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Topology Optimization Design of Typical Functional Structural Parts

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Abstract: Topology optimization is a commonly used lightweight design method that involves reducing the weight of structural parts while retaining their function. It is widely used in the lightweight design of auto parts. In this paper, the topology optimization of a typical structural part was analyzed by using the relative density method. Calculations indicated that the strength of the structural part could be maintained under 70% mass reduction. The results of the analysis showed that this method helps improve the structure of parts.

Keywords: Structural parts; Lightweight; Topology optimization

1. Introduction

The purpose of lightweight design is to reduce the weight of industrial products while retaining the maximum range of use. Lightweight design helps save energy and reduce emissions, improve the efficiency of engines, and reduce exhaust emissions. Therefore, it has been widely used in automobile manufacturing and other fields. Currently, the methods used to achieve lightweight design are using lightweight materials, such as aluminum, magnesium, ceramics, plastics, glass fiber, or carbon fiber composites. The structural design involves numerical calculations, finite element analysis, and topology optimization [1].

Topology optimization is a method of structure optimization. Developed in the 19th century, structure optimization mathematical optimization theories to engineering design, which addresses various challenges in design and improve design efficiency. Structural optimization design is categorized into three levels: parameter optimization (or size optimization), shape optimization, and topological optimization [2].

2. Common topology optimization methods

Topology optimization is a widely used design method in engineering that serves to determine the best structural type of a structural part. In order to improve the structural performance of the product, it utilizes the load as a design variable, constraining the modeling outcome without the need for an initial configuration. It allows for the generation of unforeseen design results based on variations in the applied load. Topology optimization, with its many interspersed features in the modeling space, often dominated by irregular forms, can pose challenges in the production and manufacturing process despite obtaining optimized model files. The maturity of 3D printing technology accelerates topology optimization calculations and promotes the application of topology optimization in product design [3].

Topology optimization of product structures involves both discrete and continuous variable structures. Discrete structure topology optimization is limited in scope, challenging, and may yield results that are not conducive to manufacturing. Hence, continuous structure topology optimization methods are typically preferred. With the maturity of additive manufacturing processing technology, the two are often used together to achieve the optimal balance between structure and material. Currently, the most advanced topology optimization methods include homogenization, variable density, and progressive structure optimization [4].

2.1. Homogenization method

Homogeneous topology optimization involves applying size optimization to simplify the optimization process. This approach allows for calculations with fewer constraints, focusing on optimizing the relationship between the spatial distribution of materials and the material distribution of the stressed structure, with the formation of pore shapes as the primary optimization objective. Homogeneous topology optimization aims to optimize the flexibility of the entire structure. While this method has mature principles and offers optimal solutions, its drawback lies in the complex shape distribution and extensive interspersion of the structure, making processing and manufacturing more challenging [5,6].

2.2. Variable density method

The variable density topology optimization method assumes that the density of the structure is functionally related to one or several physical parameters of the material. Material density is constrained within the interval [0,1]. In optimization, if the structure is a hole, the density is 0; for a support structure, it is 1. When the density is between 0-1, the optimization tends to bias it towards either 0 or 1. The objective of variable density topology optimization is also to optimize the flexibility of the entire structure. Its strengths include high computational efficiency, a limited number of variables, and mature principles. However, a drawback is that this method optimizes the median value of the density boundary, leading to a checkerboard phenomenon at the optimized structure's boundary. This can be unfavorable for subsequent processing and manufacturing [7].

2.3. Progressive structure optimization method

Progressive structure topology optimization involves gradually removing ineffective and inefficient materials to achieve topology optimization. With stress as the constraint, the goal is to minimize mass. This method involves two processes: adjusting material distribution based on stress changes and reducing material in low-stress areas. The objective is to optimize minimum mass while ensuring structural strength. The method is practical, with a clear and simple algorithm, but drawbacks include excessive oscillations, iterations, and the occurrence of a checkerboard phenomenon [8].

3. Uses of topology optimization

Topology optimization is a mathematical method used to optimize the distribution of materials in a given area based on given load conditions, constraints, and performance indicators. It serves as a form of structural optimization. This process allows for obtaining the optimal force transmission path and achieving a structural form that meets specified material reduction requirements while maximizing structural stiffness [9]. Topology optimization technology is widely used in aerospace, machinery, construction, and other fields. Common topology optimization methods for continuum structure include homogenization method, relative density method (such as the Solid Isotropic Material with Penalization [SIMP] method), evolutionary structural optimization method, independent continuous mapping method (ICM Method), level set method, etc.

4. Application of topology optimization

(1) Structural optimization

Topology optimization can be used to design various types of structures, such as aircraft wings, car bodies, building structures, etc. By optimizing the topological shape of the structure, the amount of material used can be significantly reduced, and the performance and efficiency of the structure can be improved. In mechanical structure design, topological optimization can be used to determine the optimal distribution of materials in a structure to maximize the strength and stiffness of the structure while minimizing the weight of the structure. This is very useful for lightweight design in aerospace, automotive, marine, and other fields [10].

(2) Material optimization

Topological optimization can be used to optimize the distribution and morphology of materials to achieve the best material properties [11]. For example, when a design involves using composite materials, the distribution and orientation of fibers can be determined through topological optimization, thereby improving the strength and stiffness of the material. In manufacturing, topological optimization can be used to optimize the machining path of parts to minimize material waste, reduce processing time, and increase production efficiency [12].

(3) Heat transfer optimization

Topological optimization can be used to optimize the heat transfer path for optimal thermal management. For example, in the design of electronic devices, the shape and position of the heat sink can be determined by topological optimization, thereby improving the heat dissipation effect[13].

(4) Fluid optimization

In the field of fluid dynamics, topological optimization can help determine the optimal path of a fluid in a given geometric space to improve fluid transfer, reduce drag, etc [14]. Topological optimization can be used to optimize the flow path and distribution of a fluid to achieve optimal hydrodynamic performance. For example, in the design of wind turbines, the shape and layout of blades can be determined by topological optimization to improve the efficiency of wind energy conversion [15].

Topology optimization is an optimization method based on finite element analysis. It involves optimizing the structure's quality by altering its topology under specified constraint conditions [16]. The basic principle of topology optimization is to discretize the initial design domain into finite elements and then obtain the optimal form through iterative calculation according to the constraints and objective functions [17]. In this paper, we designed a connective structure of a motorcycle using topology optimization (relative density method) [18].

4. Topology optimization analysis of motorcycle structural parts

4.1. Establishment of topology optimization model

Figure 1 shows the connector of a motorcycle with the main load coming from the shock absorber and the frame connection.

Figure 1. Motorcycle connector

Parts material and load conditions: Material - ABS (Young's modulus 2000 MPa, Poisson ratio 0.35, density 1060 kg/m³, yield stress 45 MPa). The load includes Position 1 with 3500 N parallel to the *XZ* plane at a 45° angle in the negative direction of *Z* (direction vector: -0.70711, 0, -0.70711), Position 2 with 350 N parallel to the *XZ* plane at a 45° angle from the negative direction of Z (direction vector: -0.70711, 0, -0.70711), Position 3 with 1350 N parallel to the *XZ* plane at a 45° angle in the positive direction of *Z* (direction vector: 0.70711, 0, 0.70711), and Position 4 in the negative direction of *X* with 900 N at the central position of the two-hole connection (connector connection).

4.2. Setting topology optimization parameters

In accordance with the actual situation, a unit size of 2.5mm was chosen, and sequentially, "single load condition" and "use inertia release" were selected. The primary section of the motorcycle structural component was defined as the design space, while the installation part of the three sets of mounting holes connected with the shock absorber end and the frame connection end was considered the non-design space. Based on the experience of other researchers and considering the characteristics of the 3D printing process, the shape control type was determined to be a "symmetrical + two-way drawing" scheme, with a quality control of 30%. Figure 2 illustrates the outcome after topology optimization. The initial mass of the optimized structural part was 0.078686 kg. However, due to small surfaces in certain positions, the optimized mass after smoothing increased to 0.087435 kg.

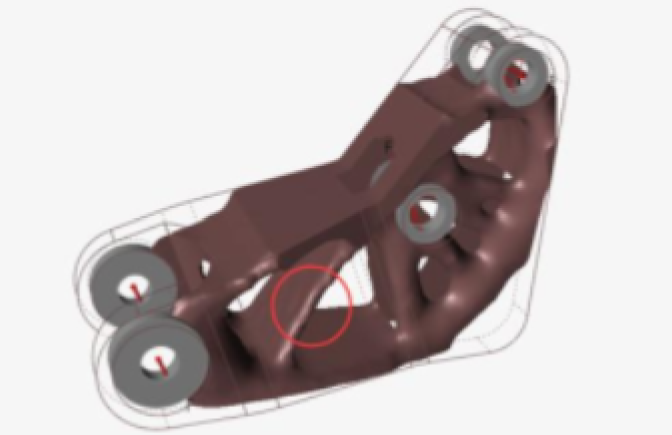

Figure 2. Topology optimization results

4.3. Geometric reconstruction

The model shown in Figure 2 was manually refactored using the PolyNURBS tool, as presented in Figure 3. A single solid three-dimensional model was formed by geometrically intersecting the optimized reconstruction results with the non-design space using Boolean operation tools, as depicted in Figure 4.

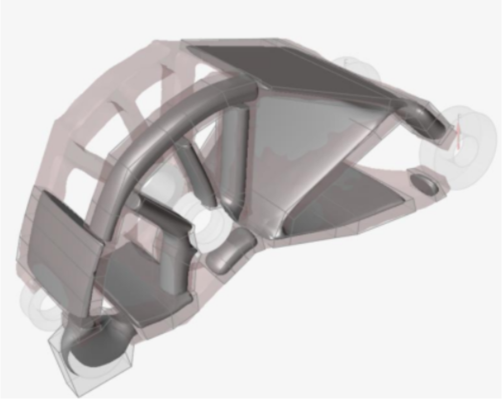

Figure 3. Geometric reconstruction

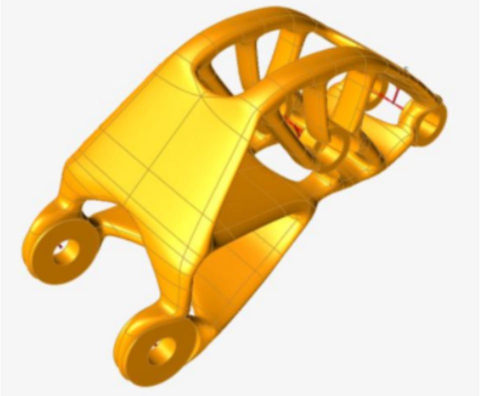

Figure 4. Boolean operations form a single entity

On this basis, the rounded corner tool was used to process the connection between the reconstruction result and the non-design space, and the final lightweight design was obtained [19].

4.4. Strength check

The strength analysis of the topologically optimized model revealed a maximum deformation displacement of 0.8506mm and a maximum stress of 41.78MPa, which is less than the yield stress of the ABS material (45MPa). This fully met the application requirements. [20].

5. Conclusion

During topology optimization analysis, using a larger element size results in shorter calculation times but lower accuracy, increasing the likelihood of errors in the final optimization result. It is generally advised to conduct strength analysis based on the default size of the system. When reconstructing the topology optimization model, the size and shape of connecting parts play a crucial role in determining the model's strength. It is recommended to smooth these parts as much as possible to prevent the formation of sharp, thin-walled structures.

Disclosure statement

The authors declare no conflict of interest.

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