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Исследование жесткости композитной спицы зонтичной антенны космического аппарата

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Антенны зонтичного типа часто применяются в современных космических аппаратах. Их преимущество состоит в возможности компактного размещения во время вывода на орбиту. При этом они должны обеспечивать необходимую стабильность в развернутом виде в космосе. Жесткость антенны главным образом зависит от жесткости спиц, проектирование которых выливается в комплексную задачу научного поиска. Антенны космических аппаратов должны обеспечивать функциональную работоспособность и в то же время обладать минимальной массой. Кардинальное направление совершенствования космических антенн состоит в применении новых конструкционных материалов. Композиты отличаются высокими удельными механическими свойствами, что позволяют создавать конструкции с высокой степенью весового совершенства. Проблема связана с наличием большого количества проектных параметров, сложным образом влияющих на работоспособность композитных конструкций. Определение оптимального сочетания этих параметров для каждой конструкции и конкретного расчетного случая приводит к необходимости проведения комплексного численного эксперимента, базирующегося на специализированных алгоритмах, методиках и программах.

Целью исследования является проектирование композитной спицы зонтичной антенны космического аппарата, обеспечивающей требуемую несущую способность и максимальную жесткость при заданном ограничении массы конструкции. Оно предполагает разработку конечно-элементных моделей композитной спицы различного исполнения, в которых была бы заложена возможность оптимизации проектных параметров по критериям прочности, несущей способности и жесткости. В результате численного эксперимента определяются способы повышения несущей способности и жесткости разворачиваемой антенны космического аппарата.

Ключевые слова: спица зонтичной антенны, композиционные материалы, МКЭ.

Design of a flexible spoke for a spacecraft umbrella antenna

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Umbrella type antennas are often used in modern spacecraft. Their advantage is the possibility of compact placement during orbital insertion. At the same time, they must provide the necessary stability when

deployed in space. Antenna stiffness mainly depends on the stiffness of the spokes, the design of which is a complex task of scientific research. Spacecraft antennas must provide functional performance and, at the same time, have a minimum mass. The cardinal direction of improvement of space antennas consists in application of new structural materials. Composites are characterized by high specific mechanical properties, which allow to create structures with a high degree of weight perfection. The problem is related to the presence of a large number of design parameters that affect the performance of composite structures in a complex way. Determining the optimal combination of these parameters for each structure and a particular design case leads to the need for a complex numerical experiment based on specialized algorithms, methods and programs.

The aim of the study is to design a composite spoke for the umbrella antenna of a spacecraft, providing the required load-bearing capacity and maximum stiffness at a given mass limit of the structure. It involves the development of finite element models of the composite spoke of various designs, which would include the possibility of optimizing the design parameters by the criteria of strength, load-bearing capacity and stiffness. As a result of numerical experiment, the ways of increasing the bearing capacity and stiffness of the deployed spacecraft antenna are determined.

Keywords: Umbrella antenna spoke, composite materials, FEM.

Introduction

To ensure high-quality satellite communications, it is necessary to use large-diameter antennas. Due to the spatial limitations of the launch vehicle, such antennas can only be made in the form of transformable structures, one of the options of which is an umbrella-type antenna. The main requirements for umbrella antennas are the reliability of the deployment system and ensuring high accuracy of the shape of the reflective surface of the reflector, which theoretically should be an ideal paraboloid of revolution. The practical accuracy of the reflector shape is determined by the system of radial spokes, which in the deployed state should provide the required rigidity, and at the stage of launching into orbit - the stability and strength of the structure. At the same time, the basic requirement for the elements of the spacecraft must be met - high functionality with a minimum of their weight. The latter circumstance, on the one hand, has led to the widespread use of composite materials with high specific mechanical characteristics, on the other hand, it has significantly complicated the procedure for the optimal design of composite structures due to the increased number of variable design parameters affecting the functioning of these structures, and due to the behavioral characteristics of the composite itself.

When analyzing complex composite structures such as satellite antennas and spacecraft antennas, one should keep in mind both theoretical research on methods for modeling composites [1–3] and the accumulated experience in the design and production of directly transformable umbrella-type antennas [4–15].

Designing an umbrella antenna spoke is a complex multi-stage task. Our work focuses on ensuring the maximum possible rigidity of the antenna in the deployed state in orbit.

The work is of a theoretical nature and has an applied purpose. It is based on a numerical study of the influence of various factors on the rigidity parameters of a composite spoke of an umbrella antenna. The study involves performing numerous calculations in the environment of the integrated FE package of COSMOS/M programs, the quality of the analysis in which depends on the accuracy of the geometric and FE modeling of the spoke with the ability to take into account the real design features and properties of the object.

Study of the elliptical section spoke

In this paper, we will keep in mind the results of the previous study performed by the authors for the flexible spoke of an umbrella antenna. In the study, the values (Table 1) of the frequencies of natural oscillations were obtained for the first two modes corresponding to the cantilever bending oscillations of the spoke relative to the vertical (Y) and horizontal (Z) axes (Fig. 1). The data correspond to

models with a stepwise variable thickness of the elements (Table 1). They indicate that strengthening the elements adjacent to the fixed end significantly increases the rigidity of the spoke.

Let us perform a modal calculation of a solid composite spoke of elliptical cross-section (Fig. 1) 200 mm high and 90 mm wide, taking into account the weight of the web sector (Fig. 2). The results correspond to the models (without weighting) with different values of the thickness of the shell elements (Table 2). They show that of the two types of models with a constant thickness of elements of comparable masses (No. 1 from Table 1 and No. 2 from Table 2), the spoke of elliptical cross-section has an advantage, and by almost 2 times in the first frequency.

Table 1

Values of the first natural frequencies in the model with variable element thickness

Option	Thickness h_s , mm	First frequency, f_1 , Hz	Second frequency, f_2 , Hz	Weight, kg
1	0.60	2.11	7.05	1.658
2	0.48	2.41	7.88	1.650
3	0.36	2.76	8.83	1.642
4	0.24	3.19	9.96	1.634
5	0.12	3.75	11.39	1.627
6	0.00	4.56	13.31	1.619



Рис. 1. Спица с эллиптическим поперечным сечением

Fig. 1. Spoke with elliptical cross section

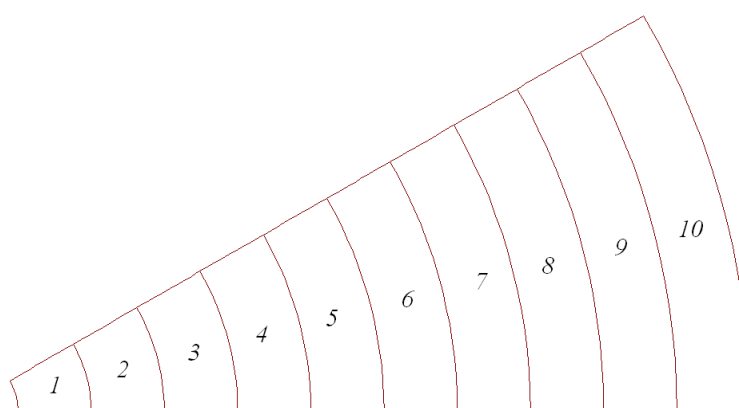


Рис. 2. Сектор полотна в 30°

Fig. 2. Sector of the canvas at 30°

Table 2

Values of the first frequencies of oscillations of a spoke of elliptical cross-section without taking into account the mass of the curtain

№	Thickness of elements, mm	Spoke weight, kg	First frequency, Hz	Second frequency, Hz
1	0.24	1.026	3.767	6.960
2	0.36	1.540	3.898	7.117
3	0.48	2.053	3.953	7.180

Let's add elements of concentrated mass MASS along the upper generating spoke (Fig. 3).

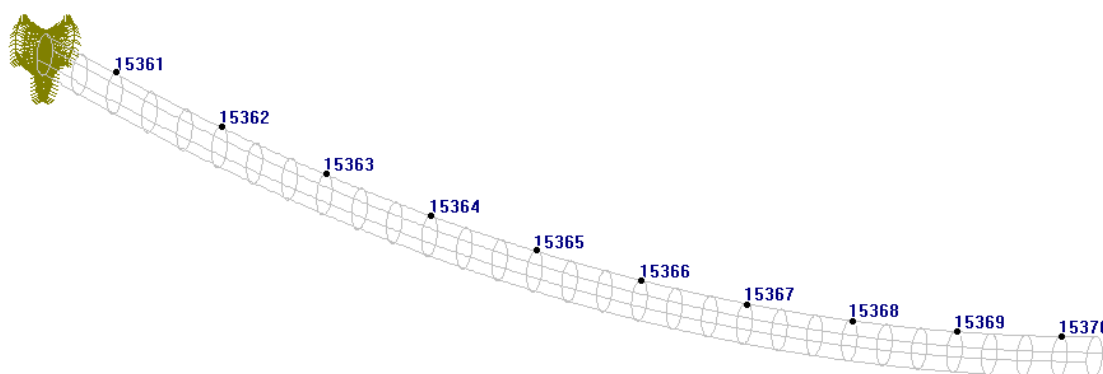


Рис. 3. Местоположение элементов сосредоточенной массы, имитирующих полотно

Fig. 3. Location of concentrated mass elements simulating canvas

The values of the inertial parameters in these elements (Table 3) are equal to the masses of the curtain strips of the corresponding zones of the sector (see Fig. 2).

Table 3

Masses of curatin sectors

Sector number	Sector area, m ²	Sector mass, g	Sector number	Sector area, m ²	Sector mass, g
1	0.2514	68.48	6	1.2383	337.31
2	0.4411	120.16	7	1.4537	395.99
3	0.6333	172.51	8	1.6779	457.06
4	0.8294	225.93	9	1.9119	520.80
5	1.0306	280.74	10	2.1566	587.46

The values of the natural oscillation frequencies of the spoke decrease (Table 4) due to the inertial effect of the mass of the web. It should be noted that the frequency of the first mode (Fig. 4) is higher than in a similar case for the basic model (1.065 Hz). The frequency of the vertical oscillation (Fig. 5) for thicknesses of shell elements from 0.36 to 0.48 mm is almost the same as in the basic model (3.602 Hz).

Table 4

Values of the first frequencies of oscillations of a spoke of elliptical cross-section taking into account the mass of the curtain

№	Thickness of elements, mm	Spoke weight, kg	First frequency, Hz	Second frequency, Hz
1	0.24	1.026	1.527	2.789
2	0.36	1.540	1.861	3.358
3	0.48	2.053	2.102	3.774

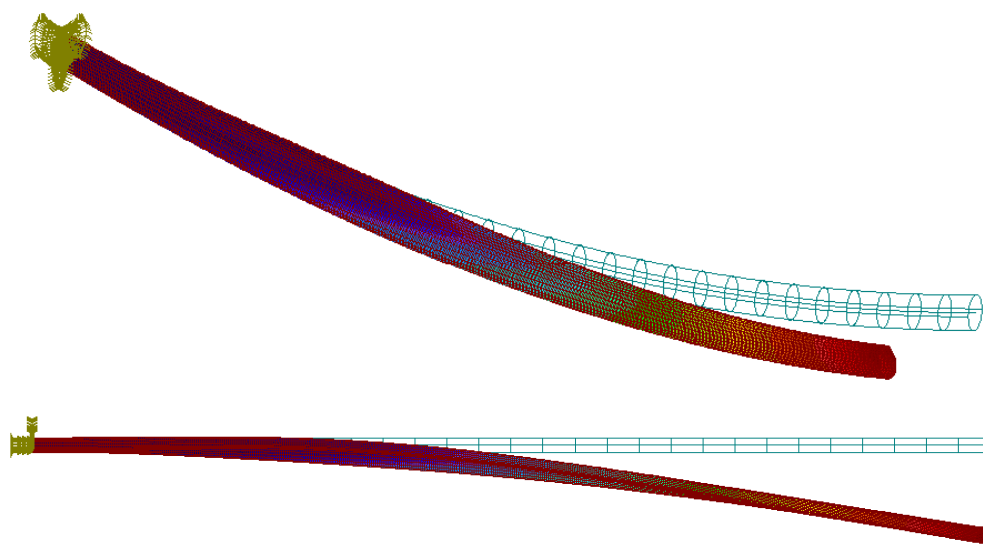
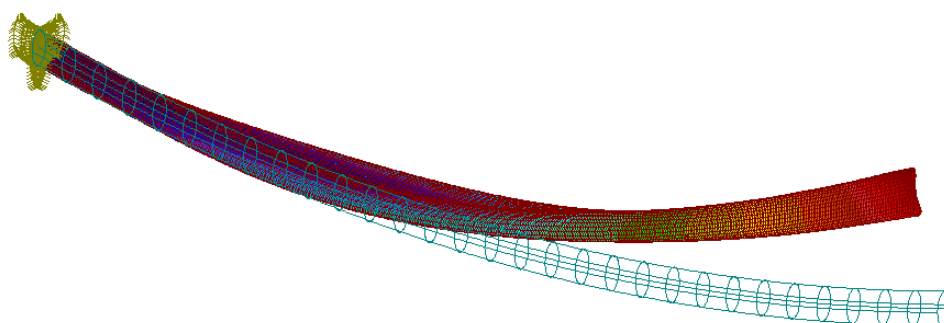


Рис. 4. Первая форма колебаний (внизу – вид сверху)

Fig. 4. First vibration mode (below – top view)

These values of natural oscillations (Table 4) correspond to a quasi-isotropic model with a fiber orientation angle in the composite $\varphi = 45^\circ$. When changing the reinforcement angle, the frequencies under study can be increased. This is evidenced by the results of a numerical experiment (Table 5) performed for a spoke of elliptical cross-section with a wall thickness of 0.36 mm. It should be noted that in the range of angle φ changes from 45° and below, there are maxima of the oscillation frequency values for the first two modes, which can be refined if necessary. However, even according to the available data, it is noticeable that the frequency of the first mode is approximately 2.2 times higher than that of the original version of the basic model (Fig. 6).



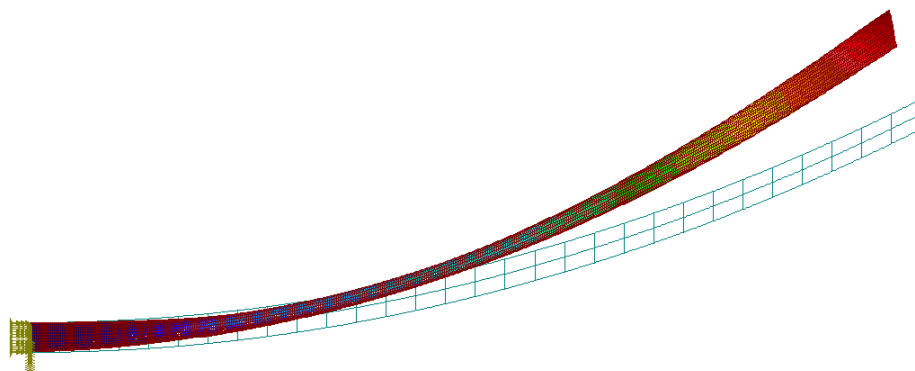


Рис. 5. Вторая форма колебаний (внизу – вид сбоку)

Fig. 5. Second vibration mode (below - side view)

Table 5

The values of the first frequencies of oscillations of a spoke of elliptical cross-section with different values of the winding angles of the composite fiber

№	Thickness of elements, mm	Reinforcement angle φ , deg	First frequency, Hz	Second frequency, Hz
1	0.36	45	1.861	3.358
2		35	2.253	4.177
3		25	2.183	4.292
4		15	1.778	3.697

An even greater increase in the rigidity of a cantilever-mounted spoke can be achieved by redistributing the thicknesses of the shell elements and reinforcing the sections close to the butt. This is shown in the following experiment, the results of which are presented in Table 6. The data correspond to a model with a fiber reinforcement angle of $\varphi = 25^\circ$. Three zones with different wall thicknesses are distinguished in it (Fig. 7). From the data in Table 6 it is evident that thickening the elements of the first zone leads to an increase in bending rigidity. The wall thickness in the third zone is proportionally reduced so that the total mass of the spoke remains unchanged.

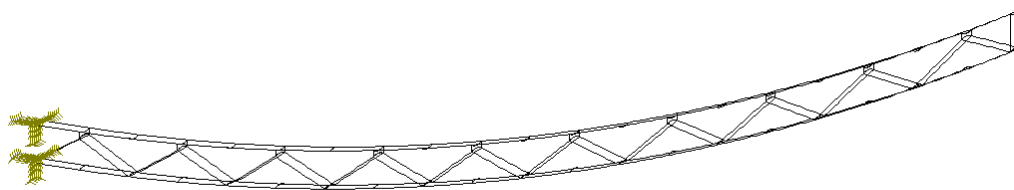


Рис. 6. Спика с десятью типовыми секторами

Fig. 6. Spoke with ten standard sectors

Table 6

The values of the first frequencies of oscillations of a spoke of elliptical cross-section with zones of different wall thickness (reinforcement angle $\varphi = 25^\circ$)

№	Thickness of elements by zones, mm			First frequency, Hz	Second frequency, Hz
	1	2	3		
1	0.36	0.36	0.36	2.183	4.292
2	0.48	0.36	0.24	2.652	4.843
3	0.60	0.36	0.12	2.964	5.142

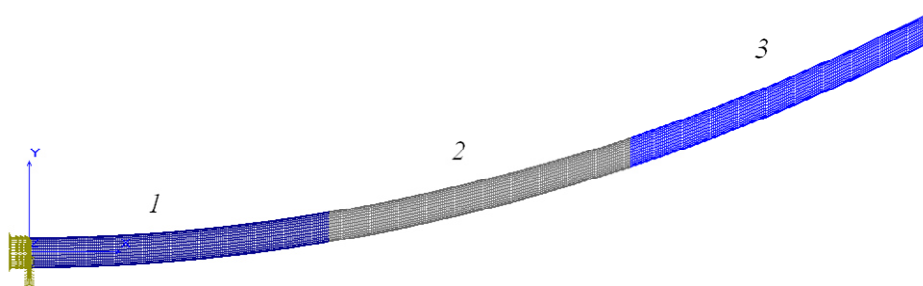


Рис. 7. Три зоны спицы с различной толщиной стенки

Fig. 7. Three spoke zones with different wall thicknesses

Study of the elliptical mesh spoke

Let us consider a mesh spoke of elliptical cross-section (axis values of 200 and 90 mm), produced by the method of continuous winding of composite fiber (Fig. 8). The design represents three families of ribs: spiral and annular (Fig. 9). The first two are formed by winding composite fibers along the geodesic lines of the surface at angles of $\pm\varphi$ to the longitudinal axis of the spoke. The third (annular) are located in sections spaced along the axis at equal distances from the intersection points of the spiral ribs.

The main design parameters for constructing a mesh structure for a specific spoke are:

- the number of spiral ribs of each family;
- the winding angle of the spiral ribs φ ;
- the height and width of the ribs of the spiral and ring groups.

It should be noted that the sections in both groups of spiral ribs must be the same, while the sections of the ring ribs may be different.

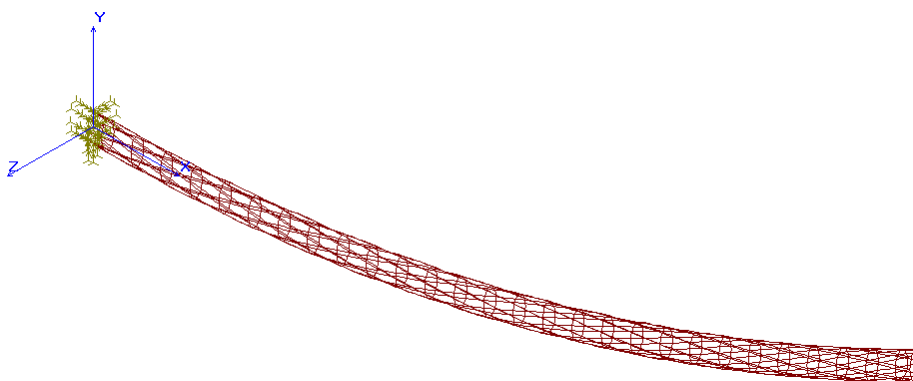


Рис. 8. Сетчатая спица с эллиптическим поперечным сечением

Fig. 8. Mesh spoke with elliptical cross section

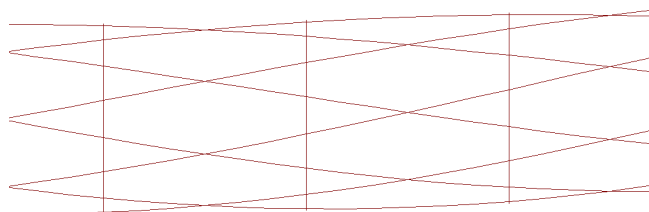


Рис. 9. Два семейства ребер анизогридной спицы

Fig. 9. Two families of anisogrid spoke ribs

Let us first perform a modal calculation of an anisogrid spoke of elliptical cross-section (Fig. 8) with a height of 200 mm and a width of 90 mm without taking into account the weight of the web. In the initial model, we will set 8 pairs of spiral ribs with an angle of their winding $\varphi = \pm 10^\circ$. We will study the dependence of the bending rigidity of the spokes on the values of the orientation angle of the spiral ribs φ . It should be noted that with an increase in this parameter, firstly, the length of the spiral ribs increases and, secondly, the number of annular ribs. We can say that the grid thickens (Fig. 10). Therefore, in order to maintain the total mass of the structure (with an increase in φ), it is necessary to adjust the dimensions of the cross-sections of the ribs (slightly decrease).

The results of the numerical experiment for a number of values of the orientation angle of the spiral ribs φ are presented in Table 7. When analyzing these data, we can conclude that the winding angle of the spiral ribs has a decisive effect on the bending rigidity of the anisogrid structure. The frequencies of natural oscillations are higher for models with small values of the angle φ , since they have a higher value of the reduced modulus of elasticity of the material of the structure, which clearly affects the frequencies of natural oscillations. Taking into account the revealed dependence, in further research we will use a model with the smallest of the technologically permissible values of the winding angle of the spiral ribs, namely $\varphi = \pm 10^\circ$.

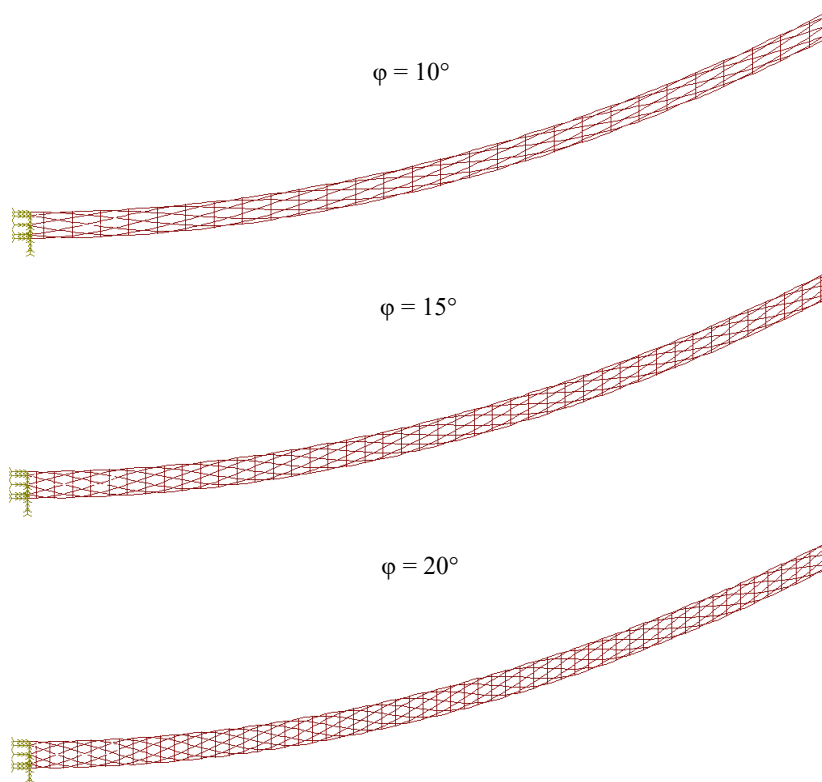


Рис. 10. Сетчатая спица с эллиптическим поперечным сечением с различными значениями угла намотки спиральных ребер

Fig. 10. Mesh spoke with elliptical cross-section with different winding angles of spiral ribs

Table 7

The values of the first frequencies of oscillations of a mesh spoke of elliptical cross-section

№	Winding angle of spiral ribs, φ , deg.	Rib cross-section, $h \times h$, mm $\times$ mm	Spoke weight, kg	First frequency, Hz	Second frequency, Hz
1	10	3.3	1.856	4.507	10.437
2	15	3.2	1.880	4.403	9.674
3	20	3.1	1.881	4.12	8.961

In the next experiment we will analyze the effect of the number of spiral ribs in the first two groups on the bending rigidity. In fact, here we will consider models with different mesh densities (Figs. 11–14).

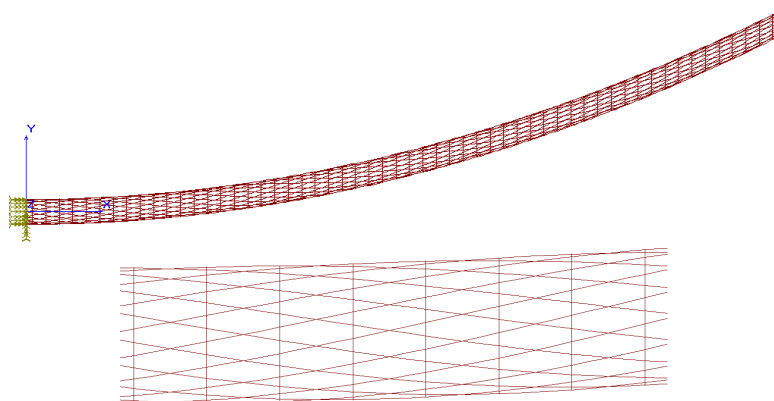


Рис. 11. Сетчатая спица с 16 спиральными ребрами одного семейства

Fig. 11. Mesh spoke with 16 spiral ribs of the same family

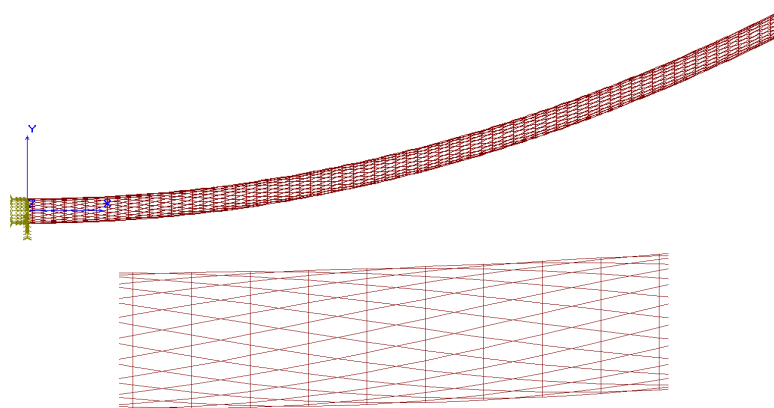


Рис. 12. Сетчатая спица с 20 спиральными ребрами одного семейства

Fig. 12. Mesh spoke with 20 spiral ribs of the same family

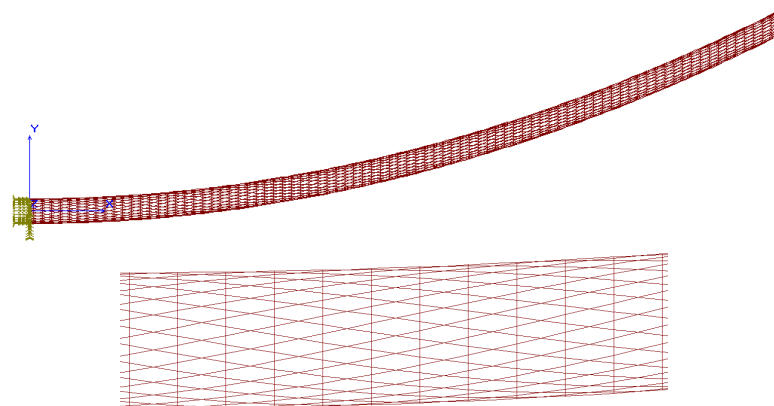


Рис. 13. Сетчатая спица с 24 спиральными ребрами одного семейства

Fig. 13. Mesh spoke with 24 spiral ribs of the same family

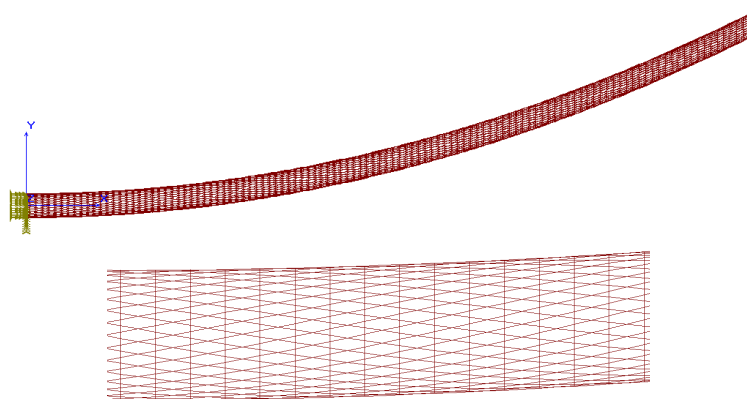


Рис. 14. Сетчатая спица с 32 спиральными ребрами одного семейства

Fig. 14. Mesh spoke with 32 spiral ribs of the same family

The results of modal calculations for spokes with different numbers of spiral ribs are presented in Table 8. The rib sections vary so that the total mass of the spoke remains within the specified limits (no more than 2 kg). These data indicate that spokes of equal mass with different and uniform mesh density have approximately the same bending rigidity.

Table 8

The values of the first frequencies of oscillations of a mesh spoke of elliptical cross-section with a different number of spiral ribs

№	Number of spiral ribs of one family	Rib cross-section, $h \times h$, mm $\times$ mm	Spoke weight, kg	First frequency, Hz	Second frequency, Hz
1	16	2.3	1.80	5.003	12.487
2	20	2.0	1.702	5.021	12.606
3	24	2.0	2.04	5.057	12.735
4	32	1.5	1.53	4.994	12.547
5	32	spiral – 1.7 ring – 1.5	1.914	5.024	12.588

Adding curatin mass

When adding the mass of the web sector (Fig. 2), the frequencies of natural oscillations decrease (Table 9), however, for all the studied models with different mesh densities, they are approximately 2.5 times higher (at the first frequency) than for the base model.

Table 9

The values of the first frequencies of oscillations of a mesh spoke of elliptical cross-section with a different number of spiral ribs, taking into account the mass of the fabric

№	Number of spiral ribs of one family	Rib cross-section, $h \times h$, mm $\times$ mm	Spoke weight, kg	First frequency, Hz	Second frequency, Hz
1	16	2.3	1.80	2.492	6.422
2	20	2.0	1.702	2.479	6.415
3	24	2.0	2.04	2.695	6.990
4	32	1.5	1.53	2.368	6.142
5	32	spiral – 1.7 ring – 1.5	1.914	2.595	6.699
6	32	1.7	1.965	2.626	6.809

Note that the mass of the curtain is taken into account by adding concentrated mass elements MASS to the FE model. Fig. 15 shows the numbers at the location of these elements in a mesh spoke with 16 spiral ribs of one family.

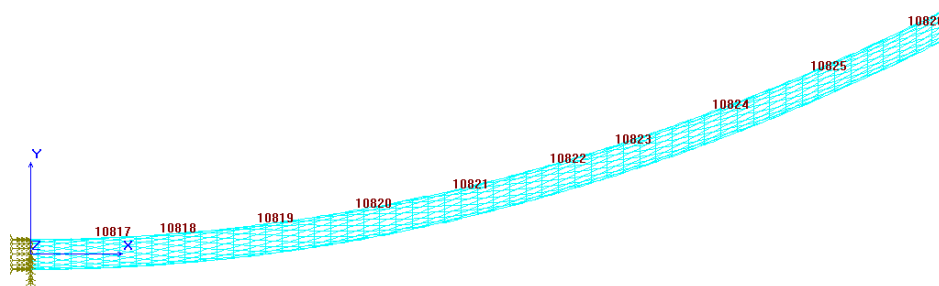


Рис. 15. Элементы сосредоточенной массы MASS в сетчатой спице с 16 спиральными ребрами одного семейства

Fig. 15. Mass elements MASS in a mesh spoke with 16 spiral ribs of the same family

Sustainability

The studied models of equal mass with different numbers of spiral ribs provide practically the same rigidity (Table 9). However, they revealed different behavior in the stability experiments under their own weight in the initial and inverted positions. The results of these calculations are given in Table 10. They show that as the grid becomes denser, the critical loads increase. This is due to the fact that the length of the rib sections in a typical segment is shortened, which leads to an increase in the stability factor, i.e., the load-bearing capacity increases.

The zones of stability loss in all cases are localized at the butt (Fig. 16): sections of individual ribs of those segments that are closer to the fixed end bend. However, the pattern of the anisogrid structure with a regular dense mesh corresponds to the shell form of stability loss.

The critical load of the mesh spoke is significantly higher than in the original base model (see Fig. 6).

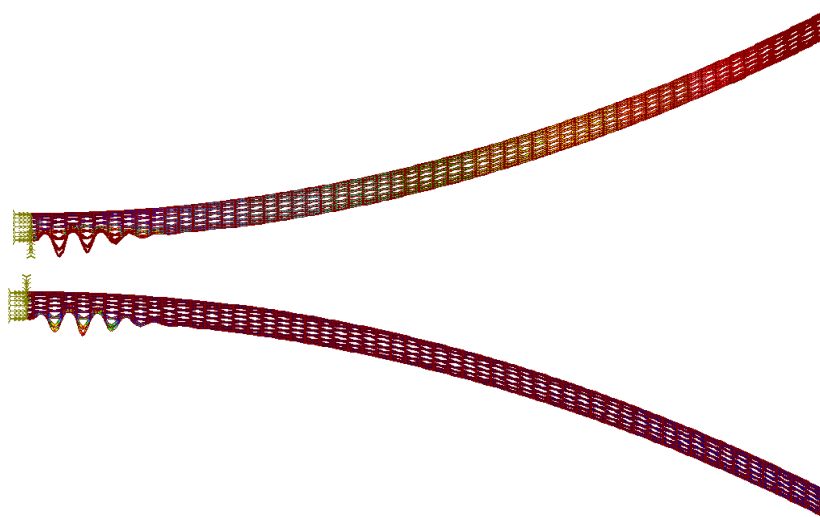


Рис. 16. Формы потери устойчивости сетчатой спицы с 16 спиральными ребрами одного семейства под действием собственного веса в исходном (вверху) и перевернутом положениях

Fig. 16. Buckling modes of a mesh spoke with 16 spiral ribs of the same family under its own weight in the original (top) and inverted positions

Table 10

Safety factors of a mesh spoke of elliptical cross-section with different numbers of spiral ribs

№	Number of spiral ribs of one family	Rib cross-section, $h \times h$, mm $\times$ mm	Spoke weight, kg	Safety factor	
				Initial position	Inverted position
1	16	2.3	1.80	9.458	9.702
2	20	2.0	1.702	9.906	9.921
3	24	2.0	2.04	15.065	15.308
4	32	1.7	1.965	17.691	16.61

Model with zones of different sections of elements

Taking into account the results of previous studies of the basic model spoke and the solid wound elliptical cross-section spoke, it can be assumed that strengthening the sections adjacent to the fixed end (butt) will increase the flexural rigidity of the structure. These sections can be strengthened in two ways: by thickening the grid by increasing the number of spiral ribs and by "thickening" the ribs themselves.

Since in the anisogrid models we are considering the grid of beam elements is quite dense and the structure works in many ways as a shell (this was demonstrated in the analysis of the bearing capacity), the two above methods of strengthening the sections are equivalent.

In the next experiment, we will perform a modal calculation of a spoke with different sections of beam elements in three zones (Fig. 17).

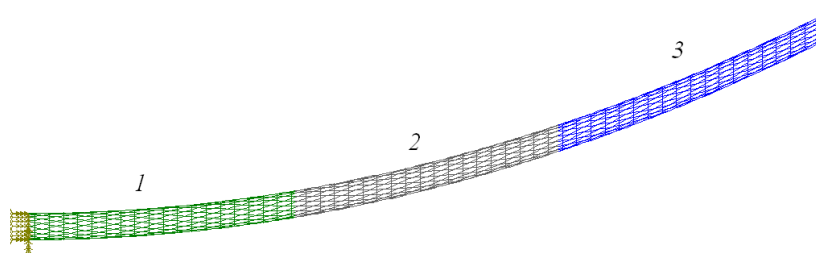


Рис. 17. Три отрезка спицы с различными размерами поперечного сечения балочных элементов

Fig. 17. Three spoke lengths with different cross-sectional dimensions of the beam elements

As the initial one we take a mesh spoke with 16 spiral ribs in each of the two families with their winding angle at angles $\varphi = \pm 10^\circ$.

We will successively reduce the size of the square section of the beam elements in the third zone (Fig. 17), located closer to the free end, and proportionally increase the sections of the ribs in the first zone adjacent to the butt. Here, in order to maintain the constant mass of the entire structure, a linear law of change in the cross-sectional areas in three zones was chosen. The results of calculating the frequencies of natural oscillations are summarized in Table 11 - for a "bare" spoke and Table 12 - for a spoke that perceives the inertial effect of the mass of the curtain, which, as before, is simulated by elements of concentrated mass MASS (see Fig. 15).

Analysis of the obtained data shows that due to the redistribution of masses, it is possible to increase the bending rigidity by 26% (at the first frequency).

To increase the efficiency of this method, it is necessary to conduct an additional study, which should take into account the technological features of the manufacture of anisogrid structures.

Table 11

The values of the first frequencies of oscillations of a mesh spoke of elliptical cross-section with different sizes of cross-sections of ribs in individual zones (excluding the mass of the curtain)

№	Rib cross-section, $h \times h$, mm $\times$ mm by zones			Spoke weight, kg	First frequency, Hz	Second frequency, Hz
	1	2	3			
1	2.3	2.3	2.3	1.80	5.003	12.487
2	2.57	2.3	2.0	1.792	6.169	15.311
3	2.89	2.3	1.5	1.778	8.429	20.652

Table 12

The values of the first frequencies of oscillations of a mesh spoke of elliptical cross-section with different sizes of cross-sections of ribs in individual zones (taking into account the mass of the curtain)

№	Rib cross-section, $h \times h$, mm $\times$ mm by zones			Spoke weight, kg	First frequency, Hz	Second frequency, Hz
	1	2	3			
1	2.3	2.3	2.3	1.80	2.492	6.422
2	2.57	2.3	2.0	1.792	2.780	7.176
3	2.89	2.3	1.5	1.778	3.144	7.867

Solid composite spoke with annular cross-section and tapered butt

One of the significant disadvantages of the spoke models considered above is the low frequency of horizontal natural oscillations, which is approximately 2.5 times lower than the frequency of vertical oscillations. This is due to the shape of the spoke cross-section, elongated in the vertical direction. Obviously, a spoke of circular cross-section is free from this disadvantage. However, the width of the spoke cross-section at the butt is limited by design features and cannot exceed 90 mm. Let us model a spoke of solid cross-section, taking this limitation into account (Fig. 18). Most of the spoke has a constant circular annular cross-section, and in the zone (800 mm long) adjacent to the butt, the cross-section is of a variable type: transitioning from a round shape to an elliptical one (towards the fixed end).

The modal calculation for this model (taking into account the mass of the curtain) gave the following values for the first two frequencies (Figs. 19 and 20) of natural oscillations: 3.083 and 3.346 Hz, respectively. This is significantly better than the basic model (see Fig. 6).

The solution presented above is implemented for a model with the same wall thickness of 0.36 mm along the entire length. The total mass of the "bare" spoke is 2.04 kg. The reinforcement angle of the longitudinal fibers $\varphi = \pm 45^\circ$.

If we redistribute the thicknesses by zones (as in Fig. 17), then we can increase the bending rigidity by a third (at the first frequency). This is clearly seen in the data in Table 13.

This model can be considered optimal in rigidity, since the oscillation frequencies of the horizontal (Fig. 19) and vertical (Fig. 20) directions almost coincide.

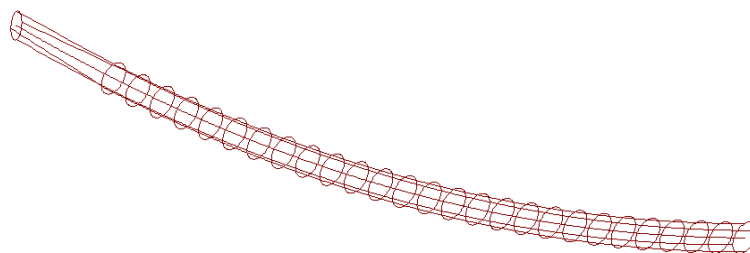


Рис. 18. Сечения спицы с сужением у комеля

Fig. 18. Cross-sections of a spoke with a narrowing at the butt

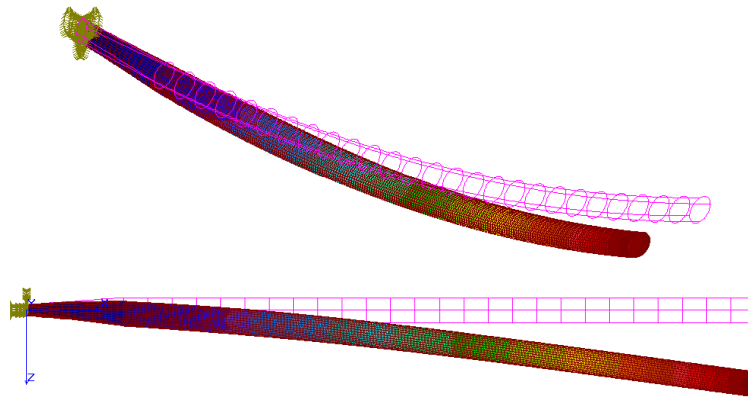


Рис. 19. Первая форма колебаний спицы с сужением (внизу – вид сверху)

Fig. 19. The first vibration mode of a spoke with a narrowing (below – top view)

Table 13

The values of the first frequencies of oscillations of a solid spoke of annular cross-section with a narrowing at the butt and zones of different wall thickness

№	Wall thickness, h , mm by zones			Spoke weight, kg	First frequency, Hz	Second frequency, Hz
	1	2	3			
1	0.36	0.36	0.36	2.04	3.083	3.346
2	0.48	0.36	0.24	2.02	3.654	3.959
3	0.60	0.36	0.12	2.00	4.160	4.166

Table 14

The values of the first frequencies of oscillations of a solid spoke of annular cross-section with a narrowing at the butt and zones of different wall thickness in models with different fiber winding angles

№	Thickness by zones, mm	Reinforcement angle, φ , deg	Natural oscillation frequencies, Hz	
			First mode	Second mode
1	0.60-0.36-0.12	45	4.160	4.166
2		35	4.701	4.296
3		25	4.270	3.626
4		15	3.379	2.811782

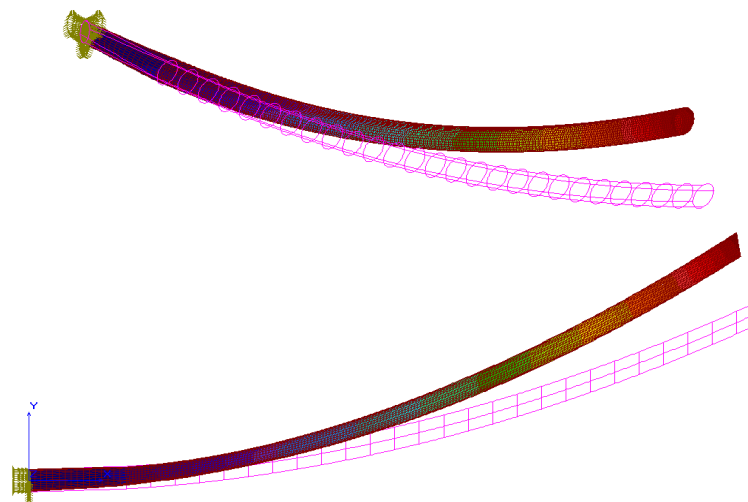


Рис. 20. Вторая форма колебаний спицы с сужением (внизу – вид сбоку)

Fig. 20. The second vibration mode of the spoke with a narrowing (below – side view)

If necessary, in order to increase the values of the studied frequencies of natural oscillations, the orientation of the longitudinal fibers can be optimized. For example, for model No. 3 (Table 13), a slight decrease in the reinforcement angle of the longitudinal fibers φ within the range from 45 to 35 degrees leads to a noticeable increase in the rigidity of the horizontal bending and to a slight increase in the rigidity of the vertical direction (Table 14).

Mesh composite spoke with annular cross-section and tapering at the butt

Let us consider a model of a mesh composite spoke with a ring cross-section and a narrowing at the butt (Fig. 21).

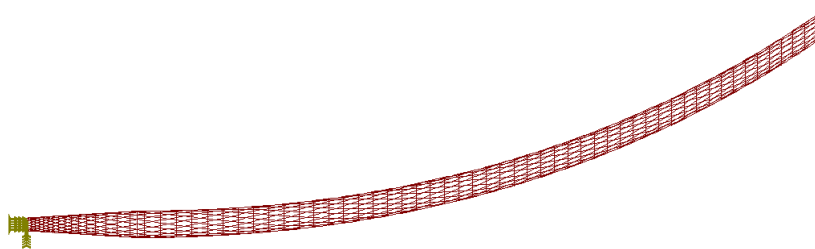


Рис. 21. Сетчатая композитная спица кольцевого сечения с сужением у комеля

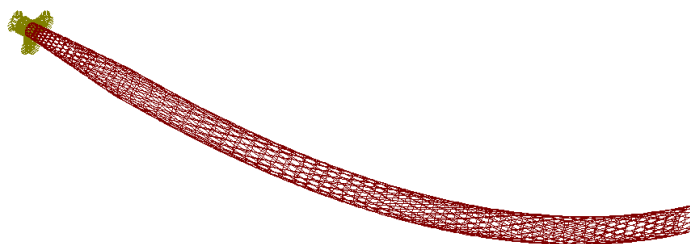
Fig. 21. Mesh composite spoke of circular cross-section with a narrowing at the butt

On a 0.8 m long section, immediately adjacent to the fixed end, the mesh structure has a linearly variable cross-section. On the rest of the spoke, the cross-section is constant – annular, with a diameter of 200 mm. The number of spiral ribs on both sections of the spoke is 16. On a section of constant cross-section, the orientation angle of the spiral ribs is also constant $\varphi = \pm 10^\circ$. In the zone of variable cross-section (on the section near the butt), the magnitude of the reinforcement angle changes along the spoke axis according to Clairaut's law. It is equal to $\varphi = \pm 10^\circ$ at the cross-section of the junction of zones with variable and constant cross-sections and increases in the direction toward the fixed end (Fig. 22).

The "bare" spoke has a mass of 1.961 kg (the cross-sections of all edges are the same 2.3 x 2.3 mm). In the modal calculation, the frequencies of natural oscillations were obtained: 7.859 and 8.523 Hz for the first (Fig. 23) and second (Fig. 24) modes, respectively.

Taking into account the mass of the fabric sector (see Fig. 2), the following values were obtained: 4.171 and 4.643 Hz for the first (Fig. 23) and second (Fig. 24) modes, respectively. This is even better than that of a solid wound needle (with a narrowing at the butt) with optimized thicknesses in the zones (see Tables 13 and 14).

If we increase the power of the ribs of the conical part (adjacent to the butt), then we can further increase the rigidity of the structure. For example, if we set the rib section here to 3.5×3.5 mm, and in the remaining (cylindrical) part of the spoke – 2.0×2.0 mm (while the total mass remains unchanged), then the frequencies of the first and second modes of natural oscillations will increase to 4.564 and 5.181 Hz, respectively.



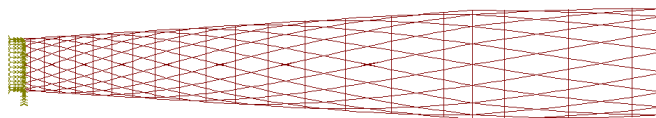


Рис. 22. Место стыковки зон с переменным и постоянным сечениями

Fig. 22. The junction of zones with variable and constant sections

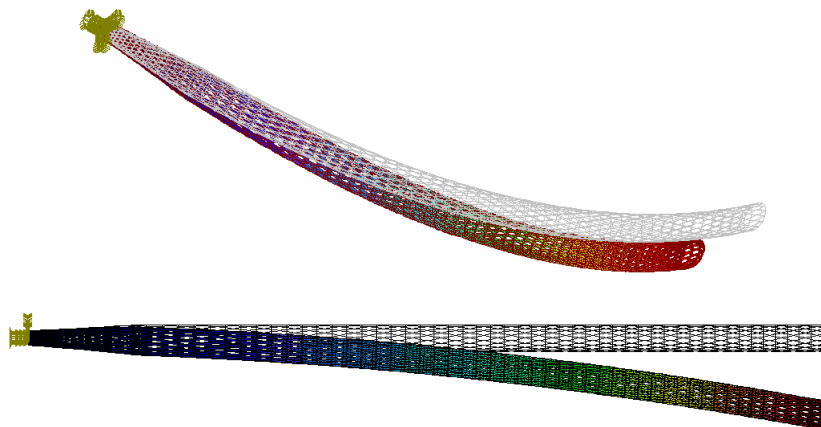


Рис. 23. Первая форма колебаний сетчатой спицы с сужением (внизу – вид сверху)

Fig. 23. The first mode of vibration of a mesh spoke with a narrowing (below – top view)

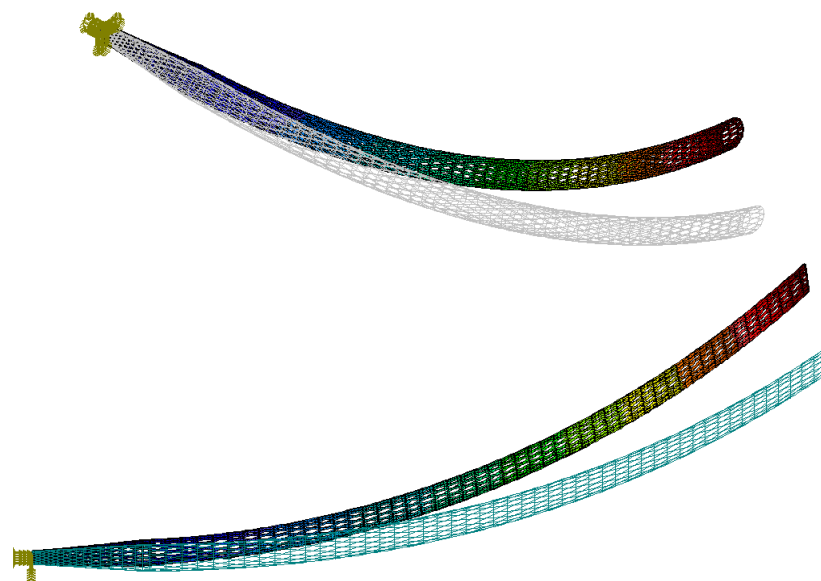


Рис. 24. Вторая форма колебаний сетчатой спицы с сужением (внизу – вид сбоку).

Fig. 24. The second mode of vibration of a mesh spoke with a narrowing (below – side view)

Conclusion

The accuracy of the reflective surface profile of the reflector is mainly achieved by ensuring a stable position of the radial spokes in the deployed state. This stability depends on the rigidity of the cantilever-mounted spokes. Based on a numerical experiment, the paper shows the possibilities of increasing the rigidity of the spokes while maintaining the regulated mass. This can be achieved, firstly, by changing the annular cross-section of a solid composite spoke manufactured by the method of continuous winding of fibers, in particular, by giving it an elliptical shape with a vertical orientation of the

major semi-axis, secondly, by optimizing the reinforcement angles of the fibers in the layered structure of the composite material of the spoke and, thirdly, by rationally redistributing the thicknesses of the elements along the generating surface in such a way as to strengthen the sections adjacent to the fixed end of the spoke. The mass efficiency of the spoke can also be increased by using the mesh structure of its walls. It is possible to optimize the anisogrid model with a rational choice of the orientation angles of the spiral ribs. The indicated methods for increasing the rigidity and stability of the spoke are confirmed in calculations taking into account the mass of the antenna mesh and verified in the analysis of the bearing capacity of the spoke in the initial and inverted positions.

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