Finite element modeling of a multifaceted composite lattice anisogrid payload adapter for launching several spacecrafts

A A Khakhlenkova, E V Moskvichev and A V Lopatin

Institute of Computational Technologies SB RAS, PO box 25515, Krasnoyarsk, 660049, Russia

E-mail: jugr@ict.nsc.ru

Abstract. The paper presents the design of an adapter to launch several spacecraft. The adapter is a multifaceted composite lattice anisogrid shell. The technique for creating a finite element model of the presented lattice adapter is developed. The influence of structure parameters on the fundamental frequency of oscillations is studied. The results of solving the stability problem for flat lattice panels of the adapter during compression and bending are presented.

1. Introduction

Launching of several spacecrafts by one rocket can significantly reduce the cost of forming an orbital satellites constellation. Such a launch requires the creation of an adapter which can carry the required number of spacecraft. Examples of such designs are adapters for the “Soyuz” launch vehicle [1], operated by Arianespace shown in figure 1.

Figure 1. The adapters for the “Soyuz” launch vehicle, operated by Arianespace.

Nowadays, lattice anisogrid structural elements, due to their high weight efficiency, are widely used in modern space applications [2-4]. Therefore, this paper proposes the design of a multifaceted composite lattice anisogrid adapter for carrying several spacecraft.
An adapter is structurally designed for the constructive and functional connection of a spacecraft with a launch vehicle or booster block. An adapter structure must carry loads that occur during ground transportation of a spacecraft and during launching of a flying vehicle. This determines the stiffness requirements regulated by a flying vehicle developer for an adapter with installed spacecraft in the terms of natural frequencies of oscillations. Considering the design requirements that shall be taken into account for launching a spacecraft by the “Soyuz” launch vehicle [5], the transverse oscillation frequency of the adapter should be in range from 8 Hz to 12 Hz and the longitudinal vibration frequency must be greater than 25 Hz.

To verify these requirements, it is necessary to perform a finite element simulation and develop an appropriate methodology for creating the finite element model of the adapter. This will allow analyze the influence of the parameters of the lattice structure on the natural vibration frequencies and stiffness of the adapter.

2. Design description
The adapter for launching several spacecraft, shown in the figure 2, is a multifaceted lattice anisogrid shell (1) formed of helical (2), hoop (3) and longitudinal (4) ribs. These ribs are made of polymer composite material. The number of faces of the shell is determined from the quantity and dimensions of carried spacecraft. The mountings (5), made in the form of overlays with holes (6), serve to fix the spacecraft (7) on the adapter. Docking mechanisms (8), separation mechanisms (9) and electrical connections (10) are installed at the mountings. The adapter is mounted on the launch vehicle (11) using the mounting holes (12) made on the lower frame (13) of the shell.

3. Finite element model
The finite element model of an adapter was created in MSC Nastran software [6]. The multifaceted lattice shell was modeled as a space frame using two-node BEAM finite element. This finite element has six degrees of freedom – translations in three axes and three rotations. The lattice model is based
on repeating of a mesh segment, shown in figure 3, which consists of two fragments of helical ribs of different directions and a fragment of hoop ribs.

\[ \sin^2 \alpha R c = 2 \sin^2 \alpha R \]

\[ \alpha = \frac{360^\circ}{N} \]

\[ H = R - R \cdot \left( \cos \left( \frac{\alpha}{2} \right) \right), \quad c = 2 \cdot R \cdot \sin \left( \frac{\alpha}{2} \right), \]

\[ a = \frac{2 \cdot R \cdot \sin \left( \frac{\alpha}{2} \right) \cdot N}{n}, \quad h = \frac{\alpha}{2 \cdot \tan(\phi)}, \]

Figure 3. The repeating mesh segment of the multifaceted lattice shell.

The main parameters of a multifaceted shell are: \( R \) – the radius of circumscribed circle; \( N \) – the number of faces; \( L \) – shell height; \( n \) – the number of helical ribs of one direction; \( \phi \) – the angle of inclination of the helical ribs. The dimensions of the mesh segment required to create the finite element model of the adapter, shown in the figure 4, are determined by formulas:

Figure 4. The dimensions of the segment.
The stages of creating a finite element model of the multifaceted lattice adapter are presented in figure 5.

![Figure 5. The stages of creating the finite element model.](image)

Initially, a finite element model of the repeating mesh segment is created. Then, using mirror reflection tool, a finite element model of several linearly connected repeating segments is assembled. Next, the linear segments are copied around and along the main axis of the shell. The modeling completes by creating the upper and lower frames of the adapter.

4. Numerical analysis
Using the created finite element model, a modal and stability analysis of the multifaceted lattice adapter were performed. To assess the transverse stiffness of the shell the value of the first oscillation frequency was used.

The considered adapter shell had the following parameters: the height \( L = 3000 \text{ mm} \), the radius of circumscribed circle \( R = 500 \text{ mm} \) and the number of faces \( N = 8 \). Helical, longitudinal and hoop ribs were made of unidirectional composite material [7] with the elastic modulus of \( E = 180 \text{ GPa} \) and the density of \( 1550 \text{ kg/m}^3 \). The angle of inclination of the helical ribs \( \varphi \) is varied and takes the values of
10°, 15°, 20°, 25°, and 30°. Helical and hoop ribs have a rectangular cross section with a height and width of 20 mm and 5 mm, respectively. The longitudinal ribs had a square cross-section of 25 mm wide. The number of helical ribs of one direction \( n \) takes the values 32, 40, 48, and 56. Thus, in the calculations performed below, the variable parameters are the angle of inclination of the helical ribs \( \phi \) and the number of helical ribs of one direction \( n \).

In the process of modal analysis, the first oscillation frequency of the adapter was calculated for several loading cases. In the first case one edge of the adapter was rigidly fixed. The other edge was loaded by a concentrated mass of 1500 kg which was applied in a central node of the RIGID finite element. Table 1 presents the values of the first natural frequency \( f_1 \) calculated for this case for various values of \( \phi \) and \( n \).

Table 1. The first natural frequency \( f_1 \) (Hz) of the adapter.

| \( \phi \)° | 32  | 40  | 48  | 56  |
|------------|-----|-----|-----|-----|
| 10         | 8.980 | 10.068 | 10.815 | 11.524 |
| 15         | 11.722 | 13.003 | 14.159 | 14.985 |
| 20         | 13.596 | 14.936 | 16.138 | 17.009 |
| 25         | 14.603 | 15.953 | 16.930 | 18.038 |
| 30         | 15.305 | 16.185 | 17.383 | 18.111 |

The figure 6 shows the dependences \( f_1(n, \phi) \). The characteristic first form of natural vibrations of the multifaceted lattice shell is shown in figure 7.

![Figure 6. The dependences \( f_1(n, \phi) \).](image-url)
After analyzing the resulting data, it was found that the highest value of the first natural frequency $f_1$ was achieved for adapter with the angle of inclination of the helical ribs $\varphi = 30^\circ$ and the number of helical ribs of one direction is $n = 56$. The lowest value of $f_1$ for each $n$ is realized in the combination with $\varphi = 10^\circ$. It should be noted that in the range from $\varphi = 25^\circ$ to $\varphi = 30^\circ$ for all cases, the value of $f_1$ practically does not change. This indicates that increasing the angle of inclination of the helical ribs more than $\varphi = 25^\circ$ is ineffective.

At the next stage of numerical simulation, the stability of the lattice shell of the adapter compressed along the longitudinal axis was studied. The bottom edge of the adapter was rigidly fixed, and the top edge could move freely. A compressive force $Q$ was applied to the top edge of the adapter in the central node of a rigid finite element as shown in figure 8. Table 2 presents the critical force values $Q_{cr}$ for the adapter with different values of the angle of inclination $\varphi$ and the number of helical ribs of one direction $n$.

| $\varphi$ $^\circ$ | 32   | 40   | 48   | 56   |
|---------------------|------|------|------|------|
| 10                  | 3138.9 | 4882.8 | 7017.7 | 9086.9 |
| 15                  | 5782.9 | 8940.7 | 11870.4 | 13692.3 |
| 20                  | 9118.0 | 13459.6 | 16028.2 | 17619.9 |
| 25                  | 13054.0 | 17911.4 | 20217.2 | 21618.6 |
| 30                  | 17679.8 | 22757.1 | 24826.2 | 26399.8 |

Figure 7. The characteristic first form of natural vibrations of the adapter shell.

Figure 8. The adapter loaded by compressive force.
Figure 9 shows the dependencies $Q_{cr}(n, \varphi)$. The typical buckling modes of the adapter with different values of $\varphi$ and $n$ are presented in figure 10.

![Figure 9](image1)

**Figure 9.** The dependencies $Q_{cr}(n, \varphi)$ for the adapter under axial compression.

![Figure 10](image2)

**Figure 10.** The typical buckling modes of the adapter under axial compression.

Next, the stability of the adapter under transverse bending, loaded by a concentrated force was considered. The bottom edge of the adapter was rigidly fixed. The top edge was free and loaded in transverse direction by force $P$ as shown in the figure 11. The table 3 presents the critical force values $P_{cr}$ for the adapter with different values of the angle of inclination $\varphi$ and the number of helical ribs of one direction $n$. 

![Figure 11](image3)

![Table 3](image4)
Figure 11. The adapter loaded by transverse force.

Table 3. The critical transverse force $P_{cr}$ (kN).

| $\phi^\circ$ | 32  | 40  | 48  | 56  |
|------------|-----|-----|-----|-----|
| 10         | 265.4 | 496.8 | 792.2 | 1138.4 |
| 15         | 678.7 | 1116.8 | 1504.5 | 1675.4 |
| 20         | 1116.8 | 1644.5 | 1895.9 | 2068.9 |
| 25         | 1575.2 | 2045.9 | 2272.5 | 2497.5 |
| 30         | 2142.6 | 2464.5 | 2747.1 | 2947.1 |

The figure 12 shows the dependencies $Q_{cr}(n, \phi)$. The typical buckling modes of the adapter under transverse loading are presented in figure 13. As the results show, the adapter shell loaded by a transverse force experience buckling in the compressed zone near the fixed edge.

Figure 12. The dependencies $P_{cr}(n, \phi)$ for the adapter under transverse loading.
5. Conclusion
In this article the design of a multifaceted lattice adapter carrying several spacecrafts was proposed. The technique was developed for a finite element modeling of the adapter shell. A finite element analysis was performed to assess the influence of the number of helical ribs and the angle of inclination on the natural frequency of vibrations. A study was performed to evaluate the effect of the structure parameters on the stability of the adapter under compression and transverse loading. The results can be used in the design of adapters and structures of spacecraft.

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