Current Research Status of Self-Supporting Structure Topology Optimization in Additive Manufacturing

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Abstract. In practical additive manufacturing (AM) processes, printed components often involve overhanging structures. Conventional strategies merely generate external support structures in a simplistic manner, which not only significantly impairs printing efficiency but also may compromise the outer surface quality of components during support removal. Unlike traditional approaches, the design and optimization of self-supporting structures can effectively enhance structural stability and foster design innovation throughout the printing process. This paper first outlines the development prospects of additive manufacturing in contemporary industrial contexts, then systematically reviews the latest research progress of topology optimization from two perspectives: continuum structure-based and discrete structure-based methods. Various optimization strategies corresponding to different structural types are summarized and analyzed in detail. As well as, this paper conducts an in-depth study on the design and optimization of self-supporting structures, which holds significant theoretical and engineering importance for enhancing the structural performance, material efficiency, and process feasibility of additive manufacturing.

Keywords: Additive manufacturing; Self-supporting structures; Topology optimization;

1 Introduction

With the rapid advancement of technologies in related fields, additive manufacturing—characterized as a template-free and adaptive production technique—has been extensively adopted in modern industrial sectors. In comparison to traditional subtractive manufacturing, additive manufacturing offers superior precision, lower costs, and greater flexibility in producing components with complex shapes and multifunctional performances. As a disruptive manufacturing technology, it not only transforms the production paradigm of traditional manufacturing industries but also provides innovative solutions for addressing intricate engineering challenges.

With the further development of additive manufacturing technologies, its application scope is expanding to key fields such as aerospace, architecture, automotive manufacturing, and medical devices. For example, in the aerospace industry, additive manufacturing enables the fabrication of high-precision, high-performance lightweight components[1]; in the medical field, it

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facilitates the production of customized implant prostheses and biological materials [2-3], thereby improving the efficacy of clinical treatments.

However, amid the growing market demands and increasing structural complexity of components, the efficient design of self-supporting structures and process optimization have remained a research focus over the past decade. The core objective lies in ensuring more stable interlayer bonding during printing through rational modeling design and material selection. As a unique form of engineering structure, self-supporting structures are playing an increasingly pivotal role in modern engineering applications.

Traditional structural design typically relies on external supports to maintain stability, whereas self-supporting structures achieve self-equilibrium through their internal geometric configurations and material distribution characteristics. This design concept not only reduces reliance on external foundations or supporting structures but also enhances the safety, durability, and production efficiency of the structures themselves. For instance, in the aerospace sector, when lightweight, high-precision components with non-uniform density distributions are required, self-supporting structures can deliver more efficient production solutions by virtue of their optimized design philosophy and weight distribution mechanisms.

In addition, the application of self-supporting structures in additive manufacturing for modern biomedical engineering is gradually expanding. Conventional biological materials or implant prostheses often involve complex modeling design and production processes, while self-supporting manufacturing technology enables more efficient fabrication of components with complex geometries. This not only facilitates the production of medical implants with intricate external shapes and internal structures but also shortens the production cycle, reduces material waste, and improves product quality according to individual patient needs, thereby advancing the realization of precision medicine.

In summary, self-supporting structures in additive manufacturing exhibit significant application value in fields such as aerospace and biomedical engineering, while also playing a crucial role in promoting engineering optimization and technological innovation. With the continuous advancement of 3D printing technology and the in-depth research on self-supporting structure design and optimization, this field is expected to achieve broader applications and breakthrough progress. Therefore, an in-depth exploration of the importance and future development trends of self-supporting structures in additive manufacturing holds great significance for driving the innovative development and practical application of engineering technologies.

This paper first elaborates on the basic principles and core advantages of self-supporting structures, then reviews the recent development status of topology optimization from two perspectives: continuum structure-based and discrete structure-based methods. Finally, key conclusions are drawn, and future development directions are discussed and predicted, considering that the current topology optimization methods for self-supporting structures in additive manufacturing are still in the preliminary development stage.

2 Principles and Advantages of Self-Supporting Structures

2.1 Basic Principles of Self-Supporting Structures

After the pre-printed 3D model is fully sliced (as shown in Fig. 1), each printed layer must maintain a bonding force greater than a critical threshold—referred to as the minimum interlayer bonding strength [4]. Only when each printed layer can firmly adhere to the underlying layer without morphological collapse [5] can the printed component be deemed to meet the self-supporting requirements.

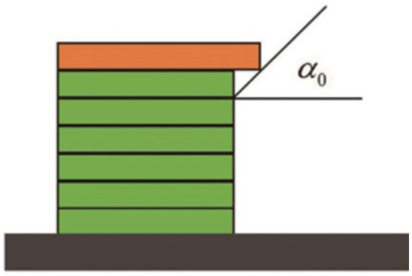

Fig. 1. Schematic diagram of self-supporting structure.

In the optimization design process of self-supporting structures, researchers usually introduce overhang constraints to impose restrictive conditions on all structural elements. Langelaar proposed a mathematical model for self-supporting structures based on the maximum density of the support region [6], adopting a 45° critical overhang angle as the core constraint condition. Structural elements that violate this constraint are eliminated, and geometric configurations failing to meet the overhang constraint (i.e., those not satisfying self-supporting requirements) are excluded from the design scheme.

2.2 Advantages of Self-Supporting Structures

In additive manufacturing processes, printing components with special shapes or high-precision requirements is inevitable, and most of these components have obvious overhanging structures (as shown in Fig. 2). Failure to properly address the overhanging structure issue will result in printed products that do not meet design expectations. Without external supports, the surface quality of components will exhibit various defects depending on the overhang angle of the structure. For traditional 2.5-axis printing technology, achieving self-support of printed components through structural design and optimization has become a primary research objective and development trend [7]. This design approach contributes to material conservation, printing time reduction, and improvement of product surface precision.

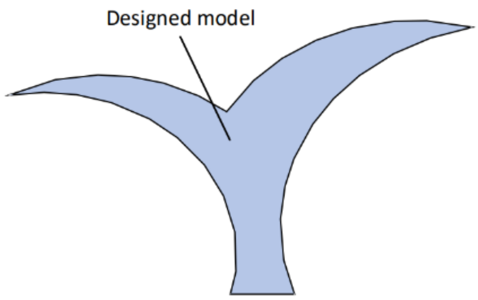

Fig. 2. Typical overhanging structure.

3 Continuum-Structure-Based Topology Optimization Methods

3.1 Topology Optimization Based on the SIMP Method and Its Improved Approaches

Most traditional self-supporting structure topology optimization methods belong to continuum structure-based approaches, among which the Solid Isotropic Material with Penalization (SIMP) method—also known as the density method [8-9]—is the most representative. This method defines the "pseudo-density" of each structural element to vary within the range of 0 to 1, establishes a correlation function between pseudo-density and elastic modulus, and reduces the intermediate density values by adjusting the penalty factor p, thereby obtaining a relatively clear topological structure.

A series of models and related detection programs proposed by scholars in the early stages, such as the wedge space filter, are mostly incompatible with relatively complex overhang angle constraint conditions. Subsequent researchers addressed the limitation that previous studies could not accommodate arbitrary overhang angle constraints, but these improved models have not yet been extended to the field of 3D printing applications. In 2022, Wu et al. proposed a density-based topology optimization method incorporating three self-supporting factors [10]. This method characterizes overhang angles and overhang lengths through grid division, and imposes constraints on the grids and their adjacent supporting grid elements, thereby achieving a self-supporting design with consistent constraints between the design and manufacturing processes. Its main advantage lies in the comprehensive consideration of overhang angles, overhang lengths, and printing directions, realizing the integration of design and manufacturing throughout the entire process. However, this method has not yet incorporated stress constraints, and there is room for further improvement in practical application scenarios.

Ye et al. proposed a SIMP-based optimization framework [11], which utilizes a rotating base to adjust the angle between the printed component and the direction of gravity, thereby minimizing the loss of structural performance. Comparative studies show that compared with the unconstrained optimal cantilever beam, the increase in final compliance of the cantilever beam considering overhang constraints is almost negligible. Nevertheless, this method has not been extended to the field of 3D printing and lacks verification in practical engineering applications.

3.2 Topology Optimization Based on the Level Set Method and Its Improved Approaches

Liu et al. proposed a multi-layer level set framework [12], which takes into account the building direction and in-plane grid orientation to address the problem of local material anisotropy and assist in structural topology optimization. This method not only achieves self-support of the structure but also effectively resolves the issue of local material anisotropy. In 2020, Liu's research team further proposed a structure decomposition method based on skeleton extraction [13]. This method optimizes components through the level set method and comprehensively considers the threshold conditions of component overhang size and inclination angle, thereby realizing the design of self-supporting structures. Compared with the previously proposed self-supporting design method, the new method features a larger design space, enables self-supporting printing with a zero critical overhang angle, and exhibits wide applicability to various types of additive manufacturing equipment.

4 Discrete-Structure-Based Topology Optimization Methods

Traditional continuum structure-based methods face significant challenges in acquiring structural boundaries during self-supporting structure design. To address this issue, researchers have proposed discrete structure-based topology optimization methods, which have shown unique advantages in boundary processing and constraint integration.

He et al. proposed an interactive "human-in-the-loop" optimization framework [14], which incorporates human intervention as an inherent component of the optimization process. This enables designers to consider a series of issues not explicitly described in the original optimization problem definition. The framework uses geometric optimization to restore structural equilibrium after user modifications, and the operator integrates layout optimization with geometric optimization steps to consider overhang constraints during the optimization process. These two constraint processing methods further improve computational efficiency, and compared with the density method, the proposed method has the advantages of shorter computation time and better structural flexibility.

Lin X Y et al. also proposed a self-supporting optimization framework based on layout optimization and geometric optimization [15]. Through layout optimization, components that fail to meet self-supporting requirements are eliminated; meanwhile, geometric optimization constrains the overhang angles of all components within a reasonable range. By means of node merging and component consolidation, this method removes redundant structural components during the geometric optimization process while considering structural mechanical properties to achieve the simplification of the structural layout. In addition, manufacturing constraints are incorporated into the optimization process to generate optimized self-supporting structures in accordance with preset critical overhang angles. Notably, when the critical overhang angle for self-support is set at 50°, the performance gap between the final feasible solution generated by this optimization method and the theoretical optimal solution does not exceed 5%, indicating high optimization efficiency and reliability.

In summary, compared with the SIMP method—which requires calculating element density values first to determine structural boundaries and has relatively low computational efficiency—discrete structure-based topology optimization methods offer higher efficiency in solving structural boundary-related problems. Moreover, the computational cost does not increase significantly when incorporating constraints related to printing directions, making them more suitable for complex 3D printing application scenarios.

5 Conclusion

This paper systematically reviews the current research progress of topology optimization for self-supporting structures based on different methods in the field of additive manufacturing, and summarizes and comments on the advantages, disadvantages and applicable conditions of several mainstream strategies.

It is found that existing studies are highly concentrated on the geometric optimization methods based on continuum structures, especially the Solid Isotropic Material with Penalization (SIMP) method, which has obvious advantages in modeling maturity and application universality. However, such methods generally suffer from problems such as high computational resource consumption and slow iterative convergence, reflecting their efficiency bottlenecks in dealing with complex three-dimensional self-supporting structures. Therefore, improving sensitivity analysis strategies, developing efficient optimization algorithms, and reducing computational complexity have become the key directions to promote the further practical application of such methods.

On the other hand, non-continuum-based topology optimization strategies, such as the level set method and graph theory-aided design, although showing potential for constructing self-supporting structures in specific scenarios, are still in the initial stage of development. Relevant research is mostly limited to 2D printing examples, and the theoretical frameworks are largely dependent on early topology optimization fundamentals, lacking in-depth integration and innovation targeting the process constraints of additive manufacturing. Thus, expanding these methods to 3D practical application scenarios and developing process-compatible topological theories matching them are the directions that urgently need to be strengthened in future research.

In general, the research on topology optimization of self-supporting structures is gradually transitioning from method exploration to engineering practicality. There remains broad room for further development in aspects such as improving computational efficiency, integrating multi-dimensional processes, and fusing multi-disciplinary theories. With the continuous advancement of additive manufacturing technology and the deepening of related research, self-supporting structures are expected to play a more important role in promoting the innovative development of engineering technologies.

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