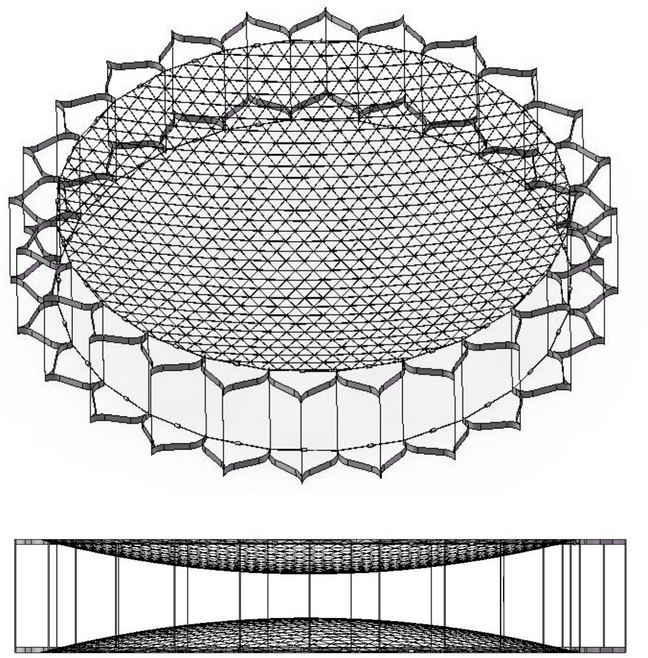


Fig. 5. Deployable antenna with attached net system

The initial parameters for designing are the internal rim diameter in the deployable configuration and the external rim diameter in the folded configuration. The first size defines the aperture diameter and the second size defines the diameter of space for storage of the folded antenna in the carrier rocket fairing.

3 Model of composite strip

First we consider the problem of the shape determination of bent strip. It would appear reasonable that the shape can be found from a solution of so-called inverse problem, where rectangular strip deforms to the required bent position as shown in Fig. 6. The corresponding system of nonlinear equations, describing the strip deformation as beam deformation, has the following form [6]

$$\frac{dN}{dx} = 0 \tag{1}$$

$$\frac{d^2M}{dx^2} + N\frac{d^2w}{dx^2} = 0 \tag{2}$$

$$N = B\left[\frac{du}{dx} + \frac{1}{2}\left(\frac{dw}{dx}\right)^2\right] \tag{3}$$

$$M = -D\frac{d^2w}{dx^2} \tag{4}$$

where N is the axial force, M is the bending moment, u is the displacement along the axis x, w is the deflection of the strip, B is the axial stiffness of the strip, and D is the bending stiffness of the strip.

Stiffness parameters of an orthotropic strip are defined by the following formulas

$$B = E_x hb \qquad D = E_x b\frac{h^3}{12} \tag{5}$$

where h is the strip thickness, b is the strip width, and E_x is the elastic modulus of strip material in the direction of the axis x.

Assume that the strip is clamped at the left end, and the right end of the strip moves along the axis w over a distance δ and rotates through the angle θ about the axis as shown in Fig. 6. The parameters δ and θ define the deformation of the strip inside the sector which is occupied by the major bent element of the rim (Fig. 1a). The strip is not loaded by the longitudinal forces, and, therefore, as follows from Eq. (1), $N = 0$.

Solving jointly Eqs. (2) and (4), we obtain

$$w = -\frac{1}{D}\left(C_1\frac{x^3}{6} + C_2\frac{x^2}{2}\right) + C_3x + C_4 \tag{6}$$

In order to obtain the integration constants C_i (i=1,..,4), we utilize the following boundary conditions

$$x = 0 \quad w = 0 \quad \frac{dw}{dx} = 0$$
$$x = l \quad w = \delta \quad \frac{dw}{dx} = \theta \tag{7}$$

where l is the strip length. Substituting Eq. (6) into Eq. (7), we obtain

$$C_1 = \frac{12D}{l^3}\left(\delta - \theta\frac{l}{2}\right)$$

$$C_2 = -\frac{6D}{l^2}\left(\delta - \theta\frac{l}{3}\right) \qquad (8)$$

$$C_3 = C_4 = 0$$

Taking into account Eq. (8), we obtain the following expression for the deflection

$$w = -2\frac{x^3}{l^3}\left(\delta - \theta\frac{l}{2}\right) + 3\frac{x^2}{l^2}\left(\delta - \theta\frac{l}{3}\right) \qquad (9)$$

Now we obtain the displacement u. From Eq. (3), taking into account that $N = 0$, we obtain

$$\frac{du}{dx} = -\frac{1}{2}\left(\frac{dw}{dx}\right)^2 \qquad (10)$$

Substituting Eq. (9) into Eq. (10), and solving the derived equation with $u(x = 0) = 0$, we obtain

$$u = -18\left[\frac{x^5}{5l^6}\left(\delta - \theta\frac{l}{2}\right)^2 - \frac{x^4}{2l^5}\left(\delta - \theta\frac{l}{2}\right)\left(\delta - \theta\frac{l}{3}\right) + \frac{x^3}{3l^4}\left(\delta - \theta\frac{l}{3}\right)^2\right] \qquad (11)$$

Eqs. (9) and (11) define the shape of the bent strip which can be obtained by molding. Next, we estimate the maximum energy which the strip is capable to store during deformation from a rectilinear to a bent state. The expression for the potential energy of bent beam has the following form

$$U = \frac{1}{2}D\int_0^l \left(\frac{d^2w}{dx^2}\right)^2 dx \qquad (12)$$

Substituting Eq. (9) into Eq. (12), we have

$$U = \frac{3D}{l^3}\left(3\delta^2 - 3\delta\theta l + \theta^2 l^2\right) \qquad (13)$$

Note, that the total stored energy of antenna rim is equal to sum of deformation energies of all curved strips. Deformation of strip takes place inside a sector with central angle θ. The value of the angle is given by $\theta = \pi/n$, where n is the number of elastic elements, consisting of two curved strips as shown in Fig. 1b. Let R is the internal radius of the deployed antenna rim. For given values R, l and θ (Fig. 6) and considered character of deformation, the deflection δ at the right end is dependent variable. Let us establish the correlation between the parameters R, l, θ and δ.

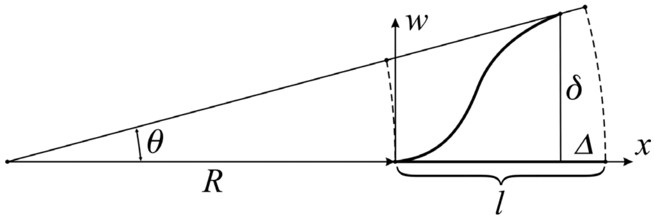


Fig. 6. The deformation of the strip

From Fig. 6 it follows that

$$\frac{\delta}{R + l - \Delta} = tg\theta \qquad (14)$$

where $\Delta = |u(x = l)|$ is the absolute value of the displacement of the right end of the strip. Assuming that angle θ is small, from Eq. (14) we have

$$\delta = \theta(R + l) - \theta\Delta \qquad (15)$$

Assuming in Eq. (11) $x = l$, we obtain

$$\Delta = \frac{3}{5l}\left(\delta^2 - \frac{1}{6}\delta\theta l + \frac{1}{9}\theta^2 l^2\right) \qquad (16)$$

Substituting Eq. (16) into Eq. (15), we obtain the following quadratic equation

$$\frac{3}{5}\frac{\theta}{l}\delta^2 + \left(1 - \frac{\theta^2}{10}\right)\delta + \frac{\theta^3 l}{15} - \theta(R + l) = 0 \qquad (17)$$

Now, we transform Eq. (17) into dimensionless form. To accomplish this, we introduce the following dimensionless displacement

$$z = \frac{\delta}{(R + l)\theta} \qquad (18)$$

Taking into account Eq. (18), Eq. (17) will have the following form

$$18z^2 + 3\frac{10-\theta^2}{\theta^2} s\,z + 2s^2 - 30\frac{s}{\theta^2} = 0 \quad (19)$$

where $s = 1/(1+r)$ and $r = R/l$.

The results of analysis of the influence of the parameters n and r on the dimensionless deflection z is given in Table 1.

Table 1. Influence of the parameters n and r on the dimensionless deflection z

n \ r	5	10	15	20
12	0.834	0.750	0.691	0.645
18	0.911	0.855	0.810	0.773
24	0.946	0.908	0.875	0.847
32	0.968	0.944	0.922	0.902

As shown in Table 1 the dimensionless deflection reduces with a rise of r and increases with a rise of n.

Using Eq. (19), we transform the equation for potential energy of deformation (13) to the following form

$$U = \frac{3D}{l} f \quad (20)$$

where

$$f = \theta^2\left[3z^2(1+r)^2 - 3z(1+r) + 1\right] \quad (21)$$

The values of f for different values of n and r are given in Table 2.

Table 2. Influence of the parameters n and r on the f values

n \ r	5	10	15	20
12	4.183	12.373	22.903	35.004
18	2.263	7.260	14.207	22.625
24	1.382	4.634	9.381	15.353
32	0.818	2.828	5.878	9.837

From the results shown in Tables 2 we can conclude that for a given values of elastic and geometrical parameters of a strip, the stored potential energy of deformation increases with a rise of r and decreases with a rise of n.

In summary, the performed analysis allows to define the shape of elastic strips which form the antenna rim. The obtained equations allow to estimate the energy of curved strip, and, subsequently, to calculate the total stored energy required for antenna unfolding. The equations also define the values of the bending moments and with it the values of the stresses inside a composite strip during deformation. The analysis above is necessary in an early stage of a design of antenna rim.

4 Stress and modal analyses

The finite element modeling of stresses and displacements arising in the composite strip at its deformation from the curved state to the rectilinear state has been performed. The strip length l is 1.3 m, the thickness h is 0.001 m, the radius R is 5 m and the basic element number n is 24, the modulus of elasticity E_x is 100 GPa. The finite element mesh of the curved composite strip is shown in Fig. 7. The deformed shapes and the stress distributions are illustrated in Fig. 8.

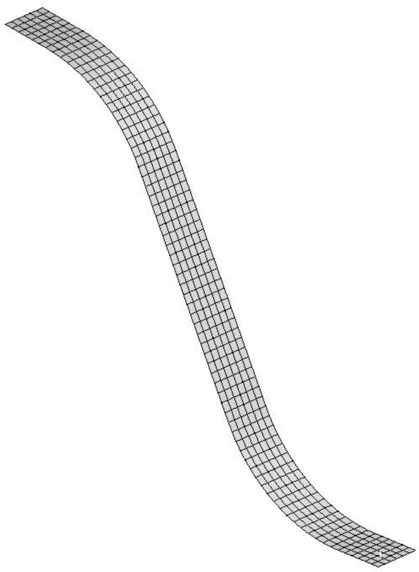


Fig. 7. Finite element mesh of the curved composite strip

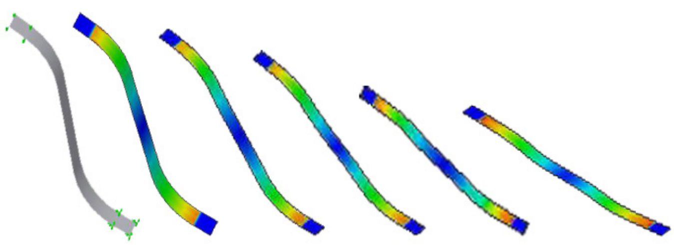


Fig. 8. Deformed shapes of the curved composite strip

In addition to the stress analysis the analysis of the vibration frequencies and forms of the deployed antenna rim has been executed. The shell finite element has been used for modeling of the curved strips and tubes connecting them. The finite element mesh of the part of the rim is shown in Fig. 9. The rim is fixed in four points as is shown in Fig. 10.

Fig. 9. Finite element mesh of the part of the rim

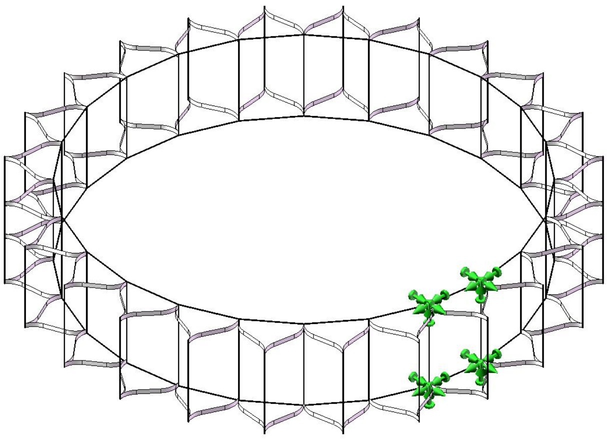
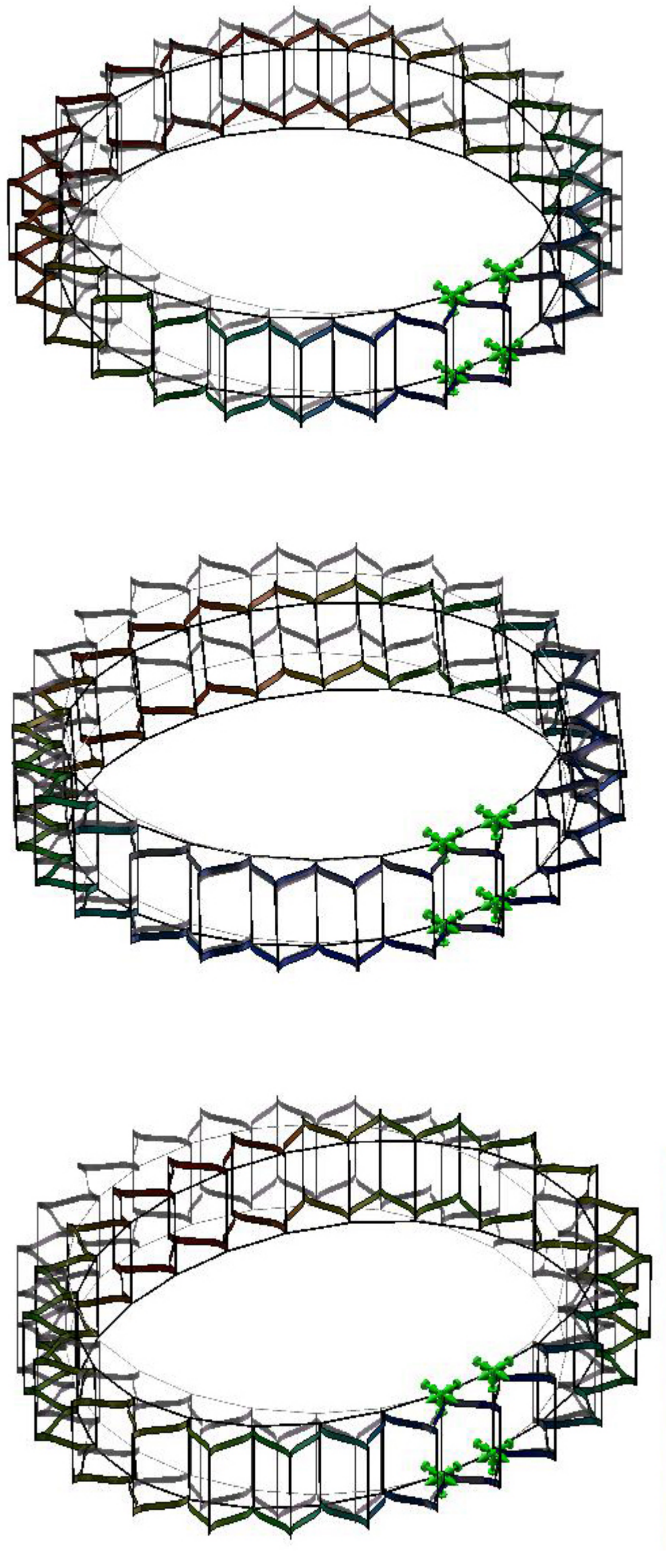


Fig. 10. Fixed rim

The fixing simulates fastening of the rim to a space vehicle or to its extending bar. The rim material density is 1500 kg/m^3. The rim mass is 32 kg. Five vibration forms are shown in Fig. 11. The vibration frequencies are 0.12 Hz, 0.14 Hz, 0.35 Hz, 0.43 Hz, and 0.75 Hz respectively.



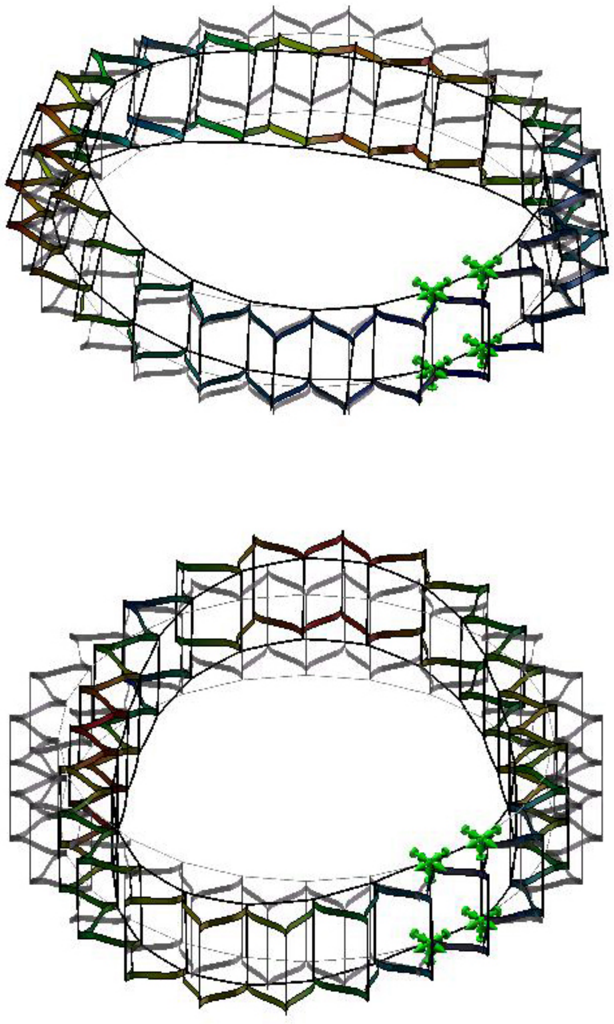


Fig. 11. Five vibration forms of the rim

Thus, the new model of the deployable composite rim of the large space antenna is developed in the present paper. Deployed antenna rim consists of two circles of the carbon-epoxy curved strips and carbon-epoxy tubes connecting them. In the folded configuration the curved strips are straightened and reserve the energy owing to structural deformation. Opening of the antenna on the orbit is accounted for by the release of the reserved energy. The solution of the equations describing nonlinear deformation of a composite strip during transformation of the antenna rim will allow to define the optimum form of the curved strip and to estimate the reserved energy. The finite element modeling of stresses arising in the composite strip at its deformation from the curved state to the rectilinear state has been performed. The modal analysis of the antenna rim has been executed.

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