Numerical optimization of geometric configuration of large space structure

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Abstract. The paper considers a development project of an observation satellite with diffractive optical system. The problem of stable orientation of the optic system elements is being solved. The design layout suggested by the authors earlier is used for the purpose. The authors studies influence of geometrical parameters on stiffness of the design. With the help of numerical optimization optimal values of design parameters are found, optimized for minimum of mass.

1. Introduction
A mirror-based optical system of observation spacecraft characterized very large aperture have an unacceptable value of its mass. Using of diffractive lenses is a promising way to decrease the optical system mass [4-5]. Using a diffractive optics demands solving a number of problems [6-7]. The project MOIRE (MOIRE - Membrane Optical Imager for Real-Time Exploitation) proposed by the US Agency DARPA [1-3] shows one of the problems. In this project, the diffractive lens diameter is ten meters and the lens has to place in 60 meters from the spacecraft body. It is necessary for a rigid structure having low mass in order to keep the relative position of lens and spacecraft body. The earlier papers of the authors consider a development of the design layout [8-9] which affords an opportunity to meet the requirements. Figure 1 shows a preliminary configuration of this observation spacecraft.

Figure 1. The project MOIRE of geostationary observation satellite with diffractive optical system [1].
2. Requirements to the lens frame design
An element of an optical system has to be in a fixed position relative to other elements with high precision. Therefore the lens frame design has to keep the relative position of optical system elements. Obviously, the construction has to be folded during orbital injection and has to be unfolded to operational position on orbit. To develop large, rigid, low weight and foldable construction is a difficult problem. Dimensions of the lens frame can change with a number of causes. These are plastic strains appeared during orbital injection, temperature strains and vibration of the construction. Problems of plastic and temperature strains can be solved with construction material choice. Vibrations of spacecraft construction are excited with inertial forces when there is a setting of spacecraft orientation to an object of observation. If the amplitude of the vibration of optics is sufficiently large in order to distort the image then it is impossible to take a photograph before the vibration has decayed. If decay times of such the vibrations are sufficient long operation of the observation spacecraft is difficult. To prevent vibrations with large amplitude and long decay time it is necessary that the lens frame design has big enough stiffness. The traditional observation spacecraft successfully operate with the lowest mode frequency from 1.0 to 2.5 Hz. If the lens frame design is enough rigid and light that a spacecraft consisting of the frame has the lowest mode frequency in the same range we can hope that spacecraft operation will succeed.

3. The design layout of the lens frame
In the paper [4] the authors suggested a design layout of the lens frame that allows meeting the above requirements. Trusses connect the lens and the spacecraft body. Joining of the trusses by tensioned cables turns the number of single trusses into the joint design. The joint design has much greater stiffness then single trusses without the tensioned cables. The tensioned cables act on trusses with transversal forces. It can produce large deformations of trusses because of the ratio between the long and transverse size of the truss is large (Figure 2). To avoid that trusses in the design are arch-shaped and longitudinal cables connect their ends (Figures 3 and 4). Such trusses have large transversal stiffness that allows stretching of transversal cables. Figure 5 shows the design layout of the lens frame.

![Figure 2](image2.png)

**Figure 2.** Internal forces in a straight truss due to transversal cables stretching. Solid arrows represent internal forces in a part of a truss and thin arrows represent forces acting from adjacent parts of a truss.

![Figure 3](image3.png)

**Figure 3.** Internal forces in a arch-shaped truss due to transversal cables stretching. Solid arrows represent internal forces in a part of a truss and thin arrows represent forces acting from adjacent parts of a truss.
Figure 4. Prevention of arch-shaped trusses straightening with connecting ends of the trusses by longitudinal cables.

Figure 5. The design of the diffractive lens frame.

4. Finding values of the design parameters

A method of choosing optimal values of the design parameters is a necessary part of the design development. The parameters can be divided into parameters of design elements cross sections and parameters defining of design geometry (geometric parameters). Parameters of design elements cross sections are cross-section areas of rods in arch-shaped trusses and cross-section areas of cables. The main geometric parameters are the spacecraft body diameter, the diameter of the diffractive lens, the distance between lens and spacecraft body and geometrical configuration of arched trusses. All these parameters except the geometrical configuration of arched trusses are determined from considerations unrelated to strength work. We can change the geometrical configuration of arched trusses only.

The paper [2] describes the method of finding the best values of the parameters in terms of the design mass minimization. The basis of the method is the assumption that arch is the optimal geometrical configuration of arched trusses. The overall geometry of the design is defined by radii of arch-shaped trusses, $r$. The finding of the best design is performed as follows.

A number of finite element models with different $r$ are created. For each of the models the procedure of numerical optimization is performed:

− The optimization criterion is the design mass minimization;
− The design variables are parameters of the design elements cross sections, $s$;
− The constraints are followed: strength and buckling of the design under the tension of the cables and under inertial forces; five lowest mode frequencies have to greater than their minimum allowable value $[f]$. The optimum value $s$ of $r$ and $s$ is related to this best design:

$$r_{opt} = \arg \min \{ M(\bar{x}_k, r_k) \mid k = 1..n \}.$$
where $M$ is the spacecraft mass; $\mathbf{s}$ is the vector of parameters of the design elements cross sections; $\mathbf{s}_k$ is the vector of optimal values of parameters of design elements cross sections with value of radii of arch-shaped trusses $r_k$; $f_j$ is $j$th mode frequency of spacecraft; $[f]$ is the minimum allowable value of mode frequencies (in case of this spacecraft it is 1.4 Hz), $\sigma$ is the value of stress in materials of rods and cables; $n$ is the number of $r$ values that are considered.

The disadvantages of this approach are follows:

1) It needs to create many finite element models;
2) The optimum $r$ value has low tolerance because of finite number of $r$ values;
3) The approach is useful to a design which has only one geometric parameter. There are many combinations of geometrical parameters values. For each of these combinations, it is necessary to create own model and to perform own numerical optimization analysis.

The geometric configuration of the design has only one parameter due to the assumption of the arch-shape of trusses. It is not clear that arc is the best geometric configuration of arched trusses.

The paper considers the method of optimization of this design with including geometric parameters in the number of design variables.

5. Modelling methods
The structural behavior was modeled in the finite element system MSC. Nastran. Within optimization analysis the approximation of design strength and stiffness is based on the following responses:

- stresses, acting in elements of the construction under a load of inertial forces and cables tension forces;
- the critical load of buckling for the same loads;
- cables tension forces (its have to be positive for cable sagging prevention)
- five lowest mode frequencies.

The paper [8] discusses the methods of the calculation of the responses.

6. Geometrical design variables
The finite element system MSC. Nastran allows relating of a grid point coordinate to design variable. Model of the design has the number of grid points along the axes of arched trusses. The change of distance from a grid point on the arched truss to the axis of the whole construction is considered as design variables $\Delta R_i$ (Figure 6). Any grid point on an arched truss, there are grid points on other arched trusses with the same longitudinal coordinate value. Position the grid points with the same longitudinal coordinate value are in control by one design variable. In this case, the design keeps axial symmetry during the optimization process. Such the design variables are able to describe arbitrary geometry of arched truss.

![Figure 6. The effect of changes of the design variables to the design geometry.](image)
7. Results of numerical optimization
The numerical optimization analysis performed with the procedure of numerical optimization of the finite element system MSC. Nastran. The procedure realizes the gradient method of optimization. [9].

The best design is found on the 285th iteration of optimization (fig. 7.). The optimal geometric configuration of arched trusses approximately has arc-shape. The radius of arched trusses rises from 60 meters in the initial design to 98 meters in the best design.

![Figure 7. The shape of the spacecraft design before optimization (a) and after optimization (b).](image)

Figure 8. Oscillations of a design variable value during optimization of geometric configuration of arched truss.

Note that the iteration process converged very slowly. It can be explained by analyzing the situation. Imagine that arched trusses have axes in the form of arcs. (fig. 8). One grid point deviates from the axis of the truss arch in the direction of reducing its distance from the optical axis. Then the local curvature of the arched truss decreases sharply, which leads to a change in the nature of its strong work. The arch of the constant radius at the tension of the cables works for compression, and the arch with a local increase of the curvature of the axis works for bending. This reduces the longitudinal stiffness of not only the curved section of arched truss but also the whole arch (as if a supple spring is inserted into a rigid rod), falls. We see that the deviation of the value of one design variable greatly changes the rigidity of the entire system. To prevent this from happening, all geometric variables must...
change together, uniformly increasing the radius of the entire arc. Thus, the deviation of one grid point leads to a violation of the constraints on structural rigidity, which leads the optimization algorithm to straighten the local curved section of the arched truss at the next iteration. To do this, the grid point deviated in the previous iteration moves in the opposite direction, and the neighboring grid points in the direction of the initial deviation. Changes in the design variables are oscillatory in nature, which explains the slow convergence of the process.

Figure 9 and figure 10 shows changes in the optimization criterion and the maximum value of the normalized constraints. Most of the reduction in mass of the structure is achieved in the first twenty iterations (Figure 9). From figure 11 that this rapid change in mass occurred at the expense of design constraints reaching the boundary (a violated constraint has a positive value).

Figure 9. Changes in the optimization criterion in the iterative process.

Figure 10. Changes in the maximum value of the normalized constraints in the iterative process.

Figure 11. The changes of one of the geometric design variables in the iterative process.

Figure 11 shows the changes in one of the geometric design variables. We see that after a quick change in the first 20 iterations, the value of the variable is oscillating. These oscillations are similar to those shown in Figure 8.
Figure 12 shows the changes of an arched truss geometric configuration of the arched truss. We see that the radius of the arched truss increases to the optimum in the first 20 iterations. During the rest of the iteration process, the geometric shape of the arched truss is smoothed.

The best solution contains nonidealities of shapes of arched trusses axes. Note that nonidealities are smaller in the first iterations. This is explained by the fact that the longitudinal stiffness of the arched truss increases with increasing radius of the truss curvature and the constraint on the stiffness of the structure begins to be satisfied with a margin. Therefore, the local curvature of the arched truss, reducing their longitudinal rigidity, is not critical in terms of design constraints on late iterations. These local curvatures change the length of the truss arches insignificant, and therefore these curvatures increase the weight of the structure insignificant. Thus, neither from the point of view of constraints nor from the point of view of the optimization criterion, the considered imperfections of the form are not important. The exit from the optimization iterative process is made according to formal criteria. One of these criteria is the relative change in the value of the optimization criterion from iteration to iteration. If this change is less than a certain value, then the iteration process ends. For the above reason, smoothing curvatures with large radius truss arches will lead to a slight relative change in the criterion. Smoothing will increase the stiffness margin, but it is already satisfied with the margin.

8. Conclusions

Numerical optimization of the geometric configuration of large space construction was performed. The gradient method of numerical optimization implemented in the finite element system MSC. Nastran was used.

The results of the optimization calculation produced the best shape of the element of a large-sized structure (arc-shaped truss). This reduces the number of structural parameters describing its geometry, which makes it easier to find structural parameters.

The statement of the numerical optimization of the geometrical shape of construction was previously successfully performed only for a limited number of structures. The solution of this problem for the construction of the spacecraft is interesting both from the point of view of designing
this structure and from the point of view of gaining experience in applying numerical optimization in this area.

9. References

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