Multipoint and Multi-objective Optimization of Airfoil Considering Boundary Layer Ingestion

Rubing Ma and Jianghao Wu(✉)

School of Transportation Science and Engineering, Beihang University, Beijing, China
{marubing, buaawjh}@buaa.edu.cn

Abstract. Blended-wing-body (BWB) aircraft concept coupled with distributed propulsion is proposed as a potential configuration to meet the N + 3 goals. In this configuration, the boundary layer ingestion (BLI) effect resulting from the distributed propulsion enhances the aircraft's aerodynamic performance significantly. The inlet&outlet boundary interacts with the upper airflow strongly, so that the pressure distribution differs from a clean airfoil. However, previous optimization design works mainly aimed at clean airfoil design at cruise conditions. Thus, in this paper, a two-dimensional section of this configuration considering the inlet&outlet boundary conditions of the propulsion system is designed through a multipoint optimization at cruise and climb conditions. We achieve a high lift to drag ratio 2D shape at cruise conditions while improving its climb performance. In addition, we use a weighted-integral method to improve the robustness of the optimal solution and enlarge the drag-divergence Mach number of the solution significantly. Our results may provide qualitative guidance on the future three-dimensional optimization design of the advanced aircraft aerodynamic shape.

Keywords: Boundary layer ingestion · Multi-objective optimization · Weighted sum method

1 Introduction

The concept of Blended-wing-body (BWB) aircraft, a potential configuration to reduce the fuel consumption and noise dramatically in subsonic flights, was first proposed by Liebeck in 1988 [1]. In recent years, the N + 3 goal aiming to reduce noise, pollution and fuel consumption significantly was proposed by NASA [2]. Consequently, the BWB coupled with distributed propulsion system gets the scholars attention again [3, 4]. In this configuration, the propulsion system strongly interacts with the airframe, leading to the boundary layer ingestion (BLI) effect. The BLI effect can change the flow field around the airframe and therefore bring benefits to the aircraft, e.g. wake filling which reducing the pressure drag significantly, engine performance improvement, etc. [5].

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Thus, a model considering the propulsion inlet and outlet boundary conditions rather than a clean airfoil is much more suitable for optimal design of the kind of configuration. In addition, negligible difference can be seen from the two-dimension sections of a BWB coupled with distributed propulsion system along the span. Consequently, an aerodynamic optimal design based on the two-dimension section of the BWB aircraft with distributed propulsion system, which considers the inlet and outlet boundary conditions, is conducted here.

To date, for the aerodynamic optimal design, the computational fluid dynamics (CFD) has been well developed. It can provide comparable predictions of aerodynamic performance with the wind-tunnel experiments. Therefore, a combination of CFD and optimization algorithms is widely used for the optimal design, a classic application of which is the optimal design of cruise configuration [4, 6]. However, practical experience reveals that the optimal solution under one operating condition may result in dramatically inferior performance when the operating condition is changed [7]. In addition, previous review shows that most aviation mishaps happen during take-off and approach stages. Therefore, it is necessary to proceed a multi-objective and multipoint optimization so that the aerodynamic performance during the take-off and approach stages can be taken into the consideration.

The objective of this paper is to carry out a multipoint and multi-objective optimization of a two-dimension section of the BWB aircraft with distributed propulsion system. The advantages of the following three optimal methods: (1) multi-objective weighted-sum method, (2) multipoint weighted-sum method and (3) multipoint weighted-integral method are discussed with the scope of our research. The following criteria: (1) the lift to drag ratio while cruise, (2) the stalling angle while climb and (3) the drag-divergence Mach number are monitored during the optimization and compared with those of a single point optimization.

2 Problem Formulation

2.1 Optimization Method

The aerodynamic shape optimization problem consists of determining values of design variables $\boldsymbol{d}$, such that the objective function J is minimized,

$$\min_d J(\boldsymbol{d}, \boldsymbol{Q}), \tag{1}$$

subject to constraint equations C_i,

$$C_i(\boldsymbol{d}, \boldsymbol{Q}) \leq 0, \qquad i = 1, \ldots, N_c \tag{2}$$

where the vector $\boldsymbol{Q}$ denotes the conservative flow variable and N_c denotes the number of constraint equations.

In this paper, most of optimization in our work was done using the following two optimal method: the weighted-sum method and the weighted-integral method. The weighted-sum method is a widely- used approach solve multipoint and multi-objective problem [8]. It assigns a coefficient to each objective according to their relative importance. Then all the weighted-objectives are summed up and the sum is regarded as the evaluated function:

$$J_m = \sum\nolimits_{i=1}^{N_m} \omega_i J_i, \tag{3}$$

where N_m is the number of objectives, and ω_i is a user-assigned weight for each objective.

In addition, to further improve the robustness of the optimal scheme, we try to use an adjusted method based on the weighted-sum method, i.e. weighted-integral method [7]. It assumes that the dependent variables of the objective function are random variables. Then the statistical expected value is computed as the evaluated function and the decision is made according to the Maximum Expected Value criterion:

$$\rho = \int\limits_X J(\boldsymbol{d}, X) f_X(X) dX, \tag{4}$$

where $f_X(X)$ is the probability density function of the random variable X.

To simplify this equation, when the variability of X is not too large, a second-order Taylor series expansion of objective function around the mean value $\overline{X}$ may be a sufficiently accurate model of the variation of J with respect to X:

$$J(\boldsymbol{d}, X) \cong J\left(\boldsymbol{d}, \overline{X}\right) + \nabla_X J \cdot \left(X - \overline{X}\right) + \frac{1}{2} \nabla_X^2 J \cdot \left(X - \overline{X}\right)^2. \tag{5}$$

When the $J(\boldsymbol{d}, X)$ in Eq. 4 is substituted by the expanding form (5), the linear term $\nabla_X J \cdot \left(X - \overline{X}\right)$ disappears after integration over X because the Taylor series is built around the mean value $\overline{X}$. Finally, the expected value is:

$$\rho = J\left(\boldsymbol{d}, \overline{X}\right) + \frac{1}{2} Var(X) \left.\frac{\partial^2 J}{\partial X^2}\right|_{\boldsymbol{d}, \overline{X}}, \tag{6}$$

where *Var(X)* is the statistical variance of the random variable X.

2.2 Modeling Method

To process our two-dimension optimization, a typical 2D section is extracted out from the BWB aircraft with distributed propulsion, as shown in Fig. 1. There are two parts in the geometric model: a basic airfoil and a simplified engine model. The chord length (c) of the airfoil is 1. The position of the engine-inlet (L_s) is 0.84c. The length of the engine (L_e) is 0.139c. The height of the engine inlet and outlet (E_H) is 0.02c.

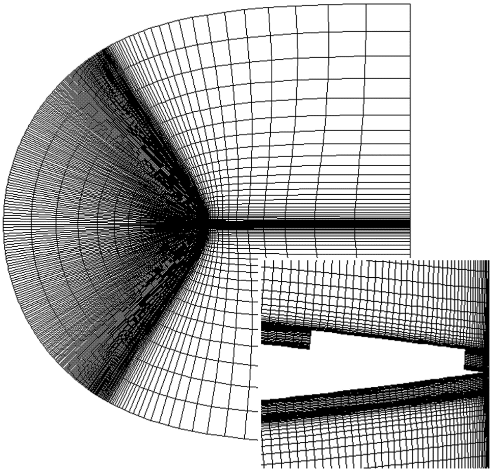

Fig. 3. Typical mesh

The far field boundary conditions is given as the free flow conditions. The engine boundary condition is set to address BLI effect into the flow field. The engine-inlet is set as pressure outlet and the engine-outlet is set as mass flow inlet. We specify the same mass flow rate for engine-inlet and engine-outlet and this rate changes according to different operating conditions.

4 Method Validation

The optimization algorithm, including the CFD scheme, was first validated to ensure an accurate optimal solution given the constrains. Thus, an optimization of two objectives is carried out following the previous work of Nemec and Zingg [9]. We consider the design of a clean airfoil shape to achieve specified lift and drag. Using the weighted-sum method, the objective function is given as follow:

$$\mathrm{J} = \omega(1 - \frac{C_L}{C_L^*})^2 + (1 - \omega)(1 - \frac{C_D}{C_D^*})^2, \quad (8)$$

where ω is the weighted coefficient.

The free flow conditions are $M_\infty = 0.7\, Re = 9 \times 10^6$. And we specify a target lift coefficient at 0.55 and a target drag coefficient at 0.0095. The initial airfoil is the NACA 0012 airfoil. Following the input parameter space introduced by Marian Nemec and David W. Zingg, 14 design variables are used to define the airfoil shape and the angle of attack is also set as an input variable [9]. The comparison of our results and the reference with respect to the aerodynamic coefficients for a few selected solutions are provided in Table 1, where the subscript r refers to the results in the reference [9]. On the one hand, our optimization code achieves almost the same aerodynamic characteristics as Nemec's results. The differences in the angle of attack may result from the

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