



OPTIMIZATION OF COMPOSITE WING STRUCTURE FOR TILT-DUCT AIRCRAFT CONSIDERING DISCRETE AND CONTINUOUS DESIGN VARIABLES

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Abstract

This paper focuses on the design and optimization of composite wing structure for tilt-duct aircraft, encompassing both discrete and continuous design variables. The study is conducted based on a laboratory-developed reference aircraft featuring four tilt-ducts. The primary objective is to identify a structural configuration for the wing that minimizes mass while meeting the structural design constraints. The design and optimization process is divided into two key phases: i.e. an initial phase that emphasizes the selection and determination of structural layouts under extreme load conditions during both forward flight and vertical takeoff and landing, followed by structural analyses to verify the design's soundness. The subsequent phase involves structural optimization, utilizing the finite element model of the wing box to conduct combinatorial optimization of the associated composite components. The optimization results showed that the mass of the wing box was reduced from 1.34 kg to 0.73 kg, achieving a weight reduction of 45.5%. These significant results highlight the customizability and efficiency of composite materials in the field of aerospace structural design.

Keywords: Tilt-duct, Composite Wing, Structure Optimization, Discrete and Continuous Design Variables

1. Introduction

In recent years, the development of low-altitude economy has become an important direction for the aviation industry, and the development of the related technology of unmanned aerial vehicles (UAVs) determines the direction of low-altitude economy. In the realm of UAVs, the pursuit of high performance, and cost-efficiency has propelled the development of multi-role UAVs capable of integrating vertical takeoff and landing (VTOL) capabilities with extended endurance. Tilt-duct aircraft emerge as a pivotal branch, combining the advantages of both rotor and fixed-wing aircraft, thereby expanding the operational versatility of UAVs and demonstrating significant advantages in terms of efficiency, flight speed, range, and safety. Since the feasibility of the tilt-duct concept was demonstrated in 1950s by the Doak VZ-4 test aircraft [1], the related technology has been rapidly developed. However, the design of tilt-duct aircraft, particularly regarding the wing structure, necessitate considerations to accommodate complex technical and functional requirements.

The application of composite materials provides a new direction for the optimization of the design of the wing structure of the tilt-duct aircraft. Unlike metallic materials, composites can be used to improve the mechanical properties of the structure by varying the thickness, angle, and sequence of the layups. However, the advantage of designability of composites also pose serious challenges for their design

and optimization. During the design and optimization of composite wing structures for tilt-duct aircrafts, complex manufacturing constraints need to be considered in addition to mechanical constraints such as stresses, strains and displacements. This implies that this optimization work is a combination of continuous and discrete design variables.

In terms of continuous variables, Ref. [2] has introduced a methodology in the conceptual and preliminary design of a tiltrotor wing, which focuses on the optimization of the thickness of the wing structural components. Ref. [3] presents a case study of a full aircraft wing internal load-bearing structure design based on the NASA Common Research Model (CRM), and utilizing giga-voxel resolution topology optimization techniques that resulted in a 2%-5% mass reduction in the wing. Ref. [4] discusses the shape optimization of a stringer-skin configuration for a typical aircraft wing structure, which improves the performance of the structure by minimizing the stress and maximizing the stiffness of the original base material without compromising on material selection.

In terms of discrete variables, Ref. [5] demonstrates a novel laminate parameterization technique that can be used to determine the stacking sequence of laminates for composite structures, and has been applied to the optimization problem of composite wing. Ref. [6] presents a mixed integer distributed ant colony optimization (MIDACO)-based optimization framework for composite wing, and optimizes the layout of the wing components. Ref. [7] presents an effective framework for the conceptual and preliminary structural optimization of composite materials for modern aircraft wing, and optimization of composite layup thickness based on CRM wing model.

In addition, some work considers both continuous and discrete design variables. Ref. [8] presents a bi-step method for the application of a set of constraints to the aeroelastic optimization of variable stiffness wing, which can reduce the mass of the wing by modifying the thickness distribution over the wingspan and smoothing the change in stiffness distribution and orientation. Ref. [9] demonstrates the use of a two-stage optimization approach for detailed sizing of composite aircraft wing skins, optimizing the thickness as well as the stacking order, respectively.

Previous literature reveals that numerous studies have been undertaken on wing structures, especially for composite materials. However, there are few studies on the design and optimization of composite wing structures for tilt-duct aircraft, especially when involving both discrete and continuous variables. This study is based on a laboratory-developed tilt-duct aircraft to conduct research related to the design and optimization of composite wing. The combinatorial optimization of composite structures in this paper is divided into shape optimization, thickness optimization and sequence optimization, with emphasis on continuous and discrete variables in the optimization process.

2. Aircraft Layout and Wing Structure Design

2.1 Aircraft Layout

The reference tilt-duct aircraft, shown in Figure 1, is configured with four tilt-ducted fans, two of which are mounted on the wingtip. The tilt-ducted fans allow the aircraft to perform vertical takeoff and landing as well as cruising. In addition, the aircraft's upper monoplane design layout allows enough space to carry a variety of equipment for different missions. The aircraft is powered by lithium batteries and has a maximum takeoff weight of 50kg.

Figure 2 shows the two flight modes of the tilt-duct aircraft, the multi-rotor flight mode by four tilting ducted fans to provide lift, and through the control of the four ducts to produce the difference in thrust can be completed a series of maneuvering actions. In the fixed-wing flight mode, the four tilting ducted fans point to the nose direction, and the flight attitude is coupled and controlled by the rudder surfaces of the ailerons and the thrust difference of the left and right ducts. It is the need for this aircraft to meet the requirements of different flight modes that poses a considerable challenge to the structural design of the wing.

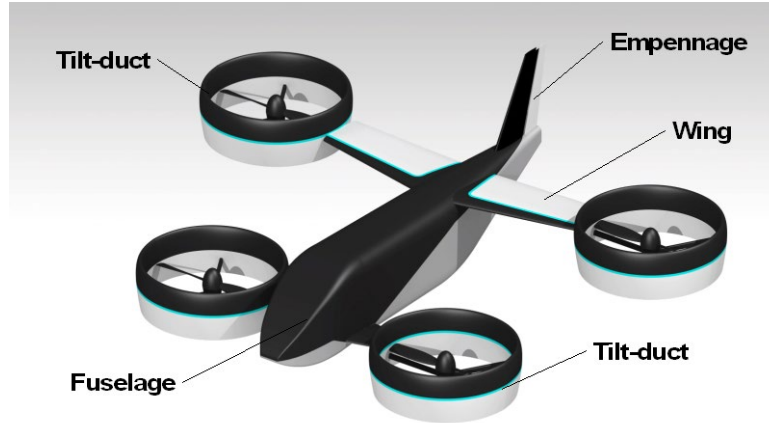
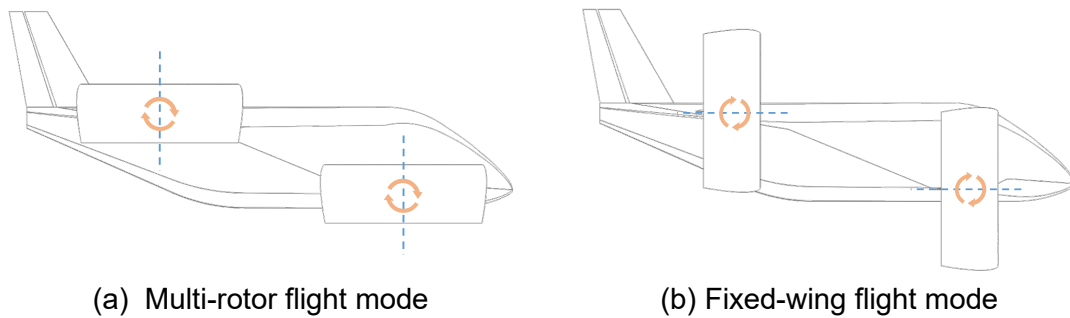


Figure 1 – The laboratory-developed tilt-duct reference aircraft.



(a) Multi-rotor flight mode

(b) Fixed-wing flight mode

Figure 2 – Two flight modes of the tilt-duct aircraft.

2.2 Wing Structure Design

The core feature of a tilt-duct aircraft is that its wing-mounted duct fans can be tilted to enable the transition between two flight modes: fixed-wing mode and multi-rotor mode, which requires careful considerations of more technical and functional constraints. In this paper, a double main spar wing structure configuration is proposed, as shown in Figure 3, with detailed design ideas described below.

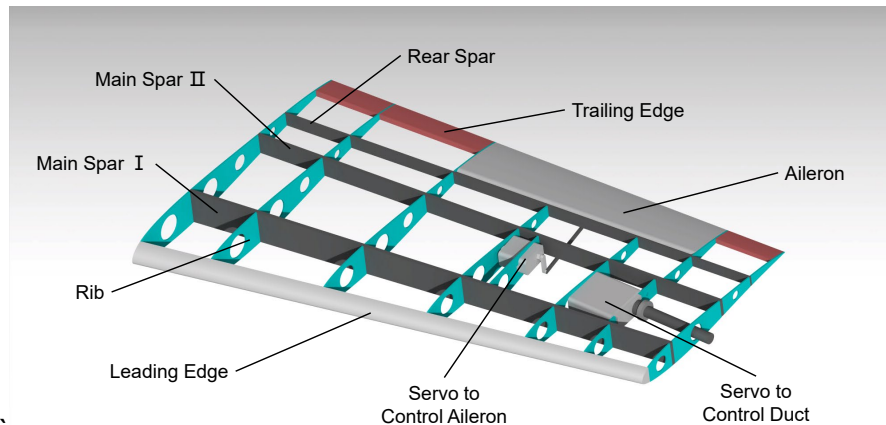


Figure 3 – Double main spar wing structure configuration.

Before carrying out the preliminary structural design of the wing, information such as geometric parameters obtained from the overall design of the aircraft, material selection, flight loads, are required. The dimensional parameters of the wing and duct, as well as the relative position between the duct and the wing are shown in Figure 4. To realize light-weight design, carbon fiber composites are selected for the wing designs.

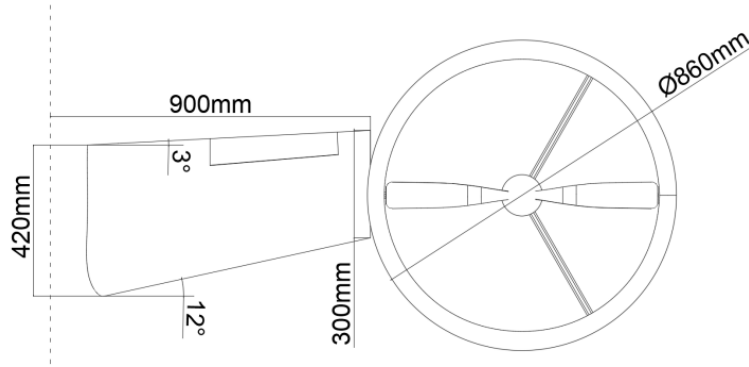


Figure 4 – The dimensional parameters of the wing.

It is important to evaluate the load conditions at different flight modes of the aircraft before the design of the wing structure. Figure 5 shows the critical load cases at two flight modes. According to Ref. [10], we chose a safety factor of 1.5, an overload factor of 3 to -1 for the multi-rotor mode, and an overload factor of 3.8 to -1.5 for the fixed-wing mode.

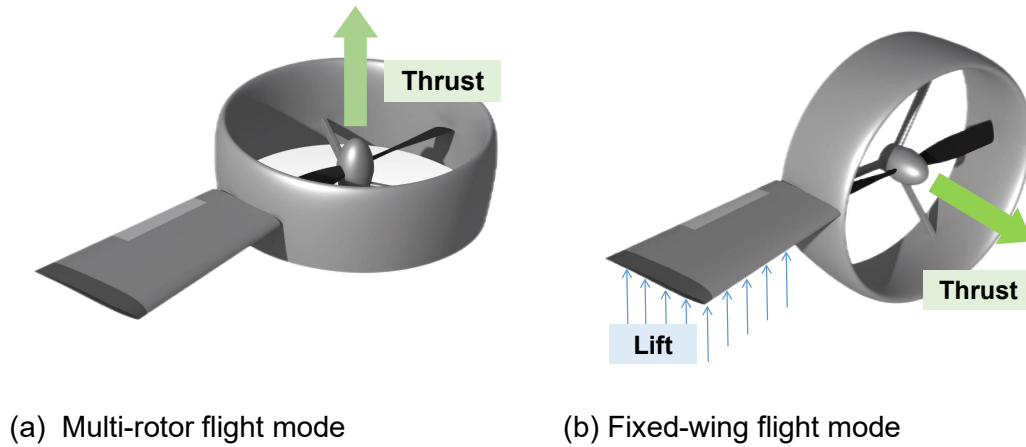


Figure 5 – Loading of the wing in two flight modes.

For the tilt-duct aircraft, which needs to switch between different flight modes, the double main spar structure can provide sufficient strength and stiffness to accommodate these modes. In addition, this configuration can better distribute the stress concentration, which improves the fatigue resistance and prolongs the service life of the wing.

2.3 Wing Structural Analysis

The wing box is the main load-bearing structure of the wing, so its structural performance is the focus of our analysis and optimization. In order to evaluate the design, we first establish the corresponding finite element model (FEM) of the wing box, as shown in Figure 6. In order to improve the computational efficiency, parts such as the servo are ignored, and the simplified wing box consists of the wing spars, wing ribs and skins, all of which are all made of carbon fibre composite material. As the structure of the wing box needs to meet the structural strength requirements at two flight modes, we select one representative working condition in each of the two flight modes and carry out the strength analysis to verify the feasibility of the design. Note that in this work we only focus on the beginning and end of tilting, without discussing the transition process.

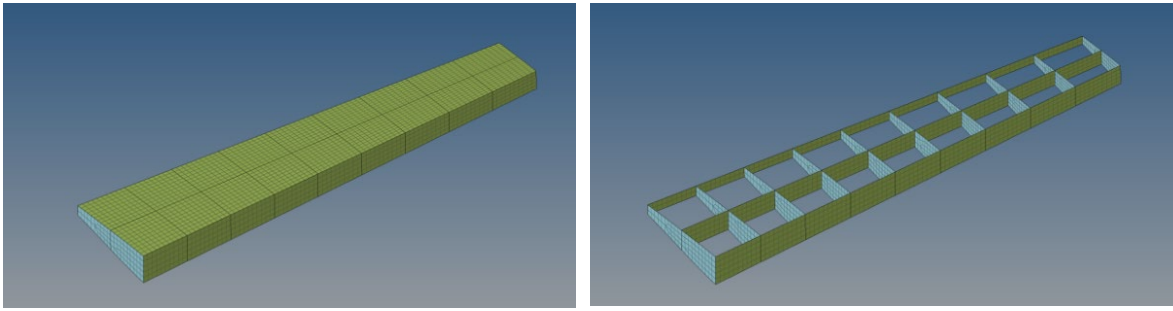


Figure 6 – Wing box finite element modeling.

In the multi-rotor flight mode, the loads generated by the tilt-ducts located at the wingtips, as well as the mass of the wing structure and internal equipment, need to be considered. In the fixed-wing flight mode, the aerodynamic loads, the loads generated by the tilt-ducts at the wingtips, and the mass are taken into account, where the aerodynamic loads are determined by means of aerodynamic analysis. It should be noted that we should multiply the theoretical loads by the relevant design factors mentioned in Section 2.2. The results of the analysis are shown in Figure 7.

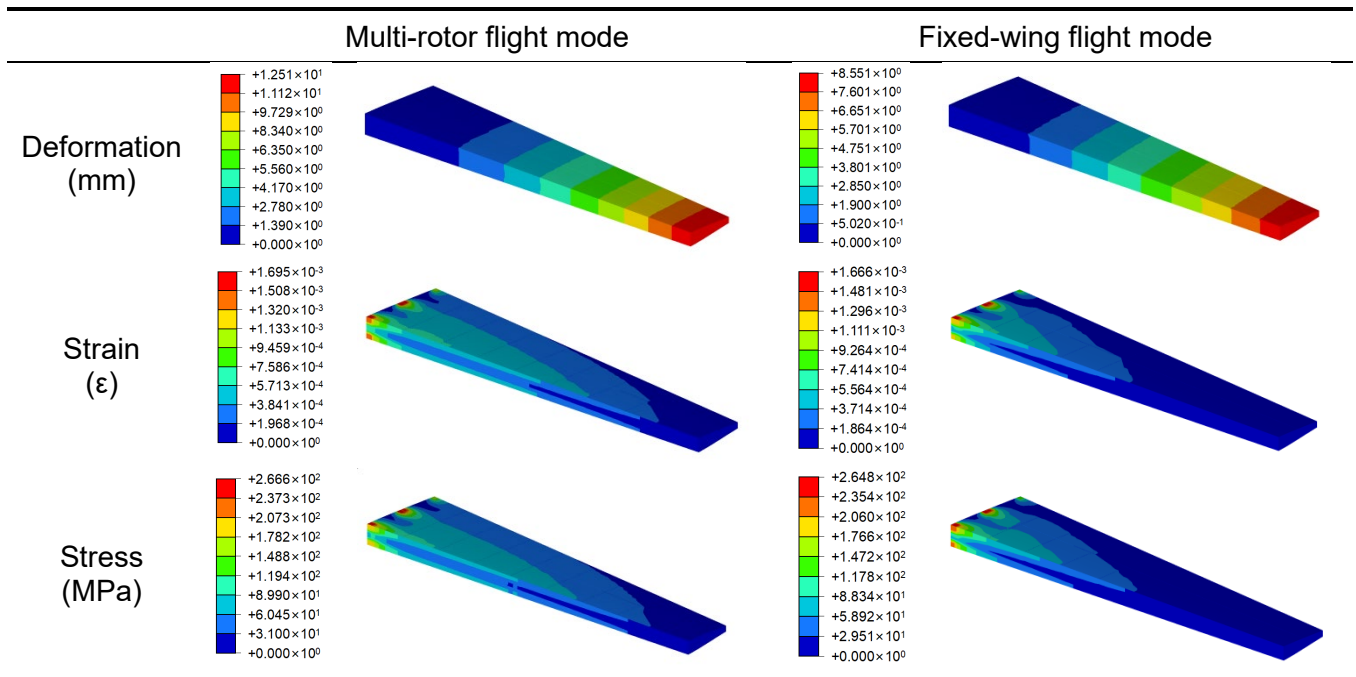


Figure 7 – Results of the structural assessment of the wing box.

In the multi-rotor mode, the wing tip displacement is 12.51 mm, the maximum strain is 1695 $\mu\epsilon$, and the maximum application is 266.6 MPa; in the fixed-wing mode, the wing tip displacement is 8.51 mm, the maximum strain is 1666 $\mu\epsilon$, and the maximum application is 264.8 MPa. All the results obtained above satisfy the corresponding design requirements. According to the analysis results we can find that most of the loads are transferred to the fuselage through the two main spars, which leads to the high stress-strain level at the root of the main spars, which also proves the feasibility of the structural design.

3. Wing Structural Optimization

Composites have the advantage of being designable, e.g., the overall mechanical properties can be changed by varying the ply thickness, stacking sequence and orientation. As constraints, the ply

orientations of composite material are 0° , 45° , -45° , 90° , and the thickness of a single manufacturable ply is required. The process of the combinatorial optimization for composite layup is shown in Figure 8. The design objective is to reduce the structural mass under the condition of meeting the structural stiffness and strength requirements, which can be specifically divided into the optimization of layup shape, thickness and sequence. It is worth noting that continuous and discrete variables are considered in this paper and will be reflected in these three optimizations.

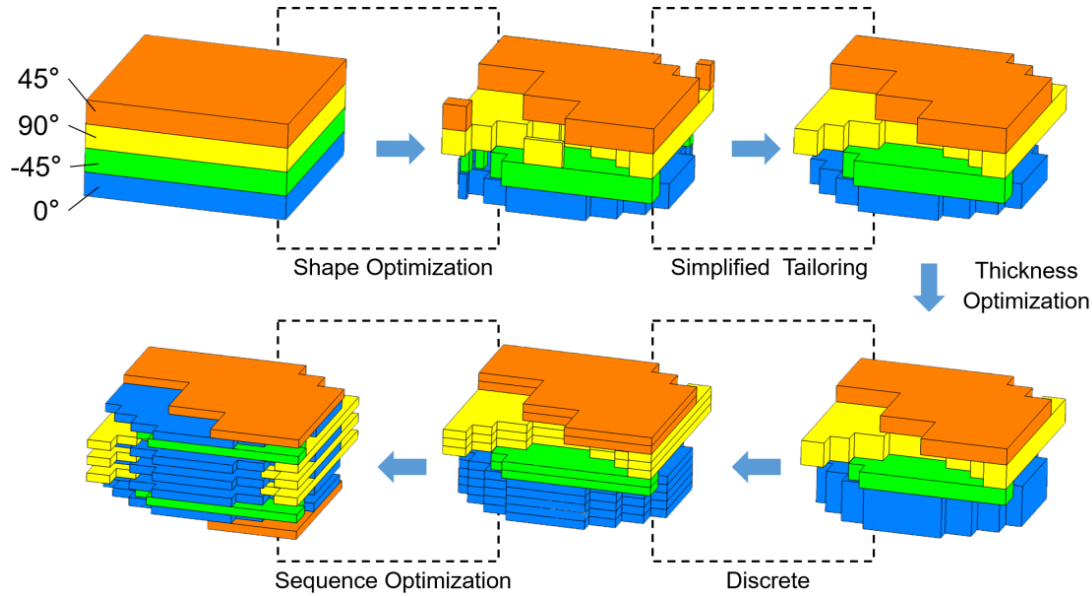


Figure 8 – Combinatorial optimization flowchart.

Although the mechanical properties of composites can be improved by the scientific design of the parameters of the layup, the seemingly perfect design results in serious challenges for the actual manufacturing. Despite their theoretical manufacturability, these designs often lead to substantial increases in processing costs, contrary to the original design intentions. Therefore, optimizing composite material must account for the practical feasibility of the manufacturing process by incorporating manufacturing constraints. These constraints ensure that the design adheres to industry standards and norms while controlling costs.

3.1 Shape Optimization

Composite layup shape optimization involves determining the optimal shape of each layer within a composite laminate, similar to topology optimization, which reduces the thickness of elements contributing less to the overall structural mechanical properties until their thickness reaches zero. In our approach, we combined layers with the same orientation into a single super layer, encompassing four orientations: 0° , $\pm 45^\circ$, and 90° . By adjusting the thickness of the super layer in each cell, we determined the laminate shape that satisfies the design constraints. The thickness of the super layer in each cell serves as the design variable, while the mass of the wing box structure is the objective function. These design variables are continuous in nature, facilitating precise adjustments for optimization.

The wing box converged after 113 iterations, as illustrated by the curve of the objective function versus the number of iterations in Figure 9. The mass of the optimized wing box is 0.49 kg, compared to the initial design mass of 1.34 kg, representing a mass reduction of 62.8%. The overall thickness distribution results for the wing spar and skin of the optimized wing box are depicted in Figure 10. It is evident that the material distribution is thickest at the root of the two main spars.

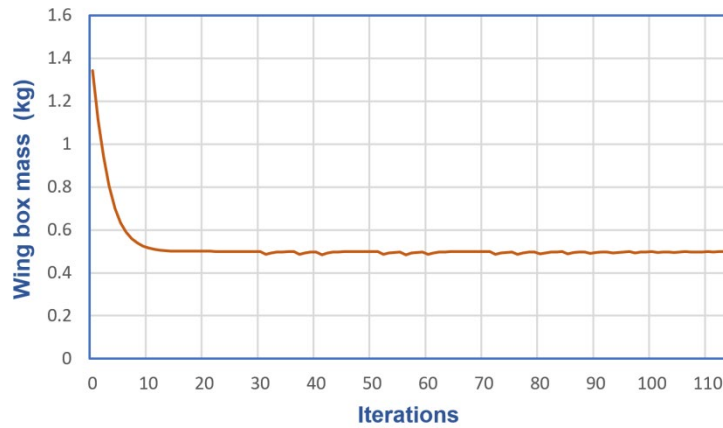


Figure 9 – Optimization history of the wing box weight with number of iterations.

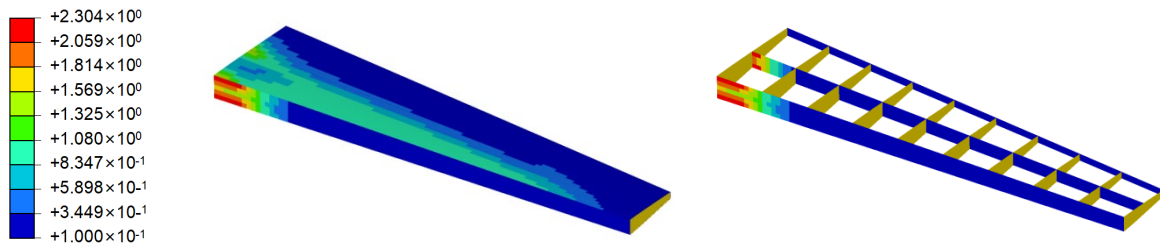


Figure 10 – Thickness distribution of shape-optimized wing box components(Unit in mm).

3.2 Simplified Tailoring

The shape of the layers obtained after layup shape optimization is irregular, characterized by many discontinuous and independent regions, which can lead to increased manufacturing costs. Therefore, it is essential to tailor the individual layers to align with actual manufacturing process requirements and prepare for the subsequent optimization of layup thickness. The effect of this cropping process is shown in Figure 11. The total mass after tailoring is 0.51 kg, representing a slight increase in mass compared to the shape-optimized wing box.

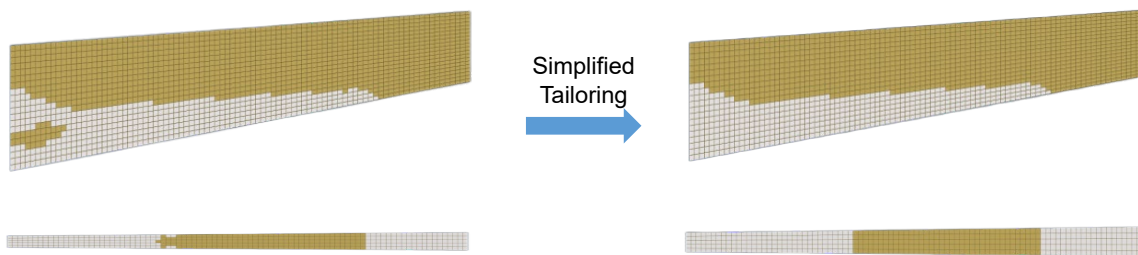


Figure 11 – Example of tailoring process for irregular layups.

3.3 Thickness Optimization

The shapes of the layers obtained after tailoring meet practical manufacturing requirements, but the thickness of these layers still needs to be optimized. The objective of layup thickness optimization is to determine the specific thickness for each layer at different orientations and shapes. This involves discretizing the layer thicknesses obtained from the simplified tailoring process into plies that conform to manufacturing constraints, taking into account both design and manufacturing constraints on load response. Given that the minimum manufacturable single ply thickness is established at the beginning of the design process, the thickness values from the optimization are idealized and may not be integer multiples of this minimum thickness. Therefore, it is necessary to divide the optimized thicknesses into

many manufacturable single plies of uniform thickness, a process known as discretization. It's important to note that the design variable in the thickness optimization is the thickness of the layer, which is a continuous variable.

The minimum ply thickness that can be fabricated in this study is 0.1 mm. The optimization process converged after 7 iterations, resulting in a wing box mass of 0.73 kg, which represents a 43% increase compared to the mass after tailoring(0.51 kg). This increase is likely due to the optimization process favoring ply group shapes that enhance the strength of the laminate. The thickness distribution of the wing box components is illustrated in Figure 12.

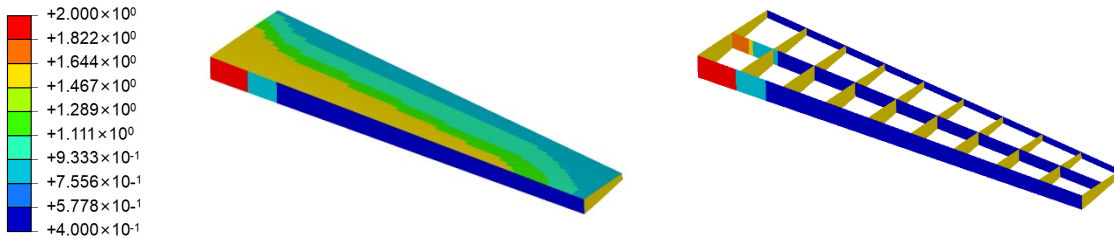
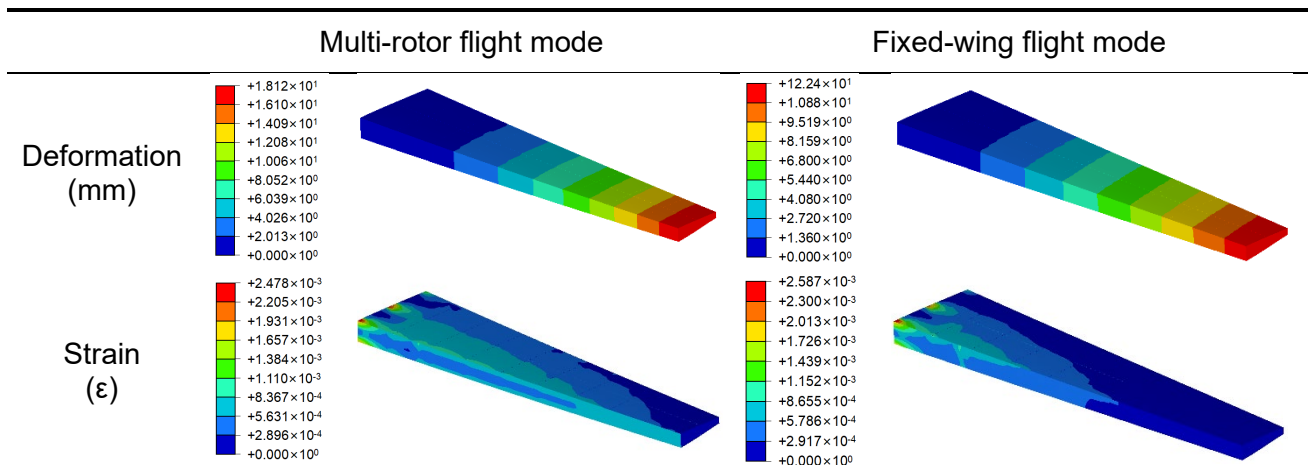


Figure 12 – Thickness distribution of thickness-optimized wing box components(Unit in mm).

3.4 Sequence Optimization

The optimization of the layup sequence is the final step in the overall optimization process. In this step, the thickness and orientation of the plies are kept constant, and only the sequence of the layup is altered. The objective of optimizing the layup sequence is to ensure that the stacking sequence adheres to the layup rules and manufacturing constraints of composites, while maintaining or potentially improving the overall performance of the laminate. This step addresses a search problem within a discrete and nonlinear space, with the design variables being discrete in nature. By optimizing the sequence, the method aims to refine the structural integrity and performance of the composite laminate, adhering to practical manufacturing requirements.

Since the layup sequence optimization did not alter the thickness of the wing box components, the final optimization result (depicted as a contour diagram of composite layup thickness distribution) is shown in Figure 12. The results of the analysis, including displacements, strains, and stresses, are presented in Figure 13: In the multi-rotor mode, the wing tip displacement is 18.12 mm, the maximum strain is 2478 $\mu\epsilon$, and the maximum application is 388.2 MPa; in the fixed-wing mode, the wing tip displacement is 12.24 mm, the maximum strain is 2587 $\mu\epsilon$, and the maximum application is 405.3 MPa. All the results obtained above satisfy the corresponding design requirements.



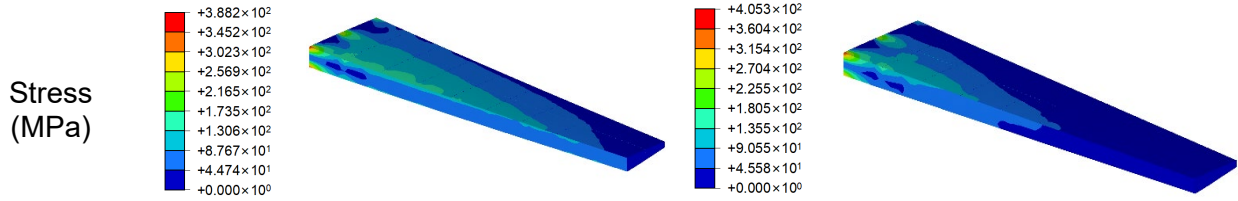


Figure 13 – Mechanical performance analysis results of optimized wing box structure.

The initial total weight of the wing box was 1.34 kg. After optimization, focusing on the skin and wing spars, its weight was reduced to 0.73 kg, achieving a 45.5% weight reduction, demonstrating a significant improvement. Although the original load-carrying capacity remains unchanged, the displacements, strains, and stresses of the wing box structure have increased compared to pre-optimization values. The mechanical properties of the original wing box structure are shown in Figure 7, it is evident that some sacrifices in strength, stiffness, and stability were made to achieve weight reduction. However, the resulting displacements, strains, and stresses still meet the design requirements.

4. Conclusion

The tilt-duct aircraft is a significant branch of VTOL aircraft, merging the VTOL capabilities of rotary-wing aircraft with the high-speed cruise capability of fixed-wing aircraft. Exploring a highly integrated, lightweight wing structure for such aircraft is crucial, and the application of composite materials offers a promising research direction. To achieve a composite wing structure with superior performance, it is necessary to consider both discrete and continuous design variables in the optimization process. This paper focuses on the design and optimization of the wing structure for a laboratory-developed tilt-duct aircraft, which features ducted fans installed in its wings. This unique configuration introduces additional challenges and requires consideration of more technical and functional requirements in the design process. We first propose an adapted double main spar structural configuration tailored to the characteristics of this aircraft. Subsequently, we conduct combinatorial optimization of the composite components related to the wing box to achieve a lightweight design while satisfying both design and manufacturing constraints. The wing configuration and the corresponding design optimization method proposed in this study can serve as a valuable reference for related fields. The main conclusions are as follows:

- The double main spar configuration applied to the wing design of a laboratory-developed tilt-duct aircraft offers several advantages: it optimizes the utilization of internal space, enhances structural stiffness and load-carrying capacity, and improves overall structural reliability.
- In the optimization process of composite parts, both discrete and continuous design variables are considered. The optimization sequence includes shape optimization, thickness optimization, and sequence optimization of composite layups. To ensure that the optimization results are feasible for actual processing and manufacturing, various manufacturing constraints are imposed.
- Compared to the initial design scheme, the weight of the optimized wing box structure is reduced by 45.5%. The optimized structure better exploits the material's load-bearing capacity while meeting all required performance criteria, highlighting the customizability and efficiency of composite materials in aerospace design.

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