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NUMERICAL MODELING OF THE STRESS-STRAIN STATE OF POWER FRAMES OF LIQUID ROCKET ENGINES OF LOW THRUST

ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ СИЛОВИХ РАМ РІДИННИХ РАКЕТНИХ ДВИГУНІВ МАЛОЇ ТЯГИ

Today, the space industry is experiencing a period of significant technological advancement. Continuous progress in additive technologies and the use of modern materials for 3D printing contribute significantly to this process. This development trend has led to increased competition among various space companies — both state-owned and private. Each of them strives to present something truly new and unique. FlightControl Propulsion is one of these private space companies in Ukraine. This work investigates the design of the power frame of a small thrust liquid rocket engine. Power frames in rocket engines support significant mechanical loads. The use of topology optimization and high-strength steels allows for the creation of compact and efficient power frames that are significantly lighter than traditional ones. Additive manufacturing significantly reduces the time for manufacturing various parts and assemblies and also opens up almost unlimited possibilities for the geometric shapes of products. What was previously difficult or even impossible to manufacture using traditional methods is now accessible. This work examines an assembly manufactured using the SLM (Selective Laser Melting) technology. A structured algorithm of topology optimization and the fundamental principle of the SIMP (Solid Isotropic Material with Penalization) topology optimization method are presented. Numerical modeling of the stress-strain state for the design variant is carried out using the finite element method (FEM) in the computer-aided engineering (CAE) system. A computational finite element mesh is constructed, and the safety margins of the design are determined. After topology optimization, the final design variant is identified, and numerical modeling of the stress-strain state is conducted again for the optimized design. The latter is then transferred to production for manufacturing and further experimental testing.

***Keywords**:3D printing, additive technologies, rocket engine, SIMP method, strength, CAE systems, topology optimization, finite element method, numerical modeling.*

Сьогодні космічна індустрія переживає період значного техногологічного розвитку. Неперервний прогрес у сфері адитивних технологій та використання сучасних матеріалів для 3D-друку вносить значний вклад у цей процес. Цей напрямок розвитку призвів до посилення конкуренції між різними космічними компаніями — як державними, так і приватними. Кожна з них прагне представити щось дійсно нове й унікальне. FlightControl Propulsion — одна з цих *приватних космічних компаній в Україні. У роботі досліджено конструкцію силової рами рідинно ракетного двигуна малої тяги. Силова рама в основних конструкціях ракетних двигунів і підтримують значні механічні навантаження. Застосування топологічної оптимізації та використання високоміцних сталей дозволяють створити компактні та ефективні силові рами, які будуть значно легше за класичні. Адитивне виробництво відчутно скорочує час на виготовлення різних деталей та агрегатів, а також відкриває майже необмежені можливості щодо геометричних форм виробів. Те, що раніше було складно або навіть неможливо виготовити за допомогою традиційних методів, зараз стає доступним. У даній роботі розглянуто агрегат, виготовлений за технологією SLM (Selective Laser Melting). Подано структурований алгоритм топологічної оптимізації та основний принцип методу топологічної оптимізації SIMP (Solid Isotropic Material with Penalization). Проведено чисельне моделювання напружено-деформованого стану для варіанту конструкції за допомогою методу скінчених елементів (МСЕ) у системі CAE (Computer-Aided Engineering). Побудовано розрахункову скінчено-елементну сітку й визначено запаси по міцності конструкції. Після проведення топологічної оптимізації було визначено кінцевий варіант конструкції й знову проведено чисельне моделювання напружено-деформованого стану для оптимізованої конструкції. Остання була передана на виробництво для виготовлення та подальшого есперементального відпрацювання.*

***Ключові слова**: 3Д-друк, адитивні технології, ракетний двигун, SIMP-МЕТОД, міцність, топологічна оптимізація, метод скінчених елементів, чисельне моделювання.*

Problem's Formulation

The problems of power elements in rocket engines remain relevant today. The need to improve the performance characteristics of power elements in rocket engines is clearly evident in the development trends of the modern space industry. Technological advances and growing interest in space exploration have led to the need to improve rocket engine designs to achieve higher performance and efficiency. In particular, the use of advanced materials and production technologies can reduce the weight of power elements and increase their efficiency. Integration of composite materials, carbon fibers, and titanium, nickel, and aluminum alloys are an important step towards creating lighter and stronger structures.

Topological optimization using advanced algorithms and computational methods allows us to design the optimal shape and structure of the power element, reducing weight and material consumption. This is especially important for the efficient operation of rocket systems, where every kilogram of weight is crucial for the amount of fuel and the mass of the rocket's payload that it can place into a particular orbit.

Innovative technologies and numerical modeling contribute to the development of reliable and efficient rocket systems, allowing for a comprehensive analysis of power elements under various operating conditions. Thus, improving the characteristics of power elements is an important area of launch vehicle improvement that meets the requirements of the modern space industry and contributes to the development of new generation launch vehicle systems.

Analysis of recent research and publications

The study of the problems of power frames and elements in general has been the subject of several papers [1, 2]. Various authors have performed numerical modeling of topologically optimized structures [3, 4].

Formulation of the study purpose

The purpose of the research and publication is to improve the mass efficiency for the existing power structure of the frame of a low thrust liquid rocket engine in order to obtain a rational design that will be lighter than the original structure and at the same time meet the strength standards $[\eta_B] \geq 1.5$ for this type of structure.

Presenting main material

The problem of efficient material distribution in structures is one of the key challenges in engineering science and industry. It arises in the context of maximizing the strength and stability of structures while minimizing the use of materials. Optimal material distribution reduces the weight of a structure while maintaining the required strength and stiffness. This is especially important in the aerospace industry, where every kilogram of weight can affect the amount of payload a launch vehicle can carry into a particular orbit. The development of topological optimization and additive manufacturing technologies allows engineers to create structures with optimal material distribution, which leads to compliance with the main criterion — minimum weight.

Implementation of topological optimization in the design of rocket engine power frames is critical, as these structural components are subjected to significant mechanical loads in complex structures. Typically, such frames are made of steel, aluminum, or titanium, and composite materials can also be used to reduce weight and increase strength. Optimization of their shape and the use of high-strength steels contribute to more compact and efficient solutions. Topological optimization determines the most advantageous location of the material within the power frames, ensuring maximum strength and reliability with minimum weight. Therefore, the following objectives were formed for this study:

- to study the problem using modern methods, using innovative CAE programs;
- to carry out numerical modeling of the stress-strain state of the power frame;
- to obtain a rational design of a force element that meets the criteria of strength standards and minimum mass by means of topological transformations in the design model.

Topological optimization therefore considers the distribution of the material in the structure. The elastic modulus determines the material stiffness of a material. In the case of minimizing the mass of a structure, it can be advantageous to use materials with a high Young's modulus, as they can provide high stiffness with minimal mass. However, variations in Young's modulus can also be taken into account in topological optimization problems to account for material anisotropy or the use of different materials in different parts of the structure. In such cases, topological optimization formulas can include Young's modulus as a parameter. One of the key elements of topological optimization is an objective function, which should be reduced or increased depending on the specific goals. A general view of such a function for minimizing the mass:

$$minimize\, M(\Omega) = \int_{\Omega} \rho(\boldsymbol{x})d\Omega, \tag{1}$$

where Ω — construction domain, $\rho(\boldsymbol{x})$ — material density at each point $\boldsymbol{x}$.

In the process of topological optimization, the SIMP (Solid Isotropic Material with Penalization) method is used, the key task of which is to adjust the density of the material in different parts of the structure in order to achieve minimum weight while ensuring the required strength and stiffness. The SIMP method is considered a powerful tool in the field of topological optimization, as it aims to create optimal structures through the rational placement of materials to achieve minimum weight with certain mechanical properties. The basic principles of the SIMP method include controlling the availability of materials in different parts of the structure using a penalty function that regulates the optimization process. The use of penalty coefficients for areas with low material density allows you to create density gradients and influence the distribution of the material. The formalization of the SIMP method involves determining the material density in individual areas of the structure, where each area is represented by a value from 0 (no material) to 1 (full material). The optimization process involves adjusting the material density to minimize the weight of the structure while ensuring certain mechanical properties.The main idea of the SIMP method is to represent the material topology using parameters that can vary from 0 to 1, determining the presence of material in each element (node) of the structure. The SIMP method uses penalization to consider non-continuous topology functions. [6] The penalization function can take the form:

$$\rho_i(x) = \frac{1}{2}[1 + \tanh(\beta\eta_i)], \tag{2}$$

where β — penalization parameter, η_i — is the local effective Young's modulus for the i element.

The topology parameters are updated in each optimization iteration to achieve the optimal topology that minimizes the weight of the structure while meeting the constraints and taking into account the mechanical properties.

One of the key components is the power frame of the upper stage of a low thrust liquid rocket engine, which carries significant loads and has a major impact on the overall mass characteristic of the rocket. Therefore, this design was developed for a liquid rocket engine with a thrust of 250 kgf. That is, the geometry of the small and large bases was limited to the maximum printable limits of the 3D printer of 400 mm. [5] Therefore, the large base is 400 mm, and the small base is the diameter of the engine's mixing head 80 mm. The load conditions are motor thrust, motor weight, and quasi-static overloads. A conventional classical frame has a less complex shape and is manufactured using traditional methods. However, such frames are characterized by a significant weight, which creates the need to reduce the weight while maintaining the required strength and stability of the structure. The only limiting condition was the diameters of the bases. They had to be constant. It is also important that there is free access to all necessary fittings or tubes.

Taking into account all the factors, topological optimization was performed. The final result of the design of the power frame for the upper stage is shown in fig. 1.

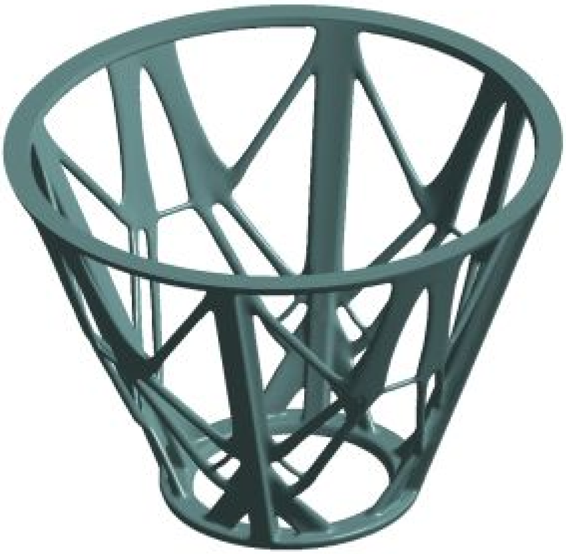

Fig. 1. Optimized design of the power frame of the upper stage of a liquid rocket engine

From fig. 1 shows that the geometry has a complex shape, but at the same time there are openings for complete unhindered access to the necessary elements of the mixing head or pressure sensors, thermocouples, etc. The next step was to build a finite element mesh in the ANSYS Meshing CAE environment. Special attention was paid to transitional elements and rounded edges. Thus, a computational finite element mesh was constructed, which is shown in fig. 2.

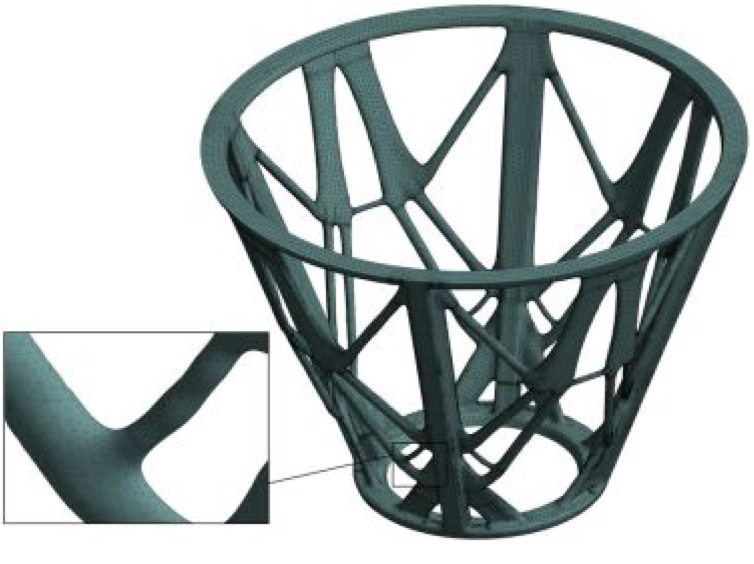

Fig. 2. Finite element mesh for the power frame of the upper stage of a liquid rocket engine

The finite element mesh is constructed as a tetrahedron, with local condensation of elements and nodes for more accurate results of further calculations. The material of this power frame structure is a chromium-nickel alloy for 3D printing Haynes230 [7], the mechanical properties of which are given in tabl. 1.

Table 1. Mechanical properties of Haynes230 chrome-nickel alloy for 3D printing

Temperature t,˚C	Modulus of elasticity E, MPa	Tensile strength σ_B, MPa	Yield strength $\sigma_{0.2}$, MPa	Elongation δ, %
20	200900	838	422	47

Numerical modeling was performed, where equivalent stresses (Mises stresses) were considered when assessing the stress-strain state of the structure. The formula for equivalent stresses is given by:

$$\sigma_e = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}}, \tag{3}$$

where σ_1, σ_2, σ_3 — principal stresses.

The safety factor is determined by the formula:

$$n_в = \frac{\sigma_в}{\sigma_e}, \tag{4}$$

where σ_B — tensile strength, σ_e — equivalent stresses

The results of the strength calculation, von-Mises distribution of equivalent stress fields, are shown in fig. 3.

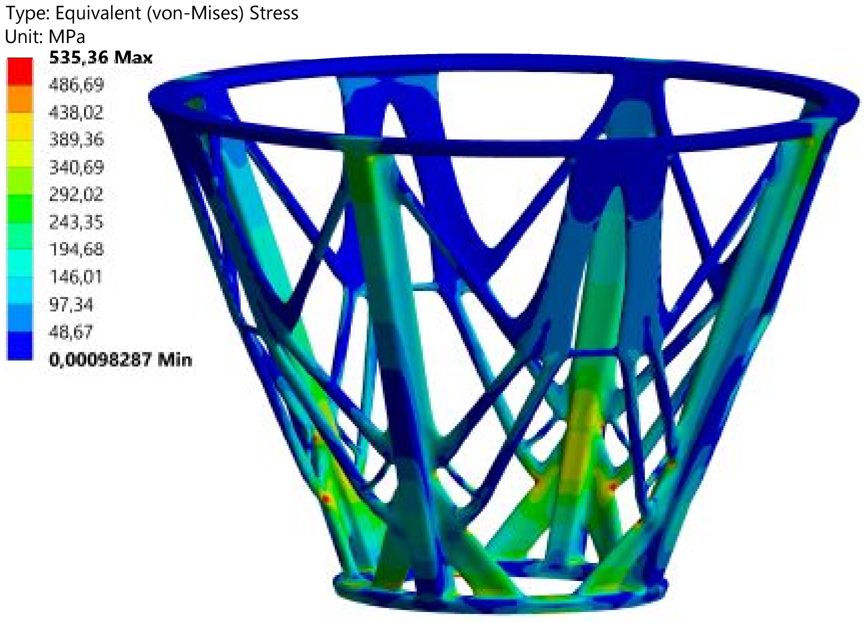

Fig. 3. Equivalent von-Mises stresses of the structure of the power frame of the upper stage of a liquid rocket engine

The calculation results showed that for this design of the power frame, the safety factor is **2.29**, which corresponds to the strength standards for this type of structure and ≥1.5. There are no plastic relative deformations in the structure. The red stress gradient is due to the peculiarities of the design model, namely sharp corners and stress concentrators. Such areas are localized and are not taken into account in the further strength assessment. According to the results of the numerical modeling of the stress-strain state, the structure has a sufficient safety margin.

For this type of structure, it is necessary to perform a stability calculation, because it is necessary that the structure retains its shape and there is no loss of stability. The results of the calculation and the shape of the loss of stability are shown in fig. 4.

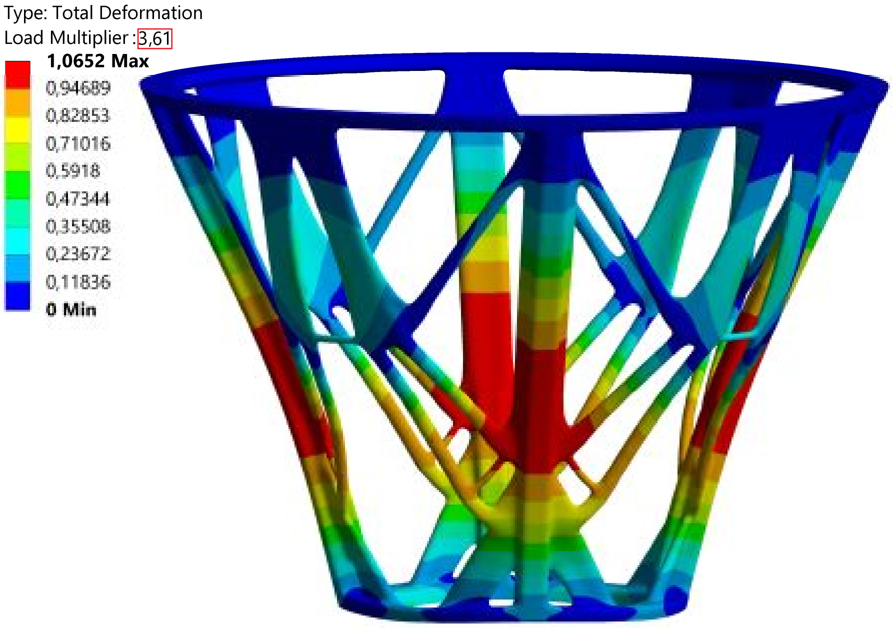

Fig. 4. Buckling form of the structure of the power frame of the upper stage of a liquid rocket engine

The results of the eigenvalue buckling calculation show that for such a structure under compressive force loading equivalent to engine thrust, the structure has a safety factor of 3.61, which is also sufficient, since the safety factor for power frames should be at least 2. We believe that the structure is ready for manufacturing and operation.

Conclusions

This article demonstrates that numerical modeling is an effective tool for analyzing the stress-strain state of the power frame of a liquid rocket engine. This approach allows for a detailed study of various aspects of the structure's behavior under load. The use of numerical modeling makes it possible to optimize the design of the power frame in order to reduce weight while maintaining the required mechanical properties. This is important for achieving rocket engine efficiency. It is also important to note that this design has already been transferred to the private company FlightControl Propulsion for further manufacturing and testing.

To assess the mass efficiency, we compared the designs of the power frame, which was made by the additive method and optimized in terms of topology, as well as the classical one, which was made by traditional methods. Tabl. 2 shows the results of this comparison.

Table 2. Comparative characteristics of power frames of the upper stage of a liquid rocket engine

Construction	**Classical**	**Optimized**
Mass of the structure	3.33 kg	1.053 kg

It can be stated that the weight of the power frame structure of the upper stage has been reduced by **68 %**. Concurrently, the structure satisfies all the requirements for its continued use as an integral part of the propulsion system. Topological optimization has proven to be highly effective in achieving this significant weight reduction.

However, despite these promising results, further research is essential in this field. Enhancing numerical modeling techniques, incorporating additional factors, and broadening the scope of analysis can contribute to more effective optimization of the power frame design for liquid rocket engines. This ongoing research is crucial to address potential limitations and to push the boundaries of current engineering capabilities, ensuring that future designs are not only lighter but also maintain or exceed current performance and safety standards.To advance the optimization process, it is imperative to focus on several key areas. First, refining the accuracy of simulation models is necessary. This includes developing more sophisticated algorithms that can better predict real-world performance and account for a wider range of variables. Second, considering the impact of various environmental and operational conditions on the power frame structure will lead to more robust designs. For example, factors such as thermal expansion, vibrational stresses, and material fatigue need to be meticulously analyzed and integrated into the optimization process.

Additionally, interdisciplinary collaboration can foster innovation in the design and optimization of rocket engine components. Leveraging expertise from fields such as materials science, mechanical engineering, and computational physics can provide new insights and methodologies. Advanced materials, such as high-strength composites and alloys, should be explored for their potential to further reduce weight while maintaining structural integrity.

In summary, while significant progress has been made in reducing the weight of the upper stage power frame structure through topological optimization, ongoing research and development are vital. By improving numerical modeling methods, incorporating a broader range of factors, and expanding the analytical scope, we can achieve even greater advancements in the design of liquid rocket engine power frames. These efforts will ultimately lead to more efficient, reliable, and high-performing propulsion systems for future aerospace applications.

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