Lightweight Design of a Support Based on Topology Optimization and 3D Printing

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Abstract. The lightweight design of a support is completed with combination of topology optimization and 3D printing technology. Based on reverse engineering, the three-dimensional model of the support is established. The minimum volume is taken as the design objective, the maximum von Mises stress and the maximum displacements at the two holes are taken as constraints, and the material density is taken as design variable. The variable density method is used to realize the optimization of the support. Then, the origin model and the optimized model are printed by FDM technology. The results show that: the support’s mass is reduced by 50% under all constraints after optimization; the combination of optimization design and 3D printing technology is an effective method of structural design.

1. Introduction
The constraints of manufacture process must be taken into account in the traditional structural design, so the final design is usually not the optimal solution. The emergence of 3D printing technology has solved the processing problem of structural optimum design. Subsequently, a series of researches are carried out under this framework. The high stiffness structural design of a spacecraft instrumentation support structure is executed based on topology optimization technology and SLM technology [1]. And, a topological optimization design method for rapid investment casting parts is proposed, which has been successfully applied to the design of a robot gripper structure [2]. For thin-walled structures with complex surface constraints, the external surface strengthening method based on MMC topology optimization method and the internal support optimization method based on minimal surface are proposed, then, the lightweight design of the model is realized by 3D printing manufacturing process [3]. Also, based on porous structure and additive manufacturing technology, the optimal design of aircraft joint structure is realized [4]. Moreover, with 3D printing technology and mechanical experiments, lightweight design of shaft parts is realized [5]. Besides, the lightweight and stiffness maximization design of the support base structure is realized by means of topology optimization design and metal 3D printing technology [6]. In addition, the design methods of rapid prototyping, topology optimization and reverse engineering for power grid equipment design are summarized [7]. Furthermore, two-way evolutionary optimization method and 3D printing technology are adopted to carry out structural optimization design of a T-shaped structure [8]. Also, lightweight design and manufacture of helmet liner are realized by means of topology optimization and 3D printing...
technology [9]. A topology optimization algorithm for minimizing the volume of 3D printing is also proposed. This optimization method can not only better reflect the load transfer path of the model, but also effectively save 3D printing materials [10]. In the medical field, the applications of porous metal materials such as bone scaffolds and orthopaedic implants are summarized, which are oriented to topology optimization and material-adding manufacturing technology [11]. Furthermore, a new multi-resolution topological optimization method is used to maximize the structural stiffness of bone substitutes. And the design’s feasibility is verified by digital assembly simulation. Also, the bone substitutes of ABS materials are manufactured by FDM technology. Then, mechanical properties and structural functions of bone substitutes are verified by experiments [12].

In this paper, the three-dimensional numerical model of a support is established based on reverse modeling. The minimum volume is taken as the design objective, the maximum von Mises stress and the maximum displacement at the two holes are taken as constraints, and the material density is taken as design variables. Subsequently, the topology optimization of the support is executed by means of variable density method. Then, the support’s origin model and optimized model are printed by FDM technology.

2. Reverse design
Firstly, the point cloud data of the support are obtained by three-dimensional scanning, and the finite element model of the support is established. Two preparations are needed: surface treatment and reference point pasting. Because the support’s surface is black, it needs increase brightness to improve the scanning effect. Then, several reference points are pasted on the support’s surface for combination of multi-view scanning data, as shown in Figure 1. The point cloud data of the support are obtained as shown in Figure 2.

After removal of error points, noise reduction, smooth, the point cloud data of the support is converted into the model with high quality which consists of many triangular patches (Figure 3). Subsequently, the solid model of the support is built, as shown in Figure 4.

3. Topology optimization

3.1 Problem formulation
The topology optimization used in this work optimizes the design variable which is the elemental densities in a design domain that would minimize the volume of the final structure while satisfying the stress constraints and displacement constraints. The objective function and constraints can be
mathematically expressed as follows:

$$\begin{align*}
\text{Find } & \rho = [\rho_1, \rho_2, \ldots, \rho_n]^T \\
\text{Min } & V = \sum_{i=1}^{n} \rho_i v_i \\
\text{S.t. } & F = Ku \\
& u \leq u^* \\
& \sigma \leq \sigma^* \\
& 0 \leq \rho_{\text{min}} \leq \rho_i \leq \rho_{\text{max}}
\end{align*}$$

(1)

where $\rho$ is the design variable, $V$ is the volume of the structure, $F$ is the load vector, $K$ is the global stiffness matrix, $u$ is the global displacement vector, $u^*$ is the displacement constraint, $\sigma$ is the von Mises stress vector, $\sigma^*$ is the stress constraint. Employing the solid isotropic material with penalization (SIMP [13-15]) method, the problem is relaxed for density to have any value between 0 and 1 with small lower bound of $\rho_{\text{min}} = 0.001$ to avoid singularities when calculating for equilibrium. Also, with penalization power parameter ($p$) that is greater than 1 (generally, $p = 3$), the intermediate density values are steered to either extreme and Young’s modulus of each element is computed as follows:

$$E_i = \rho_i^p E^0$$

(2)

where $E^0$ is the Young’s modulus of the material in the solid state ($\rho = 1$). When $p$ changes, the relationship between $E$ and relative density $\rho$ is shown in Figure 5.

![Figure 5. The relationship between E and relative density $\rho$ with $p$ in SIMP method](image)

3.2 Determining the constraint conditions

The support’s 3D structure model is established based on reverse engineering, then the finite element model is built as shown in Figure 6. With the load and constraint conditions, the maximum von Mises stress of the support and the maximum displacements at node 1 and node 36213 under two cases are obtained by finite element analysis. The calculation results are taken as the constraints of the subsequent optimal design. The loads and constraints of the support under two cases are shown in Table 1. The stress and deformation contour of the support under two cases are shown in Figure 7 and Figure 8. The maximum displacements and von-mises stress of the support are shown in Table 2.
Figure 6. The FEM of the support

Table 1. Load and constraint of the support.

| Constraint | Load(N) |
|------------|---------|
| Node 36216 | Node 1  | Node 36213 |
| case 1     | all freedoms | Fx=10000 | 0 |
| case 2     | all freedoms | 0       | Fx=-20000 |

Figure 7. The stress and deformation contour of the support, case 1

Figure 8. The stress and deformation contour of the support, case 2

Table 2. The maximum displacement and von Mises stress of the support.

| Maximum von Mises stress (MPa) | Maximum displacement (mm) |
|---------------------------------|---------------------------|
| Node 1                          | Node 36213 |
| case 1                          |               |
| case 2                          |               |
| 619                             | ux=1.385      | ux=0.244 |
| 612                             | ux=-0.489     | ux=-0.347 |

Based on the Table 2, the constraint conditions for optimization of the support are established as follows:

\[
\sigma_{\text{max}} \leq 650\text{MPa} \\
\text{S.t.} \quad -0.5 \text{mm} \leq u_{\text{Node 1,x}} \leq 1.4 \text{mm} \\
-0.35 \text{mm} \leq u_{\text{Node 36213,x}} \leq 0.25 \text{mm}
\]  (3)

where \(\sigma_{\text{max}}\) is the maximum von Mises stress of the support, \(u_{\text{Node 1,x}}\) is maximum displacement of node 1 along x direction, \(u_{\text{Node 36213,x}}\) is maximum displacement of node 36213 along x direction.

3.3 Topology optimization of the support

The material distribution space is redefined (Figure 9), the minimum member sizes are defined, and the topological optimization design of the support structure is carried out.
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**Figure 9.** Redefining the design space of the support

The minimum member sizes are 6 mm, 10 mm, 15 mm, 20 mm respectively with the same relative density. The optimization results are shown in Figure 10 – 13.

**Figure 10.** The minimum member size is 6 mm, relative density $\rho \geq 0.3$

**Figure 11.** The minimum member size is 10 mm, relative density $\rho \geq 0.3$

**Figure 12.** The minimum member size is 15 mm, relative density $\rho \geq 0.3$

**Figure 13.** The minimum member size is 20 mm, relative density $\rho \geq 0.3$

The maximum displacements at node 1 and node 36213, and the maximum von Mises stress of the support under different minimum member sizes and load cases are summarized in Table 3.

| Minimum member size (mm) | Case   | Maximum von Mises stress (MPa) | Maximum displacement (mm) | Weight reduction |
|--------------------------|--------|--------------------------------|---------------------------|-----------------|
|                          |        | Node 1                        | Node 36213                |                 |
| 6                        | case 1 | 558                           | 1.398                     | 0.189           | 51.87%          |
|                          | case 2 | 647                           | -0.378                    | -0.350          |                 |
| 10                       | case 1 | 542                           | 1.396                     | 0.188           | 50.99%          |
|                          | case 2 | 649                           | -0.376                    | -0.349          |                 |
| 15                       | case 1 | 574                           | 1.393                     | 0.181           | 50.22%          |
|                          | case 2 | 648                           | -0.216                    | -0.129          |                 |
| 20                       | case 1 | 591                           | 1.391                     | 0.175           | 49.47%          |
|                          | case 2 | 645                           | -0.350                    | -0.349          |                 |

The constraint conditions of support optimization are satisfied. Also the weight of the support has been reduced obviously.

### 3.4 Numerical verification

Taking the optimization results of the minimum member size 20 for example, the elements which relative density are less than 0.3 are deleted (Figure 14), the finite element model of the support is
rebuilt. With the same constraints and loads, the static analysis is executed. The maximum and minimum displacements at node 1 are 1.132 mm and -0.280 mm respectively. The maximum and minimum displacements at node 36213 are 0.140 mm and -0.286 mm respectively (Figure 15 - 16). The maximum von Mises stress of the support is about 648 MPa (Figure 17 - 18). Numerical analysis shows that the results of topology optimization are reliable.

4. Prototype build with 3D printing

Based on the finite element model of the support shown in Figure 6 and Figure 14 respectively, the polygon mesh models for 3D printing are obtained in Figure 19 - 20. The surface of the support has been smoothed.
The main rapid prototyping technologies include selective laser sintering (SLS), fused deposition modelling (FDM) and stereolithography apparatus (SLA). Consideration of manufacturing cost, the low cost FDM machine (Figure 21) and the PLA material are used. The apparatus employs open source software to exchange the polygon mesh models into machine readable files. The manufacturing process is shown in Figure 22. The final products are shown in Figure 23 – 24.

5. Conclusions
The lightweight design of the structure could be realized based on topology optimization and rapid prototyping technologies. This method is applied to the design of a support, and the results show that:
1) The support’s mass is reduced by about 50% under all constraints after optimization;
2) The combination of optimization design and 3D printing technology is an effective method of structural design.

References
[1] Qu B. (2017) Optimal design and process research of Aluminium alloy bracket based on SLM fabricating. (Doctoral dissertation, Beijing University of Technology.).
[2] Zhang L.L. (2017) Research on the topology design and analysis of rapid investment casting parts (Doctoral dissertation, Nanjing University of Aeronautics and Astronautics.).
[3] Jiang H. (2017) Optimization of thin walled structures with complex surface constraints for 3D printing (Doctoral dissertation, Dalian University of Technology.).

[4] Liu J.Z. (2016) Research on design method of complex metal component for additive manufacturing. (Doctoral dissertation, Hebei University of Science and Technology.).

[5] Wang L, Sun J.H., Meng Z.S., et al. (2019) Internal structure design and research of lightweight axial parts based on 3D printing. Mechanical Research & Application, 32(02):50-52.

[6] Fu Y, Luo Z, Xin Z.N., et al. (2016) Integration molding of pedestal using topological optimization and 3D printing. Mechanical Engineer, 11:36-39.

[7] Fan Z.G., Zhu D.C., Wu M, et al. (2016) Application of 3D printing in structure design and manufacturing for network equipment. Machine Building & Automation, 45(06):56-59.

[8] Fan X.N., Wen G.L. (2018) Structural Topology Optimization Based on Python and Experimental Research with the Aid of 3D Printing. Computer Simulation, 35(08) : 170-174+276.

[9] Jiang M.W., Chen J.M., Yan J.Z. (2017) Personalized and lightweight research on the Olympic winter helmets for 3D printing technology. Mechanical Engineer, 37(03) : 424-429.

[10] Xu W.P., Wang W.M., Li H, etc. (2015) Topology Optimization for Minimal Volume in 3D Printing. Journal of Computer Research and Development, 52(01):38-44.

[11] Wang X.J., Xu S.Q., Zhou S.W., et al. (2016) Topological Design and Additive Manufacturing of Porous Metals for Bone Scaffolds and Orthopaedic Implants: A Review. Biomaterials, 83:127-141.

[12] Sutradhar A., Park J., Carrau D., et al. (2016) Designing patient-specific 3d printed craniofacial implants using a novel topology optimization method. Medical & Biological Engineering & Computing, 54(7):1123-1135.

[13] Bendsoe M.P., Kikuchi N. (1988) Generating optimal topologies in structural design using a homogenization method. Computer Methods in Applied Mechanics and Engineering, 71:197-224

[14] Bendsoe M.P. (1989) Optimal shape design as a material distribution problem. Structural Optimization, 1:193-202.

[15] Bendsoe M.P., Sigmund O. (1999) Material interpolation Schemes in topology optimization. Archive of Applied Mechanics, 69: 635-654.