An approach to design of large-sized deployable hoop space antenna reflector

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Abstract. Amongst the large-sized transformable space antennas, the most attention is currently paid to developing of antennas with hoop-shaped reflectors. The developers are faced with the necessity of looking for optimal design concepts. This paper shows the various concepts of building of the reflectors of the cable-rod scheme, containing a circular load-bearing framework (load-bearing rim) with a deployment drive set on it and the reflecting surface shape-generating structure, assembled into a single construction by the cable and rod elements. The difference between the proposed design concepts of the reflectors is the various structures of the controllable unfolding mechanisms. In the first alternative of the reflector structure, the unfolding process is supported by the cable, which restrains relative displacements of the tips of the initially compressed springs. The second alternative supposes the cable not to be the restraining element, but an active unit of the unfolding mechanism. This paper also describes various alternatives for connection between tension tie cables and the load-bearing rim. It is shown that the alternative of connection of the tension tie cables to the middles of the load-bearing rim edges allows to perform stress analysis of the structure elements and to obtain required characteristics of the spring drive. The numerical calculations for optimal angular position of the deployment drive pulleys holder relative to the sections of the load-bearing rim for the second alternative of the reflector design, which provides the most force effect on shape-generating structure of the reflector, when the knitted mesh fabric is being pulled, are under consideration in this article. The calculations are confirmed by experimental investigations.

1. Introduction
The increasing demand for transformable reflectors with aperture of more than 12 meters used in telecommunication applications makes the developers of such systems search for the best conceptual solutions, fulfilling the requirements of minimal mass, high accuracy of the reflecting surface and necessary dynamic stiffness [1-13]. The most widely used reflectors are the hoop-shaped reflectors, which are built of a peripheral hoop, two networks, and the inner cable web, interconnecting the networks. One of the networks is a shape-generating network, with the reflecting surface, made of the knitted mesh fabric, attached to it. The main characteristics of the reflector are defined by the design of its framework, and that is why such reflectors are known as the hoop-shaped ones.
The hoop-shaped design concept appeared as an alternative to the umbrella-shaped variant of the tension truss structure. Initial investigations had been carried out by TRW and Astro companies, which are currently parts of NGST subdivision of Northrop Grumman corp. Essentially, NGST company claimed the possibility of developing reflectors for any actual task, ranging from an enlargement the $K_u$ band reflectors’ dimensions up to 6–8 meters to creating the very large-scaled reflectors with dimensions up to 50 meters.

ESA specialists also believe the hoop-shaped structures to be promising, and so they have chosen the “cylindrical double pantograph” and “V” fold conical ring” design concepts for their further investigations. The following investigations have resulted in establishing the Large Space Structures company (LSS) on the basis of the Technical University of Munich (TUM), Germany, which showed their ultimate variant of the hoop-shaped reflector based on the double pantograph concept.

On the example of the large-sized transformable hoop reflector design, this article shows the alternatives of the topological schemes of the reflector construction, along with the rational choices for the reflector’s units and drives efficient design solutions, fulfilling the requirements of both experimental and operating mode of the antenna under design. Two alternatives for the deployment drives are under consideration: the spring and the cable ones.

2. Design characteristics of the reflector structure and the topological schemes

The space antenna reflector (figure 1) is a structure composed of the hoop load-bearing framework with the deployment drive – hereinafter, the load-bearing rim or the hoop – and the antenna’s reflecting surface shape-generating structure (SGS), assembled into a single construction by the cable and rod elements, as shown in figure 1a.

The antenna’s reflecting surface shape-generating structure (figure 1b) includes facing and rear networks, symmetrical relatively to the load-bearing rim plane and fixed to the upper and bottom ends of the twelve load-bearing rim rods with the help of the upper and bottom cable ribs. In order to create a parabolic surface of the facing network, bearing the reflective knitted mesh fabric, tension ties are used. The tension tie cables link the nodes of the facing and the rear networks in specifically calculated points and they have certain lengths. It allows building a cable-rod scheme, consisting of SGS and the struts, which is fixed to the load-bearing rim by the upper and the bottom tension tie cables.

3. The spring drive of the load-bearing rim

The load-bearing rim is a closed polygon consisting of twelve rotatable elements (tubes), connected to each other by hinges with the help of twelve supports. In the hinges of the supports the spring drives with restraint system are placed, providing a controllable deployment of the load-bearing rim and the SGS, connected to it by the tension ties, from the transporting state to the operating position. The load-bearing connection unit of the large-sized space reflector along with its design scheme are shown in figure 2.
The reflector deploys by means of elastic energy, accumulated in the springs, placed in the load-bearing units, and connecting the sliding pieces with the axes (p. B), when the construction is being folded. The elastic energy is accumulating in the springs when the whole construction is being folded to the transporting state. During the reflector’s deployment, in every moment of time, elastic force of previously strained spring acts along the moving around straight line BD, causing a movement of the sliding piece (p. D), which is movable along the pivotally connected guide rail (BG) towards its rotation axis (p. B). Thus, this elastic force is following to relative position of points B and D and is, essentially, a tracking force.

![Diagram of the load-bearing rim fragment](image)

**Figure 2.** The load-bearing rim fragment.

- a) Solid model of the load-bearing connection unit;
- b) Design scheme of the load-bearing connection unit.

During the first stage of deployment from the release moment, the cable system isn’t fully spread and stressed yet, and the struts can appear in space in a fairly arbitrary manner. This is happening before the time moment, corresponding to some angle of inclination $\alpha_0$ of the tubes to the plane of $Oxy$ of the deployed hoop (figure 2b). From this very moment, the SGS is being spread along with tension ties, struts, and ribs, which provides shaping of a single elastic preliminary stressed construction of the reflector. This is the second stage that defines the stressed state of the entire reflector and the necessary characteristics of the spring load drives. This feature of the reflector deployment greatly complicates defining the parameters of the construction because in this case one has to model a constructively nonlinear system, implying a successive coming of the different units of the construction into the deployment process, which may also cause their dynamic interaction.

4. The problem statement of finding of the reflector load-bearing rim construction characteristics

When it is a controllable, quite slow deployment process, it is possible to neglect the dynamic effects of the process and to consider the task as a quasistatic one. To be able to solve the quasistatic task it is necessary to define initial conditions, which are positions of the hoop elements and the struts at the moment of the second stage of the deployment process beginning.

One of the made assumptions relates to coinciding at the current moment of the middle plains of the struts and the load-bearing connection units. The middle plain of the struts is a plain passing through the center points of the struts, while the middle plane of the load-bearing connection units is a plane about which the adjacent load-bearing connection units (the set of the load drives connected to the same support) are found placed symmetrically (figure 3).

Out of the uncontrollable movements of the struts, the tension ties and the cable ribs during the deployment process, the center points of the struts, when the SGS starts spreading, can take various positions in relation to the middle plain of the load-bearing units. One of the possible relative positions of the struts and load-bearing units middle plains is shown on figure 3a, where the plains are offset with
respect to each other over a distance of $\Delta h$. In this case the lengths of the upper and bottom tension tie cables are different, which causes that they are being deformed in different ways, while the SGS is spreading, and, consequently, how the cable ribs and the SGS itself work becomes undefined.

The case put for calculation, which provides uniform deformations for all the elements of the cable system and the SGS, is the case when both middle plains of the struts and the load-bearing units are coinciding ($\Delta h = 0$) (figure 3b). This case can provide equal lengths of all the cable system tension ties.

![Figure 3](image1.png)

**Figure 3.** The alternatives for possible relative positions of the struts and the loading-bearing units.

a) The middle plains are offset with respect to each other; b) The middle plains are coinciding.

Another one made assumption relates to various variants of connection of the tension ties and the load-bearing rim. Figure 4 shows two variants of binding of the tension tie cables to the hoop: to the bases of the connection unit supports and to the middles of the tube edges of the load-bearing rim.

![Figure 4](image2.png)

**Figure 4.** The variants for connection of the tension ties and the load-bearing rim.

a) Binding of the tension ties to the bases of the connection unit supports; b) Binding of the tension ties to the middles of the tube edges of the load-bearing rim.
5. The results of the numerical analysis of the load-bearing rim deployment process

Below is an example of the reflector with diameter of 20 m deployment process calculation, taking into account the chosen variants of binding of the tension tie cables to the load-bearing rim and the initial tension of the cable system at $\alpha_0 = 5^\circ$.

First variant of the tension ties binding is characterized by the different lengths of the tension tie cables (figure 4a) which is common to such kind of a reflector’s design scheme. Table 1, in particular, shows the calculation results for the load-bearing cable ribs and the tension tie cables lengths’ change. It is clear that some cable ribs lengths’ change is negative, while the tension ties are stretched nonuniform.

As the flexible cable ribs don’t operate in compression, the negative values of the length change show that these structure elements aren’t stretched and that they don’t bear any load, i.e., they don’t operate as a part of the cable system, which surely isn’t acceptable. In this case, the results of the made calculations are mostly qualitative in nature and they can’t give a complete answer to the question of the strength properties of the structure.

As to the second variant, in this case all the tension ties have equal lengths, which causes the uniform deforming of all the elements of the cable system and the SGS, and thus the nonuniform tension of the cable system is impossible.

It should be noticed that when unfolding the load-bearing rim according to the first variant, moment $M$ caused by the tube rotation (figure 4a) could lead to the cable system twisting. At the same time, when it is the second variant of the tension ties binding (figure 4b), the moment $M$ doesn’t lead to the cables twisting if the tension ties are connected to the tubes by spherical hinges.

Table 1. The load-bearing cable ribs and the tension tie cables lengths’ change when unfolding.

|       | cable ribs | tension ties |
|-------|------------|--------------|
|       | upper zone | bottom zone  | upper zone | bottom zone |
| 1     | -1.9679    | 51.4683      | 18.7195    | 43.3007     |
| 2     | 52.7785    | -3.1173      | 44.3197    | 18.3109     |
| 3     | -2.0997    | 51.5112      | 18.6790    | 43.5929     |
| 4     | 52.8025    | -3.1720      | 44.1701    | 18.4175     |
| 5     | -2.1275    | 51.2890      | 18.6254    | 43.4487     |
| 6     | 52.7656    | -3.3750      | 44.0282    | 17.9453     |
| 7     | -1.9805    | 51.4498      | 18.7553    | 43.3603     |
| 8     | 52.7355    | -3.1972      | 44.2641    | 18.1395     |
| 9     | -2.0619    | 51.6060      | 18.7464    | 43.5327     |
| 10    | 52.7321    | -3.1264      | 44.2112    | 18.5053     |
| 11    | -2.1400    | 51.2913      | 18.6105    | 43.4745     |
| 12    | 52.7450    | -3.4320      | 44.0058    | 17.8743     |

In accordance with the above, the stress analysis has been carried out for the second variant of the connection of the tension ties – to the centers of the tubes. To the alternatives for the reflector construction design that are under consideration, which are the reflectors with aperture of 12 m and with the diameters of the load-bearing rim of 16, 18, and 20 meters, there are results of the carried-out stress
analysis of the the structure rod and cable elements, performed by means of finite element method with the help of MSC.Patran-Nastran, for different values of the angle of initial tension of the cable system.

It should be noticed that as the shape-generating structure has quite complicated mesh structure, all the calculations within the current analysis have been carried out using an elastic model of the SGS in the form of the combination of cables that have the same mechanical parameters as the real SGS cables.

| diameter of the hoop, m | α  | averaged stresses, arising in the SGS cables, MPa | averaged stresses, arising in the tension ties, MPa | averaged stresses, arising in the cable ribs, MPa | internal forces in the springs, N |
|------------------------|----|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|----------------------------------|
| 18                     | 5.0| 62                                               | 31                                               | 65.5                                             | 705                              |
| 17                     | 5.2| 62                                               | 36.5                                             | 65.5                                             | 700                              |
| 16                     | 5.4| 61.5                                             | 42.5                                             | 66                                               | 830                              |
| 15                     | 5.9| 62.5                                             | 57.5                                             | 66                                               | 875                              |
| 14.5                   | 6.2| 58.5                                             | 68                                               | 62                                               | 875                              |
| 14                     | 6.0| 41                                               | 66.3                                             | 43.3                                             | 660                              |

Table 2. Averaged stresses, arising in the elements of the load-bearing rim structure.

The performed stress analysis shows that if the angle $\alpha$ is being decreased, when diameter of the load-bearing rim is 14.5 mm, then there are quite loose cables, and if the angle $\alpha$ is being increased, then there are tightly stretched tension tie cables.

When the angle of $\alpha$ is the same for every analysis, increasing of the hoop diameter value leads to increasing of the centers of the tubes displacement values and also leads to large the tension tie cables elongating, which, of course, leads to increasing of the stresses, arising in the elements of the load-bearing rim (table 2). In a view to decreasing of the stress values, the best solution is to decrease the diameter of the hoop. However, in this case, in order to provide necessary tension in the SGS it is needed to increase the initial angle of inclination of the tubes, which comes to the necessity of the more powerful deployment drive.

As regards to minimization of the mass of the hoop, it is clear that this can be achieved by decreasing of the diameter. Yet it is necessary to have the more powerful deployment drive, which leads to increasing of the stresses, arising in the elements of the drive, and this also leads to increasing of the drive’s mass. The above remarks show that it is necessary to carry out more detailed optimization calculations with the help of developed software.

The analysis of the deployment kinematic of the reflector shows that both the cable ribs and the tension ties, connecting the struts with the load-bearing rim – bearing in mind the variants for the connection mentioned above – come to the SGS tightening process in different ways.

The first variant implies not simultaneous coming into the work process of the cable ribs and the tension ties, resulting from the geometry itself of the connection of the struts to the supports of the hoop at the initial moment of the SGS being stressed. Such behavior of the tension tie cables significantly increases the difficulty of the numerical stress analysis of the reflector and makes it necessary to model the elastic system with variable connections, taking into account probable positions of the all elements of the SGS and the struts at the initial moment of time. Providing by means of designing process the initial equidistant positions of the ends of the struts from the adjacent supports, which the struts is connected to via tension ties, seems to be impossible.

The second variant of the tension ties connection to the hoop is rid of mentioned above drawback. In this case, all the tension ties come to work process simultaneously, which allows to carry out the investigations of the stressed state of the reflector by means of numerical methods with the help of known finite-element software.
6. The cable deployment drive for the hoop of the reflector

The alternative for the drive for synchronized rotation of each pair of the tubes, pivotally connected to each of twelve supports of the deployable hoop, is under consideration in this chapter. Figure 5a shows the proposed construction in unfolded state with the identification all the core elements.

![Diagram of the cable deployment drive for the hoop of the reflector](image)

**Figure 5.** a) The alternative for the load-bearing rim with the drive for synchronized rotation of the tubes: 1 – vertical strut; 2 – central vertical strut; 3, 4 – rotating links; 5 – the angle of rotation synchronizer; b) The construction of the drive for rotation.

The principle of the drive for the links rotation is based on creation a torque on each deploying rotating link, caused by couple of forces, arising when the cable is moving on a two-pulley roller holder, which is mounted on the rotating link, as it is shown on figure 5b. The possibility for the drive to work is provided by the cable length contraction, which is going along the pulleys of the two-pulley roller holders of all the links, due to being wound on the roll of the drive.

The method for the structure characteristics calculation of the cable drive has been developed, in particular, for the calculation of the optimal angle of inclination of the double-pulley bracket with respect to the axis of the rotating link, providing given value for the torque at the moment when it is the end of the hoop deployment process and the beginning of interaction between the struts of the hoop and the mounted on them SGS.

7. Dependence of the torque on the angle of inclination of the holder with respect to the rotating link axis

The issue of the impact of the angle of inclination of the pulleys’ holder with respect to the rotating link axis to the magnitude of the acting on the holder torque when the cable is moving, is under consideration in this chapter. Figure 6 shows a scheme of the load-bearing rim segment for two alternatives for locations of the pulleys, through which the cable is moving during the reflector is opening. The figure provides for each of two alternatives three consecutive positions of the unfolding rotating link when the hoop is opening, defining by angle \( \varphi \) (\( 0 \leq \varphi \leq \pi/2 \)).

In the first alternative (figure 6a), when the angle of inclination of the pulleys’ holder with respect to the rotating link axis is \( \alpha = 90^\circ \), magnitude of the distance \( h \) of the force couple, when the link is rotating, remains little changed. In the second alternative (figure 6b), when the angle of inclination of the pulleys’ holder with respect to the rotating link axis is different from the right angle, magnitude of the distance \( h \) is increasing, while the link is rotating from the initial position (\( \varphi = 0^\circ \)) to the end position (\( \varphi = 90^\circ \)).

The second alternative (figure 6b) is more acceptable, because in this case the torque is changeable, which is increasing to the end of the opening process when the elastic SGS starts interacting with the opening hoop of the reflector. Besides, the layout of the drive pulleys locations is more acceptable in the second alternative from the perspective of the reflector configuration in the transport state.
Figure 6. Defining of the distance of the force couple when the load-bearing rim rotating link is moving.

a) Angle of inclination of the pulleys’ holder with respect to the rotating link axis is $\alpha = 90^\circ$:

1 – vertical strut; 2 – bracket; 3 – rotating link; 4 – the pulleys’ holder; 5 – the cable;

b) At an angle $\alpha$ with respect to the rotating link axis.

8. Law of variation of the distance of the force couple

The law of variation of the distance of the force couple, when the link is rotating, can be described with the help of a functional relationship $h = f(\alpha, \varphi, G)$, where $\alpha$ is an angle of inclination of the pulleys’ holder with respect to a vertical line ($0 \leq \varphi \leq \pi/2$), $G$ – geometrical dimensions of the load-bearing rim, shown in figure 7b and put in table 3.

| Element of the hoop      | Identifications of the geometrical dimensions of the hoop elements |
|--------------------------|--------------------------------------------------------------|
| Vertical strut           | $2a$                                                        |
| Bracket                  | $2b$                                                        |
| Rotating link            | $2c$                                                        |
| Pulleys’ holder          | $2d$                                                        |

The way of searching of the functional relationship for the force couple distance $h = f(\alpha, \varphi, G)$ is based on a planar geometry problem which implies describing the value under consideration $h$ via all the known parameters $\alpha, \varphi, a, b, c, u, d$ and then taking one of them as a variable (e.g., angle of inclination of the load-bearing link $\varphi$) in a view to analyzing the impact of the angle $\alpha$ to the target $h$.

Total relationship for finding the value of $h$ can be written as

$$h(\varphi) = 2d \cos \left( \pi - \arctg \frac{a + c \cos \varphi}{b + c \sin \varphi} - \varphi - \alpha \right).$$

The calculation has been conducted for the following values of the geometrical dimensions of the load-bearing rim prototype: $a = 80 \text{ mm}$; $b = 24 \text{ mm}$; $c = 66 \text{ mm}$; $d = 19 \text{ mm}$ (figure 7a).

Figure 7b shows the graphs of the functions, describing how the force couple distance $h$ changes, when the link is rotating, for various values of the holder angle of inclination $\alpha$ with respect to its axis.
Table 4 shows values of the distance $h$ for initial and final positions of the load-bearing link for various values of the angle $\alpha$, as well as maximum values $h_{\text{max}}$, which are achieved within the borders of variation of angle of inclination $\varphi$ ($0 \leq \varphi \leq \pi/2$) of the load-bearing link.

![Diagram](https://via.placeholder.com/150)

**Figure 7.** a) The geometrical dimensions of the load-bearing rim prototype; b) The graphs for changing the force couple distance $h$ upon rotation of the link for different values of the angle of inclination $\alpha$ of the holder.

The obtained results confirm the assumptions made before. Indeed, when the angle $\alpha = 90^\circ$, the distance $h$ is not increasing and, consequently, the torque, acting on the rotating link, is not increasing as well. Moreover, when the angle $\varphi > 16.7^\circ$, the distance $h$ value is getting lesser. At the same time, upon the lesser values of the holder angle of inclination $\alpha$ ($50^\circ; 30^\circ; 10^\circ$), function $h(\varphi)$ increases along the entire stretch of change of angle $\varphi$ (figure 7b).

| $h$, mm | $\alpha = 90^\circ$ | $\alpha = 70^\circ$ | $\alpha = 50^\circ$ | $\alpha = 30^\circ$ | $\alpha = 10^\circ$ |
|---------|---------------------|---------------------|---------------------|---------------------|---------------------|
| $h(\varphi = 0^\circ)$ | 37.5 | 33.1 | 24.8 | 13.4 | 0.441 |
| $h(\varphi = 90^\circ)$ | 28.4 | 35.3 | 37.9 | 36.1 | 29.8 |
| $h_{\text{max}}$ | 38 $(\varphi = 16.7^\circ)$ | 38 $(\varphi = 53.4^\circ)$ | 38 $(\varphi = 87.2^\circ)$ | 36.1 | 29.8 |

The operability of the drive that uses a cable system is provided by contraction of length of the cable, passing through the pulleys of the two-pulley brackets of all the links due to the cable being wound of on the roll of the drive by means of an electric motor. To confirm and visualize the kinematic of the unfolding process of the loading-bearing rim, which uses the cable system, an operating model of the deployable reflector on the scale of 1:20, containing the load-bearing rim together with the cable drive and the elastic analog for the SGS, has been created. There have been the series of experiments, which confirm the possibility and the repeatability for the cable drive to operate, as well as for the entire process of the model unfolding.
9. Conclusion

Available studies of the topological layouts of the load-bearing framework of the hoop-shaped reflector allow giving proof to the most advantageous design scheme of the hoop reflector for the purposes of the next stage of the transformable reflector design process.

During the carried-out investigations, there have been developed a package of software, which allows constructing both geometrical and finite-element models of the reflector at the different moments of time of its unfolding process. On the basis of these programs, the alternatives for connection the tension ties to the hoop have been checked out, which shows that the alternative for connection the tension ties to the to the middles of the tube edges of the load-bearing rim from the perspective of the theoretical investigations is more acceptable but, apparently, such design solution is not allowable for the structures, elements of which are made of polymer composite materials and are loaded with bending loads. As a result, here is the situation when some design alternative allows us to carry out theoretical investigations of the stressed state of the structure but in doing so, this approach makes us doubt about the structure’s lifetime in the case when the load-bearing segments of the hoop are made of carbon fiber-reinforced plastic out of their high creeping when being loaded with flexure loads, as well as out of unwanted moments caused by bending, arising in the hinges of the hoop segments fastening assemblies. Another one alternative, apparently, can satisfy the demanded lifetime, however, as it has been shown, the theoretical investigations are difficult in high degree.

It should be also noticed that the carried-out laboratory experimental investigations on the deploying of the models of the hoop-shaped reflectors have confirmed the operability of the design schemes of the load-bearing frameworks under consideration.

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