Analysis and use of SIMP method in optimization of a car hood design

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Abstract. The article shows the relevance of creating digital twins and conducting topological and topographic optimizations as part of improving the physical and mechanical properties of car parts using the example of a car hood. A description of the existing optimization methods is given and the principle of the SIMP method is described. The results of optimizing the design of the hood of the car using this method are presented. We demonstrate that using modern approaches to modelling and optimization of automobile parts makes it possible to achieve targets in the design and redesign, to achieve sufficient structural strength while maintaining or reducing the mass of the original structure. It is shown that modelling allows providing an array of information on the optimized part as soon as possible, as well as reducing the consumption of materials used to create it.

1 Introduction

When designing the hood of a new generation car, high demands are made on strength, stiffness and frequency characteristics. In addition, the hood must comply with the general requirements of manufacturability and passive safety of the car, which are formed based on the results of crash tests.

Currently, the practice of creating and researching the so-called Digital Twin is widespread: digital copies of products with a certain set of characteristics and properties that duplicate it. Digital twin is a computer-aided engineering (CAE) mathematical model that is described by a system of partial differential equations. The use of digital twins allows exploring the behaviour of the product in various conditions with different sets of its characteristics and properties. This is necessary in order to be able to influence the design of the product before or instead of conducting full-scale tests, providing a difference between them and virtual tests of ± 5% [1]. For this reason, such modelling can significantly reduce production costs. Digital counterparts allow the creation of a competitive new generation of products in the shortest possible time, but this requires world-class multidisciplinary engineering competencies [2]. The centres of such competencies are digital factories, such as the product of the fourth industrial revolution (Industry 4.0).

Topological and topographic optimization are widespread and used in various fields of life, including biomechanics [3] and technology. Optimization of the digital model allows reducing the number of production cycles of the same product in production with a view to its modernization. When designing a car bonnet, this process is a key step. The goal of topological optimization is to determine the optimal use of the material for the part in such a way that, while reducing the weight of the structure, the stiffness indicators and the natural frequency of the structure are consistent with those in the catalogue of target indicators and limitations. The method of topological optimization is preferably used in the initial stages of part design. The results of topological optimization are sensitive to the finite element mesh [4-6], which means that the resulting form of the structure may differ when calculating on different sizes of structured grids. So, the optimal mesh size is selected so that the minimum number of elements fits in the thickness of the smallest face of the part geometry.

The topographic optimization method allows changing the shape of the structure by adding punching and flanging. If it is impossible to manufacture a stamping, it can be replaced with an additional amplifier. This approach allows maximizing the stiffness of the components and / or the frequency of the model with minimal addition of mass.

The purpose of this study is to determine the optimized shape of the car bonnet design.

2 Methods

Various methods are used to solve optimization problems, among them: SIMP (Solid Isotropic Material with Penalization) [7], ESO (Evolutionary Structural Optimization method) [8], Level- Set (a method of establishing a level or a set of levels) [8-11], BESO (Bi-directional Evolutionary Structural Optimization method) [4, 8], or their modifications, such as ESO-SIMP. In this work, we use the SIMP method, the fundamental task of which is to create a virtual density

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field. As the most popular mathematical method for optimizing topology, SIMP predicts the optimal distribution of material in a given space for given load cases, boundary conditions, production constraints, and performance requirements. The result of using the method is the optimal structural topology, which is achieved by redistributing the material.

Form optimization in the general sense consists of determining for each point in the space the presence of material in it. For this, a domain is discretized by a finite element mesh called isotropic solid microstructures. Each element is either filled with material for the areas that need it, or cleared of material where it can be removed. Material density distribution ρ in the calculation area Ω is discrete, so each element is assigned a binary value: $\rho_e = 1$ where material is required (black color), and $\rho_e = 0$ where the material is removed (gray). Figure 1 shows an image of an optimized arrangement of material of a loaded beam.

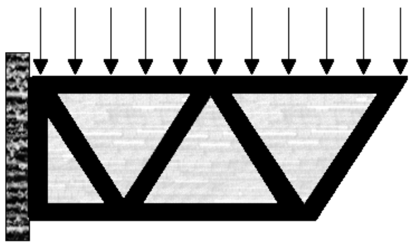

Fig. 1. Example of topological optimization of a loaded beam.

Solid elements with densities $\rho_e = 1$ are black; empty elements with $\rho_e = 0$ are removed.

A continuous distribution function of the relative density is introduced; for each element, the assigned relative density may vary between the minimum value $\rho_{\min}$ and 1, which allows to assign intermediate densities for elements (characterized as porous elements). $\rho_{\min}$ is the minimum allowable relative density for empty elements that are greater than zero. Since the relative density of the material can continuously change, the Young's modulus of the material of each element can also change continuously. For each element, the relationship between the coefficient of relative density of the material ρ_e and Young's modulus of a given model of an isotropic material E_0 calculated according to the power law:

$$E_{(\rho_e)} = \rho_e^p E_0 \qquad (1)$$

Rejection factor p reduces the contribution of elements with intermediate densities (gray elements) to the total stiffness. It directs the optimization solution to elements that are either solid black $(\rho_e = 1)$, either blank white $(\rho_e = \rho_{\min})$. Numerical experiments show that the value of rejection factor $p = 3$ is appropriate.

The decrease in the elastic modulus of the material of the element leads to a decrease in its stiffness. According to the SIMP method, the total stiffness is modulated in accordance with:

$$K_{SIMP(\rho)} = \sum_{e=1}^{N} [\rho_{\min} + (1 - \rho_{\min})\rho_e^p] K_e , \qquad (2)$$

where K_e – element stiffness matrix, $\rho_{\min}$ – minimum relative density, ρ_e – relative density of an element, p – rejection factor, N – number of elements in the design field.

The general stiffness of the structure is often used as a maximized function. This can also be considered as minimizing compliance for a given reduction in mass. Compliance is a measure of overall mobility or softness of a structure; it is the inverse of rigidity. The total compliance is equal to the sum of the strain energies or the elastic energy in the elements. Minimizing overall compliance is equivalent to maximizing overall stiffness. The optimization algorithm through an iterative process seeks to resolve the densities of elements that minimize the overall compliance of the structure:

$$\min C(\{\rho\}) = \sum_{e=1}^{N} (\rho_e)^p [u_e]^T [K_e][u_e] , \qquad (3)$$

where $[u_e]$ – this is the displacement vector in the element node e, $[K_e]$ – element stiffness e, $\{\rho\}$ – vector containing relative densities of elements ρ_e. During each optimization iteration, restrictions on the target mass and the balance of internal and external efforts must be observed:

$$\sum_{e=1}^{N} \{v_e\}^T \rho_e \le M_{target} , \qquad (4)$$

where v_e – element volume, M_{target} – target mass;

$$[K\{\rho\}]\{u\} = \{F\} , \qquad (5)$$

where $[K\{\rho\}]$ – general stiffness matrix depending on the relative density vector, $\{u\}$ – displacement vector, $\{F\}$ – vector of external efforts;

$$\theta(\{\rho\},\{u\})_1 \le \theta_1^* , \theta(\{\rho\},\{u\})_2 \le \theta_2^* ,... \qquad (6)$$

Formula (6) contains such limitations of the response of the structure as restrictions on stresses, displacements, natural frequencies, etc. [12-20].

3 Results and Discussion

View of the original design of the car hood is shown in Figure 2.

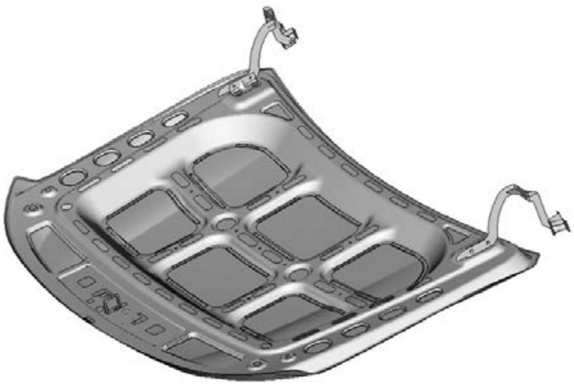

Fig. 2. The initial design of the hood of a car.

The goal of optimizing the design of the hood is to minimize weight while maintaining stiffness and frequency characteristics. The mass of the original design without loops is 21.3 kg. The torsional stiffness of the structure is 98.4 N·m / °, which corresponds to the target value of ≥ 80N·m / °. The stiffness of the leading, trailing and lateral edges is 88.8 N / mm, 57.3 N / mm and 72 N / mm, respectively, with a target value of ≥ 70 N / mm. The natural frequencies of the structure are 27.7 Hz and do not satisfy the target value of ≥ 30 Hz.

The volume to optimize the design is created with the filling of all holes and punching (except for essential ones). The hood model filled for optimization is shown in Figure 3.

Fig. 3. Filled car hood model.

The analysis of the obtained model and further topological and topographic optimization are carried out, during which parts of the volume that are not bearing are excluded from the "overstressed" structure.

The hood optimization study is conducted using OptiStruct software. The exported data is used as a reference object for constructing optimized geometry of the analyzed part. The stages of topological optimization of the hood model are presented in Figure 4.

The most loaded parts of the structure are shown in red, while the parts of the volume to be excluded from the model are indicated in blue.

During the topographic optimization of the model, the parameters of punching and flanging were optimized, due to which, at one of the stages of the process, a new design option was obtained, which is more strengthened and reliable. The result of topographic optimization is presented in Figure 5.

The red color shows the places where, during the development of the structure, it is necessary to have the deepest sub-stampings.

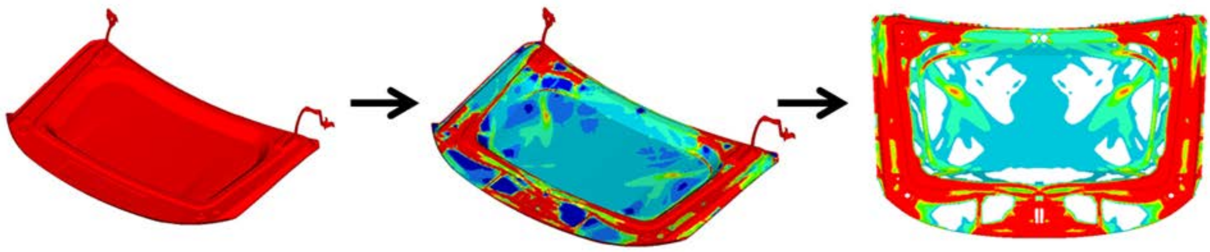

Fig. 4. Stages of topological optimization.

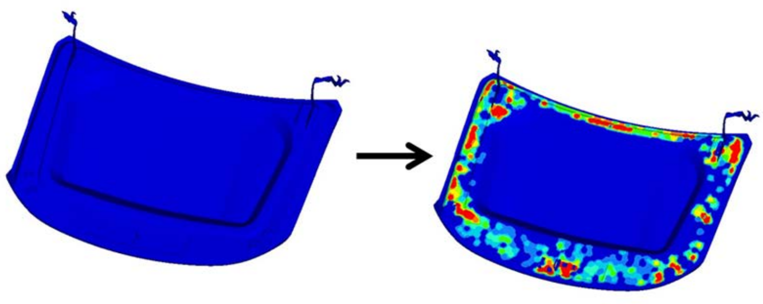

Fig. 5. Stages of topological optimization.

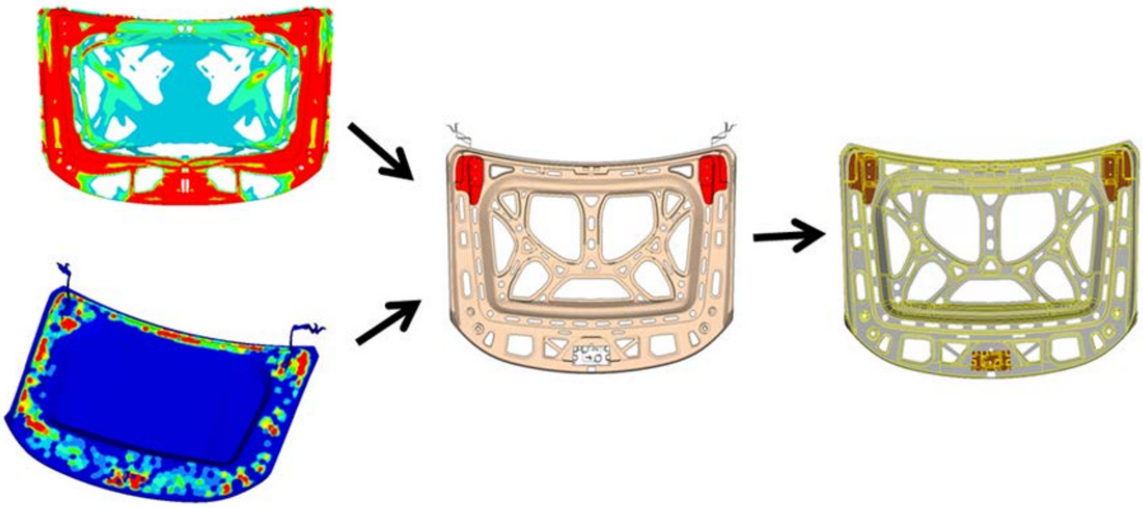

Fig. 6. The result of optimizing the hood of a car.

The final optimized model has a mass equal to 18.9 kg (which is 2.4 kg lighter than the original design), and has the necessary values of stiffness and frequency characteristics. As a result of topological and topographic optimization of the design, an alternative model of the car bonnet is obtained that satisfies the main criteria from the catalog of targets and limitations. So, the torsional stiffness of the optimized model is 137 N·m / °, exceeding the value of the original model and satisfying the target value of ≥80 N·m / °. The stiffness of the leading, trailing and lateral edges is 88.8 N / mm, 57.3 N / mm and 72 N / mm, respectively, with the target value of ≥ 70 N / mm, also exceeding the values of the original model. The natural frequencies of the new design are 35.2 Hz, which also corresponds to the target limit and exceeds the value of the original model. The result of the research is presented in Figure 6.

4 Conclusions

In this article methodology for topological and topographic optimization by the SIMP method was developed. Results of optimizing the digital model of the car hood using this method is shown. The solution to the problem of optimizing the hood according to the proposed methodology shows full physical adequacy and compliance with the requirements put forward, which allows it to be used along with new production technologies, to provide projects of stronger structures as soon as possible, as well as to reduce the consumption of materials used to create parts.

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