



TILT-DUCT AIRCRAFT WING AERODYNAMIC DESIGN AND OPTIMIZATION BASED ON ADJOINT METHOD

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Abstract

Tilt-duct aircraft is an important trend in the development of future aircraft. Improving aerodynamic and structural performance through optimization design methods is an important means to enhance the overall performance of tilt-duct aircraft. This paper uses an optimization method based on adjoint method to carry out aerodynamic design optimization on the wings of a tilt-duct aircraft. Compared with traditional gradient solving methods such as finite difference method, the adjoint method can obtain the gradient of the objective function by solving the equation in one go, which has higher computational efficiency. It has great advantages for aerodynamic design optimization problems containing large-scale design variables. This paper uses ADflow for aerodynamic analysis calculation, TACS for structural analysis, and OpenMDAO to construct an aerodynamic analysis and optimization framework. An aerodynamic design optimization based on the adjoint method and aero-structural coupling analysis were conducted on the wing of an in-house designed tilt-duct electric vertical take-off and landing (eVTOL) aircraft. Under the requirements of cruising lift coefficient, the drag coefficient was reduced by 1.3% and the KS failure function at the wing root was reduced. The results indicate that optimization based on adjoint method is feasible for solving the aerodynamic design optimization problem of tilt-duct aircraft design.

Keywords: Tilt-duct Aircraft, Adjoint Method, Wing Aerodynamic Design, Aerodynamic Optimization

1. Introduction

Tilt-duct aircraft combines the advantages of helicopters and fixed wing aircraft, and can vertically takeoff and hover, as well as fly at high speed and efficiency. Previous work in literature has focused on conceptual design, disciplinary studies of tilt-duct aircraft [1]. Vigevano [2] optimized the aerodynamic components of the ERICA tiltrotor aircraft model, including the fuselage/wings and airfoil, and then used different CFD software for numerical calculations. The numerical results were compared and analyzed to verify the effectiveness of the optimized model. Haftka [3] combined the lifting-line model with simplified finite element analysis for aero-structure analysis, to iteratively obtain the aerodynamic shape caused by structural deformation. However, coupling analysis and design with high-fidelity aerodynamic and structural models is challenging. Gradient based optimization algorithms and adjoint methods can effectively handle such problem. Martins et al. [4][5] proposed the lagged-coupled adjoint (LCA) for aero-structural design optimization, based on Euler CFD and linear finite element analysis. The method has been successfully applied to the optimization design of supersonic business jet involving 97 shape and size variables [6]. Maute et al. [7][8] have applied discrete adjoint analysis to design optimization problem of flexible multibody dynamic systems such as rotorcraft. Boopatho et al. [9] proposed a parallel finite element framework that utilizes discrete adjoint method for high-fidelity structural dynamic analysis and gradient evaluation. Bombardieri and Cavallaro [10] proposed a gradient based high-fidelity wing aero-structural optimization method assisted by algorithmic differentiation. Gray et al. [11] utilized high-fidelity models to simultaneously optimize the aerodynamic shape and structural size of wings, and applied to the fuel burn minimization analysis of transport aircraft wings with 578 design variables and 1287 constraint conditions.

In this paper, we firstly introduce the methods used for aerodynamic optimization and aero-structural coupling analysis. Then, we conduct aerodynamic design and optimization of the wing for a baseline tilt-duct aircraft based on the adjoint method. While satisfying the requirements of the cruise mode

wing lift coefficient, we achieve the design goal of minimizing the wing drag coefficient. A wing box is designed for the baseline wing and the optimized wing, and aero-structural coupling analysis is further carried out.

2. Methods

2.1 Aerodynamic Analysis

For aerodynamic analysis, open-source code ADflow is used, which is a finite volume CFD solver for structured multi-block and overlapping grids [12]. ADflow solves compressible Euler equations, laminar Navistok equations, and RANS equations. ADflow can also solve discrete adjoint equations, thereby efficiently calculating derivatives, and the computational cost is independent of the number of design variables, making it suitable for large-scale aircraft aerodynamic design optimization problems [13] [14]. The solution of discrete adjoint in ADflow uses algorithmic differentiation (AD) to calculate partial derivatives and Krylov method to solve linear systems.

2.2 Geometric Parameterization

In order to parameterize the geometric shape of the aerodynamic model during optimization, pyGeo [15] was used, especially its free-form deformation (FFD) implementation. This method embeds the grid nodes of the model into a volume defined by a set of control points. Then spline-based interpolation is used to smoothly map the deformation at the control points to the embedding points. Due to the analytical nature of the mapping, it is possible to quickly and accurately calculate the derivative of the embedded point coordinates relative to the user-defined design variable (indicating control point deformation) [16].

2.3 Structural Analysis

The open-source Toolkit for the Analysis of Composite Structures (TACS) is used for structural analysis, which is a gradient based integrated parallel optimization design finite element analysis tool aimed at using specialized parallel solving methods to solve large-scale high-fidelity structural optimization problems with thousands of design variables, millions of state variables, and hundreds of load conditions [17]. TACS uses gradient based methods to achieve large-scale high-fidelity applications and solves the problem of effectively evaluating the gradient of objective and constraint functions in design optimization problems. The KS failure function used in TACS calculates the failure load based on the strain failure criterion, which can characterize the overall strength of the structure and reduce the number of constraints during optimization design.

2.4 Optimization Algorithm

To solve the optimization problem, we use open-source platform OpenMDAO for system analysis and multidisciplinary optimization, which can decompose models and solve them using tightly coupled and efficient parallel numerical methods [18]. In our study, the SLSQP (Sequential Least Squares Programming) method is selected, which is capable of solving mathematical problems with constraints and objective functions that are quadratic continuous differentiable [19]. In the SLSQP solver, each step solves two sub problems: linear programming (LP) and equality constrained quadratic programming (EQP). LP is used to determine the effective set, and EQP is used to calculate the total number of steps, which can handle constraints on the problem. The SLSQP algorithm has fast local convergence speed and global convergence.

3. Results

3.1 Optimization problem settings

The work of this paper is based on an in-house designed tilt-duct electric vertical take-off and landing (eVTOL) aircraft. Figure 1 shows the 3-D view of the reference tilt-duct aircraft. The aerodynamic design optimization is carried out on the wing of the reference tilt-duct aircraft. Figure 2 and Table 1 show the geometric layout and parameters of the wing. The aerodynamic mesh and FFD points are presented in Figure 3.

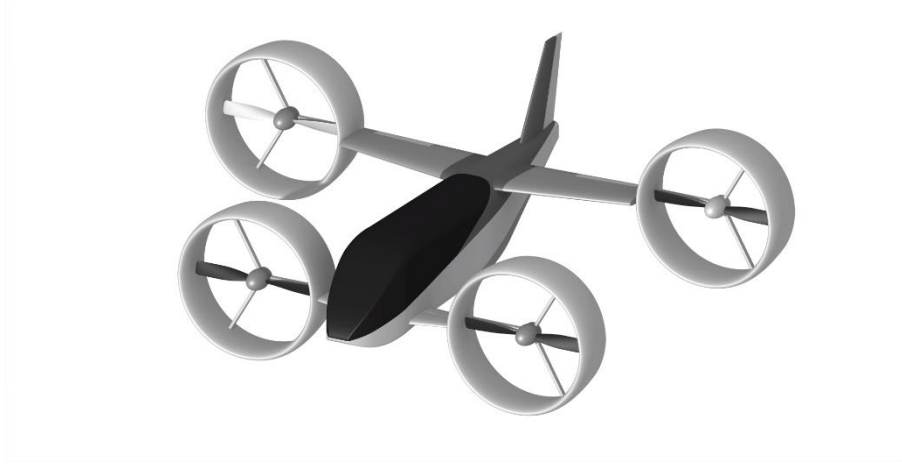


Figure 1 – Reference tilt-duct aircraft.

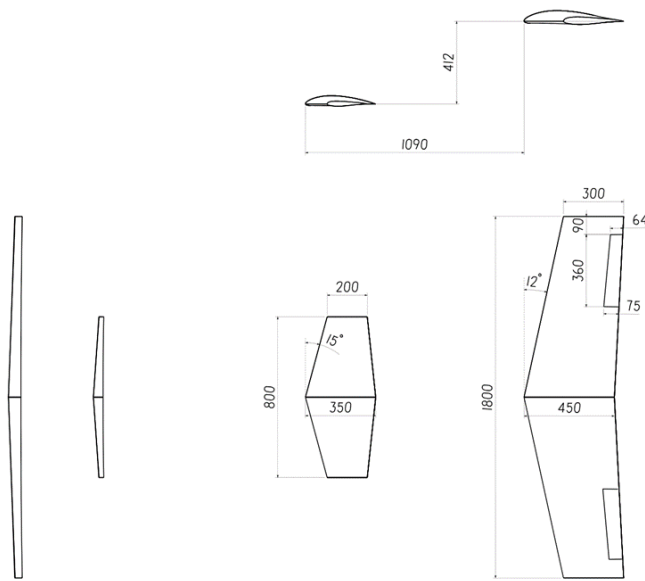


Figure 2 – Wing layout of reference tilt-duct aircraft.

Table 1 – Geometric parameters of wing.

	Main Wing
Span, m	1.8
Wing Area, m ²	0.675
Aspect Ratio	4.8
Root Chord, m	0.45
Tip Chord, m	0.3
Taper Ratio	0.67
LE Sweep angle, °	12.3
Dihedral Angle, °	0

In this paper we focus on the aerodynamic design optimization problem of the reference tilt-duct aircraft wing, mainly considering the aerodynamic characteristics of the main wing under the cruise mode, where the flight speed and altitude of the aircraft are fixed. The wing's twist angle, thickness,

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and angle of attack are optimized under specific lift coefficient to obtain the minimum drag coefficient. Table 2 summarizes the formulation of the aerodynamic optimization. The objective function is the drag coefficient. 96 FFD points were used to control the local wing shape at 8 spanwise positions, as shown in Figure 3. In addition, 8 wing twist angles at spanwise positions are selected as the design variables. The total number of design variables is 105. We constrain the lift coefficient to 0.5. In addition, we limit the local wing thickness to be greater than or equal to the baseline thickness. Finally, we constrain the total volume of the optimized wing to be greater than or equal to the volume of the baseline wing. In total, we have 118 design constraints including fixed leading and trailing edges.

Table 2 – Aerodynamic optimization settings of wing.

	Function or variable	Description	Quantity
Minimize	C_D	Drag coefficients	
With respect to	Δz	Displacement of FFD points in the vertical direction	96
	γ	Wing twist	8
	α	Angle of attack	1
	Total design variables		105
Subject to	$C_L=0.5$	Lift-coefficient constraint	1
	$t \geq t_{\text{baseline}}$	Minimum-thickness constraint	100
	$V \geq V_{\text{baseline}}$	Minimum-volume constraint	1
	$\Delta z_{LE}^{\text{upper}} = -\Delta z_{LE}^{\text{lower}}$	Fixed leading-edge constraint	8
	$\Delta z_{TE}^{\text{upper}} = -\Delta z_{TE}^{\text{lower}}$	Fixed trailing-edge constraint	8
	Total constraint		118

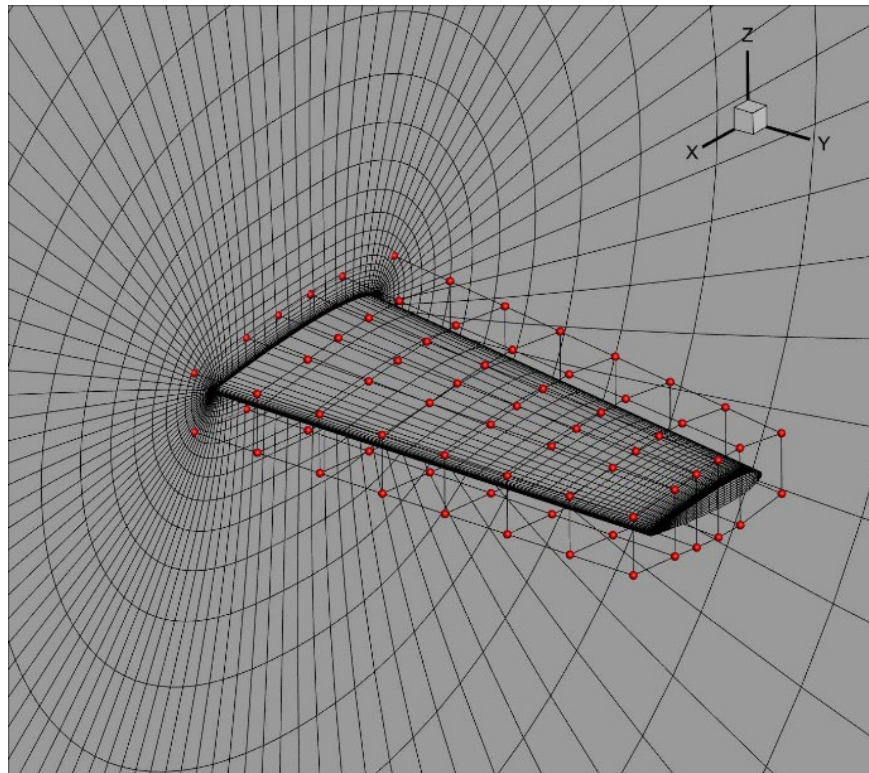


Figure 3 – Aerodynamic mesh and FFD points of wing.

3.2 Wing aerodynamic optimization results

The pressure coefficient distribution on the wing surface between the baseline wing and optimized wing is shown in Figure 4, and the wing shape and pressure distribution at different cross-sections along the spanwise direction are shown in Figure 5. After 64 steps of iterations, convergence was achieved, resulting in a 1.3% reduction in drag and a 1.4% increase in lift to drag ratio. This was achieved by fine-tuning the wing shape and twist angle distribution. The variation of the lift to drag ratio of the wing before and after optimization with the angle of attack is shown in Figure 6. The maximum lift to drag ratio that the optimized wing can achieve increases by 1.3%. When the angle of attack is less than 6° , the lift to drag ratio of the wing increases.

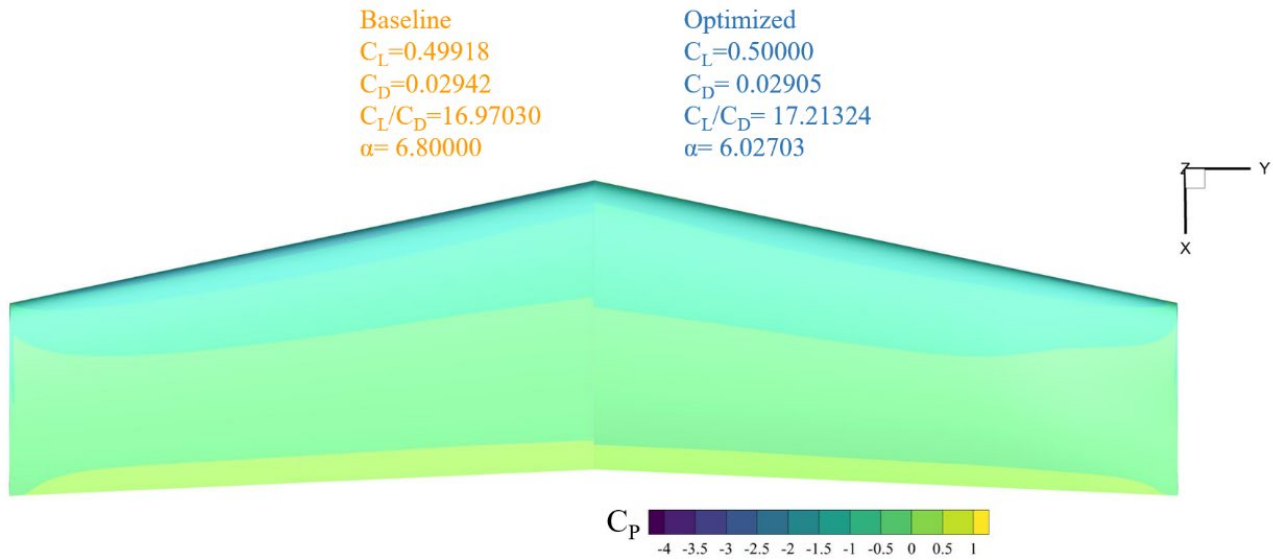
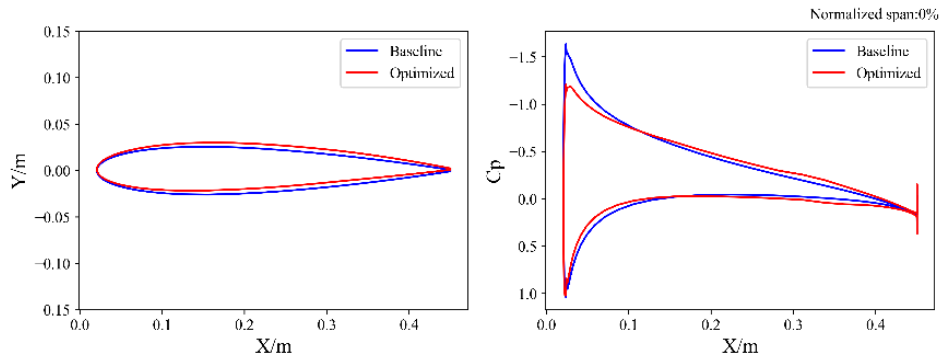
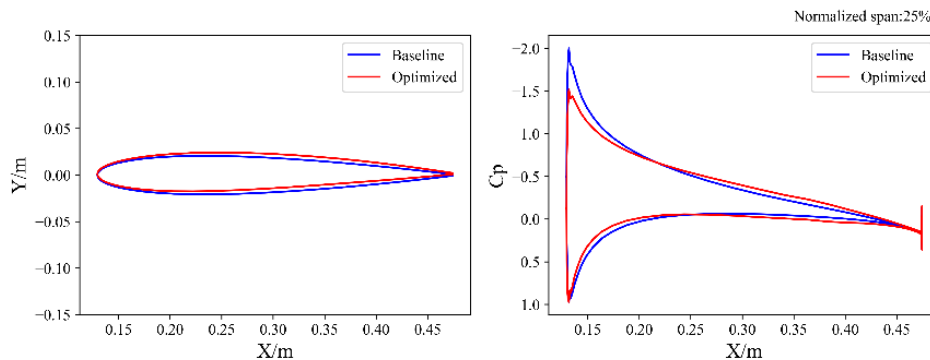


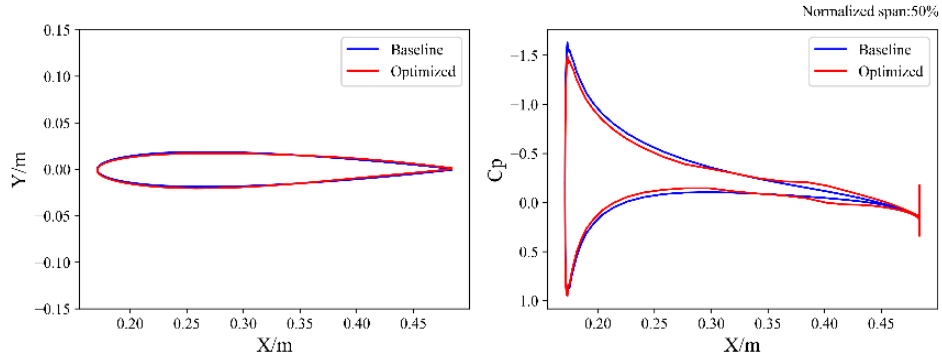
Figure 4 –The surface pressure distribution of baseline wing and optimized wing.



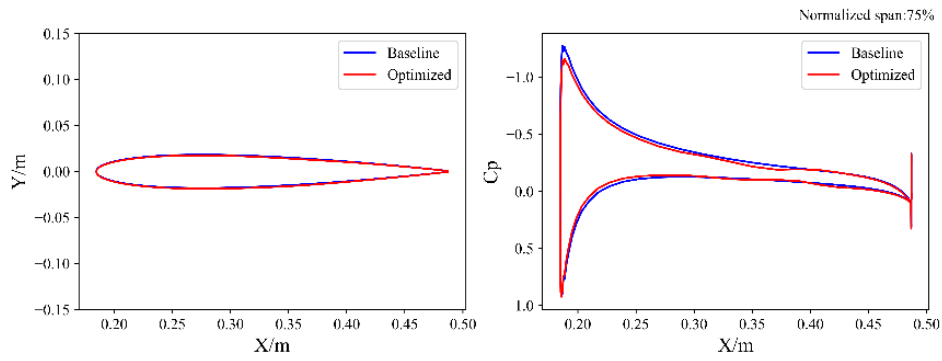
(a) Comparison of geometric shape and surface pressure coefficient of wing root cross-section.



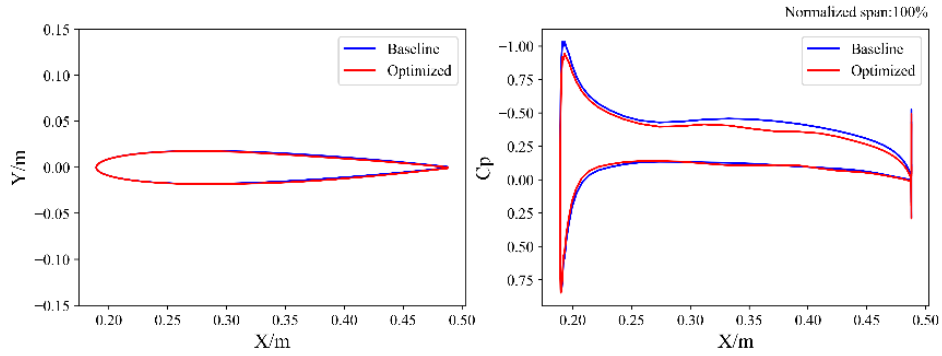
(b) Comparison of geometric shape and surface pressure coefficient of 0.25 wingspan cross-section.



(c) Comparison of geometric shape and surface pressure coefficient of 0.50 wingspan cross-section.



(d) Comparison of geometric shape and surface pressure coefficient of 0.75 wingspan cross-section.



(e) Comparison of geometric shape and surface pressure coefficient of wing tip cross-section.

Figure 5 – Comparison of wing cross-section geometric shape and surface pressure coefficient before and after optimization.

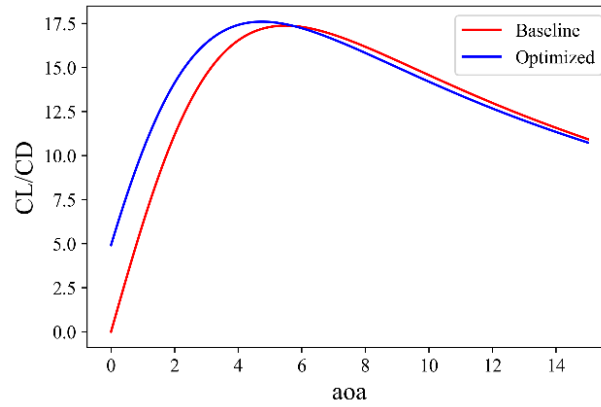


Figure 6 – Comparison of wing lift to drag ratio with angle of attack before and after optimization.

3.3 Aero-structural coupling analysis

After the wing aerodynamic optimization, we also carried out the aero-structural analysis. First, we have constructed the wing box for both the baseline and optimized wing, as shown in Figure 7. The leading edge is located at 10% chord length and the trailing edge is located at 80% chord length, with 4 ribs in total. The baseline wing box structural mesh is shown in Figure 8. The optimized wing box structural mesh is shown in Figure 9. The aero-structural coupling analysis was conducted on the baseline wing and the optimized wing, and the results are shown in Figure 10. Due to the small wing span of the reference tilt-duct aircraft, the deformation of the wing during flight is relatively small. Aero-structural coupling analysis does not significantly improve the prediction of wing aerodynamic performance. However, aero-structural coupling analysis can indicate a significant reduction in the KS failure function at the connection between the wing box and the fuselage after optimization.

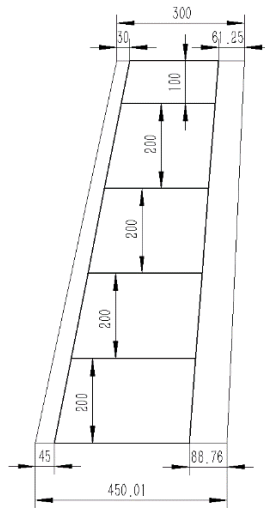


Figure 7 – Wing box layout.

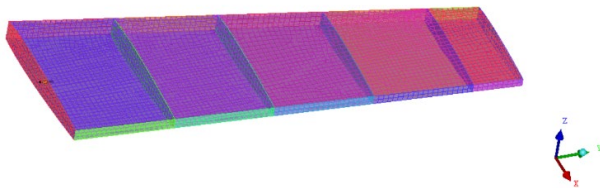


Figure 8 – Baseline wing box structural mesh.

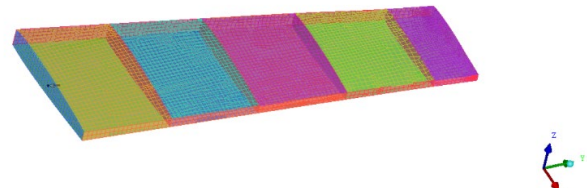
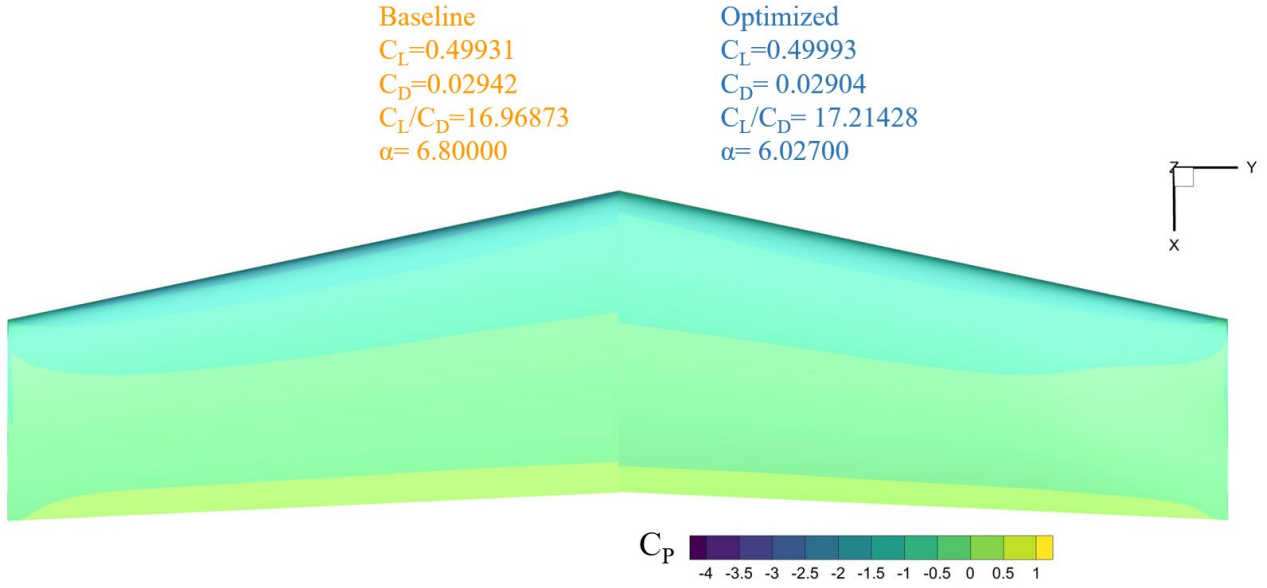
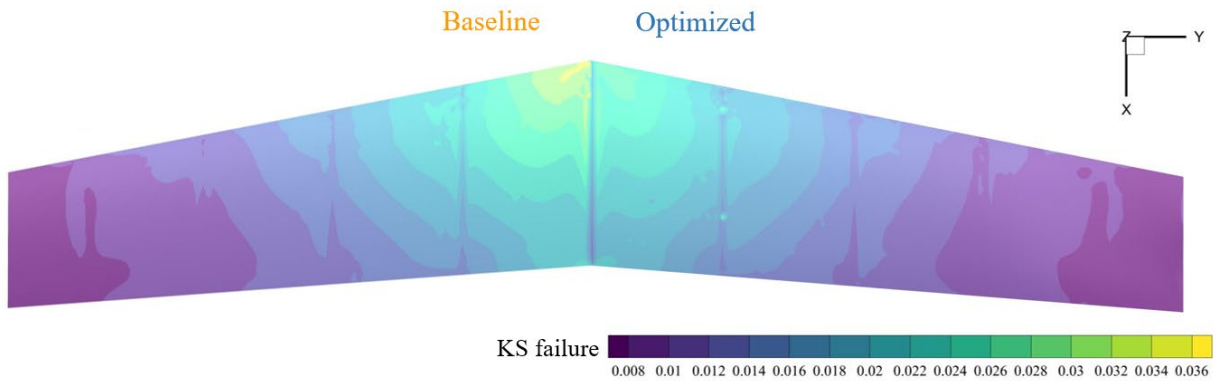


Figure 9 – Optimized wing box structural mesh.



(a) Comparison of wing surface pressure coefficients obtained from aero-structural coupling analysis before and after optimization.



(b) Comparison of KS failure functions obtained from aero-structural coupling analysis before and after optimization.

Figure 10 – Results of wing aero-structural coupling analysis before and after optimization.

4. Conclusion

This paper attempts to optimize the wing of an in-house designed tilt-duct aircraft using an adjoint based aerodynamic optimization method. In order to optimize the aerodynamic performance of the main wing of the tilt-duct aircraft, a high-fidelity aerodynamic optimization method based on the adjoint method was adopted. Then, we have optimized the aerodynamic shape of the wing using 105 design variables and 118 design constraints. The optimized wing shape reduces drag and improves the aerodynamic performance of the wing. In order to verify the aerodynamic performance of the optimized wing geometry, aero-structural coupling analysis was conducted on the wing, and it was found that the optimized wing shape can reduce the KS failure function at the wing root.

As the work is quite preliminary, further study on the overall aircraft component as well as the aero-structural coupled design and optimization can be carried out to explore the design space and further improve the performance of the aircraft.

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