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Topology Optimization for High-Performance UAV Structural Design: Theoretical Framework and Case Study

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Abstract. The need to achieve flight efficiency, load capacity, and stability has led to the rising requirements of lightweight but structurally sound designs of unmanned aerial vehicles (UAVs). This paper provides a systematic theoretical approach to the application of topology optimization to UAV structural design and justifies the theoretical approach by a case study of a UAV wing rib. The study shows the application of density-based and boundary-based optimization techniques, including SIMP, Level Set, and ESO/BESO, to various UAV components in a strategic way to provide the most fitting solution between weight and stiffness. Findings of the case study indicate that topology optimization creates counter-intuitive material distributions along main load paths which can greatly improve the stiffness-to-weight capabilities relative to traditional designs. The practical constraints such as manufacturing constraints, post-optimization refinement, which is necessary, and future directions to integrate the multi-objective criteria, full-system optimization, and experimental validation are also discussed in the study. These results offer a systematic method of using topology optimization in high-performance UAV structure development.

Keywords: Topology Optimization, UAV Structural Design, High-Performance Structures, Multi-Objective Optimization, Stiffness-to-Weight Ratio

1. Introduction

Unmanned aerial vehicles (UAVs) have found more and more applications in diverse areas, such as aerospace engineering, logistics, environmental monitoring, and disaster management [1]. As the sphere of application grows faster, the UAV performance, especially the flight efficiency, the ability to withstand the load, and the operational stability are increasingly demanded. The needs are directly linked to the structural design of the UAVs, and the high-performance structural optimization is a highly important research area [2]. One of the main problems in the UAV structural design is the need to reach an optimal solution to a number of conflicting factors such as the weight, the stiffness, the strength, and the cost. The conventional design approach to design tends to be based on the use of empirical design or trial and error, and thus constrained in exploring new structural forms. It is thus becoming necessary to have more sophisticated design approaches that will be able to methodically tackle these trade-offs and improve the overall performance. This is the main research driving force of this study.

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Topology optimization as a more sophisticated computing design technique has shown great promise in developing lightweight and high-performance structures by optimizing the distribution of material in a given design space [3]. It is observed that over the past years it has increasingly been used in aerospace and mechanical engineering, but its systematic theoretical use in designing UAV structures remains to be explored. The purpose of this study is to explore the application of topology optimization in the high-performance structural design of UAVs based on theoretical discussion and a case study. Particularly, the paper gives a methodical theoretical explanation of how topology optimization techniques can be applied to UAV structures and illustrates a real-life design practice and its results based on the case study.

2. Background on topology optimization and UAV structural design

Topology optimization has become an influential computational method in the structural design, which seeks to find the optimum material distribution in a defined design space within certain constraints and objectives [4]. The Solid Isotropic Material with Penalization (SIMP) method is one of the most popular approaches, which is density variable-based and has been widely adopted owing to its numerical stability and ease of implementation [5]. The Level Set method is an implicit representation of structural boundaries and allows the evolution of boundaries smoothly, making it appropriate to problems of high geometric accuracy. Moreover, Evolutionary Structural Optimization (ESO) and its bi-directional extension (BESO) is an iterative, stress or energy-based approach to removing or adding material, providing an intuitive and effective method of structural refinement. All of these approaches have their own strengths and weaknesses concerning convergence, computational cost, and manufacturability.

Structural design is also important in the context of unmanned aerial vehicles (UAVs) with regard to overall performance. Sometimes, size optimization, shape optimization, and empirical simplification of structures have been heavily applied as traditional lightweight design techniques to decrease weight without compromising structural integrity [6]. Nevertheless, these methods can be constrained by predefined design spaces and be strongly dependent on the experience of designers, which can limit the search of unconventional and yet effective structural designs. These limitations are also a major problem when it comes to optimal performance as UAV applications are becoming complex.

The recent research has shown the successful implementation of topology optimization in aerospace engineering, such as UAV wings, fuselage skins and landing gear component designs. These applications demonstrate how topology optimization can be greatly used to enhance stiffness-to-weight ratios and structural efficiency under real loading conditions. Although all these are encouraging outcomes, the majority of current studies are centered on numerical modeling and experimental confirmations of particular parts, as opposed to offering a single theoretical outlook.

Thus, there is still a significant gap in the systematic theoretical framework development of the topology optimization application in UAV structural design. Specifically, it is not thoroughly analyzed methodologically to combine several design goals and respond to the larger design logic on a system level. This gap restricts generalizability and theoretical depth of existing research and supports further studies in the field.

3. Theoretical framework

This part forms the theoretical basis of the application of topology optimization on high performance UAV structural design. It incorporates the basic optimization principles, multi-

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objective design aspect, and applicability of methods in varying elements of UAVs.

3.1. Fundamental principles of topology optimization

The topology optimization objective is to identify the optimal material distribution in an established design space in order to attain the desired structural performance under some constraints [7]. The design field is normally broken down into finite elements, each element being given a design variable to show material presence, commonly as a density variable $\rho_i \in [0,1]$.

A general formulation of the topology optimization problem can be expressed as:

$$\min_{\rho} C\left(\rho\right) = F^T U\left(\rho\right) \tag{1}$$

subject to:

$$K(\rho)U = F \tag{2}$$

$$V\left(\rho\right) \leq V^* \tag{3}$$

$$0 \leq \rho_i \leq 1, \quad i = 1,2,\ldots,n$$

where C(ρ) represents structural compliance (inverse of stiffness), K is the global stiffness matrix, U is the displacement vector, and V(ρ) denotes the material volume constrained by a prescribed limit V*. This formulation reflects the classical compliance minimization problem widely used in structural optimization.

Different methods, such as SIMP, Level Set, and ESO/BESO, implement this framework through distinct representations of material distribution and updating strategies, leading to variations in convergence behavior, boundary definition, and computational efficiency.

3.2. Multi-objective optimization in UAV structural design

In nature, UAV structural design is associated with several conflicting goals. Although it is necessary to reduce the weight of a flight to increase the efficiency of flight and increase the capacity to sustain a payload, it is important to maximize the stiffness to ensure the structural integrity and stability. These are usually the goals that are incompatible and they need a balanced strategy of optimization.

A multi-objective formulation can be generalized and can be formulated as:

$$\min_{\rho} \left[w_1 C(\rho) + w_2 V(\rho)\right] \tag{4}$$

Where w1 and w2 are weighting factors representing the relative importance of stiffness and mass. Other performance criteria will have to be considered in practice as well. These are fatigue resistance at long-term cyclic loading, mechanical strength to provide endurance to extreme working conditions, vibration performance to reduce risks of resonance and improve flight stability [8].

These factors are very vital to the optimization problem, and their inclusion adds so much complexity that it makes solving the problem very difficult. This leads to the need of sophisticated

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techniques like weighted aggregation techniques or Pareto-based optimisation techniques to determine suitable trade off solutions between conflicting goals. Such factors are especially important in UAV systems, in which operating conditions are severely dynamic and performance constraints are rigorous.

3.3. Method applicability for UAV structural components

The success of different topology optimization (TO) algorithms greatly depends on the functionality needs and structural aspects of UAV components. An example is the fuselage structures that require a careful balance between worldwide rigidity and multi-directional load distribution; in this context, density-based technologies such as Solid Isotropic Material with Penalization (SIMP) are of choice, since they have been demonstrated to be robust in dealing with complex load paths and tight volume constraints. Wing structures, on the other hand, require high aerodynamic efficiency and geometric accuracy [9]. In these types of applications, Level Set methods have a unique benefit of offering sharp boundary definition and better control over geometric continuity which is requisite to aerodynamic profiles. In addition, internal support structures, and load bearing connectors, Evolutionary Structural Optimization (ESO/BESO) methods are commonly used to optimize the distribution of materials through iterative steps to create efficient, lightweight truss-like structures. Finally, this comparative study highlights the fact that there is no universal best approach to TO; instead, the choice should be made in a manner that is strategically adjusted to the individual performance requirements and structural position of the particular UAV component in question.

3.4. Theoretical modeling framework

To sew the gap between the abstract optimization theory and practical aerospace engineering, the topology optimization of the UAV structures can be mapped into a single theoretical modeling framework. This structured approach starts with the strict definition of the design area, which defines the spatial limits and environmental restrictions that are involved in the operation of the UAV. This is succeeded by formulation of the objectives and constraints, performance targets (maximized stiffness or minimized mass) are mathematically codified. The framework is based upon the choice of a material representation strategy (e.g., SIMP or Level Set), which determines the way the design changes throughout the numerical solution stage. The algorithm has a series of steps that result in the optimal topology being arrived at through successive iterations, and the last step involves interpretation and refinement of the results. This is the final phase that makes sure that the perfectized mathematical layouts are converted to manufacturable layouts that consider the fabrication constraints of the real world. Through the combination of these individual steps, the framework offers a unified approach to the implementation of advanced optimization within the UAV structural design lifecycle.

4. Case study: topology optimization of a UAV wing Rib

4.1. Problem definition and boundary conditions

In order to confirm the practical applicability of the suggested framework, the framework is applied to a case study of the internal rib structure of a UAV wing. Being a major structural component, the wing rib has to be very strong structurally and aero-elastically stable, and yet, very strict in terms of weight [10]. The design domain in this work represents a simplified wing transverse section. The boundary conditions are determined by clamping at the spar connection points (cantilever support),

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and the external profile is applied to a distributed aerodynamic pressure gradient that is simulated as a vertical shear load. The optimization criterion is to have the lowest structural compliance (thus the highest stiffness) without going past a specified volume fraction limit (e.g. 30% of the original domain).

4.2. Optimization modeling

According to the theoretical framework analyzed in the section above, the optimization process can be modeled with a density-based approach. The design area is divided into a group of elements and each element may or may not keep material based on its contribution towards structural performance. The aim of optimization is to achieve optimal structural stiffness at minimum total weight. Meanwhile, other aspects of the design including structural integrity and vibration behavior are considered at the conceptual level so that the design developed is viable in the real world operating conditions. The optimization process is an iterative process, whereby material is redistributed in the design space. Areas that are least contributing to load transfer are gradually eliminated and critical load-carrying paths are strengthened resulting in an optimized structure.

4.3. Results and structural interpretation

The resultant structure shows definite pattern of material distribution as a load. Material will tend to accumulate along the main load paths between the areas of fixed support and load application to create a lightweight internal structure. Conversely, regions that have little contribution to the structure are eliminated leading to a great loss of weight. The optimized structure has shown a better utilization of material, as compared to the traditional wing rib designs, where the layouts are usually uniform or experience based. Diagonal and branching members are formed as stress distribution underline, which allows the better transfer of loads and the high level of stiffness-to-weight performance. These structural characteristics indicate the capability of topology optimization to produce non-intuitive but very efficient designs that are challenging to create through standard design methods.

4.4. Synthesis and engineering implications

The findings of this case study highlight the radical potential of topology optimization in the development of UAVs, providing an orderly channel to hitherto uncharted weight efficiency. Nevertheless, the resulting geometry is complicated in an organic way, which presents some difficulties to the traditional subtractive manufacturing. To realize the optimized model into a working component, the design would have to go through a post-optimization refinement stage, which would include manufacturing limitations, like minimum member size or overhang angle limits, in additive manufacturing (3D printing). Finally, although the optimized rib does have an obvious performance edge, its deployment needs to be a comprehensive process that considers both the outcomes of the algorithm and the realities of engineering and manufacturing.

5. Conclusion

This paper conducted a systematic investigation of the use of topology optimization to high-performance UAV structural design using a theoretical basis and a case study of a UAV wing rib. The study revealed that topology optimization offers an effective method of redistribution of material in a structural space to achieve the maximum stiffness at the minimum weight. As

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demonstrated in the case study, the optimized wing rib had non-intuitive and efficient load paths involving diagonal and branching members, which led to a much-enhanced stiffness-to-weight ratio, in comparison with conventional design. Such results support the promise of topology optimization to improve UAV performance, especially in the realization of lightweight but structurally sound designs that are hard to achieve by empirical means.

Although these are positive outcomes, there are a few limitations that must be mentioned. To begin with, the research was limited to one UAV component, and the framework is not yet tested on full UAV systems and in different operating conditions. Secondly, the theoretical model used included simple concepts like concept of stiffness, weight and vibration performance, but practical aspects like fatigue during long term cyclic loading, complicated aerodynamic influences and actual manufacturability circumstances were addressed only partially. The proposed framework should be extended to multi-component UAV structures and multi-component multi-objective optimization criteria, such as fatigue resistance, thermal loads, and aerodynamic efficiency, should be considered in future studies. The additional research on post-optimization refinements, manufacturability testing, and experimental validation will also play a significant role in ensuring that the theoretical design is translated into deployable UAV components. Also, the combination of topology optimization and new materials, including composites and hybrid structures, is an exciting path to even greater structural efficiency and operational performance. Overcoming these issues, topology optimization can become a useful and applicable tool of next-generation UAV design.

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