Аналіз існуючого досвіду щодо створення та експлуатації головних обтічників ракет-носіїв показав, що на сьогоднішній день широко застосовуються сендвічеві конструкції з композитними несучими обшивками в поєднанні зі стільниковим заповнювачем. Розглянуті конструкції містять досить велику кількість параметрів, при зміні яких істотно змінюється маса виробу.

Отримав подальший розвиток підхід до оптимізації за масою конструкцій типу головного обтічника ракети-носія. Підхід включає в себе істотно вдосконалені складові фрагментів відомих аналогів, раніше розроблених авторським колективом, а також нові фрагменти, що раніше не враховувались. На відміну від існуючих робіт, підхід дозволив вирішити складну багатопараметричну задачу оптимального проектування розглянутого класу техніки практично без втрати точності. Для цього процес оптимізації був розділений на декілька етапів відповідно до обґрунтованих рівнів значущості параметрів, що входять в цільову функцію – мінімум маси. Проведено аналіз ефективності структури армування несучих обшивок і попередня оптимізація властивостей стільникового заповнювача, що істотно спростили вибір їх оптимальних параметрів. Показано, що при мінімальному виграші в масі за рахунок оптимальної схеми армування, що дорівнює приблизно 5 % в порівнянні з квазіоднородной оболонкою, існує реальний ризик подвійного збільшення маси оболонки при виборі істотно неоптимальною структури оболонки.

В результаті досліджень отримано раціональні параметри схеми армування несучих обшивок і стільникового заповнювача, а також їх геометричні параметри, що забезпечили зниження маси головного обтічника в порівнянні з базовим варіантом на 51 % або 118,2 кг. Отримані результати допускають подальший розвиток і вдосконалення практично без змін своєї концепції і структури в напрямку включення в оптимізацію допоміжних конструктивних елементів головного обтічника

Ключові слова: оптимізація за масою, головний обтічник, сендвічеві конструкції, несучі обшивки, стільниковий заповнювач

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IMPROVING THE MASS EFFICIENCY OF A COMPOSITE LAUNCH VEHICLE HEAD FAIRING WITH A SANDWICH STRUCTURE

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1. Introduction

In today's growing competition in the global space services market, the main trend in the development of rocket and space industry is to reduce the high cost of delivering a payload into orbit. For several decades, it has ranged, when recalculated per 1 kg of payload, from USD 3...5 thousand [1] to USD 10...30 thousand [2]. In some exceptional cases, this indicator could be as high as USD 100,000 [3]. Such a high cost is due to the fact that the mass of a payload, when delivered to low orbits, accounts for not larger than 5.5 % of the launch mass of carrier rockets, and, when delivering to a geostationary orbit, less than 1.5 % [4, 5].

Therefore, there is now a significant increase in the size of head fairings [6]. This makes it possible for the placement of a large payload within it, as well as the simultaneous group delivery of several spacecraft [4, 6]. The increase in the dimensions and mass of a payload leads to an increase in the size and loading degree of the bearing structure of a head fairing [6]. Analysis of practical experience in the construction and operation of launch vehicles' head fairings has revealed the current wide application of sandwich structures with composite sheaths in a combination with a cellular filler [7]. The high effectiveness of such a structural-strength scheme is predetermined by its nature and has been reliably proven theoretically and experimentally [8, 9]. A sandwich structural-strength scheme makes it possible to implement some of the highest indicators of specific strength and rigidity at a minimum mass, which is the determining criterion for the efficiency of units related to the considered class of equipment [9, 10]. The feasibility of these capabilities depends on the effectiveness of structural-technological decisions made as a result of optimization during the product design process. The structures under consideration contain a rather large number of parameters changing which considerably alters the mass of an article. Thus, the character of change in the thickness of composite bearing sheaths is associated with the need to take into consideration the change in their physical and mechanical characteristics due to the variation in their reinforcement scheme [11]. The wide possibilities for varying the physical and mechanical characteristics of a cellular filler by changing the geometric parameters of its cell also complicate the possibility of stating and implementing the problem on optimal design [12]. Up to now, there have been no procedures for the optimal design of sandwich composite structures that would integrate such varying parameters as the thicknesses of bearing sheaths, cellular filler, and frame belts, as well as the geometric parameters of cells [3]. Under these conditions, of special relevance are the issues related to scientific substantiation of implementing the potential to improve the mass efficiency of the considered sandwich structural-strength scheme at a regulated carrying capacity of the head fairing.

2. Literature review and problem statement

Modern rocket and space equipment have a series of features that distinguish it as a separate class of equipment, which necessitates the development of specific methods for optimal design [14]. Given that for cases involving metallic products the sequence of optimal design is, to some extent, predefined, for cases involving composites each set of technical requirements implies a variety of possible combinations, as such a material is constructed at the same time as the structure [11, 13–15]. That explains the significant attention that has been paid recently to the task on optimal design of composite assemblies related to the considered class of equipment.

Most studies addressing a given issue are common in that the approaches proposed in them implement analytical mathematical models that are rather close in content [3, 12, 13]. These models require an appropriate idealization of the design representation, as well as the types of external influences it is exposed to. The errors introduced by idealization could, in addition to leveling the benefits from starting analytical models, lead to a mismatch between the actual carrying capacity of an article and that projected.

Thus, underlying an approach reported in [3] is the mathematical model, which makes it possible to establish the overall loss of stability by the conical and cylindrical sandwich sheath under the action of compressive force, uniform external pressure, and torque. The techniques for rationalizing the design tasks of composite bearing sheaths for launch vehicles have been investigated in papers [16, 17]. The authors used the examples of actual structures to show the methodology for determining the regions for rational applications of various structural-strength schemes of cylindrical composite sheaths. However, the descriptions of the applied methods for solving optimization problems and the software that implements them, reported in [16, 17], indicate a significant idealization of the representation of the considered objects and the external influences that affect them.

Work [18] tackles issues on the optimization of cylindrical sheaths, homogeneous and heterogeneous in thickness, forming an irregular periodic structure. However, the results given were obtained only under the action of isolated axial compression.

Studies [19, 20] systemized the constructed methods for determining the limit loads to sheath composite structures. The general drawback of the cited studies is that the authors pay considerable attention to the theory of calculating limit loads, based on the use of generalized characteristics of composite materials, which can only be obtained for individual samples of a structure.

Issues related to optimizing the parameters of a cellular filler were addressed in work [21]. The authors proposed a method for analytical forecasting of the maximally possible reduction in the mass of composite structures for space purposes, taking into consideration the technological capabilities of their fabrication. However, the cited work employs a simplified calculation scheme, which is the reason for the a priori approximate results that were obtained. Such simplifications are also used in papers by other authors, for instance [22].

Study [23] dealt with the optimization of structure for bearing sheaths, taking into consideration the structural and technological limitations on the thickness of a package of a composite material. However, the application of the results for sandwich sheath systems with a cellular filler under a combined loading requires an appropriate generalization of the proposed algorithms.

The above works are common in that most of the approaches proposed in them are based on some heuristic additional assumptions – equal strength, uniform deformability, etc. Adhering to such assumptions, in the authors' opinion, warrants that the articles' parameters are improved. However, the errors introduced by this idealization could, in addition to neutralizing the benefits from starting analytical models, lead to a mismatch between the actual carrying capacity of an article and that projected. It should also be noted that optimization calculations generally imply a characteristically small number of variables. Given that real composite cellular structures have a rather large number of design parameters, the generalization of the approaches proposed in the considered works appears problematic.

Study [24] accounted, in the optimization of design parameters, for a cellular filler, taking into consideration the technological mechanics of its production. However, the proposed procedure can only be used with a certain adjustment to optimize the parameters of cellular sheaths for mass when parsing them into the co-joined cylindrical panels.

Work [25] addresses the development of a procedure for optimizing sandwich-based composite structures with a cellular filler, taking into consideration technological limitations. However, the accepted estimation schemes for the considered standard technological defects of composite aggregates are extremely simplified, which does not make it possible to generalize the results obtained in order to identify the interaction between technological factors and their joint effect on the carrying capacity of the rational design of a structure.

The general drawback of available studies is that the optimization calculations generally tend to be characterized by a characteristically small number of variable parameters. Given that actual composite sandwich structures have quite a large number of design parameters, the generalization of the approaches proposed in the considered studies looks problematic. Typically, the above works examined in the optimization of rocket and space equipment separate incompatible types of loading, for each of which the rational parameters of a structure were derived.

At present, computer technologies underlie the scientific and technical substantiation of efficiency of optimal design and production of composite structures with a cellular filler. These technologies have been developed and used intensively over the past decade [26, 27]. However, a given optimization approach only solves a specific task and typically prevents the results obtained to be generalized considering the technological and other limitations [28].

An attempt to solve the task on reducing the mass of composite cellular structures for space purpose by optimizing their parameters based on the synthesis of computer technologies employing a finite-element analysis and analytical models was made in work [29]. The authors developed and implemented a method for optimizing a composite launch-vehicle head fairing. A significant disadvantage of the work is the possibility to take into consideration the thermal impact only through the deterioration in the physical and mechanical characteristics of the structural materials used. However, the proposed approach does not make it possible to generalize the results.

The above analysis testifies to the expediency of devising approaches to the optimization of parameters for composite sandwich sheath structures of a launch-vehicle head fairing, which would improve its mass efficiency.

3. The aim and objectives of the study

The aim of this work is to develop approaches to optimizing the parameters for composite sandwich sheath structures of a launch-vehicle head fairing with the improved mass efficiency.

To achieve the set aim, the following tasks have been solved:

– to analyze effectiveness of the reinforcement structure for bearing sheaths and to pre-optimize the properties of a cellular filler, which could greatly simplify the selection of their optimal parameters;

– to optimize for mass the parameters for a multi-section composite sandwich sheath structure the type of a launch-vehicle head fairing.

4. Study materials and methods

The Kirchhroff-Love hypothesis holds for composite bearing sheaths. As regards the filler, a linear law of distribution of cross-sections by height is adopted while deformations in the transverse direction are not taken into consideration. The reinforced fibers of a polymeric composite material are stacked symmetrically relative to the middle surface of the package and the curvature lines of the sheath. The analysis of effectiveness of the reinforcement structures for bearing sheaths was carried out based on the methods of technological mechanics of composites. In this case, the characteristics of a composite were determined on the basis of mathematical models from the theory of reinforcement. Preliminary optimization of the properties of a cellular filler was carried out by methods of mathematical programming. To this end, analytical dependences were used to determine the reduced physical-mechanical characteristics of a cellular filler, obtained from the scheme of even distribution of the typical element of a cellular unit in terms of volume. To determine the carrying capacity and to optimize for mass the parameters of a multi-sectional sandwich sheath structure the type of a head fairing, a programming complex that employs a finite-element analysis was applied with the developed multi-stage implementation algorithm. The problems were solved based on linear equations of elasticity and stability.

5. Statement of the problem and initial data

The head fairing, which is part of the head unit of the Cyclone-4 launch vehicle, is considered as the object of this study. Underlying the current research both in terms of the regulation of geometric parameters and the standardization of loads on the article are the data provided by the State Enterprise «Southern Design Bureau» (Fig. 1) [12, 29, 30].

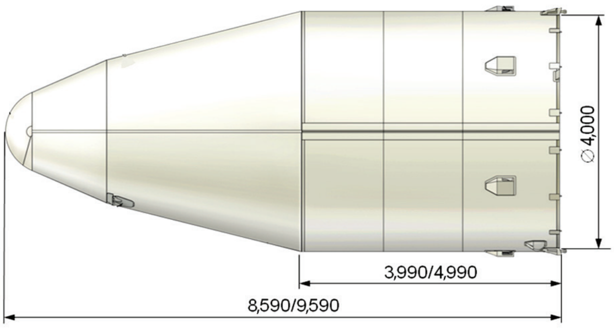

Fig. 1. General view of a launch-vehicle head fairing

The standard initial data for the optimal design of a launch-vehicle head fairing are [12, 29, 30]:

– main Technical requirements for the project;

– limitations for dimensions;

– operating conditions;

– main estimated cases, magnitudes of operational loads, safety ratios;

– materials applied and their physical-mechanical characteristics.

The head fairing is a cylindrical-biconical compartment (includes a 25-degree cone and a 15-degree cone), with a length of 8,590/9,590 mm and a diameter of 4,000 mm, with a spherical tip of radius 720 mm. The body of the head fairing consists of two semi-sheaths of the sandwich structure, which are attached to each other by the mechanical locks from a longitudinal joint separation system. All sections of the head fairing are connected to each other by metallic frames. In addition, a first conical section hosts an intermediate frame.

A spherical tip is planned to be made of fiberglass; bearing sheaths – from carbon polymeric composite material; a filler is the honeycombs made from aluminum alloy with hexagonal cells.

Based on the results of analysis [12, 29, 30], the following estimated cases of loading were considered:

– loading the elements of the structure with surface pressure at Mach number $M=M_{cr}$ (54 s);

– a maximum of aerodynamic coefficients (57 s);

– a maximum of drag (63 s);

– the zone of a speed head maximum (69 s, 71 s).

These cases of loading correspond to the flight of a launch vehicle when delivering a payload weighing 650 kg to a flight trajectory. The accepted loads on the head fairing are the estimated static components of bending moments M, cutting forces Q, axial forces T in the estimated cross sections, and the excess unevenly distributed pressure P. An example of loads on the head fairing is shown in Table 1 [12, 29, 30].

The current level of computer design technologies development makes it possible to tackle the issue of improving the efficiency of assemblies of the considered class of equipment. Thus, work [29] proposed, and paper [31] implemented, a comprehensive approach to optimizing the sheath composite structures, allowing the extension of range of the considered optimization parameters. The authors conducted a rather deep simultaneous optimization, within each compartment of a head fairing, of the scheme for arranging bearing sheaths, the geometric parameters for cells and frames when the assembly is exposed to almost the entire spectrum of external influences.

Table 1

Example of the distribution of statistical components of bending momenta (M), cutting (Q) and axial (T) forces, as well as excess pressure (P), lengthwise a head fairing, on second 71 of the flight

x, m	M, kN m	Q, kN	T, kN	P, MPa		
				φ=0°	φ=90°	φ=180°
0	0	0	0	0.081	0.081	0.081
0.41	1.1	5.2	54	0.019	0.013	0.008
0.98	–	–	–	0.036	0.03	0.023
1.572	18.07	25.01	142.4	0.028	0.023	0.018
2.11	–	–	–	0.017	0.013	0.009
3.003	75.54	55.1	189.7	0.016	0.012	0.009
3.864	130.5	72.74	228.7	0.018	0.014	0.01
4.6	189.8	87.48	263.5	0.011	0.007	0.005
5.65	287.9	99.07	267	0.002	0	-0.001
6.878	417.2	111.5	271.2	0.003	0.002	0
7.961	543.6	121.7	274.9	0.005	0.003	0.002
8.59	621.3	124.7	277.3	0.002	0.001	0

Note: φ – meridional angle, φ=0° – windward side, φ=90° – side, φ=180° – lee side; a «minus» sign corresponds to internal excess pressure; a «plus» sign corresponds to external excess pressure; axial force with the «plus» sign is understood to be compressive

The distinctive features of this approach are [31]:

– a deep level of optimization of the basic structural parameters for a head fairing: bearing sheaths and a cellular filler. This implements the almost exhaustive possibilities of polymeric composite materials and honeycombs at the modern level of their production technologies;

– the optimization of structural parameters for a head fairing for all cases of loading an object;

– taking into consideration the profile of technological imperfections of composite bearing sheaths by incorporating the regulated tolerances for basic types of technological imperfections into the optimization process;

– testing and ensuring the carrying capacity of the optimal, in terms of mass, variant of a sandwich structure with a cellular filler, taking into consideration the presence in its faces of the initial technological camber within the regulated tolerance.

However, a given optimization approach, similar to others based on computer technologies [25, 26], makes it possible to solve only a specific problem and requires significant material and time costs.

In order to be able to generalize the results obtained from optimizing the parameters for composite units of the considered equipment class when they are exposed to a combined loading, let us analyze the effectiveness of the reinforcement schemes for bearing sheaths and perform preliminary optimization of cellular filler properties. That would make it possible to realize more fully the possibilities for reducing the mass of assemblies within the considered class of equipment and to significantly simplify the selection of their optimal parameters.

6. Analysis of the effectiveness of reinforcement schemes for bearing sheaths and preliminary optimization of cellular filler properties

Choosing a scheme of reinforcement and the thickness of bearing sheaths for a head fairing requires an analysis of their weight effectiveness. It is known [11, 13, 16–20] that the reinforcement scheme of bearing sheaths significantly affects the shell's carrying capacity. At the same time, incompatible estimated cases of loading the articles such as a launch-vehicle head fairing considerably complicate the choice of the optimal reinforcement scheme for bearing shells for the entire spectrum of external loads. There are not enough studies into the optimal structures of reinforcement of sheaths made from polymeric composite materials exposed to combined loading, and they are almost missing for incompatible cases [11, 13, 16–20]. In this regard, below is the analysis of results from the optimization of a composite cylindrical sheath with various reinforcement schemes, reported in [32] and further developed in [33]. Table 2 gives optimal variants of the reinforcement of such a sheath under axial compression.

Table 2

Optimal variants of structures for reinforcing a cylindrical sheath under axial compression ($T_{cr} \geq 1.57$ MPa)

Variant number	Reinforcement structure	M, kg
1	$0_{0.2}$; $(\pm45)_{0.74}$; $90_{0.06}$	3.27
2	$0_{0.13}$; $(\pm45)_{0.78}$; $90_{0.09}$	3.26
3	$0_{0.25}$; $(\pm45)_{0.75}$; 90_{0}	3.26
4	$0_{0.33}$; $(\pm45)_{0.67}$; 90_{0}	3.28
5	Quasi-homogeneous sheath $0_{0.25}$; $(\pm45)_{0.5}$; $90_{0.25}$	3.44

Analysis of Table 2 reveals:

– the minimal mass can be ensured by different reinforcement structures;

– the mass of a quasi-homogeneous sheath exceeds the mass, optimal in terms of the reinforcement scheme, by 5 % on average. This fits into the range of errors associated with the accuracy of estimation schemes (mathematical models) and calculation techniques.

Table 3 gives the suboptimal variants of structures for reinforcing the same cylindrical sheath under axial compression, reported in papers [32, 33].

Table 3

Suboptimal variants of structures for the reinforcement of a cylindrical sheath under axial compression ($T_{cr} \geq 1.57$ MPa)

Variant number	Reinforcement structure	M, kg
1	0_{0}; $(\pm45)_{0.72}$; $90_{0.24}$	4.76
2	$0_{0.04}$; $(\pm45)_{0.66}$; $90_{0.3}$	4.52
3	0_{1}; $(\pm45)_{0}$; 90_{0}	6.59
4	0_{0}; $(\pm45)_{0.72}$; $90_{0.28}$	4.52

Analysis of Table 3 reveals that an irrationally selected reinforcement scheme results in a significant increase in sheath mass compared to optimal that amounts to 100 %.

Thus, it follows from the analysis of Tables 2, 3 that at a minimum gain in mass due to the optimal reinforcement scheme, of about 5 % compared to a quasi-homogeneous sheath, there is a real risk of a double increase in the sheath mass when choosing a substantially suboptimal structure of the sheath.

Therefore, based on the analysis of the cylindrical composite sheath, loaded with axial compression, it is possible to focus on a quasi-homogeneous structure (variant 5 in Table 2).

Table 4 gives results of the optimization of a cylindrical sheath, considered above, under a constant external pressure [32, 33].

Table 4

Results from analyzing the optimality of schemes of arranging layers in a cylindrical sheath under external pressure (q=4 MPa)

Variant number	Reinforcement structure	M, kg
1	0_0; $(\pm45)_1$; 90_0	10.41
2	0_0; $(\pm45)_{0.5}$; $90_{0.5}$	8.85
3	$0_{0.12}$; $(\pm45)_{0.77}$; $90_{0.11}$	10.2
4	$0_{0.04}$; $(\pm45)_{0.96}$; 90_0	10.27
5	0_0; $(\pm45)_{0.73}$; $90_{0.27}$	8.58
6	0_0; $(\pm45)_{0.73}$; $90_{0.27}$	8.57
7	0_0; $(\pm45)_{0,96}$; $90_{0,04}$	10.27
8	$0_{0.07}$; $(\pm45)_0$; $90_{0.93}$	9.14
9	$0_{0,38}$; $(\pm45)_{0,62}$; 90_0	9.66
10	0_0; $(\pm45)_{0,53}$; $90_{0,47}$	8.94
11	$0_{0.33}$; $(\pm45)_0$; $90_{0.67}$	8.56
12	0_0; $(\pm45)_{0.52}$; $90_{0.48}$	8.26
13	Quasi-homogeneous sheath $0_{0.25}$; $(\pm45)_{0.5}$; $90_{0.25}$	8.87

Analysis of Table 4 makes it possible to draw the following conclusions:

– over the entire spectrum of reinforcement schemes (13 variants), the maximum difference in masses between minimal and the maximal is 26 %;

– a difference between the mass of a quasi-homogeneous sheath (variant 13) and optimal (variant 12) is 7.4 %, which is also quite consistent with the level of errors of the calculation itself.

The above analysis has shown that at the isolated loading with an axial compression or with an external uniform pressure, the reinforcement schemes of the sheath carrying layers produce a minimum mass while they tend to a quasi-homogeneous structure.

Let us consider formation of the physical-mechanical characteristics of a cellular filler with the most technological and commonly applied hexagonal cell, shown in Fig. 2 [3, 8, 9].

In determining the physical and mechanical characteristics of the cellular filler with the presented cell, let us use the following adjusted formulae:

$$\rho_{hc}=\frac{\delta_c\rho_c(1+k)}{ka_c\sin\beta(1+k\cos\beta)};\qquad(1)$$

$$G_{hc}^{xz}=0.75\frac{\delta_c G_c\left(1+k\cos^2\beta\right)}{ka_c\sin\beta(1+k\cos\beta)};\qquad(2)$$

$$G_{hc}^{yz}=0.75\frac{\delta_c G_c\sin\beta}{a_c(1+k\cos\beta)};\qquad(3)$$

$$F_{hc}^{xz}=0.3\frac{\delta_c\sigma_{uts}(1{,}15+k\cos\beta)}{ka_c\sin\beta(1+k\cos\beta)};\qquad(4)$$

$$F_{hc}^{yz}=0.3\frac{\delta_c\sigma_{uts}}{a_c(1+k\cos\beta)},\qquad(5)$$

where ρ_{hc}, G_{hc}^{xz}, G_{hc}^{yz}, F_{hc}^{xz}, F_{hc}^{yz} are the reduced density, shear modules, the shear strength limits of a cellular filler; δ_c is the thickness of the foil that the honeycombs are made of; ρ_c, G_c, σ_{uts} are the density, shear module, and the ultimate tensile strength of a foil's material, respectively; a_c, k, β are the width of the connecting side of a cell along which the cells are glued together during the formation of a cellular unit, the shape factor, and the opening angle of a cellular filler, respectively.

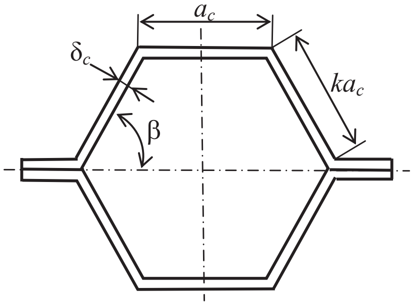

Fig. 2. Cell of a cellular filler of hexagonal shape

These formulae for determining the physical-mechanical characteristics of a cellular filler were obtained in work [33] according to a known scheme [9]. Formulae for determining the shear strength limit of a cellular filler were derived in study [12] for a cell of the irregular hexagonal shape in the general form.

The adjustment of physical and mechanical characteristics to a factor of 0.75 in (2) to (5) was based on the findings in paper [34]. In this case, it was postulated that the 0.75 factor remains constant when the configuration and size of the cell of a cellular filler is changed, that is it is only a characteristic of the honeycomb manufacturing technology.

To analyze the effectiveness of optimizing the parameters for a cellular filler, let us consider the character of their change. The range of change in the optimal opening angle of the cell in a honeycomb will be determined according to work [29]: $51°\le\beta_{opt}\le68°$ at $0.5°\le k\le3$.

Fig. 3–5 show the diagrams of surfaces of change in ρ_{hc} due to the honeycomb cell parameters k, a_c and β.

To determine the character of change in each variable parameter within the specified limits, the sign of a derivative from ρ_{hc} was analyzed for each parameter:

$$\frac{\partial\bar{\rho}_{hc}}{\partial k}=-\frac{1+2k\cos\beta+k^2\cos\beta}{\delta_c\rho_c a_c k^2\sin\beta(1+k\cos\beta)^2};\qquad(6)$$

$$\frac{\partial\bar{\rho}_{hc}}{\partial a_c}=-\frac{1+k}{\delta_c\rho_c a_c{}^2 k\sin\beta(1+k\cos\beta)};\qquad(7)$$

$$\frac{\partial\bar{\rho}_{hc}}{\partial\beta}=-\frac{(1+k)(\cos\beta+k\cos2\beta)}{\delta_c\rho_c a_c k\sin^2\beta(1+k\cos\beta)^2}.\qquad(8)$$

The «minus» sign in (6) to (8) indicates a monotonous descent in function ρ_{hc} as each parameter grows from its lower value to the highest at fixed values of the other two (Fig. 3–5).

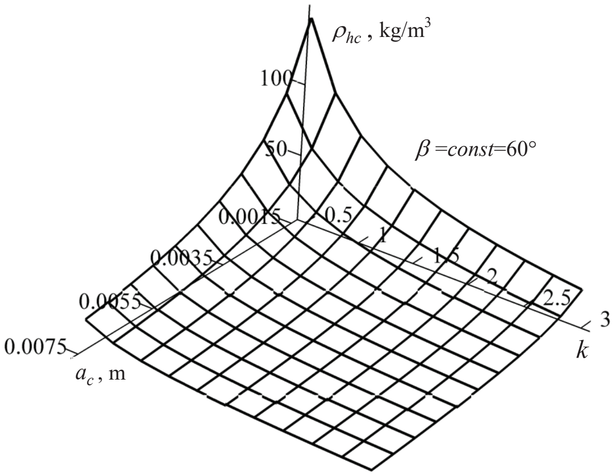

Fig. 3. Diagram of surface $\rho_{hc}=f(a_c, k)$ at β=const=60°

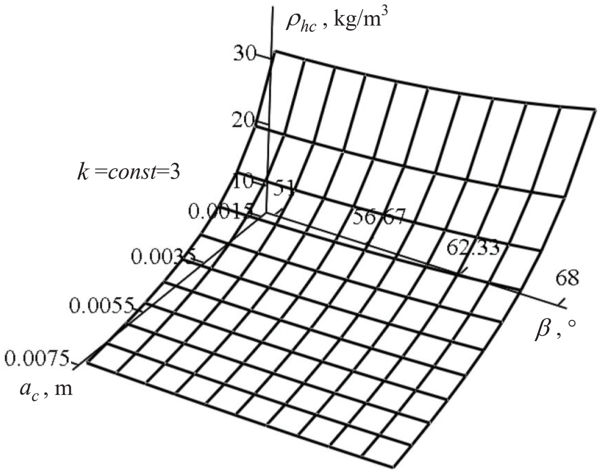

Fig. 4. Diagram of surface $\rho_{hc}=f(a_c, \beta)$ at k=const=3

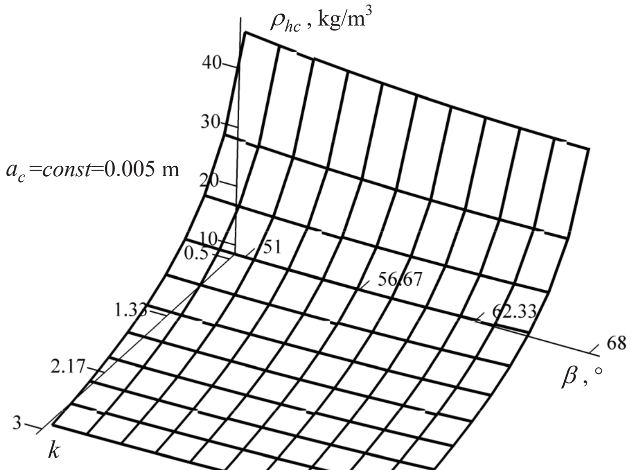

Fig. 5. Diagram of surface $\rho_{hc}=f(k, \beta)$ at a_c=const=0.005 m

Analysis based on mathematical programming methods shows that the lowest level ρ_{hc} is demonstrated at k=3; a_c=7.5 mm and β=51°, while the highest – at k=0.5; a_c=1.5 mm and β=51°.

For ρ_{hc}, based on (3), the limiting values were calculated at the thickness of a foil δ_c=0.03 mm and ρ_c=2,700 kg/m³:

$$\rho_{hc}^{\min}=\frac{0.03\cdot 2.7(1+3)}{3\cdot 7.5\cdot \sin 51°(1+3\cos 51°)}=6.4 \text{ kg/m}^3;$$

$$\rho_{hc}^{\max}=\frac{0.03\cdot 2.7(1+0{,}5)}{0.5\cdot 1.5\cdot \sin 51°(1+0{,}5\cos 51°)}=159 \text{ kg/m}^3.$$

Thus, over a predefined range of changes in the structural parameters of the cell of a cellular filler, the maximum difference between $\rho_{hc}^{\max}$ and $\rho_{hc}^{\min}$ can amount to 24.8 times. And for honeycombs with a cell of the correct hexagonal shape at boundary values a_c is 4.7 times.

This result demonstrates the feasibility of optimizing the parameters for a cellular filler.

The considered range of change in ρ_{hc} was set without taking into consideration the constraints for a cellular filler's carrying capacity in an article, primarily regulated by the level and ratio of honeycomb shear modules G_{hc}^{xz}, G_{hc}^{yz}, and the shear strength limits F_{hc}^{xz}, F_{hc}^{yz}.

In this regard, below is an analysis of the character of change in these variable parameters within the specified limits of changes in k, a_c and β.

The diagrams of surfaces of change in G_{hc}^{xz} and G_{hc}^{yz} due to parameters k, a_c and β are shown in Fig. 6–11.

By differentiating G_{hc}^{xz} and G_{hc}^{yz} from (2) and (3) according to the relevant parameters, the following is obtained, accordingly:

$$\frac{\partial G_{hc}^{xz}}{\partial a_c}=-0.75\frac{G_c\delta_c\left(1+k\cos^2\beta\right)}{a_c^2 k\sin\beta(1+k\cos\beta)}; \quad (9)$$

$$\frac{\partial G_{hc}^{yz}}{\partial a_c}=-0.75\frac{G_c\delta_c\sin\beta}{a_c^2(1+k\cos\beta)}; \quad (10)$$

$$\frac{\partial G_{hc}^{xz}}{\partial k}=-0.75\frac{G_c\delta_c}{a_c\sin\beta}\times$$
$$\times\frac{k\cos^2\beta(1+k\cos\beta)-(1+2k\cos\beta)\left(1+k\cos^2\beta\right)}{k^2(1+k\cos\beta)^2}; \quad (11)$$

$$\frac{\partial G_{hc}^{yz}}{\partial k}=-0.75\frac{G_c\delta_c\sin^2\beta}{a_c}\cdot\frac{\cos\beta}{(1+k\cos\beta)^2}; \quad (12)$$

$$\frac{\partial G_{hc}^{xz}}{\partial \beta}=0.75\frac{G_c\delta_c\sin^2\beta}{a_c}\cdot\frac{0.5k-(1+k\cos\beta)\sin\beta}{\sin^2\beta(1+k\cos\beta)^2}; \quad (13)$$

$$\frac{\partial G_{hc}^{yz}}{\partial \beta}=0.75\frac{G_c\delta_c}{a_c}\cdot\frac{k+\cos\beta}{(1+k\cos\beta)^2}. \quad (14)$$

The character of change in F_{hc}^{xz} and F_{hc}^{yz} is identical to G_{hc}^{xz} and G_{hc}^{yz}.

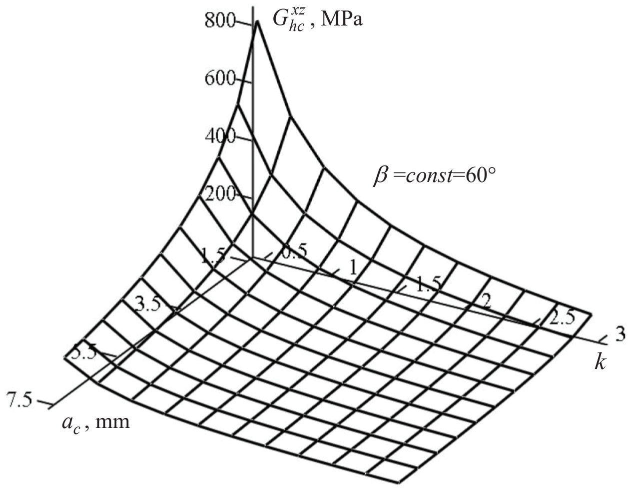

Fig. 6. Diagram of surface $G_{hc}^{xz}=f(a_c,k)$ at β=const=60°

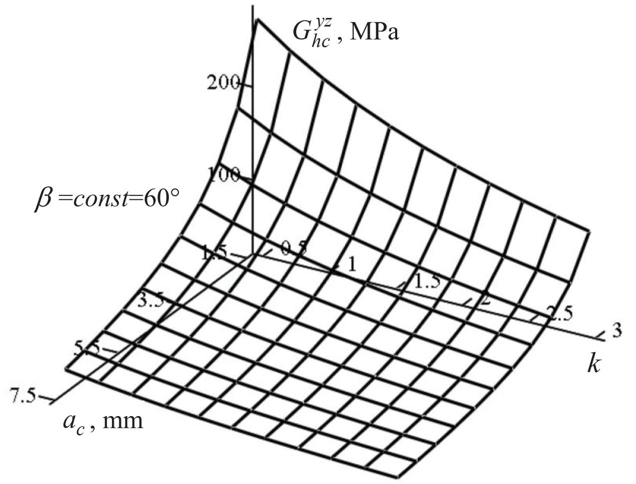

Fig. 7. Diagram of surface $G_{hc}^{yz}=f(a_c,k)$ at β=const=60°

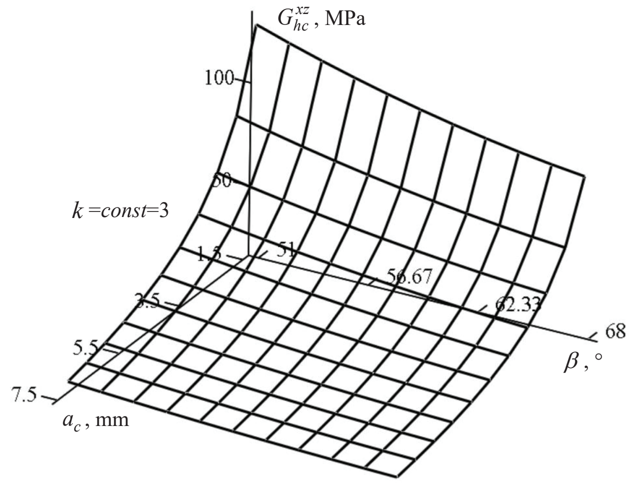

Fig. 8. Diagram of surface $G_{hc}^{xz}=f(a_c,\beta)$ at k=const=3

The findings from studying a change in G_{hc}^{xz} and G_{hc}^{yz} depending on the parameters k, a_c and β are as follows:

– the highest value G_{hc}^{xz} is demonstrated at minimal values of k, a_c and β;

– with an increase in a_c at any k and β G_{hc}^{xz} monotonously decreases;

– with an increase in k at fixed a_c and β G_{hc}^{xz} decreases;

– the highest value of G_{hc}^{yz} is demonstrated at minimal values of a_c and k and a maximal value of β;

– with an increase in a_c G_{hc}^{yz} monotonously decreases at any k and β;

– with an increase in k at fixed a_c and β G_{hc}^{yz} decreases.

Similar findings apply to changes in the honeycomb strength limits F_{hc}^{xz} and F_{hc}^{yz}.

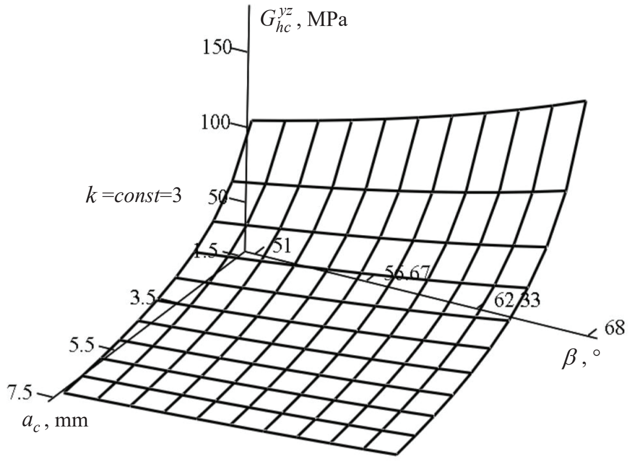

Fig. 9. Diagram of surface $G_{hc}^{yz}=f(a_c,\beta)$ at k=const=3

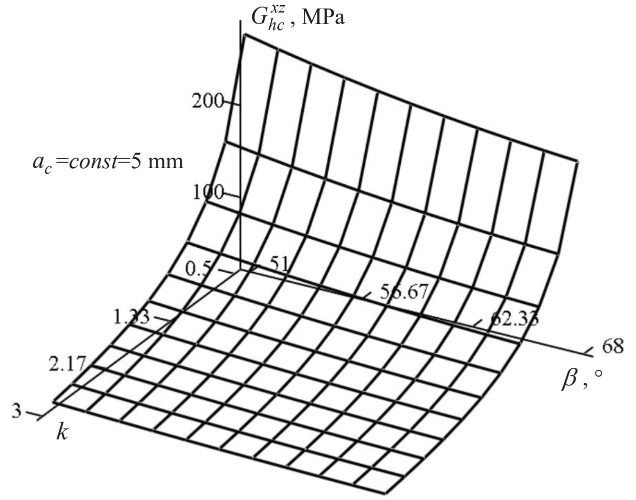

Fig. 10. Diagram of surface $G_{hc}^{xz}=f(k,\beta)$ at a_c=const=5 mm

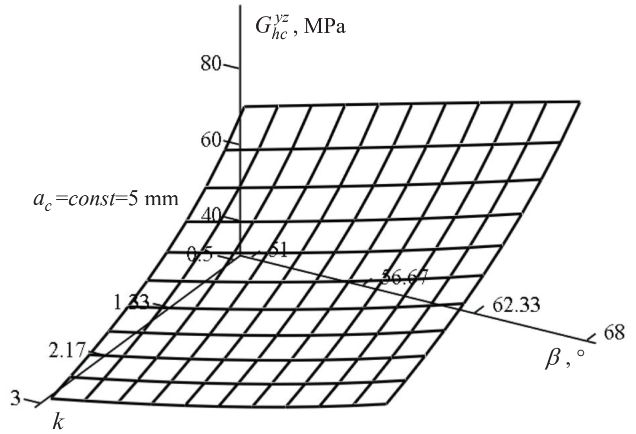

Fig. 11. Diagram of surface $G_{hc}^{yz}=f(k,\beta)$ at a_c=const=5 mm

7. Optimizing a multi-sectional sandwich sheath structure, the type of a launch-vehicle head fairing, for mass

One of the programming complexes for a finite element analysis was used to determine the stressed-strained state and to optimize the structural parameters of a head fairing. Currently, there are quite a lot of specialized and general-engineering software complexes for a finite element analysis. All these complexes are similar in the ideology of their construction, in the applied mathematical models and methods of their implementation, as well as the list of solved problems, thereby allowing the mutual exchange of data and results from calculations. That poses no fundamental issues related to applying a specific complex [26, 29].

To calculate and subsequently optimize the head fairing, using the programming complex of a finite element analysis, it is represented in the form of a system of sheaths, supported by frames. The conical and cylindrical compartments of a head fairing are represented in the form of sandwich sheaths. When they are sampled into a finite element grid, a multi-layered sheath finite element was chosen with appropriate properties. A variant of the sandwich structure was chosen, which corresponds to the character of operation of a sandwich sheath with a filler. In this case, the filler, by perceiving transverse forces, ensures the joint work of bearing sheaths and does not perceive the bending moment and the forces acting in the middle surface. The bearing sheaths are modeled in the form of a package of total thickness δ_{cl} with a full set of components of the reduced orthotropic physical-mechanical characteristics. The cellular filler is represented in the form of a conditional, homogeneous layer of a multi-layered finite element, whose orthotropic physical-mechanical characteristics depend on the geometric configuration of the cell, the thickness of the foil and its mechanical characteristics.

At sampling a spherical tip, a single-layer sheath finite element is used. The frames and elements of a longitudinal joint are simulated by the beam elements of the corresponding cross-section. To properly account for the conditions of docking the head fairing to the adjacent inter-stage compartment, it was modeled together with it. The generated finite element model of the head unit and the global coordinate system are shown in Fig. 12.

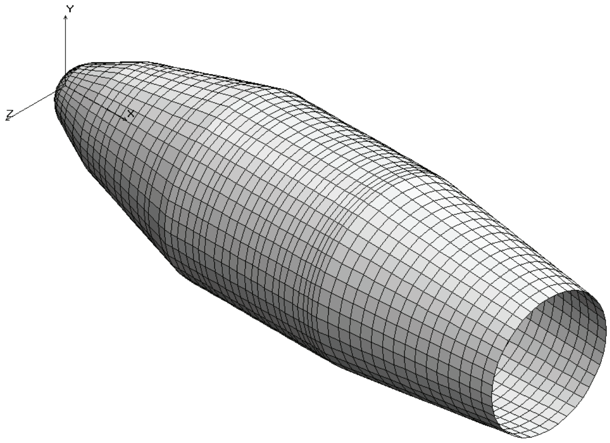

Fig. 12. A finite element model of the head unit and the global coordinate system

The load on the elements of the head unit was applied in the form of pressure normal to the surface, distributed according to the assigned law within the relevant surface and reduced to the nodes at each cross section of the equivalent longitudinal and transverse force. Bending momenta in the estimation cross sections were applied in the form of pairs of forces reduced to the nodes of corresponding cross sections. The head unit was fixed along the nodes of the lower frame of the inter-stage compartment for all movements, which corresponded to the condition of its docking to a second stage of the launch vehicle.

The problem was solved based on the linear equations of elasticity and stability [31].

Based on the analysis of various reinforcement schemes for bearing sheaths, different variants of reinforcement structures were selected for a given object (Table 5). The formation of the physical and mechanical characteristics of the reinforcement structures for bearing sheaths for the subsequent optimization was carried out in line with approximate formulae from work [35] derived from models [36]. These dependences take into consideration the integrated deviations in the technological modes of forming the composite bearing sheaths (pressure, temperature, and their change over time) from regulated ones.

Table 5

Properties of the considered variants of reinforcement schemes for bearing sheaths

Variant number	Number pf monolayers	Arrangement scheme	E_0, GPa	E_{90}, GPa	$\mu_{0,90}$	$G_{0,90}$, GPA	F_0^+, MPa	F_{90}^+, MPa	F_0^-, MPa	F_{90}^-, MPa	$F_{0,90}$, MPa
1	8	$2_0+4_{45}+2_{90}$	37.5	37.5	0.44	5.6	450	450	330	330	160
2	7	$2_0+4_{45}+1_{90}$	42	26.6	0.48	5.8	510	327	353	270	117
3	7	$1_0+4_{45}+2_{90}$	26.6	42	0.3	5.8	327	510	270	353	117
4	6	$2_0+2_{45}+2_{90}$	45	45	0.37	5.1	520	520	355	355	142
5	5	$2_0+2_{45}+1_{90}$	53	32	0.43	5.2	626	369	404	287	149
6	5	$1_0+2_{45}+2_{90}$	32	53	0.26	5.2	369	626	278	404	149
7	4	$1_0+2_{45}+1_{90}$	37.5	37.5	0.44	5.6	450	450	330	330	160

A summary of the considered variants of reinforcement structures for bearing sheaths and the corresponding physical and mechanical characteristics is given in Table 5. The number of monolayers is limited to a range of $4<m<8$.

When analyzing the efficiency of varying the geometrical parameters of the cell in a cellular filler, the above results from the preliminary optimization of cellular filler properties were used.

A procedure for optimizing the parameters of a head fairing was formed taking into consideration the contribution of the structural parameters of a head fairing to the total mass of a product, established in papers [29, 31]. In so doing, the following was found.

Ensuring the stability of a head fairing is predetermined by:

– first of all (mostly) by the separation of bearing sheaths, that is the choice of the height of a cellular filler;

– in the second place, by the choice of the thickness of bearing sheaths and the scheme for their reinforcement;

– in the third place, by the choice of the shape and size of the cell of a cellular filler, which forms its reduced physical and mechanical characteristics.

Ensuring the strength of a head fairing is predetermined by:

– first of all, by the thickness of bearing sheaths and the scheme for their reinforcement;

– in second place, by the physical and mechanical characteristics of a cellular filler.

Ensuring a minimum of the mass of a head fairing is predetermined:

– first of all, by the thickness of bearing sheaths;

– in the second place, by the separation of carrying layers, that is the height of a cellular filler;

– in the third place, by the configuration of the cell associated with the physical and mechanical characteristics of a cellular filler.

In this regard, the first unit of the optimization complex used such structural variables for a head fairing as the height of a cellular filler h_{hc} and the considered variants of reinforcement structures for bearing sheaths (Table 5). The geometric parameters of frames in a given problem were not optimized.

The second optimization unit, by varying the parameters for a cell in a cellular filler a_c, k and β, optimizes the structure of honeycombs at the fixed optimal values of the structural variables from the first unit.

A procedure developed in work [37] was used to implement a verification unit, which makes it possible to predict the character of a cellular filler's operation, taking into consideration the presence of the initial technological camber within the regulated limits of tolerance.

The optimized structural elements in [30, 33] have the mass: bearing sheaths of all compartments of a head fairing m_{cl}=179.4 kg; a cellular filler m_{hc}=60 kg. The total mass of sandwich sheaths is m_{Σ}=239.4 kg.

7. Results from optimizing a multi-sectional sandwich sheath composite structure, the type of a head fairing, for mass

To ensure comparability of results from optimizing a head fairing, the first unit was used to calculate the original variant of its structure. Results of this calculation are given in Table 6.

As shown by Table 6, the discrepancy (relative error) of the mass of bearing sheaths in comparison with [30, 33] is:

$$\Delta m_{cl}=\frac{179.4-176}{179.4}100\,\%=1.9\,\%,$$

the mass of a cellular filler –

$$\Delta m_{hc}=\frac{60-56.7}{60}100\,\%=5.5\,\%,$$

the total mass of bearing sheaths and a cellular filler –

$$\Delta m_{\Sigma}=\frac{239.4-232.7}{239.4}100\,\%=2.8\,\%.$$

This level of relative error is associated with inaccuracy, when compared to works [30, 33], in determining the side surface of a head fairing when measuring masses, and other factors. The level of relative error is not significant.

Table 6

Results from calculating the original variant of a head fairing

Maximal displacement, mm	27.38
Maximum normal stresses in a spherical tip, MPa	5.43
Spherical tip strength reserve	11.6
Maximum normal stresses in bearing sheaths, MPa	89.09
Safety margin of bearing sheaths	4.54
Maximum tangent stresses in a cellular filler τ_{xz}, MPa	0.063
Cellular filler's strength reserve for τ_{xz}	6.98
Maximum tangent stresses in a cellular filler τ_{yz}, MPa	0.023
Cellular filler's strength reserve for τ_{yz}	12.6
Minimum strength margin of a cellular filler	6.98
Maximum reduced stresses in frames, MPa	72.66
Frames' strength reserve	5.56
Head fairing's strength reserve	2.58
Mass of bearing sheaths, kg	176
Mass of a cellular filler, kg	56.7
Total mass of bearing sheaths and a cellular filler, kg	232.7

Table 7 gives a result from the first stage in the optimization of a head fairing within the framework of the considered reinforcement schemes for bearing sheaths (Table 5) for the found optimal height of a cellular filler.

The result of the first unit in the optimization of a head fairing was a decrease in its mass compared to the basic variant:

– bearing sheaths by

$$\frac{176-103.15}{176}100\,\%=41.4\,\%\ \ (72.85\text{ kg});$$

– a cellular filler by

$$\frac{56.7-46.1}{56.7}100\,\%=18.7\,\%\ \ (10.6\text{ kg});$$

– a head fairing in general

$$\frac{232.7-149.25}{232.7}100\,\%=35.9\,\%\ \ (83.45\text{ kg}).$$

Table 7

Results from calculating a head fairing with the considered reinforcement schemes for bearing sheaths

Indicator	honeycomb height h_{hc}, mm	Variant number of the reinforcement scheme for bearing sheaths						
		1	2	3	4	5	6	7
Maximum displacement, mm	20	11.35	12.21	14.58	14.72	16.64	19.58	22.13
	25	11.26	12.14	14.51	14.64	16.51	19.48	22.02
	30	11.22	12.08	14.49	14.58	16.44	19.42	21.92
Maximum normal stresses in bearing sheaths, MPa	20	71.9	81.86	81.18	94.73	113.25	112.95	144.08
	25	71.64	81.34	80.88	94.20	112.36	112.41	143.60
	30	71.47	80.97	80.61	93.88	111.82	111.97	143.18
Safety margin of bearing sheaths	20	6.26	6.23	4.04	5.49	5.52	3.27	3.14
	25	6.28	6.27	4.04	5.52	5.57	3.28	3.13
	30	6.30	6.30	4.06	5.54	5.60	3.29	3.14
Maximum tangent stresses in a cellular filler τ_{xz}, MPa	20	0.025	0.030	0.034	0.036	0.041	0.046	0.045
	25	0.027	0.029	0.032	0.035	0.037	0.043	0.044
	30	0.027	0.028	0.031	0.033	0.035	0.040	0.043
Cellular filler's strength reserve for τ_{xz}	20	28	23.3	20.59	19.44	17.07	15.22	15.55
	25	25.93	24.14	21.85	20.0	18.92	16.28	15.91
	30	25.93	25.0	22.58	21.21	20.00	17.50	16.28
Maximum tangent stresses in a cellular filler τ_{yz}, MPa	20	0.018	0.018	0.019	0.019	0.020	0.021	0.020
	25	0.021	0.021	0.022	0.023	0.023	0.024	0.024
	30	0.023	0.023	0.024	0.025	0.025	0.026	0.027
Cellular filler's strength reserve for τ_{yz}	20	27.7	27.7	26.32	26.32	25.0	23.81	25.0
	25	23.81	23.81	22.73	27.74	27.74	20.83	20.83
	30	21.74	21.74	20.83	20.00	20.00	19.23	18.52
Cellular filler's minimal strength reserve	20	27.7	23.3	20.59	19.44	17.07	15.22	15.55
	25	23.81	23.81	21.85	20.00	18.92	16.28	15.91
	30	21.74	21.74	20.83	20.00	20.00	17.50	16.28
Maximal reduced stresses in frames, MPa	20	54.77	73.46	72.85	73.05	77.4	77.01	81.52
	25	64.75	69.52	68.30	69.03	73.96	72.77	77.70
	30	61.00	65.67	64.13	65.55	70.51	68.92	73.79
Frames' strength reserve	20	7.30	5.44	5.49	5.47	5.17	5.19	4.91
	25	6.18	5.75	5.86	5.79	5.41	5.50	5.15
	30	6.56	6.09	6.24	6.10	5.67	5.80	5.42
Head fairing's stability reserve	20	2.72	2.01	2.32	2.33	1.64	1.95	1.46
	25	3.79	2.67	3.15	3.77	2.72	3.30	2.56
	30	4.80	3.87	4.08	4.79	3.46	3.35	3.32
Mass of bearing sheaths, kg	20	206.29	180.51	180.51	154.72	128.93	128.93	103.15
	25	206.29	180.51	180.51	154.72	128.93	128.93	103.15
	30	206.29	180.51	180.51	154.72	128.93	128.93	103.15
Mass of a cellular filler, kg	20	44.17	44.55	44.55	45.13	45.62	45.62	46.10
	25	56.18	56.66	56.66	57.14	57.62	57.62	58.10
	30	68.18	68.66	68.66	69.14	69.62	69.62	70.10
Total weight of bearing sheaths and a cellular filler, kg	20	250.46	225.16	225.16	199.85	174.55	174.55	149.25
	25	262.47	237.17	237.17	211.86	186.55	186.55	161.25
	30	274.48	249.17	249.17	223.86	198.55	198.55	173.25

Results from searching for the rational parameters of a cellular filler at different values of a_c are given in Table 8.

Table 8

Results from searching for the rational parameters of a cellular filler

Opening angle of a honeycomb cell β, degrees	Cell coefficient k	Head fairing's strength reserve	Honeycomb density, kg/m^3	Head fairing's mass, kg
at a_c=5 mm				
60	0.5	1.486	44.89	179.79
60	1	1.482	24.94	145.72
60	1.5	1.480	17.81	133.55
60	2	1.479	13.92	126.91
60	3	1.478	9.84	119.95
50	1	1.482	25.74	147.09
68	1	1.482	25.42	146.54
at a_c=6 mm				
60	0,5	1.484	37.73	167.56
60	1	1.481	20.81	138.67
60	1,5	1.479	14.78	128.39
60	2	1.478	11.60	122,95
60	3	1.477	8.20	117.15
50	1	1,481	21.45	139.78
68	1	1.481	21.18	139.31
at a_c=7.5 mm				
60	0.5	1.483	29.93	154.24
60	1	1.479	16.63	131.53
60	1.5	1.478	11.88	123.42
60	2	1.477	9.35	119.11
60	3	1.476	6.65	114.50
50	1	1.479	17.16	132.45
68	1	1.480	16.95	132.08

The result of the second stage of optimization was an additional reduction in mass, compared to the optimal variant of sandwich sheaths for a head fairing, in which the cellular filler had a cell of the regular hexagonal shape at a_c=5 mm, by

$$\frac{149.25-114.5}{149.25}100\,\%=23.3\,\%\ \ (34.75\text{ kg}),$$

and, when compared to the basic variant, by

$$\frac{232.7-114.5}{232.7}100\,\%=51\,\%\ \ (118.2\text{ kg}).$$

Taking into consideration that the mass of the finished article of a launch vehicle head fairing is M_Σ=800 kg, the relative total result of minimizing the mass for an actual real object could equal

$$\frac{118.2}{800}100\,\%\approx 15\,\%.$$

The analysis of reserves in the carrying capacity of a cellular filler in the implementation of a verification module to account for the presence in its facets of the initial technological camber has made it possible to draw a conclusion about acceptability of the derived optimal honeycomb parameters.

8. Discussion of results of optimizing a multi-sectional sandwich sheath composite structure, the type of a head fairing, for mass

The analysis of the optimal variants of sheath reinforcement structures under axial compression has revealed the following:

– the mass of a quasi-homogeneous sheath with the arrangement of monolayers $0_{0.25S}$; $\pm45_{0.5S}$; $90_{0.25S}$. Exceeds the mass of the optimal, in terms of a reinforcement scheme, by 5 % on average. This fits the range of errors associated with the accuracy of estimation schemes (mathematical models) and calculation techniques.

The analysis of suboptimal variants of reinforcement structures of the same sheath under axial compression has shown that the irrationally chosen reinforcement scheme leads to a significant increase in the mass of the sheath compared to optimal, reaching 100 %.

Thus, it has been shown that at a minimum gain in mass due to the optimal reinforcement scheme, of about 5 %, compared to a quasi-homogeneous sheath, there is an actual real risk of a double increase in sheath mass when choosing a substantially suboptimal sheath structure. This confirms the results from a series of works, for example [14, 31, 32, 36].

The results from analyzing the optimality of schemes for arranging layers in a cylindrical sheath under external pressure are as follows:

– over the entire spectrum of reinforcement schemes, the maximum difference in masses between the minimum and the maximum is 26 %. This is not critical given that works [31, 32] did not address the change in thickness and physical-mechanical characteristics for a sheath made from an integer number of layers;

– the difference in the mass between a quasi-homogeneous sheath and optimal is 7.4 %, which is also corresponds to the level of errors in the calculation itself.

Thus, the analysis has shown that at isolated loading, at least of a cylindrical sheath, by axial compression or external uniform pressure, the reinforcement schemes for carrying layers of a sheath produce a minimum mass while they tend to a quasi-homogeneous structure. This also confirms the results from a series of works, such as [14, 31, 32, 36].

Implementation of the previously proposed approach [31] to optimizing the parameters for a launch-vehicle head fairing has shown the following. The trends described above are enhanced at combinations of compression and external pressure even when they are unevenly distributed over the sheath surface (by circumference and height).

As it follows from Table 7, the minimum characteristics of the mass of a head fairing are ensured by variant 7 of the bearing sheath reinforcement. This corresponds to a quasi-homogeneous structure, as evidenced by the above studies. Hence, it follows that when designing assemblies related to the considered class of equipment, it is possible to proceed from a quasi-homogeneous structure of bearing sheaths, corresponding, strictly speaking, to the scheme of arranging monolayers $0_{0.25S}$; $\pm45_{0.5S}$; $90_{0.25S}$. However, this strict compliance with the quasi-homogeneous reinforcement structure can only be implemented for eight and twelve monolayers [12, 14, 32]. With fewer of them, certain deviations from the quasi-homogeneous structure of a sheath are inevitable [3, 11].

In this case, there is a significant margin of strength in a head fairing for bearing sheaths, equal to 3.14 and the stability of the head fairing in general – 1.46. This confirms the findings from a series of works, such as [12, 17–19] on that an article's carrying reserves in terms of strength are significantly higher than the stability reserves. This means that for the standard influences (Table 1), characteristic of a head fairing, the critical form of exhaustion of its carrying capacity is stability, predetermined, as shown above, by the height of a cellular filler.

Abandoning, when implementing the developed approach, the analytical models for determining a carrying capacity in favor of programming complexes that employ a finite element analysis has made it possible to exclude a series of errors associated with the application of analytical models [5, 27, 31].

The preliminary analysis of optimization results at the last stage of selecting a cellular filler's parameters has revealed the following:

– the lowest level of the variable parameter for cellular filler density is demonstrated at $k=3$; $a_c=7.5$ mm, and $\beta=51°$, and the highest – at $k=0.5$; $a_c=1.5$ mm, and $\beta=51°$;

– in the assigned range of change in the structural parameters of a cellular filler's cell the maximum difference between $\rho_{hc}^{\max}$ and $\rho_{hc}^{\min}$ can amount to 24.8 times. And for honeycombs with a cell of the regular hexagonal shape – 4.7 times. This result demonstrates the feasibility of optimizing the density of a cellular filler in articles;

– in the assigned ranges of change in parameters: $1.5 \leq a_c \leq 7.5$ mm; $0.5 \leq k \leq 3$; $51° \leq \beta \leq 68°$ the highest value of G_{hc}^{xz} is demonstrated at minimum values of k, a_c and β;

– with an increase in a_c at any k and β G_{hc}^{xz} monotonously decreases;

– with an increase in k at fixed a_c and β G_{hc}^{xz} decreases;

– the highest value of G_{hc}^{xz} is demonstrated at minimum values of a_c and k and a maximum value of β;

– with an increase in a_c G_{hc}^{yz} monotonously decreases at any k and β;

– with an increase in k at fixed a_c and β G_{hc}^{yz} decreases.

Similar findings apply to changes in F_{hc}^{xz} and F_{hc}^{yz}.

This is confirmed by an analysis of Table 8. Thus, the lowest mass is ensured by a cellular filler with cell $a_c=7.5$ mm, $\beta=60°$ and $k=3$ (Table 8). Under these parameters, the stability reserve of a head fairing has hardly changed (increased from 1.46 to 1.476).

The general conclusion from the above study confirms the conclusion from a series of works [12, 14, 25, 31] about the need to optimize the parameters of a cellular filler at the stage when its height, the thickness of bearing sheaths, and their structure have already been selected.

The results obtained make it possible to further advance and improve them, with little or no change in the concept and structure, towards incorporating the auxiliary structural elements of a head fairing (liners, inserts, internal nodes and compounds, etc.) into optimization.

9. Conclusions

1. The study reported here has made it possible to solve a complex multi-parametric problem of optimal design of a launch-vehicle head fairing with almost no loss of accuracy, by dividing the optimization process into several stages in accordance with the substantiated levels of parameters' significance that are part of the objective function – a minimum of mass.

2. The rational parameters have been established for the reinforcement scheme of bearing sheaths and a cellular filler, as well as their geometric parameters, which ensured a decrease in the mass of a head fairing, compared to the basic variant, by 51 % or 118.2 kg.

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