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Introduction to Lightweight Structures: A Review and Analysis of Topological Optimization Methods and Applications

Ochieng Dembe H.

Faculty of Engineering Kampala International University Uganda

ABSTRACT

This paper reviews and analyzes the state-of-the-art in topological optimization methods for the construction of lightweight structures. It synthesizes the key principles and stages of introducing these technologies, emphasizing their importance in modern industrial applications. The study explores various optimization techniques, their mathematical foundations, and practical implementations in different engineering fields. Case studies highlight the successful application of these methods in reducing the mass of lightweight vehicles by up to 30%, demonstrating the significant potential of topological optimization in achieving high-performance, low-weight designs.

Keywords: Lightweight Structures, Topological Optimization, Engineering Applications, Mathematical Modeling, Finite Element Analysis

INTRODUCTION

The demand for lightweight structures in engineering has grown significantly, driven by the need for efficient, high-performance designs in industries such as aerospace, automotive, and civil engineering [1-4]. Topological optimization has emerged as a critical technique for achieving these goals, allowing for the systematic removal of unnecessary material while maintaining structural integrity [5-7]. This paper provides a comprehensive review of topological optimization methods, examining their theoretical underpinnings, practical applications, and impact on various engineering fields.

Lightweight Structures

This work is a review and short analysis of the scientific research referring to various methods that enable the topological optimization [8-11]. The paper has synthetically characterized the topological optimization methods available in the literature related to the construction of lightweight node constructions. The fundamental principles and stages of introducing the technology were also presented, as well the examples of a modern industrial application of such a strengthened technique. Long experience from the point of view of traditional construction techniques, enabled intuition-based mastery of the most proper load distribution in the traditional, compact, and simplex elements of these systems. Forces redistribution in the multi-point nodes is not still so obvious and requires the numerical calculations necessary to be carried out in the optimizing procedure structure [12-13]. This study presents the concept of the topologically optimized connection vertices of nodes of degenerated truss systems and selected practitioners of such systems. The nodes are built on the basis of the optimization, according to selected criteria. Initial approaches to the optimization problem based on the direct use of optimization criteria for selected nodes were compared. They are used to design the topological optimization of the nodes connected in the regular structure of the lattice configuration. Leading scientific research has demonstrated that the average mass of lightweight vehicles around the world has been decreased by nearly 30% [14-16]. To this end, various lightweight structures have been developed with topological optimization. This allows for the increase of the efficacy of the sectional area use, to significantly reduce the weight. Topological optimization, in particular numerical methods and the available computer parametric models, technical advancements, and efficient algorithms for problem-solving, is proved as the most proper way for this work [17-19].

Importance of Lightweight Design in Engineering

Lightweight design and topology optimization have been commonly used in civil and mechanical engineering for the development of automobiles, airplanes, trains, ships, lightweight and strong components [20-24]. With advancements in 3D printing technology, it is possible to fabricate even more complex structures; topological design holds promise for the development of superior lightweight structures. Producing metal-made lightweight components has been a challenging affair because of the inherent difficulty related to modifying these structures to the desired formulation. Implementing topological optimization visualization in parallel to the survey, the opportunity to facilitate the understanding of the projected topological architectures. Starting with a basic plow-ground example composed of a density-area resource for topology optimization effort by a finite element study utilizing ANSYSLO firm and the Random field scheme, the topology research is first introduced. The FEA tools are tested to forecast worldwide reliability along with damage propagated failure. Assessing the research results and examining the variations in the topological architecture and the anticipated output for construction with ratings [25-28]. Lightweight design represents one of the most effective methods for many engineering fields, including aerospace. It is a combination of materials and structures to reach high strength and stiffness-performance with limited weight. Inadequate design with reduced energy consumption and reduced logistical and transport costs is negated by the substantial number of benefits of lightweight design. Applications related to industries such as automobile, aerospace, naval, wind and drone manufacturing have provided breakthrough research and development in the field of lightweight design [29-33]. Lightweight design strives to minimize mass by removing unnecessary material in a structure's shape and integrates the material usage in an intelligent way by innovation of new material types (composites, high strength steels, other metal alloys etc.). Fatigue life is also generally improved by decreasing stress and strain level [34-36].

Topology Optimization Techniques

The micromechanical modelling of the lattice permits to use directly the elemental diameter (beam radius) as the design variables for scale-structural-oriented designs and has the advantage to constrain the number of scale units to the actual physical manufacturing process to avoid any numerical over-design [37-39]. For instance, regarding the inverse homogenization method, in such a way only an integral number of scale units per design is a realistic approach. Furthermore, all interfaces details were integrated into the sub-scale formulation of the components, leading to lattice and component definitions dependent on the manufacturer process type [40-42]. A well-known topology optimization method based on the graded density approach, which allows evaluating the state of the material by a value between 0 and 1 of the density at each point in the design domain. In this method, the area fraction of the material at the particular point represents the global density of the material. The density is uninterrupted throughout the solid, and intermediate values form cellular solids of so-called density-based structure. The method that uses density to represent structure is also called the homogenization approach and has become popular for optimizing the continuum material distribution. Topology optimization techniques are usually performed by solving partial differential equations iteratively for finding optimal dimensions, shapes, and mix of materials in a design region [43-45]. The topology operation can be performed at discrete and continuum levels [46-47]. Discrete-level design includes strut-based constructions in which the number of nodes remains constant but the properties of the segments between the nodes are manipulated to attain the optimal configuration. In continuum level formulation, the design of optimization problem is transformed into a form that is continuous. Though topology optimization methods of the discreet phase give rise to highly efficient structures and such structures are easier to manufacture.

Definition and Principles

As an essential subcategory, density-based topology optimization is representing well-established method for weight reduction of parts while retaining structural integrity. An approach suited for metals additive manufacturing (Flexibility, Structural and Load Path), the Sizing, Shape and Topology of Structures and Composite Materials in the optimal design of parts represents one most widely-used one in combination with manufacturing constraints defined by the manufacturer [46-48]. The evolution algorithm still persists even though it comes with the disadvantage of large elastic compliance values. It includes a solution domain (Design Space) and the simulation of a representative volume element (RVE) [49-52]. The actual material layout incl. all defects, inclusions or porosities is only defined within the simulation domain (LayoutVolume). For the structural simulation an idealized geometry generated by using a uniform solid material is used. In recent years, a lot of efforts have been put towards material developments and process optimization to attain the demanded properties for parts produced by means of additive manufacturing (AM). The lattice material classes can reduce the weight significantly while keeping the performance almost unchanged [12-16]. The overall pared down of a construction itself can be achieved by the help of design techniques like shape and topology optimization. Shape and topology optimization are almost covered every standard in FEA (Finite Element Analysis) simulation software where the design space allowed to be charged on structure [19-24]. The goal of topology optimization is to provide a continuous material distribution which in theory can take any value between 0 and 1. The macroscopic structure behavior and not the internal structure boundaries will be resolved from the subsequent simulation.

Mathematical Formulation

In the topology optimization context, we consider a design domain $\Omega \subset Rd$, where d is the spatial dimension. We denote by r(.) the density in the design domain as a function of position, and the global problem is to produce a filter of a solid volume using known noise, without breaking macroscopic performance requirements. A structure under loading and support conditions is typically defined as a domain, within which solid-works, armed with mathematical tools, can be set. By a bottom-to-up argument, the physical phenomena of the deformation responds at the level of micro-topology of the material, with the assumption that material is continuous in the global scale. The contemporary theory of topological optimization was first built mimic this observation (see, e.g. [17-25]. This approach allows engineers to generate robust structures to resist loading conditions whilst minimizing the use of material at the structure scale, resulting in high-performance and bio-inspired structures [30-37]. Lately, developments in the field of additive manufacturing have permitted component-level design changes and with it came highlighted the limitations of structural design optimization when part boundaries come into play. To leverage design freedom, topological optimization was extended to design constant volume materials with tailored material composition at the expense of compatibility with finite element methods. In this setting the structure is discretized 6 and variables representing the ratio of material within each element are optimized to generate bio-mimetic design [38-43]. This viewpoint opens up the topological design process to incorporate material science and indeed, pushes engineers to optimize not only geometry splitting structures, but optimize material and geometric properties. As a means to stimulate this area of research, we begin to formulate design problems in which micro-topology is a design variable.

Advanced Materials for Lightweight Structures

From a performance point of view, composites are known to be higher performance than metals or ceramics. They can be manipulated to tune necessary material properties to suit specific design, such as low CTE required for space engineering and piezoelectric transduction. The energy can convert to be piezoelectric power output. Fiber composites are also known to have low attenuation suitable for ultrasonics. From a space claim point of view, composites are known by a high strength-to-weight and stiffness-to-weight ratio, favorable for reducing mass at the same performance. Nor having noticeable improvement in the last year, they're significantly still precious in uncertainties robustness due to the high warranty margins in the design. For repairs and maintenances, best practice suggests using processes that rely on metallic infrastructure such as finding extra concept and drilling or additive repair methods justified by wide aerospace routine [36-41]. To make an advanced structure lighter and smarter, advanced materials are necessary [42-45]. Many smart materials like piezoelectric materials and shape memory alloys have unique capabilities, such as the ability to generate electrical energy, simulate controlled and recoverable deformations and self-heal [46-48]. For decades, fiber composites have been the primary lightweight material for advanced structures [23-30]. They are stronger and stiffer than traditional metals like steel and aluminum due to the characteristics of polymer matrix and superior chemical resistance and fatigue resistance. Therefore, strength-to-weight ratio and stiffness-to-weight ratios of fiber composites are significantly higher.

Composite Materials

The composite structure, however, is tediously complex and poses challenges in nearly every process, from design through manufacture. That complexity arises from the myriad interactions and differing properties of the individual constituents and the need to be designed with these in mind all at once. This is not simply an optimization problem for the lamina where the desired performance of the final material may be controlled throughout [32-36]. The full suite of structural, electrical, and magnetic properties of the laminated materials must all be dictated and balanced, including interactions at material interfaces, and for physical spaces that are often tight, even before factoring in processes such as curing. One of the strongest examples where composites are utilized is in aerospace structures where lightness and functionality is of utmost importance. Because composites are utilized in aerospace, the Defense Advanced Research Projects Agency (DARPA) has built on this history. As part of its ICaO program, there was a call for revolutionary materials and the design of optimally performing materials through "data-driven efforts, exemplified by topology optimization". T his program works along the belief that the use of optimized composites can help lower costs and develop "best practices to significantly reduce the development cycle." The long-explored class of composites, which utilizes disparate materials incorporated according to the desired performance of the final structure, continues to grow in popularity and utility [37-40]. Intuitively, it can be posited that composite materials should outperform any individual component if we can leverage the best attributes of each material while mitigating any catastrophic weaknesses. Optimized composites may drastically outperform base materials in most of their key properties: stiffness, strength, damage tolerance and lightness. As such, they enjoy widespread use in every engineering sector from energy to electronics, for the terrestrial to celestial, and from smallest to largest parts [20-25].

Case Studies in Next-Generation Lightweight Structures

The efficiency of the proposed strategy is mainly suggested to result from the simplicity, sparsity of the design variables and linear regression models, and low mesh-based numerical and sampling numerical dispersion, leading to both sparse and more well-conditioned optimization problems. Comprehensive comparisons reported in [9-13] have put in evidence the superiority of the adopted multiscale strategy with respect to traditional double-scale optimization in terms of both performances and computational cost: up to 60% computational time reduction while solving for topologically optimized lightweight structures, thus enlarging the feasible set of possible applications, e.g. affordable large-scale applications or real-time evolving design space configurations. The results achieved have also been successfully exploited for hybrid lightweight structural applications, e.g. blended preliminary design for bridging different structural and material structural domains, effectively combining lightweight performance and tailored modelling [14-17]. Towards the realization of next-generation of lightweight structures, advanced design approaches need to be adopted and specific material deployment requests to be properly addressed, while keeping the computational cost at a reasonable level [30-32]. The vast majority of efficient and robust density-based optimization techniques mainly focus on isotropic design space characteristics and preferentially request a single-material configuration, resulting in significant limitations as far as heterogeneous anisotropic materials and design space multi-materiality are concerned. To effectively address the topology optimization of lightweight structures opting for advanced materials and microstructural levels, specific methodologies have been recently proposed in the literature [35-39]. Towards the optimization of advanced lightweight structures, the most efficient opOpstMiTO1 and multiscale compact topology optimization strategies are revisited, summarized, and integrated for the first time.

Future Trends and Innovations

Manufacturing considerations may drastically influence the potential performance of an optimized structure and their influence generally increases with the material properties, process requirements (minimum feature and minimum strut sizes achievable), complexity and length scale of the optimized structure. At the same time these factors will influence the robustness of the production process regarding their tolerances, scatter and reliability. In general, there is no clear tendency whether the inclusion of process or especially manufacturing process considerations during optimization will allow for the better performing structures due to the sometimes conflicting boundary conditions. In practical problems, it may often be beneficial to first perform an unconstrained (minimum compliance) topology optimization including a wider material library and large optimization space and subsequently use the outcomes of this optimization as a guide for the initial overlay layout for manufacturable implementation. minor structural changes may have great impact in shaping and defining boundaries and non-manufacturability aspects around details, hollow parts or on the length scale of surface roughness. Today's key enabler for the development of optimized structures, including structures with entirely novel micro-architectures designed for advanced materials, is a high level of automation [9-14]. In this respect, automatic generation of structures based on simulations of the mechanical behavior in the form of finite element analysis (FEA) is the most accurate and fundamental manner to make better design decisions [16-19]. For lightweight materials or cellular designed structures, typically multiple scales have to be simulated to accurately capture their performance. In order to ensure a more predictable performance of such a structure through control of manufacturable details, it has been suggested of separating the scales during the optimization by two-level optimization in structural mechanics [30-36].

CONCLUSION

The review highlights the pivotal role of topological optimization in the development of lightweight structures. By combining advanced mathematical modeling with practical engineering applications, significant weight reductions and performance improvements are achievable. Future research and technological advancements will continue to enhance the capabilities of topological optimization, driving innovation in lightweight design across various engineering disciplines.

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