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Параметрический анализ прочности сопла ракетного двигателя на твердом топливе

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В работе представлен подход к решению задачи проектирования сопла ракетного двигателя на твёрдом топливе (РДТТ) с использованием конструктивной особенности в виде вставной пластины из углепластика. Задачей проектирования является выбор оптимальных параметров формы и толщины пластины, обеспечивающей требуемую несущую способность при минимальной массе. В процессе проектирования проведен параметрический анализ сопла РДТТ со вставной пластиной из углепластика. Варьируя толщиной пластины, подобрана оптимальная конструктивная схема, отвечающая заданным коэффициентам запаса прочности и устойчивости. Параметрический анализ вставной пластины из композиционного материала включает в себя моделирование её основных весовых и прочностных параметров: анализ напряженно-деформированного состояния конструкции, значений собственных частот, определение запаса потери устойчивости, определение массы сопла РДТТ.

Анализ несущей способности сопла РДТТ со вставной пластиной из композиционного материала проводился с помощью метода конечных элементов с использованием программного пакета SolidWorks Simulation.

При проведении параметрического анализа были рассмотрены два варианта сопла двигателя РДТТ: со вставной пластиной и без неё.

По результатам параметрического анализа сопла РДТТ были определены его геометрические размеры и минимизирована масса конструкции.

Ключевые слова: параметрический анализ, прочность сопла РДТТ, композиционный материал, напряженно-деформированное состояние, потеря устойчивости, конструирование сопла РДТТ.

Parametric analysis of the strength of a solid propellant rocket engine nozzle

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The paper presents an approach to solving the problem of designing a solid propellant rocket engine (SPRE) nozzle using such a design feature as a carbon fiber insert plate. The design task is to select the optimal parameters of the plate shape and thickness, providing the required load-bearing *capacity with minimal mass. During the design process, a parametric analysis of a SPRE nozzle with a carbon fiber insert plate was carried out. By varying the thickness of the plate, an optimal design scheme that corresponds to the specified safety and stability factors was selected. Parametric analysis of an insert plate made of a composite material includes modeling of its main weight and strength parameters: analysis of the stress-strain state of the structure, values of natural frequencies, determination of the buckling margin, and determination of a SPRE nozzle mass.*

The analysis of the load-bearing capacity of a SPRE nozzle with an insert plate made of a composite material was carried out by the finite element method using the SolidWorks Simulation software package.

When conducting a parametric analysis, two variants of a SPRE nozzle with and without an insert plate were considered.

According to the results of a parametric analysis of a SPRE nozzle, its geometric dimensions were determined and the structure mass was minimized.

Keywords: parametric analysis, SPRE nozzle strength, composite material, stress-strain state, buckling, SPRE nozzle design.

Introduction

Due to the use of composite materials in the design of a solid propellant rocket engine (SPRE), the mass of metal in it is known to be reduced by more than 3 times for the period from 1970 to 1998. It was achieved both by improving the design of the material-intensive connection unit between the SPRE nozzle and the engine case, and by using composite materials (composites) with organic fillers and a matrix. Technological options for winding cocoon-type cases using high-strength organic fibers as a filler and various resins as matrices contributed to obtaining a SPRE design with mass perfection at the level of 0.1. However, further increasing the mass perfection of SPREs through the improvement of organic-based composites turned out to be very problematic.

The main disadvantage of SPRE structures (primarily cases) made of organoplastics as well as composites with metal components is the limitation on the permissible (operating) temperature of their operation. For example, the operating temperature of organoplastics is only 400–430 K. To ensure the strength of such a structure, powerful thermal protection is required. Therefore, efforts in the field of materials science to further increase the strength of organofiber in practice contribute little to increasing the mass perfection of the engine compared to the possibility of expanding the operating temperature range. In this regard, carbon and carbon-ceramic materials offer truly unique opportunities. Their operating temperature with a simultaneous increase in strength is 3100–3300 K, which indicates the prospects for creating lightweight uncooled SPRE cases. However, the absolute values of the strength of such materials are still much less than the strength of organoplastics due to relatively low strength levels of carbonized, ceramic or graphitized matrices. In addition, such composites have lower gas permeability characteristics compared to organoplastics. However, it is possible to eliminate the latter using various design and technological methods. At the present stage of new composites development their application in SPREs is mainly associated with the creation of designs for nozzle blocks, case thermal protection, and thrust vector control devices.

In a relatively short period of time, SPRE nozzle blocks have undergone a significant change in shape, layout, dimensions and composition of materials. Further development of nozzle block designs is determined by trends in changes in SPRE operating conditions, improvement of structural forms and, mainly, the provision of new materials. Changes in operating conditions of SPRE nozzle blocks are associated with the use of new high-energy solid fuels with increased specific thrust impulse and temperature in the combustion chamber. Lightweight nozzle designs are being created from new materials with a high level of mass perfection and high reliability indicators.

Modern SPREs operate on mixed metallized fuels with a high metal content at the pressure in the combustion chamber of the order of 10.0 MPa and the temperature of up to 3800 K. The conditions for using ballistic missiles with SPREs required the designs of nozzle blocks to ensure operating conditions when exposed to radiation from a nuclear explosion, durability to climatic factors and transport loads caused by the mobility of modern missile systems.

Increased requirements for nozzle blocks design are also caused by the tendency to increase the service life of modern rockets, during which it is necessary to guarantee the preservation of the properties of materials and parts. The contradictory requirements for increasing the SPREs energy performance and mass perfection at the required level of reliability can be resolved, first of all, through the creation of new materials.

Changes in the design forms of nozzle blocks are associated with trends in the development and improvement of nozzles partially recessed into the combustion chamber, nozzles on a flexible suspension, systems for blowing combustion products into the nozzle divergent section to control the thrust vector, sectioned, expandable and folding nozzles. At the same time, the mass of the nozzle block remains at the level of 30–45% of the case mass and the ways of design technical perfection are determined almost exclusively by the use of more efficient materials [1–3].

Thus, increasing the operational characteristics of SPRE nozzle blocks and improving their structural forms are impossible without the use of new materials, since technical ways to improve the main functional parts of modern SPRE nozzle blocks have largely been exhausted. The development of new fuels and design solutions are ahead of the modern capabilities of structural and heat-protective materials.

The relevance of the study is justified by the need to analyze the possibility of operating SPRE nozzles made of composite materials and the use of nozzle structures in a metal-composite combination.

Formulation of the problem

The main part of the nozzle, which determines the energy characteristics of the SPRE, is the nozzle throat section. It also characterizes the mass efficiency of both the nozzle throat section itself and the nozzle entrance section.

The nozzle exit section is no less important for ensuring the energy characteristics of engines and their mass perfection, this is especially true for high-altitude SPREs (used in the second and third stages of rockets) with a high nozzle expansion ratio.

The nozzle entrance section forms a flow profile and is subject to convective and radiation thermal effects of fuel combustion products; here, glass and carbon fiber reinforced plastics have proven themselves to be the best.

The nozzle throat section experiences intense convective heating and mechanical loads. Refractory metals (tungsten, molybdenum) and alloys based on them, as well as some grades of graphite have proven themselves to be the best in this section.

The nozzle exit section is subject to convective thermal effects and significant mechanical loads. In this nozzle section, glass and carbon fiber plastics reinforced with a metal shell, and structures made of molybdenum, niobium, titanium and alloys based on them have proven themselves to be the best.

Carbon materials represent a new class of materials for various purposes as their specific features and uniqueness make them differrent from hitherto known materials. Due to this fact they meet the promising goals of SPREs development. The justified use of carbon materials in the designs of SPREs and other engines requires a clear understanding of the properties, production technology and methods for studying and predicting the performance of these materials.

Carbon materials have the following general positive properties:

– high thermal erosion resistance, resistance to thermal shocks, unique strength, which increases when heated by 2–2.5 times compared to room temperature, low density and high specific physical and mechanical characteristics;

– the ability to purposefully change their properties by changing the original components and parameters of the production process, the use of optimal reinforcement schemes;

– the ability to use almost anywhere in the nozzle flow duct and in the power circuit parts of the engine design;

– the ability to combine unique heat-protective properties in contact with a wide variety of materials, the applicability of almost all types of mechanical processing;

– high preservation of properties during long-term storage in various climatic conditions and contact with various environments, resistance to radiation, high biological stability.

Anisotropy of carbon materials is another means of rational design of engine structural elements. By changing the orientation of the fillers, it is possible to obtain a material with optimal anisotropy, specially selected for any stress-strain state of the structural element.

The objective of the research is to design a SPRE nozzle made of titanium alloy with an insert plate made of a composite material (CM) and analyze its load-bearing capacity [4–15]. During the research, the following tasks were set:

1) select the nozzle wall thickness corresponding to the optimal safety factor;

2) design a composite SPRE nozzle with a CM liner;

3) select the wall thickness of the composite nozzle and the insert plate from CM, which ensures the load-bearing capacity of the nozzle.

The developed nozzle design can be used in rocket design with SPRE [8].

Calculation model of the SPRE nozzle

To conduct a comparative analysis, two SPRE nozzles were taken. The first nozzle is the classic nozzle of a solid-fuel multistage rocket with a wall thickness of 30 mm without the use of a composite material (Fig. 1), the second is using an insert plate made of carbon fiber with a nozzle wall thickness of 20 mm and a plate thickness of 10 mm (Fig. 2).

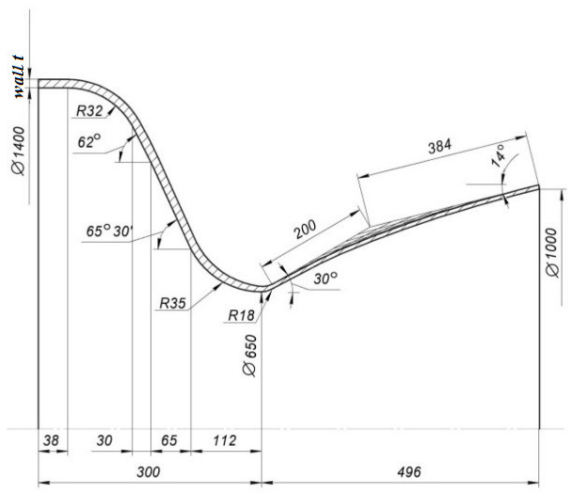

Fig. 1. SPRE nozzle

Рис. 1 Сопло РДТТ

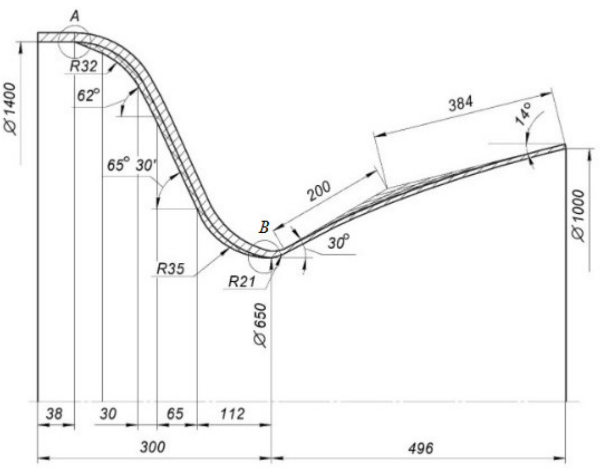

Fig. 2. SPRE nozzle with a CFRP (carbon fiber reinforced polymer) insert plate

Рис. 2 Сопло РДТТ со вставной пластиной из углепластика

For the presented nozzle designs, a static analysis was carried out in the Solidworks Simulation package. The characteristics of the materials used were taken from the Solidworks materials library in relation to the innovative composite material aristid [16], which retains its strength properties when heated to 1300° (Table 1).

Table 1

Characteristics of materials for static calculation of the nozzle

	SPRE nozzle	Insert plate
Material name	Titanium alloy Ti-8Mn annealed sheet	Carbon fiber m55j (aristid)
Modulus of elasticity, GPa	115	240
Poisson ratio	0,33	0,127
Mass density, kg/m^3	4730	1910
Ultimate tensile strength, MPa	899	3027
Yield limit, MPa	0,79	2,05

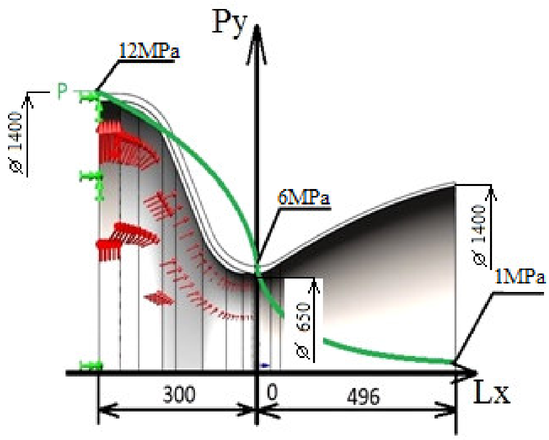

Fig. 3. Pressure distribution in the SPRE nozzle: *P* – pressure; *L* – length of the investigated zone

Рис. 3. Распределение давления в сопле РДТТ: *P* – давление; *L* – длина исследуемой зоны

The vonMises criterion was taken as the maximum stress criterion. Fastening is specified using a fixed geometry along the contour of the nozzle edge on the side connecting to the engine case shell.

For the SPRE design under study (see Fig. 1) [14], a formula was compiled for the pressure distribution inside the nozzle (1), according to the pressure distribution graph (Fig. 3).

$$P = \alpha 1\, x^2 + \alpha 2\, x + \alpha 3, \qquad (1)$$

where α1, α2, α3 are coefficients obtained experimentally.

For the case of pressure at the nozzle entrance Pen = 12 MPa, pressure in the nozzle throat Pth = 6 MPa and pressure at the nozzle exit Pa = 1 MPa (Fig. 3), formula (1) will take the form (2)

$$P = 5{,}205 * 10^{-5} x^2 - 0{,}04x + 6. \qquad (2)$$

Using equation (2), we apply loads to the nozzle. Load distribution and boundary conditions for the calculation model are shown in Fig. 4, where green (outer) arrows indicate fastenings, red (inner) arrows indicate applied loads.

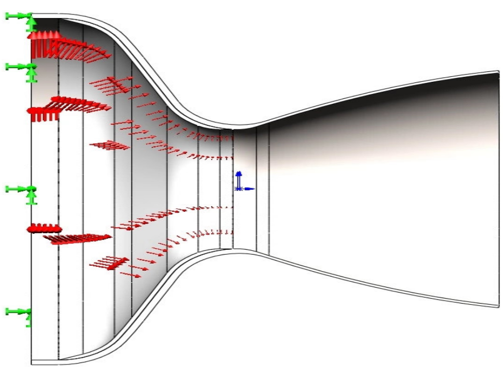

Fig. 4. Distribution of loads in the nozzle

Рис. 4. Распределение нагрузок в сопле

Strength calculation under static loading

Let us conduct research for different titanium alloy nozzle wall thicknesses without using a CM insert plate. The thickness of the nozzle wall varied from 15 to 30 mm. For example, Fig. 5–8 show diagrams of stresses and safety factors for thicknesses of 15 and 30 mm

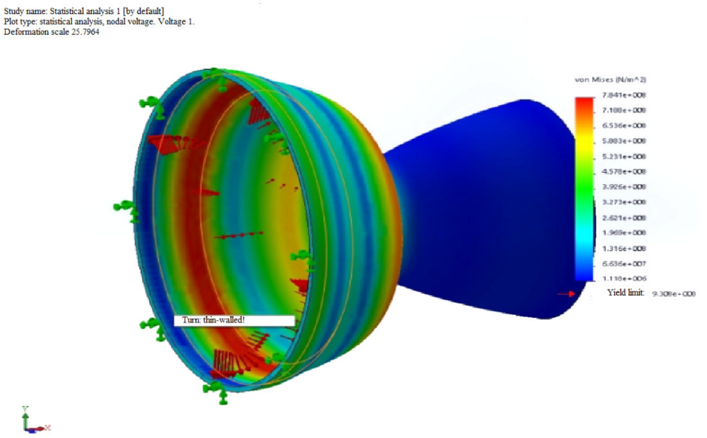

Fig. 5. Diagram of stress distribution
in the nozzle t = 15 mm

Рис. 5. Эпюра распределения напряжений
в сопле t = 15 мм

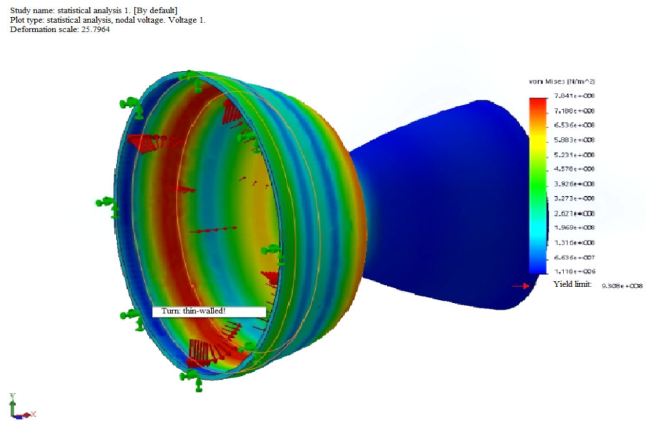

Fig. 6. Diagram of stress distribution
in the nozzle t = 30 mm

Рис. 6 Эпюра распределения напряжений
в сопле t = 30 мм

Fig. 5 and 6 show diagrams of the stress distribution in the nozzle for different wall thicknesses. The yield strength of the Ti-8Mn material from the Solidworks materials library is equal to σт = 9.308*10^8 N/m^2.

The maximum stresses in a nozzle with a thickness of 15 mm are 2.32*10^9N/m^2 (Fig. 5), which exceeds the yield limit of the selected titanium alloy and does not provide the load-bearing capacity of the nozzle. For a nozzle with a wall thickness of 30 mm, the stresses were 7.841*10^8 N/m^2 (Fig. 6), which provides the necessary safety margin.

At the point of maximum stress, the safety factor for a nozzle t = 15 mm is equal to 0.4 (Fig. 7), and for a nozzle t = 30 is equal to 1.187 (Fig. 8).

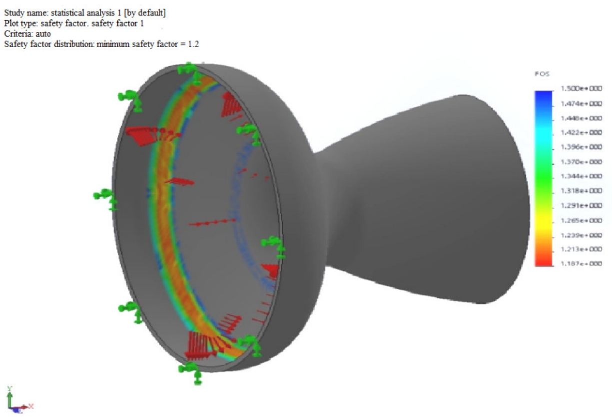

Fig. 7. Safety factor in the nozzle t = 15 mm

Рис. 7 Коэффициент запаса прочности
в сопле t = 15 мм

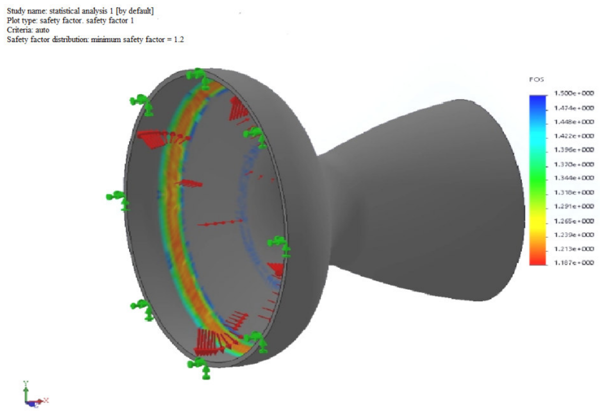

Fig. 8. Safety factor in the nozzle t = 30 mm

Рис. 8 Коэффициент запаса прочности
в сопле t = 30 мм

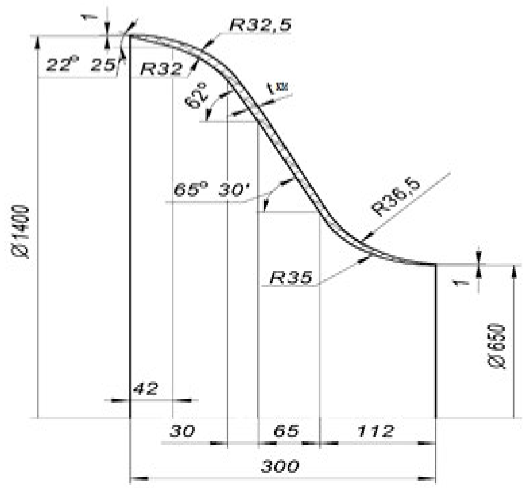

Fig. 9. Insert plate made of composite material

Рис. 9. Вставная пластина из композиционного материала

Calculation of the strength of a SPRE nozzle with a composite material liner

To reduce a SPRE nozzle mass and increase its strength characteristics, we will use a carbon fiber insert plate in the nozzle throat section (Fig. 9).

Let us carry out calculations of the designed nozzle with a titanium alloy wall thickness t_{ti} = 20 mm and a carbon fiber insert plate thickness (t_{cm}) from 7.5 to 15 mm. The stress distribution diagram for the designed nozzle is shown in Fig. 10, 11.

The safety factor (sf) was 0.9964 and 1.143 for nozzle liners of various thicknesses (Fig. 12, 13). The results of the study are shown in table 2.

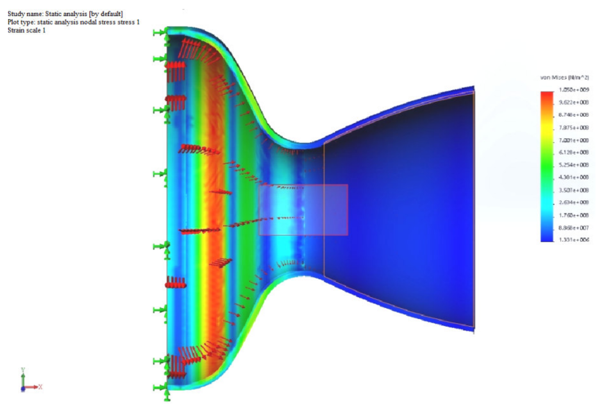

Fig. 10. Diagram of stress distribution in the nozzle t_{ti} = 20 mm; t_{cm} = 7.5 mm

Рис. 10. Эпюра распределения напряжения в сопле t_{ti} = 20 мм; $t_{км}$ = 7,5 мм

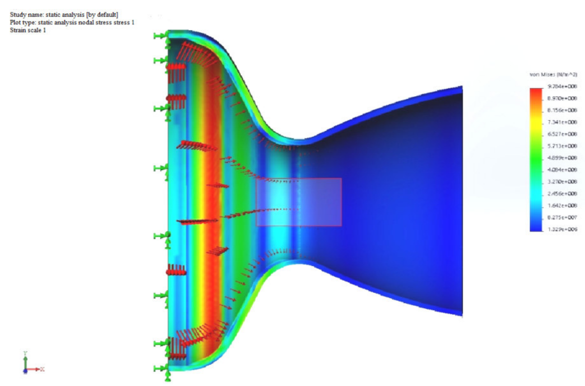

Fig. 11. Diagram of stress distribution in the nozzle t_{ti} = 20 mm; t_{cm} = 17.5 mm

Рис. 11. Эпюра распределения напряжения в сопле t_{ti} = 20 мм; $t_{км}$ = 17,5 мм

Table 2

Calculation results for a titanium nozzle with an insert plate made of composite material

Material		Safety coefficient		Mass (kg)
Titanium alloy Ti-8Mn t of a wall	Carbon fiber m55j (aristid) t of a wall	Titanium alloy Ti-8Mn	Carbon fiber m55j (aristid)	
20	7,5	0,9964	1,9	310,272
20	10	1,078	1,90	318,414
20	12,5	1,143	2	326,384
20	15	1,141	2	334,353

From the calculations performed, it follows that the design of a SPRE nozzle made of titanium alloy in combination with carbon fiber providing the required load-bearing capacity has a titanium alloy wall thickness of 20 mm, and a carbon fiber wall thickness of 10.75 mm. The use of the proposed combined nozzle design with a composite liner made it possible to reduce the total nozzle mass by 30–32 % (Table 3).

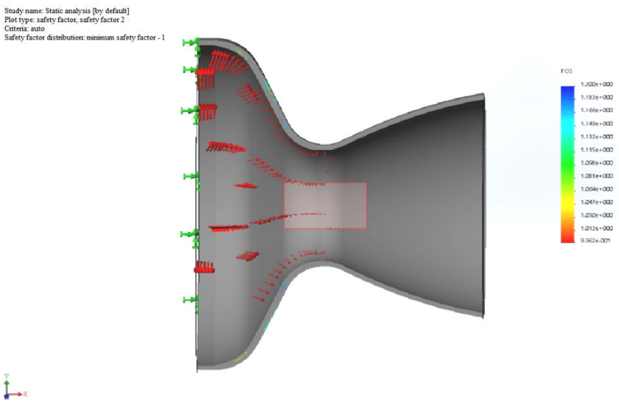

Fig. 12. Safety factor
in the nozzle t_{ti} = 20 mm; t_{cm}= 7.5 mm

Рис. 12. Коэффициент запаса прочности
в сопле t_{ti} = 20 мм; $t_{км}$ = 7,5 мм

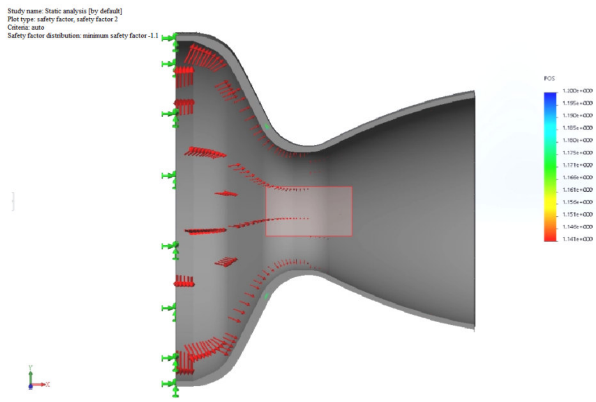

Fig. 13. Safety factor
in the nozzle t_{ti} = 20 mm; t_{cm} = 17.5 mm

Рис. 13. Коэффициент запаса прочности
в сопле t_{ti} = 20 мм; $t_{км}$ = 17,5 мм

Table 3

Nozzle mass analysis

Combination of materials	Structure mass, kg
Titanium alloy	468,214
Titanium alloy + high-strength carbon fiber	329,645

Frequency analysis of a SPRE nozzle

Analysis of vibrations natural modes and frequencies allows evaluating the behavior of the proposed SPRE nozzle design under dynamic loading during its operation. For this purpose, an analysis of the first three forms of natural frequencies of vibrations was carried out. To carry out a modal analysis, a model of a SPRE nozzle with a carbon fiber insert plate, proposed earlier, was considered. The loads and boundary conditions for the calculation are the same as in the static analysis.

The value of the natural frequency for the first mode of vibration was 123.2 Hz. The diagram is shown in Fig. 14.

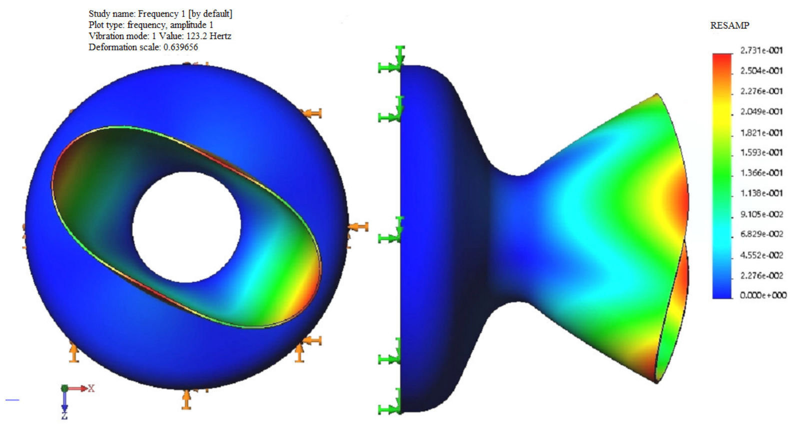

Fig. 14. Amplitude of the first mode of vibrations

Рис. 14. Амплитуда первой формы колебаний

Conclusion

According to the results of the study, a SPRE nozzle made of a combination of titanium alloy Ti-8Mn + carbon fiber m55j (aristid) was proposed, and its geometric dimensions were determined. The proposed nozzle, according to the calculation results, provides the necessary safety factor and mass reduction of 30–32 % compared to a solid titanium alloy nozzle. A modal analysis was carried out for the proposed nozzle.

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