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PHYSICALLY-BASED MULTIDISCIPLINARY DESIGN OPTIMIZATION FRAMEWORK COUPLING AIRFRAME AND PROPULSION

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Abstract

There are lots of options and tradeoff among various disciplines in aircraft conceptual design, which calls for appropriate models with adequate fidelity at lower computational costs. In this work, the models based on fundamental physical principles are promoted for the conceptual design of the civil aircrafts. Adopting a global optimization technique, a multidisciplinary design optimization framework (MDOF) is constructed that can optimize the airframe and propulsion simultaneously. The efficiency and the effectiveness of the framework are validated by optimizing a civil aircraft at minimum takeoff gross weight with nine airframe variables and two engine cycling parameters. The results indicate the interactions between airframe and propulsion. The takeoff gross weight is decreased by 2.88% through aerodynamic and propulsive improvement at the expense of increased engine weight.

1 Introduction

The process of aircraft conceptual design involves a broad design space and tradeoff among disciplines [1]. The design evaluations have been obtained from a variety of sources. In the past, the approaches relied on historical database and empirical equations that provided the majority of data required in design [2, 3]. Recently, numerical simulation techniques such as the computational fluid dynamics (CFD) and the structural finite element method (FEM) play more and more important role in aircraft design.

Historically-based design methods are unreliable when they are employed outside of their data-fit ranges. Considering the potential of new technologies for advanced aircrafts, traditional methods should be abandoned because of their limitations. High-fidelity methods offer more accurate results at the expense of high computational costs, which are typically used in detailed design.

The optimization of aircraft in conceptual design requires many repetitive calculations of numerous configurations for different disciplines. Using high-fidelity models leads to extensive computing costs, while traditional models are significantly faster but less accurate or even inaccurate when applied outside their ranges. Therefore, it is essential to find a way to balance the fidelities of analysis models and their efficiency for aircraft multidisciplinary design optimization (MDO).

Constant efforts have been made to develop appropriate models for subdisciplines. Velden et al. [4] made application of MDO for the aerostructural design of a large transport aircraft, in which the section drag of the wing was determined by the database of swept airfoils. This model cannot be employed in optimization, where the airfoil parameters are the design variables. Mariens et al. [5] built a rapid aerodynamic solver with sufficient accuracy for wing MDO. However, only the weight and lift-to-drag ratio of the wing were taken into account in the optimization with the rest weight and drag of the aircraft keeping constant, which limits its applications to the wing design rather than the aircraft design. Apart from the work done on simplified models, a well-constructed

MDO strategy could also promote the computational efficiency. Most applications combine high-fidelity models with surrogate models or the adjoint method [6-8], which decrease the computational costs dramatically. Due to the complexity of the trade studies and the lack of geometric detail in conceptual design of an aircraft, it is impractical to use high-fidelity methods at early design stages. Moreover, it is prone to converge on local optimal solution with only gradient-based optimization algorithm. Consequently, to fully optimize an aircraft, each stage of the design process needs to use the combination of the appropriate level of analysis fidelity and the appropriate type of optimization technique [9].

A multidisciplinary design optimization framework (MDOF) is constructed in this work to optimize the airframe and propulsion simultaneously. To balance the analysis fidelity and the computational costs, physically-based models are coupled to the genetic algorithm that can handle complex design spaces and overcome local minima. The weight is analysed by a quasi-analytical method that can estimate the primary structural weight according to the geometry, stresses and material properties. The aerodynamic performance is obtained by a quasi-three-dimensional (Q3D) method that is capable of predicting the drag of wing. The drag of other components is predicted by the standard flat plate skin friction formula. A component-based turbofan model is employed to analyse the engine performance and size the engine. The theories of the proposed weight, aerodynamic and engine models are described in the following sections. The validation work has established the applicability of these models. The application of MDOF to the design of a civil aircraft is included to illustrate the overall capability.

2 Design Methodology

The analysis models and the optimization techniques are the key of MDO in civil aircraft conceptual design. In this section, the structure of MDOF program is briefly described, and the analysis models for the weight, aerodynamics, engine and aircraft performance are presented.

2.1 Optimization Framework

A MDOF Matlab program with its major modules based on the low-fidelity physical models is constructed in present work, as shown in Fig. 1. The analysis starts with an initial design under specified design requirements. The weight estimation and aerodynamic analysis are applied to size the engines to meet required thrust. To trim the aircraft, the horizontal tail area S_h is adjusted according to weights and aerodynamic moments. The engine performance data together with mission profiles returns the fuel weight. The new fuel estimation then feeds back to the initial weight estimation and iterations should be taken until a converged stable takeoff gross weight is obtained. The design variables chosen among airframe and propulsion parameters are fed into the genetic algorithm [10] for global exploration. Ultimately, the optimized design is obtained after the evolution of 50 generations.

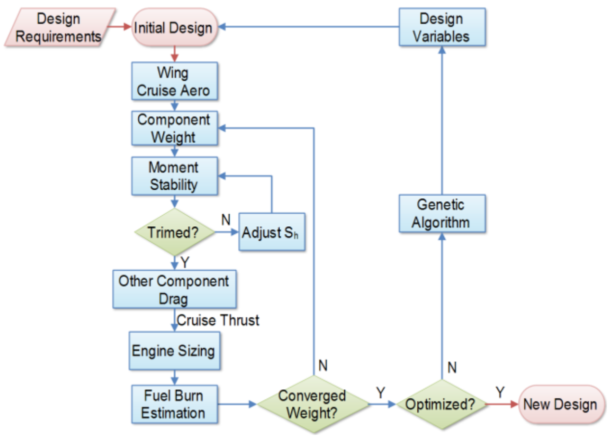


Fig. 1 MDOF Flow Chart

2.2 Weight Module

In the structure and weight module, the primary structure weights are calculated by element weights imposed at the critical loading cases [11]. Only minor structural weights and fixed weights are estimated via historical data.

The fuselage is treated as a pressure vessel with circular cross-section. Considering the stress caused by pressurization, bending and torsion loads, the weights of structural elements are determined. The wing is regarded as a cantilevered beam with a structural box cross-section consisting of spar caps and shear webs.

The aerodynamic lift distribution on wing is achieved from aerodynamics module. The concentrated engine weight load and the distributed weight loads of the structure and fuel are also imposed on the wing resulting in bending moments and shear stresses. The gauges of structural elements are sized to achieve these specified stresses. The known material density then gives the simplified wing box weight. The total wing weight is proportional to the wing box weight based on the linear regression of existing wing weight data [12]. Similarly, the weights of horizontal tail and vertical tail can be obtained.

2.3 Aerodynamics Module

The aerodynamic performance of the wing is obtained by a quasi-three-dimensional (Q3D) method which is suitable for the wing of civil aircraft with relative large aspect ratio. The approach combines sectional airfoil forces with the corrected swept wing theory [5] to get the profile drag (including the friction drag and the form drag) and the wave drag. The induced drag is calculated by an integral on the Trefftz plane. Apart from the wing drag, the drag of other components is predicted by the standard flat plate skin friction formula, and form factors are used to estimate the effect of thickness on drag.

The geometrical and aerodynamic relations between streamwise and perpendicular airfoil sections on the infinite swept wing are show in Fig. 2. The performance of a series of transonic airfoils with various thicknesses is calculated by Reynolds-Averaged Navior-Stokes Equations (RANS) under different flow conditions. The results are used to build a surrogate Kriging model [13] to predict the primary forces of sectional airfoils perpendicular to the half chord sweep line. The drag can be broken down into the friction drag and the pressure drag in terms of a nearfield calculation, and the wave drag is included in the pressure drag component. The perpendicular-plane force coefficients are then obtained from the surrogate model with the formulae:

$$C_{l_\perp} = C_l(\alpha, Ma_\perp, c_\perp, (t/c)_{\max}) \qquad (1)$$

$$C_{d_{f\perp}} = C_{d_f}(\alpha, Ma_\perp, c_\perp, (t/c)_{\max}) \qquad (2)$$

$$C_{d_{p\perp}} = C_{d_p}(\alpha, Ma_\perp, c_\perp, (t/c)_{\max}) \qquad (3)$$

where, $Ma_\perp = Ma_\infty \cos\Lambda$, $c_\perp = c\cos\Lambda$.

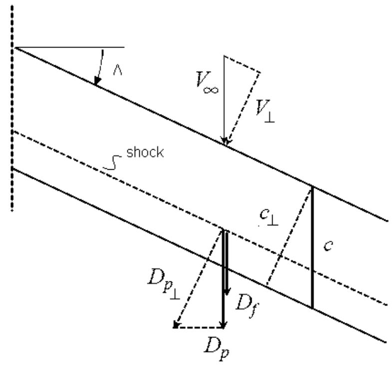


Fig. 2 Friction and pressure drag coefficients on an infinite swept wing

The 2D streamwise force coefficients are got from swept wing theory. As explained by Reference [11], the friction drag acts along the freestream flow direction, while the lift and the pressure drag are scaled with the dynamic pressure normal to the wing spanwise axis. Thus, the local streamwise aerodynamic force coefficients are given as follows:

$$C_l = C_{l_\perp} \cos^3\Lambda \qquad (4)$$

$$C_{d_f} = C_{d_{f\perp}} \qquad (5)$$

$$C_{d_p} = C_{d_{p\perp}} \cos^3\Lambda \qquad (6)$$

The aforementioned relations are exact for laminar flow on infinite swept wings, and quite accurate for turbulent flow [11]. However, these are unrealistic at the wing root, where isobars tend to curve rearwards due to the root effect on tapered swept wings [14]. The corrected formula is

$$C_{dp} = C_{d_{p\perp}} \left[f + (1-f)\cos^2\Lambda \right] \cos\Lambda \qquad (7)$$

where, $f(y) = \exp\left(-\frac{1}{k} \frac{y - y_0}{c(y)} \right)$, $k \approx 0.5$.

The Trefftz plane method is applied to obtain the induced drag coefficient C_{Di}. The wing lift and profile drag coefficients are calculated by numerical integration along spanwise direction. The summation of the induced drag and the profile drag then gives the total wing drag as follows:

$$C_L = \frac{1}{S}\int_{b_0}^{b} C_l(y)c(y)dy \qquad (8)$$

$$C_{D_{\text{prof}}} = \frac{1}{S}\int_{b_0}^{b}\left(C_{d_p}(y)+C_{d_f}(y)\right)c(y)dy \qquad (9)$$

$$C_D = C_{D_{prof}} + C_{D_i} \qquad (10)$$

2.4 Engine Module

A component-based turbofan model with variable specific heats $C_p(T)$ [15, 16] is used to analyse engine performance and to size the engines. The model consists of the parametric cycle analysis for design case and performance cycle analysis for off-design cases, allowing the simultaneous optimization of engine design parameters and the overall airframe parameters. Unlike the approaches relied heavily on established engine performance maps and correlations, the component-based model is quite suitable for highly advanced engines falling outside of historical databases.

For a civil aircraft, the cruise condition represents the design case, and the off-design cases include takeoff, climb, descent et al. The design case cycle analysis is able to examine trends in engine performance and find optimum engine design parameters. The off-design analysis gives actual components behavior in different operating conditions. The engine mass flow and components area are sized at cruise first. Then, the off-design performance of takeoff is analyzed to adjust the cruise mass flow to meet the thrust-to-weight ratio.

In terms of fuel saving, the engine will tend to reach the highest bypass ratio (BPR) and operational pressure ratio (OPR) to maximize the propulsive efficiency. On the other hand, high BPR and OPR will bring engine system weight penalty. To get a reasonable combination of design parameters, the weight of the engine system is calculated using an assumed dependence on cycle parameters. The correlations in reference [11] are applied to estimate the bare engine weight, and the whole engine system weight is proportional to it.

2.5 Performance Module

The mission fuel weight is estimated using the method presented in reference [1]. For the civil aircraft, the typical mission profile is: takeoff, climb, cruise, descent, and landing. The required fuel at cruise is got from Bréguet's range equation,

$$\frac{W_{i+1}}{W_i} = \exp\frac{-RC}{V(L/D)} \qquad (11)$$

where, R indicates range including descent distance, C represents the specific fuel consumption of the cruise condition achieving from the engine module, V is the cruise velocity and (L/D) is the cruise lift-to-drag ratio estimated by the aerodynamics module.

The statistical factors are used to estimate the fuel weight of the other flight mission segments. Assuming a 6% reverse and trapped fuel, the fuel weight can be determined from the mission segment fuel fractions and the takeoff weight using equation:

$$W_{\text{fuel}} = 1.06\left(1-\prod_{i=1}^{n-1}(W_{i+1}/W_i)\right)W_{\text{to}} \qquad (12)$$

3 Model Validations

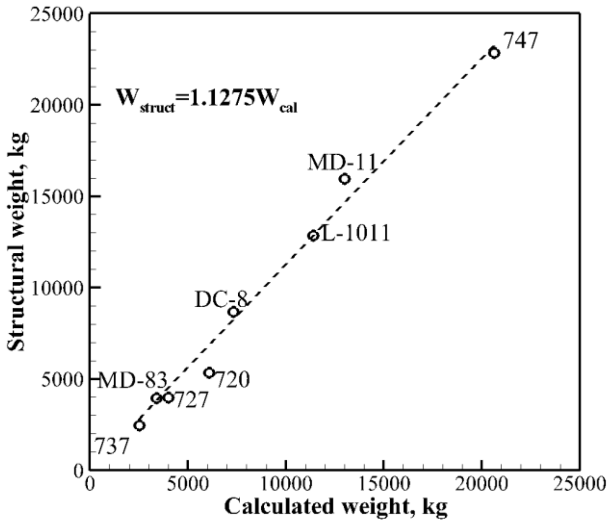
The proposed weight, aerodynamic, engine, and performance analysis methods are validated for accuracy and applicability.

3.1 Weight Estimation

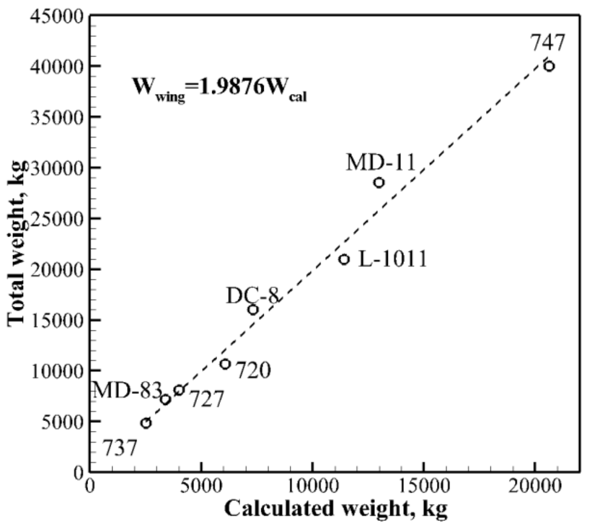
With the assumption of simplified wing box, the calculated wing structural weight is different from the real value. The relations between calculated value W_{cal} and the wing structural weight W_{struct} and the total wing weight W_{wing} could be obtained from the civil transport aircraft data by linear regression [12], as shown in Fig. 3. Using the obtained correction factor, the total wing weight could be well estimated.

$$W_{struct}=1.1275W_{cal} \quad R=0.9867 \qquad (13)$$

$$W_{wing}=1.9876W_{cal} \quad R=0.9850 \qquad (14)$$



(a) Wing structural weight



(b) Total wing weight
Fig. 3 Wing weight and linear regressions

3.2 Aerodynamic Performance

The Q3D method is validated for transonic conditions at the angle of attack 3.0° and the Mach number ranging from 0.5 to 0.85. RANS is employed as a comparable high-fidelity method. A wing of a traditional civil aircraft cruising at Mach number Ma=0.73 and Reynolds number Re=2.51×10^7 is chosen to be the validation case. Fig. 4 shows relatively high accuracy of the Q3D method in the aerodynamic coefficients for Mach number below 0.78. However, the method is unable to predict the flow separation resulting in the failure of lift and pressure drag prediction when reaching drag divergence Mach number.

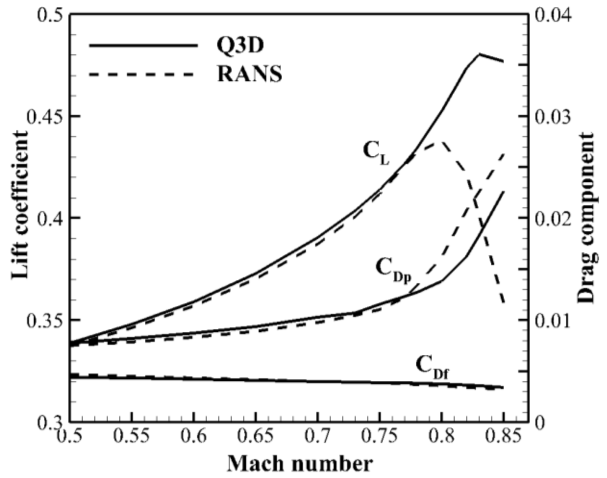


Fig. 4 Comparison of aerodynamic forces for both methods at transonic condition (α=3.0°)

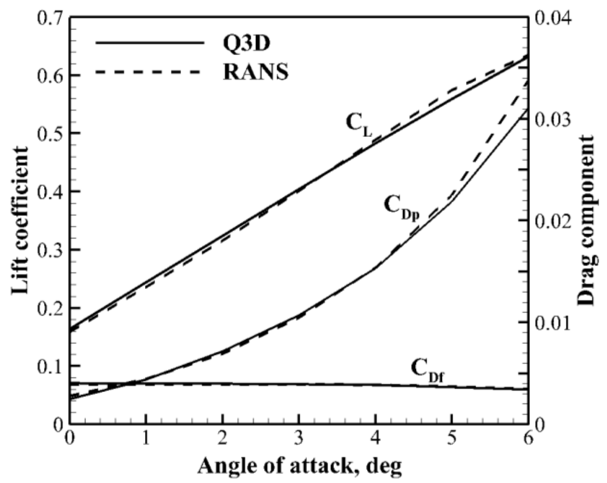


Fig. 5 Comparison of aerodynamic forces for both methods at cruise

In addition, the Q3D method is also validated using the same wing at cruise condition. Fig. 5 illustrates the comparison of aerodynamic force coefficients for Q3D and RANS method. The lift and drag coefficients are well predicted at the angle of attack below 4.0°, which is appropriate for the cruise design condition. There is a very good agreement in the friction drag component between the two methods, while the Q3D method predicts a smaller pressure drag as the flow separation begins to occur at the wing tip. As there is nearly no flow separation around cruise condition for the wing of civil aircraft, it is reasonable to apply Q3D method to estimate the aerodynamic performance of the wing of civil aircraft. The computational costs are much lower than high-fidelity methods while maintaining enough accuracy.

3.3 Engine Performance

For turbofan engines, BPR and OPR are the most important parameters among all engine system design variables for the propulsive efficiency. Fig. 6 presents the parametric results of the specific performance for variation in BPR and OPR. These results are obtained at *Ma*=0.73 and *H*=35000ft with all the airframe and engine parameters except for BPR and OPR unchanged. As can be seen in this figure, increasing either BPR or OPR generally reduces the specific fuel consumption, while increasing BPR decreases the specific thrust.

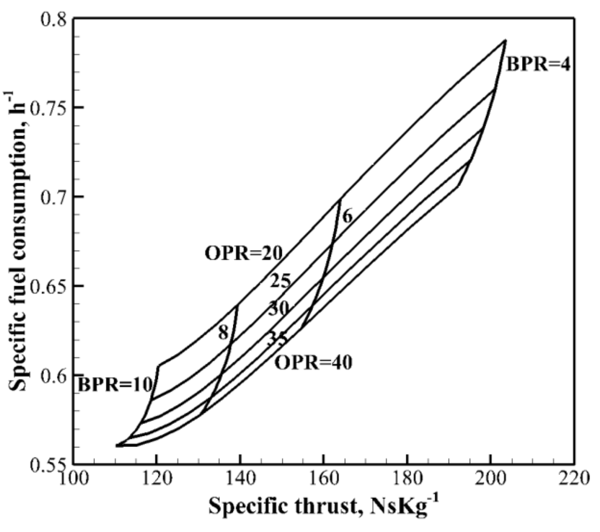


Fig. 6 Specific performance of a turbofan engine

BPR and OPR not only have impact on propulsive efficiency, but also influence the engine system weight, which affect the aircraft takeoff gross weight ultimately. The influence of BPR and OPR on the aircraft weights is studied by MDOF, as shown in Fig. 7 and Fig. 8.

Similar to the trends in propulsive efficiency, the fuel weight decreases as the BPR or the OPR increases, while the engine weight increases, which can be regarded as a whole to achieve a minimum takeoff gross weight W_{to} at specific design parameters. Both the fuel weight and the engine weight are more sensitive to the change of BPR.

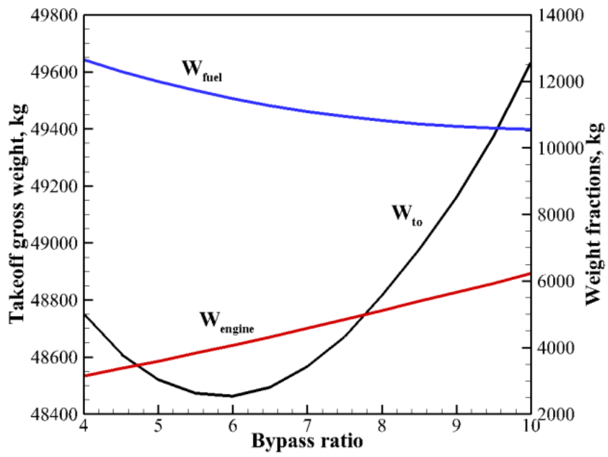


Fig. 7 BPR influence on weights

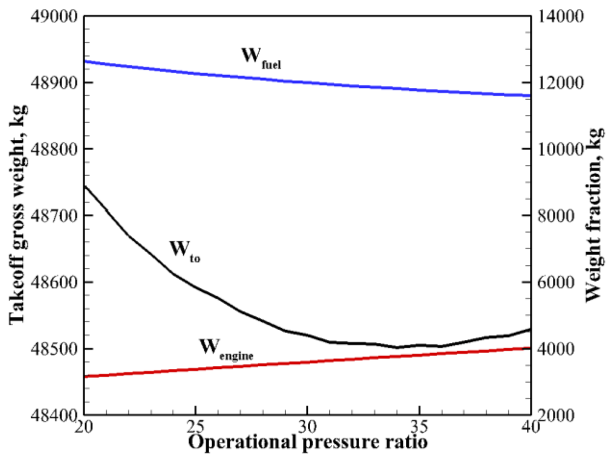


Fig. 8 OPR influence on weights

4 Optimization Case Study

A case study of civil aircraft is optimized at cruise condition (*Ma*=0.73, *Re*=2.51×10^7) to test MDOF program with the design requirements of 2000 nautical miles range and 110 passengers.

4.1 General Description

In this optimization, the takeoff gross weight is chosen as the system level objective to optimize airframe and propulsion simultaneously. There are totally eleven design variables selected from airframe and propulsion parameters, nine geometry variables of which are wing planform and sectional airfoil thickness parameters (as shown in Fig. 9). Another two are engine cycling parameters, BPR and OPR at the cruise design point. The design variables together with their initial values and bounds are listed in Table 1. The airfoil shapes are generated by the summation of the camber line and the thickness line with the rest parameters keeping constant except for the maximum thickness.

Table 1 Design variables and design space

Parameter	Initial	Upper boundary	Lower boundary
c_o/m	4.904	4	6
c_k/c_o	0.749	0.6	0.8
c_t/c_o	0.248	0.15	0.4
b/m	27.678	20	35
b_k/b	0.430	0.3	0.55
$\Lambda_{1/4}$	25°	15°	40°
$(t/c)_o$	0.126	0.10	0.15
$(t/c)_k$	0.12	0.08	0.15
$(t/c)_t$	0.112	0.08	0.15
BPR	5.0	4.0	10.0
OPR	30.0	20	40

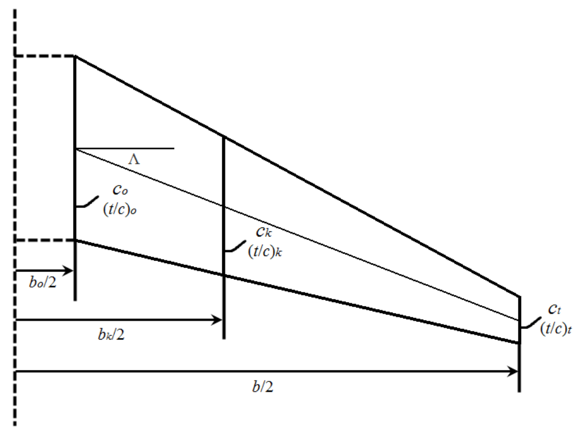


Fig. 9 Wing planform and thickness parameters

Since the design space is considerably diverse, to prevent unrealistic results, the optimization is constrained by fuel volume and wing loading. The fuel volume constraint was implemented to ensure that the required fuel for the flight mission could be stored in the available fuel volumes of the wing. The wing loading has influence on both cruise and low speed performance, and a smaller wing loading will improve the cruise performance while worsen the low speed performance. The wing loading constraint ensures the low speed performance by keeping the wing loading smaller or equal to the initial value.

The optimization problem could be described as follows:

Objective: min W_{to}

Design variables: wing planform and maximum thickness distribution along spanwise direction, BPR and OPR at cruise for a specified engine.

Constraints:

1. The required fuel for the flight mission could be stored in the wing fuel volumes.

$$(V_{\text{fuel}})_{\text{require}} \le (V_{\text{fuel}})_{\text{available}} \tag{15}$$

2. The wing loading should not increase.

$$(W_{\text{to}} / S) \le (W_{\text{to}} / S)_{ref} \tag{16}$$

4.2 Results and Discussion

The genetic algorithm is used to tackle this MDO problem. In the algorithm, the population size and the number of generations are chosen to be 100 and 50, respectively. The optimized wing planform compared with the initial one is shown in Fig. 10 and the detailed optimization results are shown in Table 2. The change of takeoff gross weight and weight fractions shows the tradeoff between airframe and propulsion.

The minimum takeoff gross weight is realized with a higher aspect ratio, thinner wing sections, lower swept angle, larger BPR and OPR. The higher aspect ratio and lower swept angle could improve the aerodynamic performance at cruise, and result in the reduction of fuel weight. The propulsive efficiency improvement is driven by larger BPR and OPR at the expense of the increased engine weight, which also reduces the fuel weight. The reduced swept angle and fuel weight contribute to the wing weight decline. Compared with the initial design, the takeoff gross weight is decreased by 2.88% with satisfying aerodynamic and propulsive efficiency improvement and weight reduction.

Table 2 Optimization result

	Initial	Opt	Change
c_o/m	4.904	4.817	
c_k/c_o	0.749	0.794	
c_t/c_o	0.248	0.197	
b/m	27.69	28.37	
b_k/b	0.43	0.359	
$\Lambda_{1/4}$/°	25	22.3	
$(t/c)_o$	0.126	0.12	
$(t/c)_k$	0.12	0.11	
$(t/c)_t$	0.112	0.082	
BPR	5	6	
OPR	30	35	
L/D	15.19	15.68	+3.22%
W_{engine}/kg	3592	3790	+5.51%
W_{fuel}/kg	11990	10766	-10.21%
W_{wing}/kg	4837	4512	-6.72%
W_{to}/kg	48883	47477	-2.88%

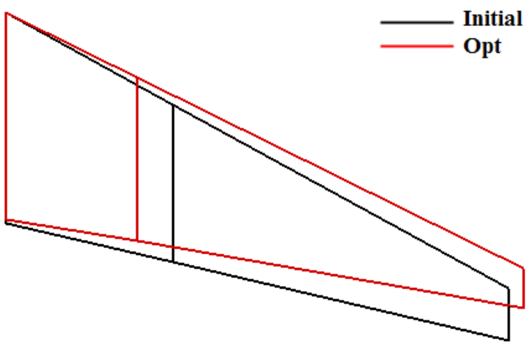


Fig. 10 Planform of initial and optimized wings

5 Conclusion

The MDOF program based its primary models on physical principles is applied to a conceptual aircraft design study with the minimum takeoff gross weight becoming a system level objective.

(1) A quasi-three-dimensional aerodynamic model has been developed to analyze civil aircraft wing aerodynamics rapidly while maintaining relative high accuracy. The validation results show that the Q3D model is appropriate to estimate transonic aerodynamic performance below the drag divergence Mach number for civil aircrafts.

(2) The weight model relied on fundamental structural theory together with the detailed component-based engine simulation allow the application of advanced materials and turbofan engines. These models are important for optimizing airframe and propulsion at the same time.

(3) The MDO results show the interactions between airframe and propulsion. The framework could be applied to the civil aircraft conceptual design considering new technologies and the coupling feature of airframe and propulsion system.

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