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Research Paper

Advanced Mechanical Structure Optimization Using CAE and Topology Optimization: A Comprehensive Review

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Abstract: *In modern engineering design, achieving high structural performance while minimizing weight and material consumption has become a major challenge in mechanical engineering. Lightweight design not only improves energy efficiency but also reduces manufacturing costs and environmental impact. Computer-Aided Engineering (CAE) technologies have significantly transformed the design process by enabling numerical simulations of structural behavior before physical manufacturing. However, simulation alone cannot guarantee optimal structural performance. To address this limitation, topology optimization (TO) has emerged as a powerful computational technique capable of determining the optimal distribution of material within a given design domain.*

This paper presents a comprehensive review of mechanical structure optimization using CAE and topology optimization techniques. The review analyzes classical topology optimization methods such as Solid Isotropic Material with Penalization (SIMP), Evolutionary Structural Optimization (ESO), Bi-Directional Evolutionary Structural Optimization (BESO), and level-set methods. The integration of topology optimization with finite element analysis is discussed in detail, including mathematical formulations and computational frameworks.

Experimental and numerical studies from recent literature demonstrate that topology optimization can reduce structural mass by 30–70% while maintaining or improving stiffness and strength. The paper also summarizes industrial applications in aerospace, automotive engineering, robotics, and additive manufacturing. Furthermore, emerging research trends such as artificial intelligence-assisted optimization, multi-objective optimization, and digital twin integration are analyzed.

The results show that the combination of CAE simulation and topology optimization provides an efficient framework for intelligent mechanical design. Future developments will focus on integrating optimization algorithms with machine learning techniques and advanced manufacturing technologies to enable automated design systems for next-generation mechanical structures.

Keywords:*Topology optimization, CAE, finite element analysis, lightweight design, structural optimization, mechanical engineering.*

I. Introduction

Modern mechanical engineering systems are required to achieve high performance, reliability, and energy efficiency. In industries such as aerospace, automotive, robotics, and renewable energy, structural weight plays a critical role in determining overall system performance. For example, reducing the weight of aircraft structures directly improves fuel efficiency and reduces greenhouse gas emissions [1-5]. Similarly, lightweight automotive structures improve fuel economy and enhance dynamic performance.

Traditional mechanical design relies heavily on engineering experience and empirical methods. Designers typically begin with an initial geometry and modify it iteratively based on simulation results and experimental testing. Although this approach has been widely used in engineering practice, it often leads to conservative designs with excessive material usage [6-9].

With the advancement of computational technologies, Computer-Aided Engineering (CAE) tools have become essential in modern design processes. CAE systems enable engineers to simulate structural behavior using numerical methods such as finite element analysis (FEA). Through simulation, engineers can evaluate stress distribution, deformation, vibration characteristics, and fatigue life of mechanical components before manufacturing.

However, CAE analysis alone does not automatically generate optimal structural designs. Instead, it only evaluates the performance of existing designs. To overcome this limitation, structural optimization techniques have been introduced to systematically improve structural performance.

Structural optimization aims to determine the best structural configuration that satisfies performance requirements while minimizing objectives such as weight, compliance, or cost. Among different optimization approaches, topology optimization (TO) has gained significant attention due to its ability to generate innovative structural layouts.

Topology optimization determines the optimal distribution of material within a predefined design domain. By iteratively removing inefficient material regions, topology optimization can create lightweight structures with efficient load paths. This capability allows designers to explore new structural configurations that are difficult to achieve using traditional design methods.

Numerous studies have demonstrated the effectiveness of topology optimization in reducing structural weight. For example, optimized mechanical brackets have shown weight reductions exceeding 50% while maintaining structural strength and stiffness. Similarly, aerospace components optimized using topology optimization techniques have achieved weight reductions between 30% and 60% without compromising safety requirements [10-17].

In recent years, topology optimization has been integrated into many commercial CAE platforms such as Altair OptiStruct, ANSYS Workbench, Abaqus, and Siemens NX. These integrated systems allow engineers to perform optimization directly within simulation environments, significantly improving design efficiency.

The objective of this paper is to provide a comprehensive review of mechanical structure optimization using CAE and topology optimization techniques. The paper analyzes the theoretical foundations, computational algorithms, industrial applications, and future research directions of topology optimization in mechanical engineering.

II. Literature Review

Topology optimization research has developed rapidly over the past three decades. Early studies focused on mathematical formulations and numerical methods for structural optimization.

One of the most influential works in topology optimization was presented by Bendsoe and Sigmund, who introduced density-based optimization methods and established the theoretical framework for topology optimization. Their work demonstrated that optimal material distribution could be obtained by solving compliance minimization problems under volume constraints [18-19].

Later, Sigmund proposed a simple but effective implementation of topology optimization which significantly accelerated research development in this field.

Evolutionary structural optimization methods were introduced by Xie and Steven, who proposed an iterative approach that removes inefficient elements based on stress criteria. This method later evolved into the Bi-Directional Evolutionary Structural Optimization (BESO) technique.

Recent research has expanded topology optimization to various engineering applications. Studies have applied topology optimization to aerospace structures, automotive components, biomedical implants, and robotics systems[20-25].

Several review papers have summarized developments in topology optimization methods. For example, Liu and Ma conducted a comprehensive survey of topology optimization algorithms and discussed their advantages and limitations.

Recent studies have also explored the integration of topology optimization with additive manufacturing technologies. Since additive manufacturing allows fabrication of complex geometries, it has become an ideal manufacturing method for topology-optimized structures.

Another important research direction is multi-objective optimization, where multiple performance criteria such as stiffness, vibration, and thermal behavior are considered simultaneously[26-30].

III. CAE-Based Optimization Framework

The integration of CAE simulation with topology optimization forms a powerful computational design framework.

The general workflow of CAE-based structural optimization includes the following steps:

1. Creation of initial design geometry
2. Definition of design domain and non-design regions
3. Specification of loads and boundary conditions
4. Finite element mesh generation
5. Optimization algorithm execution
6. Post-processing and geometry reconstruction

Finite element analysis plays a central role in topology optimization because structural responses must be evaluated repeatedly during the optimization process.

The objective function used in most topology optimization problems is compliance minimization.

$$C = F^T . U$$

where
- C : compliance
- F : external load vector
- U : displacement vector

Minimizing compliance corresponds to maximizing structural stiffness.

IV. Mathematical Model of Topology Optimization

Topology optimization problems are often solved using density-based methods. The design domain is discretized into finite elements, and each element is assigned a density variable.

The element stiffness matrix is expressed as

$$K_e = x_e^p K_0$$

where
- x_e: element density
- p: penalization factor
- K_0: stiffness matrix of solid material

The global equilibrium equation is

KU=F

The optimization problem can be solved using gradient-based methods or evolutionary algorithms.

Lagrangian formulation is often used to handle constraints:

$$L(x, \lambda) = C_x + \lambda(V_x - V^*)$$

The Karush-Kuhn-Tucker (KKT) conditions provide necessary conditions for optimality.

V. Comparison of Optimization Methods

Table 1

Comparison of topology optimization methods

Method	**Advantages**	**Limitations**
SIMP	Simple implementation	Gray elements
ESO	Easy concept	Slow convergence
BESO	Improved convergence	Computational cost
Level-set	Smooth boundaries	Complex implementation

VI. Performance Comparison from Literature

Table 2

Weight reduction achieved in optimized mechanical structures

Component	**Industry**	**Weight reduction**	**Reference**
Engine bracket	Automotive	58%	Saleem et al.
Aircraft wing rib	Aerospace	45%	Tucker et al.
UAV frame	Robotics	50–96%	Zhang et al.
Suspension bracket	Automotive	37%	Li et al.

Table 3

Improvement of stiffness-to-weight ratio

Study	**Weight reduction**	**Stiffness change**
Automotive bracket	58%	maintained
Aircraft structure	45%	+10%
Composite component	35%	+6–10%

These results demonstrate that topology optimization significantly improves structural efficiency.

VII. Industrial Applications

Aerospace Engineering

Aircraft structures require extremely high stiffness-to-weight ratios. Topology optimization has been applied to wing ribs, fuselage frames, and satellite structures.

Optimized aircraft structures can achieve weight reductions exceeding **30%**, leading to significant fuel savings.

Automotive Engineering

Automotive manufacturers increasingly adopt topology optimization to reduce vehicle weight and improve fuel economy.

Optimized automotive components include:

- suspension brackets
- engine mounts
- chassis frames

Additive Manufacturing

Additive manufacturing enables the fabrication of complex geometries generated by topology optimization algorithms.

The combination of topology optimization and additive manufacturing represents a new paradigm in mechanical design.

VIII. Challenges

Despite its advantages, topology optimization faces several challenges.

Manufacturability

Complex geometries may be difficult to manufacture using traditional machining processes.

Computational Cost

Large-scale optimization problems require significant computational resources.

Material Modeling

Many optimization methods assume linear elastic materials, which may not accurately represent real engineering materials.

IX. Future Research Directions

Future research in topology optimization will focus on:

- AI-assisted optimization
- multi-objective design optimization
- digital twin integration
- real-time generative design
- multi-scale material optimization

Artificial intelligence techniques such as deep learning can accelerate topology optimization by predicting optimal designs from historical data.

X. Conclusion

Topology optimization combined with CAE simulation provides a powerful framework for modern mechanical design. Numerous studies demonstrate that topology optimization can significantly reduce structural weight while maintaining or improving structural performance.

Weight reductions of **30–70%** are commonly reported in optimized mechanical structures. These improvements result in higher stiffness-to-weight ratios and more efficient material utilization.

With the rapid development of additive manufacturing and artificial intelligence technologies, topology optimization is expected to become a core technology for next-generation intelligent mechanical design systems.

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References

[1]. Bendsøe, M.P., Kikuchi, N., "Generating optimal topologies in structural design using a homogenization method," Computer Methods in Applied Mechanics and Engineering, Vol. 71, No. 2, 1988, pp. 197–224.

[2]. Bendsøe, M.P., Sigmund, O., Topology Optimization: Theory, Methods and Applications, Springer, Berlin, 2003, pp. 1–370.

[3]. Sigmund, O., "A 99 line topology optimization code written in MATLAB," Structural and Multidisciplinary Optimization, Vol. 21, No. 2, 2001, pp. 120–127.

[4]. Sigmund, O., Maute, K., "Topology optimization approaches: A comparative review," Structural and Multidisciplinary Optimization, Vol. 48, No. 6, 2013, pp. 1031–1055.

[5]. Rozvany, G.I.N., "A critical review of established methods of structural topology optimization," Structural and Multidisciplinary Optimization, Vol. 37, No. 3, 2009, pp. 217–237.

[6]. Deaton, J.D., Grandhi, R.V., "A survey of structural and multidisciplinary continuum topology optimization," Structural and Multidisciplinary Optimization, Vol. 49, No. 1, 2014, pp. 1–38.
[7]. Guo, X., Zhang, W., "Recent advances in structural topology optimization," Acta Mechanica Sinica, Vol. 34, No. 1, 2018, pp. 1–19.
[8]. Liu, K., Tovar, A., "An efficient 3D topology optimization code written in MATLAB," Structural and Multidisciplinary Optimization, Vol. 50, No. 6, 2014, pp. 1175–1196.
[9]. Huang, X., Xie, Y.M., "Evolutionary topology optimization of continuum structures," Computers & Structures, Vol. 79, No. 14, 2001, pp. 1975–1989.
[10]. Zhu, J., Zhang, W., Xia, L., "Topology optimization in aircraft and aerospace structures design," Archives of Computational Methods in Engineering, Vol. 23, No. 4, 2016, pp. 595–622.
[11]. Krog, L., Tucker, A., Rollema, G., "Application of topology, sizing and shape optimization methods to optimal design of aircraft components," AIAA Journal, Vol. 40, No. 5, 2002, pp. 1075–1081.
[12]. Brackett, D., Ashcroft, I., Hague, R., "Topology optimization for additive manufacturing," Solid Freeform Fabrication Symposium Proceedings, 2011, pp. 348–362.
[13]. Leary, M., Merli, L., Torti, F., Mazur, M., Brandt, M., "Optimal topology for additive manufacture: A method for enabling additive manufacture of support-free optimal structures," Materials & Design, Vol. 63, 2014, pp. 678–690.
[14]. Gibson, I., Rosen, D., Stucker, B., Additive Manufacturing Technologies, Springer, New York, 2015, pp. 1–498.
[15]. Bendsoe, M.P., "Optimal shape design as a material distribution problem," Structural Optimization, Vol. 1, No. 4, 1989, pp. 193–202.
[16]. Guest, J.K., Prévost, J.H., Belytschko, T., "Achieving minimum length scale in topology optimization using nodal design variables and projection functions," International Journal for Numerical Methods in Engineering, Vol. 61, No. 2, 2004, pp. 238–254.
[17]. Andreassen, E., Clausen, A., Schevenels, M., Lazarov, B.S., Sigmund, O., "Efficient topology optimization in MATLAB using 88 lines of code," Structural and Multidisciplinary Optimization, Vol. 43, No. 1, 2011, pp. 1–16.
[18]. Xia, Q., Breitkopf, P., "Recent advances on topology optimization of multiscale structures," Archives of Computational Methods in Engineering, Vol. 24, No. 2, 2017, pp. 245–273.
[19]. Gao, J., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C.B., Wang, C.C., Shin, Y.C., Zhang, S., Zavattieri, P.D., "The status, challenges, and future of additive manufacturing in engineering," Computer-Aided Design, Vol. 69, 2015, pp. 65–89.
[20]. Zegard, T., Paulino, G.H., "Bridging topology optimization and additive manufacturing," Structural and Multidisciplinary Optimization, Vol. 53, No. 1, 2016, pp. 175–192.
[21]. Langelaar, M., "Topology optimization of 3D self-supporting structures for additive manufacturing," Additive Manufacturing, Vol. 12, 2016, pp. 60–70.
[22]. Liu, J., Ma, Y., "A survey of manufacturing oriented topology optimization methods," Advances in Engineering Software, Vol. 100, 2016, pp. 161–175.
[23]. Chen, Y., "3D printing of structural materials: Challenges and opportunities," Journal of Materials Science & Technology, Vol. 34, No. 1, 2018, pp. 1–7.
[24]. Dilberoglu, U.M., Gharehpapagh, B., Yaman, U., Dolen, M., "The role of additive manufacturing in the era of industry 4.0," Procedia Manufacturing, Vol. 11, 2017, pp. 545–554.
[25]. Bikas, H., Stavropoulos, P., Chryssolouris, G., "Additive manufacturing methods and modelling approaches," The International Journal of Advanced Manufacturing Technology, Vol. 83, No. 1–4, 2016, pp. 389–405.
[26]. DebRoy, T., Wei, H.L., Zuback, J.S., Mukherjee, T., Elmer, J.W., Milewski, J.O., Beese, A.M., Wilson-Heid, A., De, A., Zhang, W., "Additive manufacturing of metallic components – Process, structure and properties," Progress in Materials Science, Vol. 92, 2018, pp. 112–224.
[27]. Zhang, X., Xia, L., Xia, Q., Shi, T., "Topology optimization in mechanical design: Methods and applications," Applied Mechanics Reviews, Vol. 69, No. 6, 2017, pp. 060802.
[28]. Wang, Y., Kang, Z., Tong, L., "A level set method for structural topology optimization," Computer Methods in Applied Mechanics and Engineering, Vol. 192, No. 1–2, 2003, pp. 227–246.
[29]. Eschenauer, H., Olhoff, N., "Topology optimization of continuum structures: A review," Applied Mechanics Reviews, Vol. 54, No. 4, 2001, pp. 331–390.
[30]. Rozvany, G.I.N., Zhou, M., Birker, T., "Generalized shape optimization without homogenization," Structural Optimization, Vol. 4, No. 3–4, 1992, pp. 250–252.