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GENERATIVE DESIGN OF A FRAME TYPE CONSTRUCTION

Background. In recent years, there has been a rapid development of the domestic military industry. Reducing the mass and increasing the specific strength of military products used in the field – the most pressing challenges facing engineers and scientists today. The rapid development of adaptive production has significantly expanded the possibilities of methods of topological optimization in the design of new products or improvement of existing design and technological solutions in order to reduce weight.
Objective. The purpose of the paper is to improve the efficiency of designing the technology of manufacturing a frame type construction based on the method of topological optimization, which will reduce the weight of the product, while maintaining all the specified functional parameters.
Methods. The paper presents an analysis of topological optimization methods and offers the interaction of modern ADS, namely CAD, CAM, CAE modules at the stage of design and technological preparation of production, which once again demonstrated its effectiveness in solving problems to reduce product weight.
Results. The main tasks of topological optimization were solved for the frame type constructions, such as the minimization of volume and mass under physical constraints, as well as the optimization of other parameters with given geometric constraints. As a result, the proposed method of reducing the weight of the product is improved, which due to rational design and technological measures ensured a 56 % reduction in the weight of the frame type structure from the original and reduced the complexity of the manufacturing process by 22 % due to its effective adaptation to new technological conditions.
Conclusions. The application of methods of topological optimization and rational establishment of design and technological constraints on products at the design stage can be very effective in solving problems of reducing the weight of products and optimizing manufacturing processes.
Keywords: topological optimization; penalty method for solid isotropic body; technological process; load; SIMP-method.

Introduction

As we know, sovereignty and defence always are the main key issues in ensuring the national security of any independent state, Ukraine is no exception. When these questions are not put in the first place, difficult times come in the country, which poses a threat to the very existence of the state. Due to the aggressive policy of the neighbouring country, which has been pursued in recent years, the military-political situation has worsened, acquiring all new forms of escalation, which is why in our country there is a rapid development in the field of military. Many public and private enterprises of the military-industrial complex and related organizations have resumed their activities or significantly increased production capacity to attract new and modernize existing weapons. The importance of military science and its most important component, military technology, is also rising sharply. Of particular relevance for the country's defence are the achieved and projected results of military-technical science – design and technological achievements for the development and creation of weapons, military, and special equipment, as well as the results of intellectual activity of military and dual-use. Therefore, solving even minimal tasks that will help our military to resist the enemy and maintain integrity, peace, and tranquillity in Ukraine is very important.

This paper considers and solves the real production problem obtained from the company "DELTA PREMIUM", which aims to reduce the weight of the protective case for the transportation of radio reconnaissance equipment, which the domestic military often uses in the field in the east of our country. A comprehensive approach was applied to solve this problem, namely it is proposed to develop a new design of a protective case in several stages, containing parallel-sequential design during design and technological preparation of production using modern CAD tools, namely automated methods (CAD, CAM and CAE), which in the process of designing and developing manufacturing technology made it possible to achieve the required reduction in product weight.

Problem statement

The purpose of the work is to improve the method of reducing the weight of the product on the basis of the organization and implementation of design and technological measures, including work with the topology of 3D models of structural elements and making appropriate adjustments to the manufacturing process.

The current state of development of methods of topological optimization in solving design and technological problems

Topology optimization (TO) is a mathematical method that optimizes the layout of a material within a given design space for a given set of loads, boundary conditions, and constraints to maximize system performance. TO differs from shape optimization and size optimization in the sense that the design can achieve any shape in the design space, instead of dealing with predefined configurations [1]. There are various approaches to product topology optimization developed over the last three decades. For example, the method to the set level, the method of homogenization, the SIMP method, and the method of setting different densities are among the main types of topological optimization. The application of the methodology of topological optimization began a long time ago, except for the existence of the method at that time, did not give the desired effect in the development of projects, which provided a production limitation for the obtained optimized structures.

Methods of evolutionary optimization of structures (ESO) and bilateral evolutionary optimization of structures (BESO) are intensively studied and developed in recent years [2]. The most effective is the application of this method in optimizing the topology of continuous structures in finding the best location and geometry of the cavities within the simulation area. In addition, this type of optimization can be used not only to optimize full-scale structures but also for the optimal design of materials at the micro and nanoscale.

The ESO method is based on determining the level of stresses in any part of the structure by the finite element method. An indicator of inefficient use of the material is a low level of stress (or deformation) in one or another part of the structure. Ideally, the stress level in the structure should be the same, close to the limit, but safe value [3, 4].

From this concept, we obtain the principle of material removal according to the fact that insufficiently loaded material can be removed, which will lead to the removal of individual elements of commonly produced models.

The level of intensity of each element is determined by comparison, such as the Mises stresses of this element σ_e^{vm} with a critical or maximum value of the Mises voltage in the structures $\sigma_{\max}^{vm}$. If the result of the finite element analysis is satisfied by the condition

$$\frac{\sigma_e^{vm}}{\sigma_{\max}^{vm}} < R_{Ri},$$

where R_{Ri} – the limit value (rejection factor) at which the object was removed.

The cycle of finite element analysis and their removal is repeated for several iterations using the same threshold connection to achieve a steady, in the absence of elements that satisfy this removal threshold. Then the selection coefficient can be increased according to a certain evolution coefficient H_i.

$$R_{R(i+1)} = R_{Ri} + H_i.$$

Next, with an increased rejection factor, the cycle is performed until a new steady state is reached. The iterative process continues until the desired result is achieved (for example, until all the material from those areas where the stress level does not exceed 25 % of the maximum is removed) [5, 6].

Quantitatively, the change in velocity (or auxiliary) of structures as a result of the removal of the i-th finite element is the index of sensitivity, which is determined by the average information as

$$a_i^l = \frac{1}{2} u_j^T K_j u_i,$$

where u_i – vector of nodal displacement of the i-th element; K_j – the stiffness matrix of the element.

The sensitivity function indicates an increase in the average pliability as a result of the removal of the i-th element, equal to the elementary deformation energy of the i-th element. To minimize the average pliability (i.e., maximize rigidity) by removing the elements, it is necessary to exclude elements with a minimum value of the sensitivity factor.

The mathematical basis of the ESO method is quite simple and clear, and its software implementation does not require complex programming techniques, it is evenly applicable to 2D and 3D models. The element is removed by assigning its module a zero value, which leads to its ignoring in subsequent iterations (in the subsequent calculation of the global stiffness matrix). When removing elements in the iterative process, the number of equations decreases, therefore the computational complexity of the problem decreases, which is especially important for 3D models [6].

Solid Isotropic Material with Penalization (SIMP), or the method of penalization for a solid isotropic body – is a method of maintenance, the main idea of which is to create a field of virtual density, which is analogous to some real characteristics of the object. The purpose of the method is to reduce the mass of the structure due to the redistribution of material in the field of space design under known boundary conditions. The result of its use is to obtain a uniform object within this problem. SIMP is widely used in additive technologies (3D printing technologies) capable of creating objects of the desired shape [7].

Today, the SIMP method is widely used around the world. The density of materials is considered by a qualitative design change. The optimal structural topology is obtained by redistribution of material within all boundaries of the region based on the criteria of optimality or the method of mathematical programming.

In the SIMP method, the design area Ω is sampled by finite elements. The properties of the material are constant in each of these elements and depend on the relative density x_i. The relative density should be 1 or 0 in the calculation area Ω after optimization. The rejection factor is used to limit the intermediate relative density p.

The relationship between the modulus of elasticity and the relative density is written as

$$E(x_i) = E_{\min} + (x_i)^{\text{p}} (E_0 - E_{\min}),$$

where E_0 – modulus of elasticity of the material. For numerical stability $E_{\min}$ is taken as $E_0 / 100_0$; x_i – the relative density of the i-th element; p – rejection factor.

ESO-Simp-method

$$find: X = \{x_1, x_2, x_3, ..., x_i\}_N^T, i = 1, 2, 3, ..., n,$$

$$\min: C(X) = F^T U = U^T KU = \sum_{i=1}^{n} u_i^T k_i u_i = \sum_{i=1}^{n} (x_i)^p u_i^T k_0 u_i$$

$$if: KU = F, V = f_0 V_o = \sum_{i=1}^{n} x_i v_i,$$

$$0 < x_{\min} \le x_i \le x_{\max} \le 1,$$

where the objective function C is defined as the optimal ratio; X – is a vector of constructive variables; $x_{\min}$ and $x_{\max}$ – the minimum and maximum relative density of the elements, respectively. The purpose of entering a non-zero value $x_{\min}$ is an avoidance of singularity; F – load vector; U – global shift vector; K – global stiffness tensor; k_j – the stiffness tensor of the element after density interpolation; k_0 and u_i – stiffness tensor and displacement vector of nodes of elements; V – volume of material; V_o – the initial volume of the settlement area; f_0 – given the volume ratio [7].

The ESO-Simp-method of hybrid topology is aimed at combining the previously discussed methods of ESO and SIMP, while the calculated variables are the relative densities of the elements, and the optimal function is chosen as the objective function. Then the optimization task for the minimum average match based on the ESO-SIMP algorithm can be written as

$$find: X = \{x_1, x_2, x_3, ..., x_i\}^T, \; i = 1, 2, 3, ..., n,$$

$$\min: C(X) = U^T KU = \sum_{i=1}^{n} u_i^T k_i u_i = \sum_{i=1}^{n} (x_i)^p u_i^T k_0 u_i,$$

$$if: KU = F, V = \sum_{i=1}^{n} x_i v_i \le f_0 V_o,$$

$$0 < x_{\min} \le x_i \le x_{\max} \le 1.$$

The difference between ESO-SIMP and SIMP is the volume limit. In the process of each iteration, elements whose relative density is less than or equal to the rejection coefficient are removed from the development area, and all other elements are introduced into the next iteration [8]. The total volume of all remaining elements V must satisfy the following conditions

$$V = \sum_{i=1}^{m} x_i v_i \le f_0 V_o,$$

where m – the number of all remaining elements.

However, V is not the real total volume of the remaining elements V', which is expressed as:

$$V' = \sum_{i=1}^{m} v_i.$$

When volume limitation is performed, the actual total volume of all remaining elements V' is greater than V, due to the intermediate relative density, which is unfavourable for MOT. Thus, in the process of optimization the real total volume of all remaining elements V' should be controlled.

It was found that the new ESO-SIMP method has many advantages over the ESO method and the SIMP method in terms of efficiency and reliability [8].

The basic idea of the Level-Set method is to express a curve or surface implicitly. In this case, they are taken as the set zero level of the multidimensional function. Then their deformation by means of this function is traced.

For example, in optimizing the topology of a structure, curves or surfaces depicting its boundaries are deformed to minimize the energy of elastic deformation.

For a given domain Ω with a smooth boundary, the existence of an implicit function $\varphi(x)$, is assumed, which satisfies the conditions

$$\varphi(x) = \begin{cases} > 0, x \in \Omega^{+}(material) \\ = 0, x \in \partial\Omega^{+}(border) \\ < 0, x \in \Omega^{-}(emprisess) \end{cases}$$

The two most commonly used functions in the Level-Set method are the Heaviside function $H(x)$

$$H(\varphi(x)) = \begin{cases} 0\varphi \le 0 \\ 1\varphi \ge 0 \end{cases}$$

and the Dirac delta function $\delta(\varphi)$, which is equal to 0 everywhere except the narrow band containing the material boundary:

$$\delta(\varphi(X)) = \frac{dH(\varphi(x))}{d\varphi}.$$

For the function f the volume and surface integration along the boundary can be expressed as

$$\int_{\Omega} f(x) H(\varphi(x)) d\Omega;$$

$$\int_{\Omega} f(x) d = \int_{\Omega} f(x)\delta(\varphi(x))|\nabla\varphi(x)| d\Omega.$$

From a computational point of view, the smoothed Heaviside function is better in the optimization process.

The level setting function is a Hamilton–Jacobi equation:

$$\frac{\partial\varphi}{\partial \mathrm{e}} + V_n|\nabla\varphi,$$

where V_n is the normal speed of the moving boundaries.

The task of optimizing the topology of a structure with a limited area while minimizing flexibility can be described as follows:

$$\min C(\varphi) = \int_{\Omega} \frac{1}{2} E(\varphi)\varepsilon^{T} D\varepsilon d\Omega$$

$$\nabla \cdot (E(\varphi)\varepsilon) = f$$

$$\int_{\Omega} H(\varphi) d\Omega = V^{*},$$

where the design area is represented by Ω; E – is a calculated variable, which is determined by the level surface $E(\varphi) = E_0 H(\varphi) + (1 - H(\varphi))E_{\min}$, where E_0 is the modulus of elasticity of the material; $E_{\min}$ – minimum modulus of elasticity; D – is the elastic matrix; V^* – allowable amount of material. The equation of linear elastic equilibrium is used to calculate the dislocation field u, the strain tensor ε and the stress tensor σ.

The optimization problem can be solved using the method of optimality criteria, sequential method of linear programming or the method of asymptote motion [7, 8].

By varying the target functional, the minimization problem in the two-dimensional case is formulated as a related problem of linear elasticity and the diffusion equation:

$$\Delta \cdot (E(\varphi)\varepsilon) = f$$

$$\frac{\partial\varphi}{\partial e} - \left[\frac{1}{2}(E_0 - E_{\min}\varepsilon^{T} D\varepsilon + \lambda\right]\delta(\varphi)\cdot|\nabla\varphi| = \alpha\Delta\varphi,$$

where α – is the damping factor that stabilizes the solution algorithm.

Design and preparation of a new 3D model for optimization

The design of a protective case for transporting radio reconnaissance equipment was considered as an object of optimization (Fig. 1).

Construction frame type “Rackmount” is a standardized design or housing for mounting several modules of electronic equipment (Fig. 2) [9]. Each module has a 19-inch (482.6 mm) wide front panel. The 19-inch size includes edges or “lugs” that protrude from each side of the equipment, allowing the module to be attached to the rack frame with screws. Common uses include computer servers, telecommunications and network equipment, audio-visual production equipment, and scientific equipment.

Fig. 1. Protective case

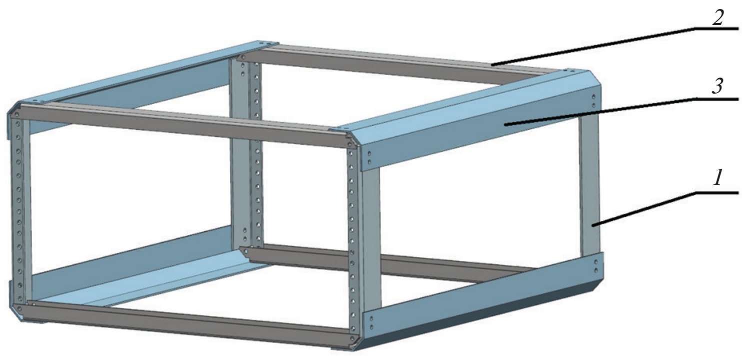

Fig. 2. The initial design of the frame type

It consists of a set of 4 units of each of the parts: unit rack (*1*), n-shaped part (*2*), and guide (*3*), interconnected by screws M6 40 pcs. The material from which the frame components are made is 08KP steel.

The unit rack, obtained by bending asheet metal, is designed to attach specialized mounting equipment to M6 screws, for this it has 15 mounting holes with M6 thread, which complicates the manufacturing process of this product. In addition, there are 6 threaded holes for assembling the frame. After analysing the existing detachable connections, it was proposed to alternatively replace the threaded holes with square holes to secure the mounting nuts.

U-shaped part is obtained by bending asheet metal. In its manufacture, 4 installation operations are performed for M6 crimping nuts, which is also time consuming. The guide is made by bending asheet metal and contains pre-cut mounting holes for connection with other structural elements of the frame type, it also has pre-made two holes for rigid attachment to the body, through anti-vibration supports with M8 screws.

In the original design, screws and crimping nuts were used to connect the elements, and to reduce the complexity of manufacturing the product, in the new design, it was proposed to use stainless power anti vibration rivets. This design solution simplified the technological process of manufacturing and assembly of parts in accordance with the initial technological process, eliminated the operations of threading and pressing, which simplified the manufacture of structural elements.

To test the impact resistance of the original structure, the test was performed as follows: the product was fixed to the housing through anti-vibration supports and pad.5 m on a rigid base with a fixed model of equipment weighing 30 kg to simulate a load of 20G. During this experiment, the following results were obtained: the unit rack and U-shaped part are subjected to the greatest loads, so it was proposed to make themof stainless steel AISI 304 t av with a height of 1 mm and 1.5 mm, respectively, and 2 mm thick aluminium guide AD0 (1050).

Replacement of materials of structural elements affected the initial technological process, because the new proposed materials are resistant to corrosion, the need to apply a coating on the parts of the product has disappeared [11].

We perform the analysis of force loads on the structure and the establishment of boundary conditions [10, 11]. The design space is an area that can be occupied by structural details, based on layout considerations. The frame design space is represented by a set of three structural elements of 4 units each, divided into unconnected elements.

Autodesk Fusion 360 CAD and its CAE module “Generative design” are used for design [12].

Since the main purpose of the frame type structure is safe transportation of high-precision equipment and ensuring its operability under working loads, a very important element of the product is the front side of the structure on which the equipment is fixed, how many holes for nuts are already designed, they will also be limited in further modelling. Additional side mounting holes will be limited only by radial “white zones” (Fig. 3). The U-shaped part was limited to two bends at 90° due to the specifics of the bending equipment, and the protrusion of the material required for bending was close to a minimum, so it was decided to leave the bend unchanged (Fig. 4).

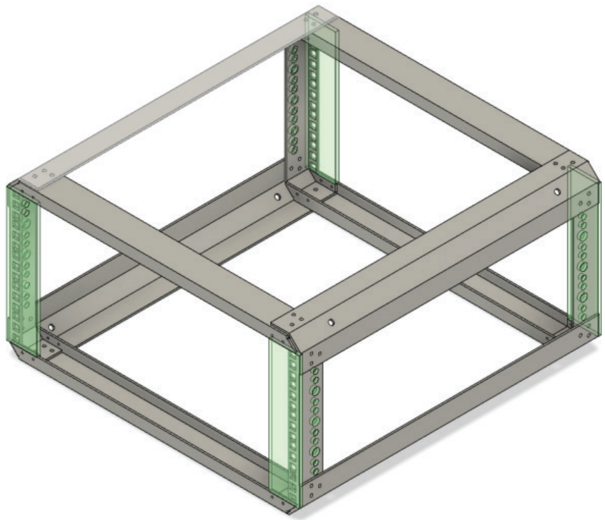

Fig. 3. Restriction of a unit rack

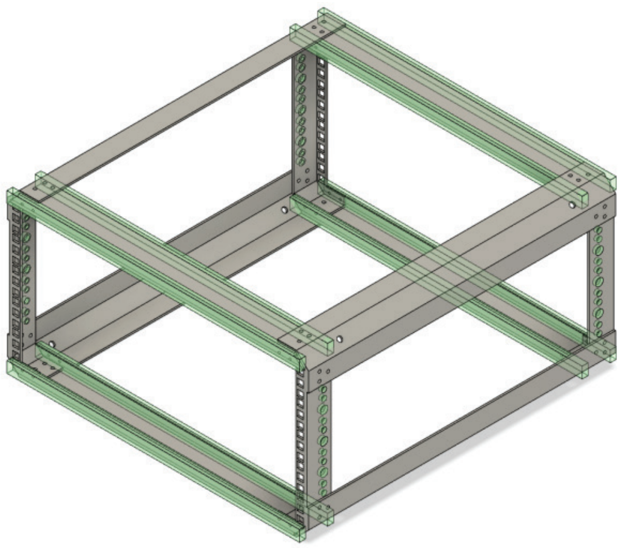

Fig. 4. Limitation of the n-shaped part

The next and very important step in CAE computation is to build a dynamic grid, which is a set of vertices, edges, and faces that describe the shape of a polyhedral object in solid-state modelling. Faces usually consist of a grid that contains a set of standard geometric objects that are easy to describe: triangles, quadrilaterals, or other polygons. The accuracy of optimization will depend on the set value of grid partitioning, accordingly, the optimization time of the model will increase (Fig. 5) [13].

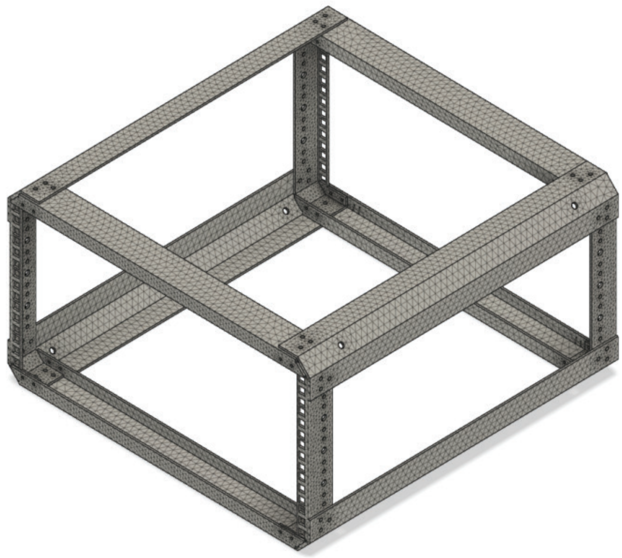

Fig. 5. 3D model with a dynamic grid

The final stage of this section is to determine the workloads, as the structure must maintain its geometry, ensure the proper condition and performance of the equipment that is attached to it. A load of 20G will be calculated according to the standard for this type of construction MIL-STD-810G and its subclause 516.6.

This load is given relative to the mass of the input 3D model of the frame-type structure before the topological optimization obtained from the previous section. The physical model of force overload can be obtained by simulating the fall of a structure with applied force.

Therefore, taking into account all the necessary boundary conditions, building a dynamic grid and taking into account the necessary load words that will act on the object of study, the procedure of optimizing the mass of the model with a given optimization criterion (Fig. 6).

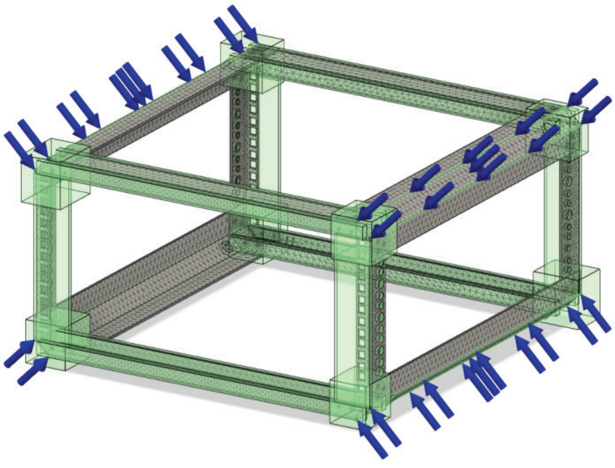

Fig. 6. Design taking into account all limit conditions and loads

Topologically optimized model of construction frame type

As a result of topological optimization, a new model of the frame-type structure was obtained. Based on the simulation results, a solid-state 3D model was designed (Fig. 7), which was additionally tested with the same force loads that were applied in the optimization process, and the results were obtained that meet the initial requirements [14]. This allowed a comprehensive solution to the problem of reducing the weight of the structure. As a result, the weight of the structure is 3.6 kg, which is 56 % less than the initial weight of the structure.

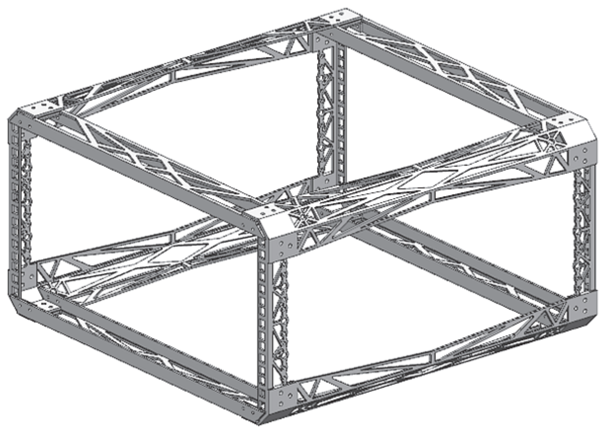

Fig.7. 3D model of the structure after topological optimization

The topological optimization procedure does not provide ready-made solutions for production, so based on the obtained topology results and the designed optimized 3D model of the frame-type structure, the design procedure of elements in the sheet metal module was performed by Siemens NX 11 CAD. The obtained sheet elements were presented as scanned and exported in .DFX format for further processing in ProNest CAD. Appropriate materials were installed using software tools and control programs were created for the CNC laser machine in Autodesk Fusion 360 CAD.

Conclusions

The analysis of topological optimization research performed in the work testifies to the urgency of the direction, its prospects and efficiency in achieving the desired result in solving modern engineering problems. As a result, new design and technological solutions for frame-type structural elements were obtained, and thus the replacement of threaded mounting holes with mounting nuts was substantiated and proposed, and anti-vibration rivets were used. Selection of materials for elements of a new design is executed.

The new 3D model of the frame-type structure was designed by means of CAD Siemens NX 11, which was later optimized. In the process of designing the part, the unit rack underwent significant changes that increased the resistance of the structure to loads in general.

The 3D model of the new design was created in the CAD module of Siemens NX 11 CAD and was later imported into the Autodesk Fusion 360 CAD for further processing in the CAE module “Generative design”. Initial data for topological optimization were imported 3D model and introduced the characteristics of the materials of structural elements, indicating the compressive forces of riveted joints. Limitations on mounting holes, geometric shape of the guide, unit post, U-shaped part and construction angles were also substantiated and established. A dynamic grid was created and the accuracy of calculation and working loads on the frame-type structure were established. As a result of topological optimization, several variants of 3D models were proposed for their further refinement by means of solid-state modelling and selection of the most optimal among them.

As a result, a new, optimized 3D model of the frame-type structure with a mass less than 56 % of the original was obtained, and the application of topological optimization methods once again proved its effectiveness.

The design and technological solutions obtained in the work and experimentally modelled data in the future can be used to verify more complex product designs, where there is a need to solve the problem of weight reduction.

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ГЕНЕРАТИВНИЙ ДИЗАЙН КОНСТРУКЦІЇ КАРКАСНОГО ТИПУ

Проблематика. Останніми роками бурхливо розвивається вітчизняна військова промисловість. Зменшення маси та збільшення питомої міцності виробів військового призначення, що застосовуються в польових умовах, – актуальні завдання, що постали перед інженерами та науковцями. Стрімкий розвиток адаптивного виробництва розширив можливості топологічної оптимізації для проєктування виробів або вдосконалення конструкторсько-технологічних рішень задля зменшення їхньої маси.

Мета дослідження. Підвищити ефективність технології виготовлення конструкції каркасного типу на базі методу топологічної оптимізації, що забезпечить зменшення маси виробу зі збереженням усіх заданих функціональних показників.

Методика реалізації. Аналіз методів топологічної оптимізації та пропозиція взаємодії сучасних САПР (систем автоматизованого проєктування), а саме модулів CAD (Computer-aided design (технологія автоматизованого проєктування)), CAM (Computer-aided manufacturing (технологія автоматизованого виробництва)), CAE (Computer-aided engineering (технологія автоматизованої розробки)) на етапі конструкторсько-технологічного підготовлення виробництва, що вкотре продемонструвала ефективність у вирішенні завдань зі зменшення маси виробів.

Результати дослідження. Розв'язано основні задачі топологічної оптимізації для проєктування конструкції каркасного типу: мінімізацію об'єму та маси за фізичних обмежень, оптимізацію інших параметрів із заданими геометричними обмеженнями. Удосконалено методику зменшення маси каркасу виробу, що внаслідок раціональних конструкторсько-технологічних заходів забезпечила зниження на 56 % маси конструкції каркасного типу від початкової та понизила трудомісткість технологічного процесу виготовлення на 22 % завдяки його ефективній адаптації до нових технологічних умов.

Висновки. Застосування методів топологічної оптимізації та раціональне встановлення конструкторсько-технологічних обмежень на вироби на етапі проєктування може бути дуже ефективним для зменшення маси виробів й оптимізації технологічних процесів виготовлення.

Ключові слова: топологічна оптимізація; метод пеналізації для твердого ізотропного тіла; технологічний процес; навантаження; SIMP-метод.

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ГЕНЕРАТИВНЫЙ ДИЗАЙН КОНСТРУКЦИИ КАРКАСНОГО ТИПА

Проблематика. В последние годы бурно развивается отечественная военная промышленность. Уменьшение массы и увеличение удельной прочности изделий военного назначения, применяемых в полевых условиях, – актуальные задания, стоящие перед инженерами и учеными. Стремительное развитие адаптивного производства значительно расширило возможности методов топологической оптимизации для проектирования изделий или усовершенствования конструкторско-технологических решений с целью уменьшения их массы.

Цель исследования. Повысить эффективность технологии изготовления конструкции каркасного типа на базе метода топологической оптимизации, что обеспечит уменьшение массы изделия при сохранении всех заданных функциональных показателей.

Методика реализации. Анализ методов топологической оптимизации и предложение взаимодействия современных САПР (систем автоматизированного проектирования), а именно модулей CAD (Computer-aided design (технология автоматизированного проектирования)), CAM (Computer-aided manufacturing (технология автоматизированного производства)), CAE (Computer-aided engineering (технология автоматизированной разработки)) на этапе конструкторско-технологической подготовки производства, которое в очередной раз продемонстрировало эффективность при решении задач по уменьшению массы изделий.

Результаты исследования. Решены основные задачи топологической оптимизации для конструкций каркасного типа: минимизация объема и массы при физических ограничениях, оптимизация других параметров с заданными геометрическими ограничениями. Усовершенствована методика уменьшения массы каркасного изделия, которая за счет рациональных конструкторско-технологических мероприятий обеспечила уменьшение на 56 % массы конструкции каркасного типа от начальной и снизила трудоемкость технологического процесса изготовления на 22 % за счет его эффективной адаптации к новым технологическим условиям.

Выводы. Применение методов топологической оптимизации и рациональное назначение конструкторско-технологических ограничений на изделия на этапе проектирования может быть очень эффективным для уменьшения массы изделий и оптимизации технологических процессов изготовления.

Ключевые слова: топологическая оптимизация; метод пенализации для твердого изотропного тела; технологический процесс; нагрузка; SIMP-метод.

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