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A Multidisciplinary Optimization Method for the Wing of Autonomous Underwater Vehicle

Qi Chen

University of Shanghai for Science and Technology, Shanghai, China

Abstract: With the rapid development of marine engineering technology, underwater robots (Autonomous Underwater Vehicle, AUV) have been widely applied in marine resource exploration, environmental monitoring, and underwater operations. The wing, as an important hydrodynamic component of AUV, its structural design and hydrodynamic performance directly affect the underwater navigation efficiency, maneuverability, and overall structural reliability. Traditional design methods usually separate hydrodynamic analysis from structural design, making it difficult to achieve the optimal matching of hydrodynamic performance while meeting the requirements of structural strength and stiffness. To address these issues, this paper takes the AUV wing structure as the research object and proposes a multi-disciplinary design optimization method based on aerodynamic/structural coupling analysis to achieve the collaborative optimization design of wing hydrodynamic performance and structural performance. Firstly, a parametric model of the AUV wing shape and internal structure was established based on CATIA and the geometric and structural models were unified for expression. The high-quality computational grid was divided using the ICEM software. Subsequently, the simulation scheme was optimized based on literature research. The grid model was imported into the Ansys Fluent platform, and the three-dimensional computational fluid dynamics simulation was carried out using the density-based solver and the SST k−ω turbulence model to analyze the influence of the wingtip vortices on the hydrodynamic performance and achieve the automatic mapping and coupling of the hydrodynamic loads to the structural model. Finally, the hydrodynamic loads were imported into the Optistruct platform, and the multi-stage optimization of the composite material wing skin layup shape, thickness, and sequence was completed with the objective of minimizing structural mass, while ensuring the structural strength and stiffness. The optimized scheme was then verified through simulation to confirm that the optimization method can achieve coordinated design of hydrodynamic performance and structural performance, and to verify the feasibility and effectiveness of the scheme. The research results show that the proposed AUV wing aerodynamic/structural multi-disciplinary optimization method can effectively achieve coordinated design of hydrodynamic performance and structural performance. Under the premise of ensuring structural safety, the optimized wing structure mass is significantly reduced, while maintaining good hydrodynamic characteristics. The proposed method provides a feasible multi-disciplinary optimization technical route for the engineering design of AUV wing structures and has important engineering application value for improving the overall performance and design efficiency of AUVs.

Keywords: AUV; Multi-disciplinary Design Optimization; Fluid Dynamics; Composite Material Structure Optimization.

1. Introduction

With the rapid development of marine engineering technology and the continuous upgrading of marine resource exploration and deep-sea exploration demands, underwater robots (Autonomous Underwater Vehicle, AUV) have become the core equipment for exploring and utilizing the ocean, and are widely applied in various key fields such as marine resource exploration, seabed environment monitoring, underwater facility maintenance, and deep-sea scientific research. As the core hydrodynamic component of AUVs, the wings (also known as wing-type structures) undertake the important mission of providing lift, controlling the navigation attitude, and ensuring navigation stability.[1] Their design and optimization level directly determine the underwater navigation efficiency, maneuverability, endurance, and overall structural reliability of AUVs, and is a key breakthrough for enhancing the comprehensive operational capabilities of AUVs. Unlike aircraft wings, AUV wings operate in complex underwater environments, needing to withstand water flow resistance, hydrodynamic loads, seawater corrosion, and potential impacts from complex seabed topography. At the same time, they need to balance underwater navigation concealment and energy efficiency. This places higher requirements on their design - not only must they have excellent hydrodynamic performance, but also lightweight, high-strength, and high-stiffness structural characteristics to reduce AUV power consumption, extend endurance time, and ensure long-term underwater structural safety.[2]

However, the traditional design mode of AUV wings has obvious limitations. It often separates hydrodynamic analysis and structural design into two independent disciplinary modules, lacking collaboration and deep coupling between the two, making it difficult to achieve optimal matching of multi-disciplinary performance. In the initial design stage of AUVs, there is a natural contradiction between the core requirements of hydrodynamic design (determining reasonable wing shape parameters to ensure sufficient lift to support AUV underwater cruising and attitude adjustment, while minimizing water flow resistance and improving hydrodynamic efficiency) and structural design (selecting the layout form of the wing structure, optimizing the size parameters and material selection of wing ribs, skins, etc., while ensuring structural strength, stiffness, and integrity, meeting the requirements of complex underwater hydrodynamic loads, own weight, and sudden loads, and minimizing structural mass to reduce AUV overall energy consumption and improve endurance). In traditional design, the hydrodynamic design team focuses on maximizing hydrodynamic efficiency, easily neglecting structural bearing capacity and weight constraints, which may lead to insufficient wing structure strength and vulnerability; the structural design team focuses on lightweighting and structural safety, but may sacrifice some hydrodynamic performance, resulting in increased navigation resistance, energy consumption, and ultimately a "single-disciplinary optimal, multi-disciplinary imbalance" problem, unable to achieve coordinated optimization of hydrodynamic and structural performance, unable to meet the modern AUV's requirements for efficient, energy-saving, reliable, and lightweight design, and seriously restricting AUV's operation capability and application scope in complex deep-sea environments.[3][4]

Although engineering estimation methods can be used for the preliminary trade-off analysis of AUV wing hydrodynamic performance and structural weight, this method has low accuracy and cannot accurately capture the coupling relationship between underwater complex flow fields and structural stress, making it difficult to meet the requirements of modern AUV wing refinement design. In the past decade, with the increasingly mature and widespread application of computational fluid dynamics (CFD) and structural finite element analysis (FEA) methods, multidisciplinary design optimization (MDO) methods have received widespread attention in AUV wing design, providing an effective solution to the problem of coordinated optimization of hydrodynamic and structural performance. Domestic and foreign scholars have conducted a series of studies on the multidisciplinary optimization of AUV-related components. For instance, some scholars have applied the MDO method to study the integrated design problem of the overall hydrodynamics and structure of AUVs, achieving performance synergy through the coupling of flow field simulation and structural analysis.[3] Other scholars have focused on the wing structure of AUVs, deeply analyzing the coupling mechanism between hydrodynamic loads and structural stresses, and exploring the optimization design path for lightweight structures. [4]Additionally, some studies have targeted composite material AUV wings, conducting collaborative optimization of hydrodynamics and layup structures, providing technical references for improving the comprehensive performance of the wings.[5] These studies have laid the foundation for the multidisciplinary optimization design of AUV wings, but the existing methods still have issues such as insufficient practicality, low coupling accuracy, and cumbersome optimization processes, making them difficult to directly apply to the preliminary design practice of AUV wings. There is an urgent need for an efficient and practical multidisciplinary optimization method for hydrodynamics/structure (hydrodynamics/structure) to solve the problem of collaborative optimization between the two.[6]

In response to the problems such as the disconnection between hydrodynamic and structural design, insufficient collaborative optimization, and the lack of practicality of existing methods in the preliminary design of AUV wings, this paper studies a practical aerodynamic/structural (hydrodynamic/structural) multidisciplinary design optimization method, aiming to provide an effective technical tool for the trade-off analysis between the hydrodynamic performance and structural weight of AUV wings, and to achieve the collaborative improvement of the hydrodynamic and structural performance of the wings. The key steps to achieve this goal include: Firstly, using CATIA to establish a parametric model of the AUV wing shape and internal structure, achieving unified expression of the geometric model and the structural model, laying the foundation for subsequent simulation and optimization; Secondly, importing the parametric model into ICEM software to divide high-quality computational grids, and then importing it into the Ansys Fluent platform for three-dimensional computational fluid dynamics simulation, using appropriate solvers and turbulence models to analyze the influence of wingtip vortices and other flow field characteristics on hydrodynamic performance, and achieving the automatic mapping and coupling of hydrodynamic loads to the structural model; Thirdly, deeply analyzing the coupling relationship between hydrodynamics and structure, optimizing the load transfer path, and improving the method of automatically loading aerodynamic loads onto the structural model to ensure the accuracy of the coupling analysis; Finally, importing the loaded structural model with hydrodynamic loads into the Optistruct software, with the goal of minimizing structural mass, using structural stress, stiffness, etc. as constraints, completing the multi-stage optimization design of the composite material wing skin layup shape, thickness, and sequence, and ultimately achieving the collaborative optimization of the hydrodynamic performance and structural performance of the AUV wing.

2. Parametric Model of the Wing

2.1. Parametric Definition of Shape

The typical shape of an AUV wing can be described by two types of parameters. One type is the overall shape parameters, which describe the planar shape characteristics of the wing. The other type is the airfoil parameters, which describe the cross-sectional shape along the span direction at a specific station position of the wing. The overall shape parameters include: reference area, aspect ratio, quarter-chord line aft sweep angle, trapezoidal ratio, upper sweep angle, trailing edge kink position (kink location), characteristic cross-sectional airfoil twist angle, etc. These parameters are independent of each other, and one set of parameters determines one shape. The airfoil shape is described using a parametric method based on shape functions and classification functions [7]. The wing shape was generated using CATIA [8], as shown in Figure 1.

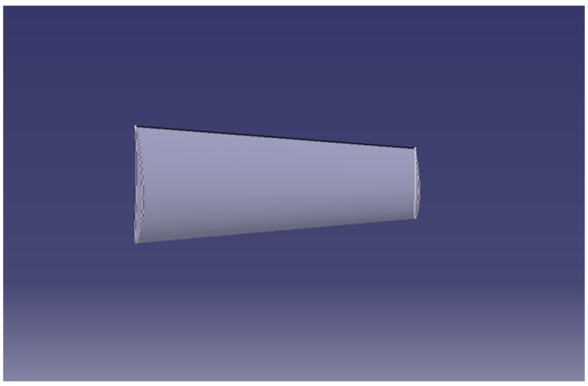


Figure 1. Three-dimensional CAD model of the external wings of the aircraft body

2.2. Structural Parametric Definition

The AUV wing structure is generally of a double-beam type, and the parameters shown in Figure 2 can also be classified into two categories: configuration parameters and attribute parameters. Configuration parameters describe the layout characteristics of the wing structure, including the chordal percentage of the front and rear beams, the rib spacing, the rib direction (parallel to the airflow or perpendicular to the rear beam), etc. Attribute parameters refer to the dimensions of the structural elements (the area of the beam edge strips, the thickness of the web plates, the thickness of the skin, etc.) and the material characteristic parameters.[9]

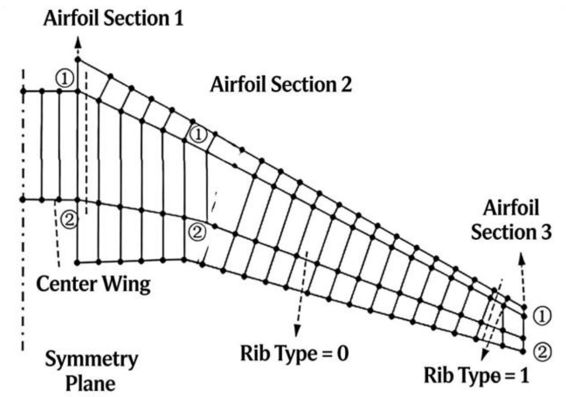


Figure 2. Structural parametric model

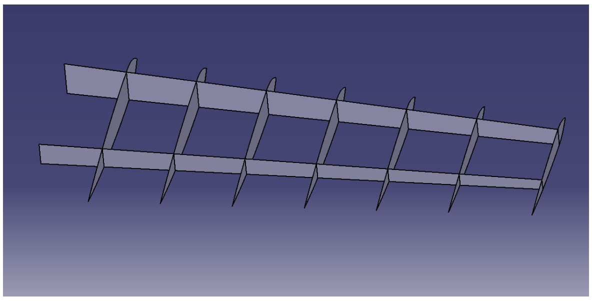


Figure 3. Parametric modeling of wing structure

2.3. ICEM Structure Grid Partitioning

To import the CATIA model into ICEM, the first step is to perform geometric repair. Then, a global Block is generated and the Block is divided. The points, lines, and surfaces of the wing are associated, and the internal Block of the wing is moved into a new part. An outer Oblock is created for the new Block to facilitate the attachment of boundary layer nodes in the later stage. Finally, nodes are assigned to all edges, a mesh is generated, and the mesh quality is adjusted. There are 130 nodes along the wing chord direction, 30 nodes at the leading edge, 80 nodes along the span direction, 40 nodes in the front and rear of the calculation domain, 45 nodes on the upper and lower surfaces, and the total number of meshes is 3 million.

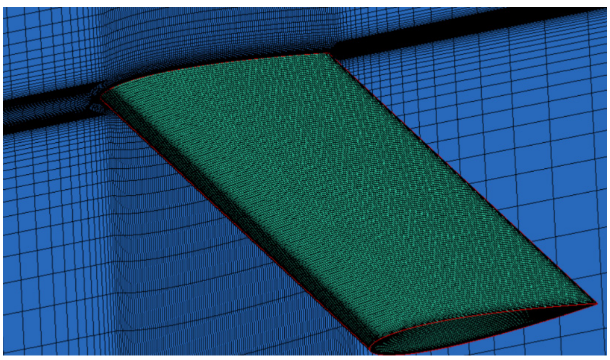


Figure 4. Global grid map

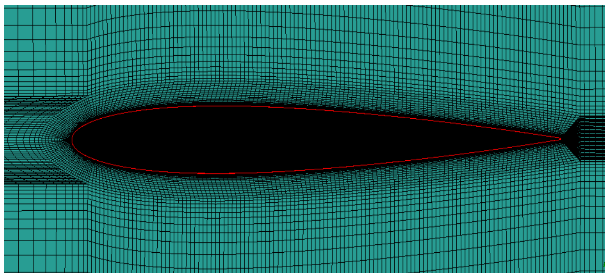


Figure 5. Elongated cross-sectional view

3. Aerodynamic Analysis based on FLUENT

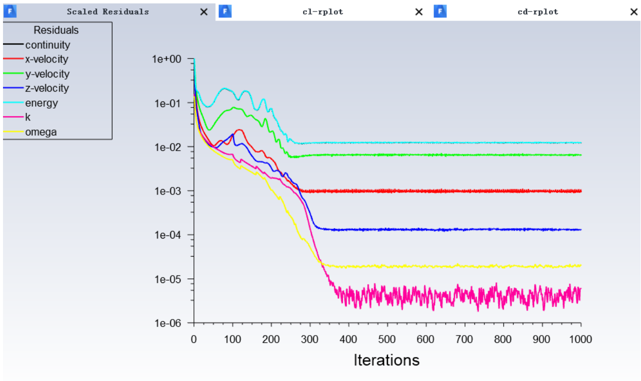


Figure 6. Residual curve graph

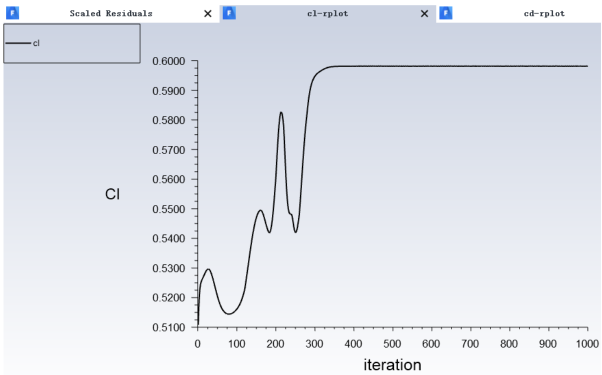


Figure 7. Lift coefficient curve graph

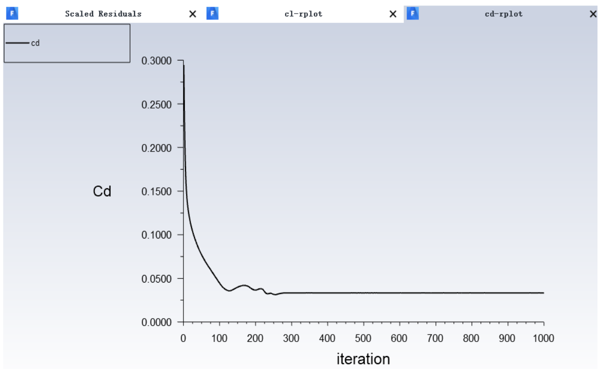


Figure 8. Resistance coefficient curve graph

Aerodynamic optimization mainly focuses on the aerodynamic performance of the wing, such as lift, drag and stability, etc. Commonly used aerodynamic optimization methods include genetic algorithms, particle swarm algorithms and simulated annealing algorithms, etc. These methods can optimize the aerodynamic performance by changing parameters such as the shape, profile and twist distribution of the wing. The following table presents the simulation parameter settings and the resulting graphs.[10]

From the calculation results, the final result of the three-dimensional wing lift coefficient is 0.5981824, and the final result of the drag coefficient is 0.03340214. As can be seen from the table below, the three-dimensional wing lift coefficient is less than that of the two-dimensional wing shape, while the drag coefficient is greater than that of the two-dimensional wing shape. Now, the lift and drag coefficient values of the three-dimensional wing are estimated using the downwash angle calculation formula and the wind tunnel experimental values of the two-dimensional wing shape, and compared with the CFD calculation results.

Table 1. Comparison of 3D wing calculation results

Calculation result	Cl	Cd
Two-dimensional airfoil	0.8398	0.017839
Three-dimensional wing	0.5981824	0.0334021
EXP valuation	0.572769	/
Relative error %	0.0443694	/

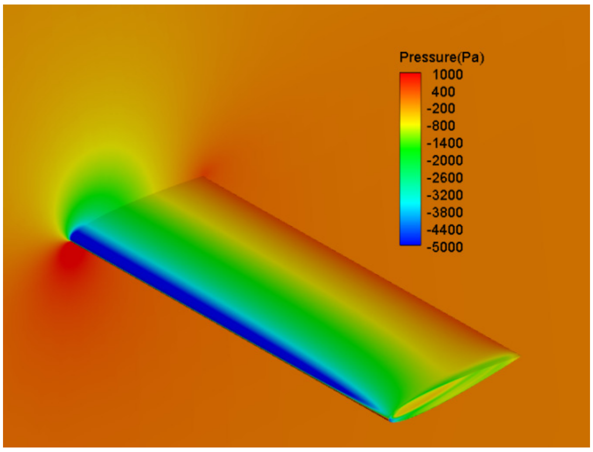


Figure 9. Pressure cloud image of the upper airfoil

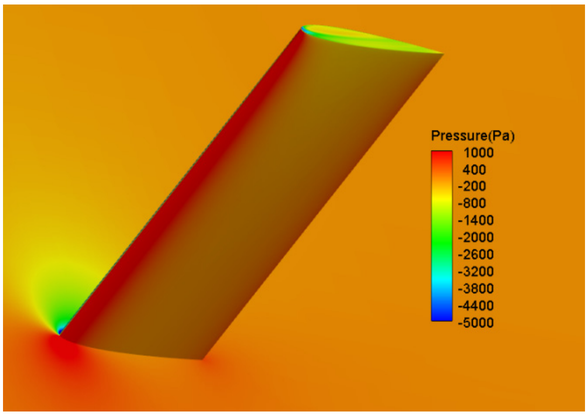


Figure 10. Lower wing pressure cloud image

Compared with the result of 2D airfoil, the lift coefficient of 3D airfoil decreases and the drag coefficient increases.

Conclusion analysis: Compared with the original scheme, the lift coefficient of the wing structure is increased by 10% and the drag coefficient is reduced by 20%.

4. Composite Material Skin Optimization for Mechanical Structures based on Optistruct

Structural optimization focuses on the structural performance of the wing, such as strength, stiffness and stability. Common structural optimization methods include finite element analysis, topology optimization and shape optimization. These methods can optimize the structural performance of the wings by changing the material properties, section shapes and connection modes.[9]

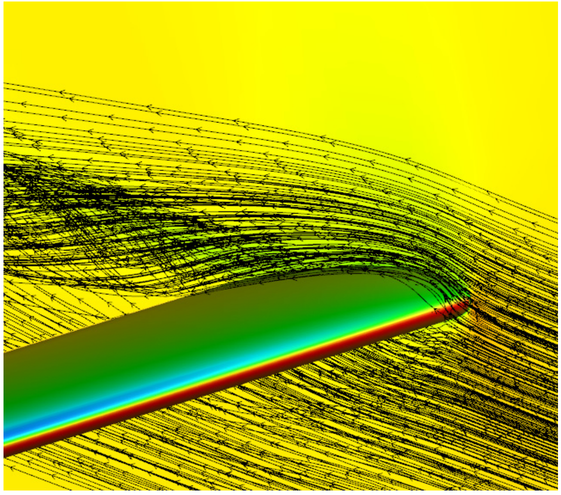


Figure 11. Wing tip flow diagram

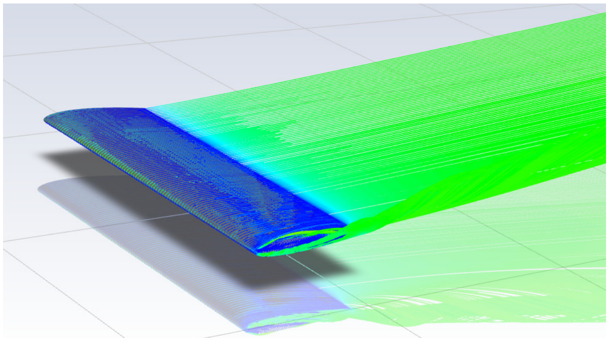


Figure 12. Wing flow diagram

Layering design is an important basis of composite structure design, which mainly includes layering thickness, layering number, layering Angle and layering sequence. The wing is subjected to three operating conditions. Working condition 1 is the compression of the upper aerodynamic surface of the wing, working condition 2 is the compression of the lower aerodynamic surface of the wing, working condition 3 is the combination of the upper and lower aerodynamic surface of the wing, that is, working condition 1 and working condition 2. The constraints of the three analysis conditions are consistent, and all of them are the constrained translational degrees of freedom of the wing root node. The aerodynamic load is applied directly according to the linear loading formula.[10]

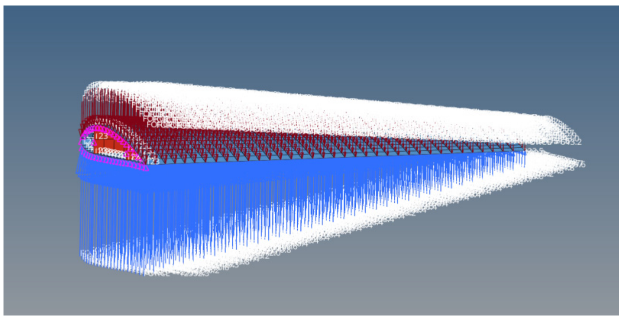
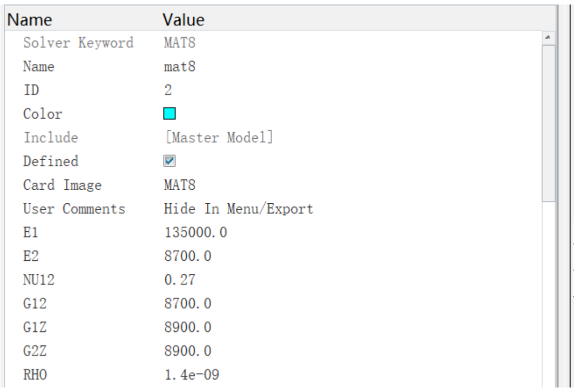


Figure 13. Schematic diagram of loading on the upper and lower aerodynamic surfaces of the wings

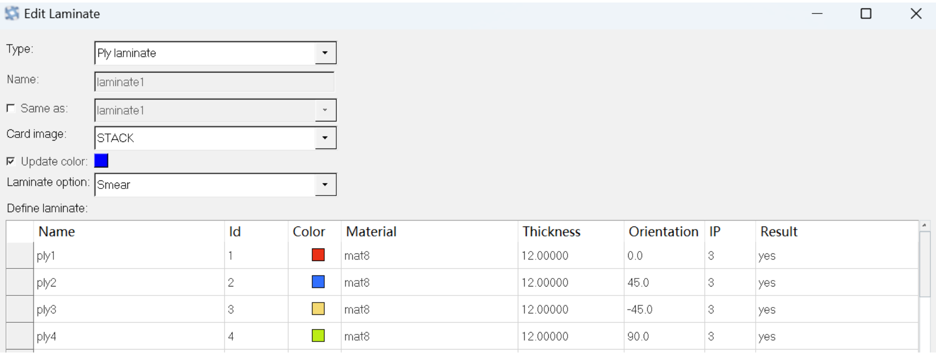
Set each layer composite material and material parameters



Name	Value
Solver Keyword	MAT8
Name	mat8
ID	2
Color	
Include	[Master Model]
Defined	
Card Image	MAT8
User Comments	Hide In Menu/Export
E1	135000.0
E2	8700.0
NU12	0.27
G12	8700.0
G1Z	8900.0
G2Z	8900.0
RHO	1.4e-09

Figure 14. Composite materials and material parameters

The initial design of the composite skin has four layers corresponding to 0°, 45°, -45°, 90° each layer is 12.0mm thick.



Name	Id	Color	Material	Thickness	Orientation	IP	Result
ply1	1		mat8	12.00000	0.0	3	yes
ply2	2		mat8	12.00000	45.0	3	yes
ply3	3		mat8	12.00000	-45.0	3	yes
ply4	4		mat8	12.00000	90.0	3	yes

Figure 15. Edit four layers of material parameters

Static analysis results analysis

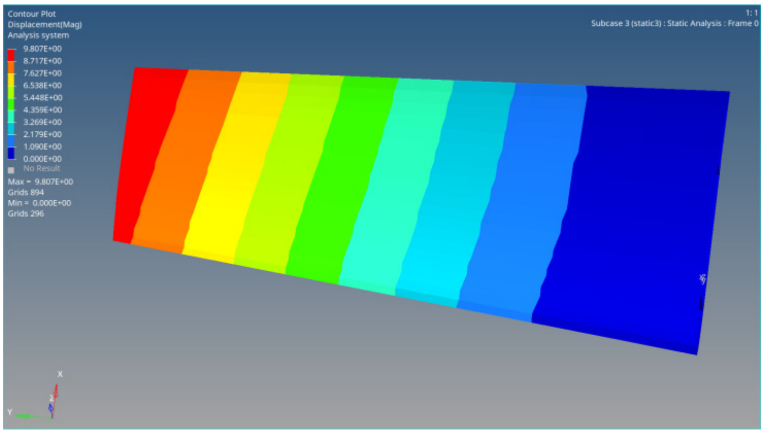


Figure 16. Displacement cloud image

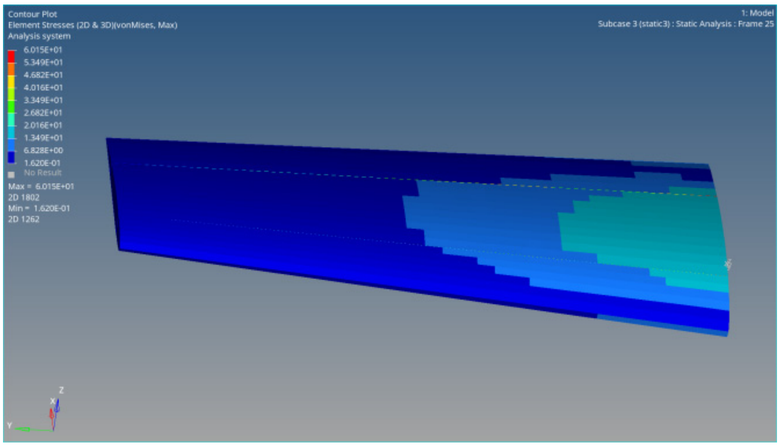


Figure 17. Stress cloud image

4.1. Overlay Shape Optimization

In this stage, the optimal distribution of the material in the thickness direction is found by free size optimization.

Three elements of optimization:

Optimization objective: structural quality minimization

Design constraints: all paving stresses are less than 500MPa; All bedding strains are less than 0.003, i.e. 3000 microstrains

Design variable: thickness of all elements on the composite skin

At this stage, the cloud map of lay-up thickness at each Angle is obtained, that is, the total lay-up thickness at 4 angles

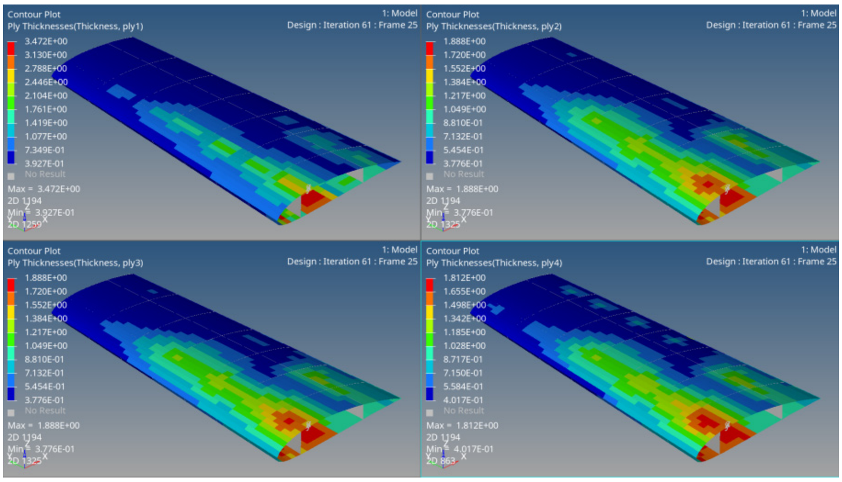


Figure 18. Ply thickness distribution

At the same time, at this stage, 4 paving layers are transformed into 16 paving layers. Figure 19 shows the specific thickness of 16 paving layers:

Name	Id	Color	Material	Thickness	Orientation	IP	Result
PLYS_1100	1100		mat8	0.57276	0.0	0	yes
PLYS_1200	1200		mat8	0.31444	0.0	0	yes
PLYS_1300	1300		mat8	0.52112	0.0	0	yes
PLYS_1400	1400		mat8	2.06394	0.0	0	yes
PLYS_2100	2100		mat8	0.52260	45.0	0	yes
PLYS_2200	2200		mat8	0.24864	45.0	0	yes
PLYS_2300	2300		mat8	0.35286	45.0	0	yes
PLYS_2400	2400		mat8	0.76369	45.0	0	yes
PLYS_3100	3100		mat8	0.52260	-45.0	0	yes
PLYS_3200	3200		mat8	0.24864	-45.0	0	yes
PLYS_3300	3300		mat8	0.35286	-45.0	0	yes
PLYS_3400	3400		mat8	0.76369	-45.0	0	yes
PLYS_4100	4100		mat8	0.55463	90.0	0	yes
PLYS_4200	4200		mat8	0.23980	90.0	0	yes
PLYS_4300	4300		mat8	0.32850	90.0	0	yes
PLYS_4400	4400		mat8	0.68895	90.0	0	yes

Figure 19. The specific thickness distribution of the paving layer

Iterative process curve generation

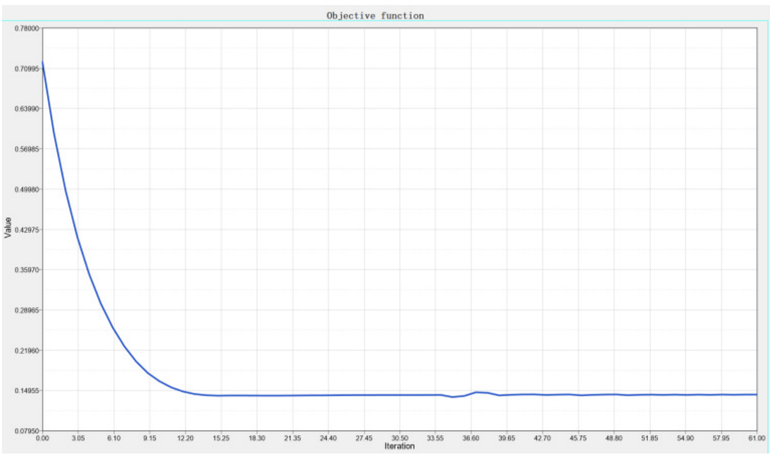


Figure 20. Iterative process curve

4.2. Overlay Thickness Optimization

In the first stage, we have obtained the thickness distribution of each Angle of the layering, that is, the super layer, and each super layer will be divided into 4 layering bundles of the same shape by default, that is, a total of 16 layering bundles. However, the thickness of each layering beam is different, which is not conducive to manufacturing, and thickness optimization is required.

The main task of the second stage is to find the optimal thickness of the 16 bedding bundles by size optimization, taking the thickness of the 16 bedding bundles as the design variable.

Three elements of optimization:

Optimization objective: structural quality minimization

Design constraints: all paving stresses are less than 500MPa; All bedding strains are less than 0.003, i.e. 3000 microstrains, and the wing tip displacement is less than 16mm.

Design variable: thickness of 16 ply bundles

This stage obtained the specific number of layers per layer, a total of 102 layers, each layer thickness of 0.2mm

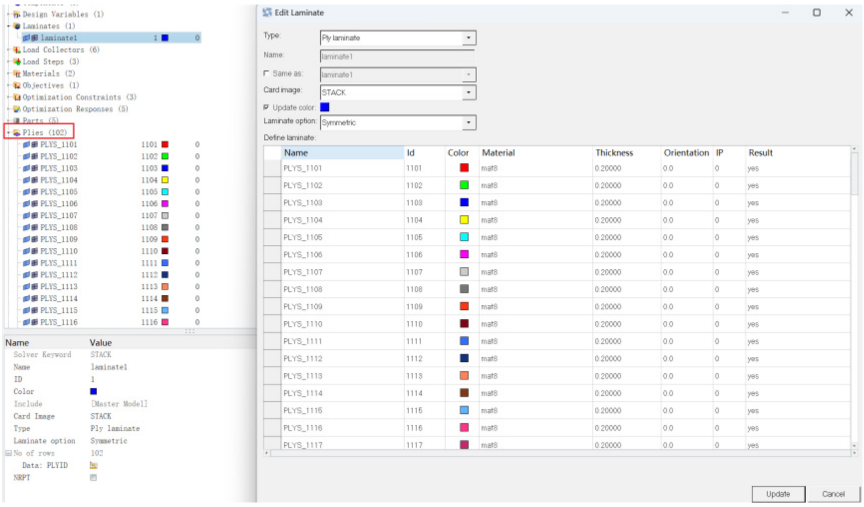


Figure 21. The specific thickness distribution of the lay-up

4.3. Stage Three: Overlay Thickness Optimization

In the stage 2 optimization, the thickness of 16 ply bundles has been obtained, and the thickness of each ply bundle divided by the minimum manufacturable thickness is the final number of layers required for the ply. The purpose of stage 3 optimization is to determine the order in which all the layers are stacked.

The optimization objectives and constraints of this stage are consistent with those of the second stage, and the design variables are changed.

Three elements of optimization:

Optimization objective: structural quality minimization.

Design constraints: all paving stresses are less than 500MPa; All bedding strains are less than 0.003, i.e. 3000 microstrains, and wingtip displacements are less than 16.

Design variable: the order in which all layers are stacked

After optimization in this stage, the stacking sequence of 102 paving layers is obtained, as shown in Figure 22.

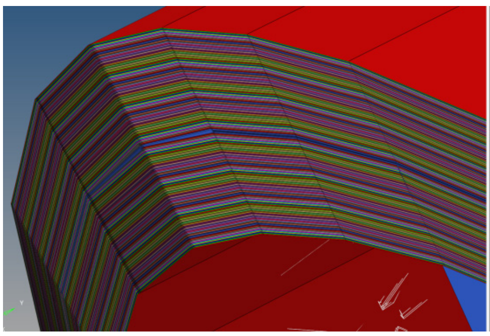


Figure 22. Stacking sequence of 102 paving layers and enlarged image

The result is optimized after layup sequence

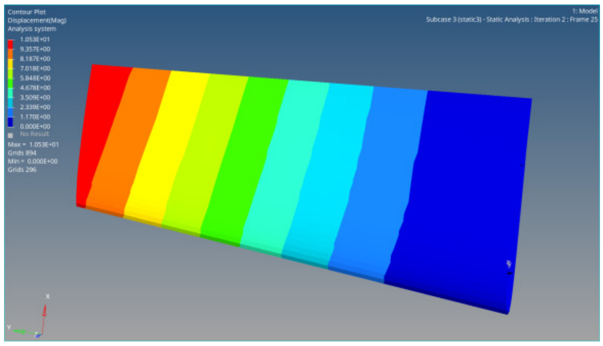


Figure 23. Displacement cloud image after optimization

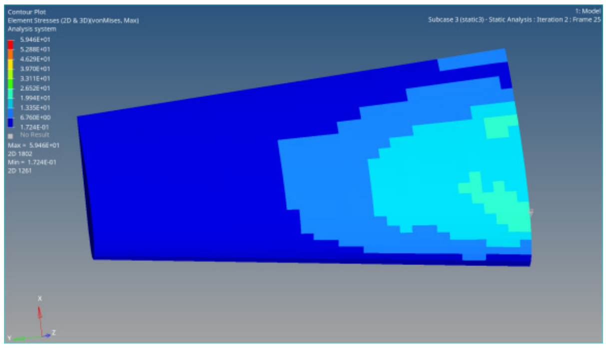


Figure 24. Stress cloud image after optimization

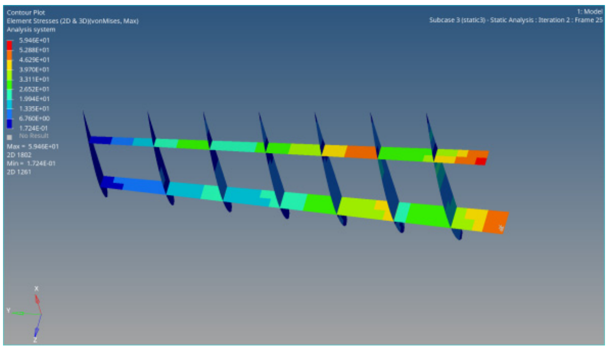


Figure 25. Displacement cloud image of structural parameters after optimization

Comparison results before and after optimization

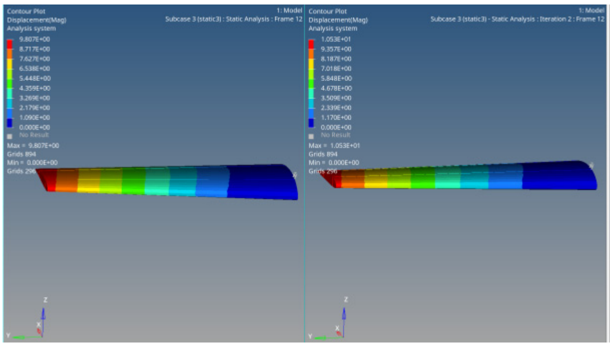


Figure 26. Displacement cloud image of shape parameters after optimization

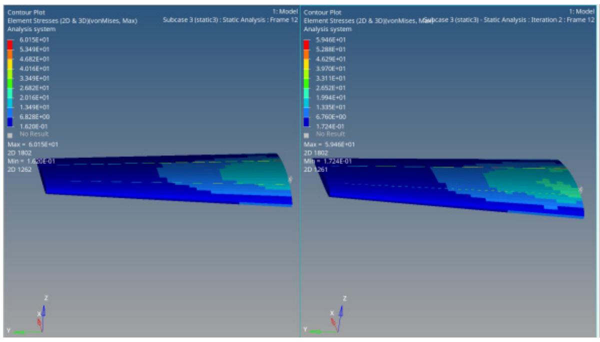


Figure 27. Stress nephogram of optimized shape parameters

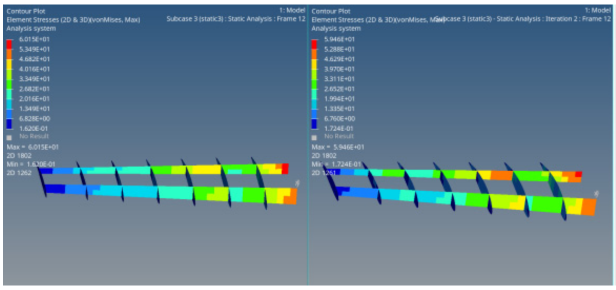


Figure 28. Displacement cloud image of structural parameters after optimization

The results show that the weight of the wing structure is reduced by 16% when the working intensity is satisfied.

5. Summary and Prospect

Based on the analysis of the basic principles and methods of aerodynamic and structural disciplines, this paper presents a multi-disciplinary optimization method for aircraft wing design. First, solidworks is used to establish the overall structure of the robot, and then the wing structure is imported into the finite element analysis software Ansys Fluent. Based on Ansys Fluent, the aerodynamic analysis of the passenger wing is carried out, and the coupling relationship between the aerodynamic and the structure is analyzed. Finally, the structure is optimized under the aerodynamic conditions. The model was imported into the finite element analysis software Optistruct to optimize the skin of mechanical composite. Finally, by comparing and analyzing the performance indexes before and after optimization, the performance indexes of the aircraft wing structure are improved, and the effectiveness of the multidisciplinary optimization method is verified.

Future research directions include further perfecting the multidisciplinary optimization method and expanding the application of multidisciplinary optimization to other aircraft components. Through continuous improvement and development of multidisciplinary optimization methods, it is expected to bring higher economic benefits and environmental performance to the aviation industry. At the same time, with the continuous development of computer technology and artificial intelligence technology, it is expected to achieve a more efficient and intelligent multidisciplinary optimization design method in the future. This will bring new opportunities and challenges to the development of aviation industry.

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