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A CONCEPTUAL DESIGN PLATFORM FOR BLENDED-WING-BODY TRANSPORTS

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Abstract

The blended-wing-body (BWB) configuration is an innovative transport aircraft concept to achieve the requirements of the future green aviation. The objective of present work is to promote a physically-based platform to perform multi-disciplinary optimization design (MOD) of a general blended wing body configuration. Low-order physical models based on fundamental structural, aerodynamic principles are used to predict the weight and the aerodynamic performance. The weight of the secondary structures and equipment are predicted by historical correlations. The optimization objective is to minimize the total gross weight and to maximize the aerodynamic efficiency under the constraints on stability using multi-objective GA method. The platform is validated and is applied on the design of a BWB configuration. The results show the feasibility and reliability of the platform.

1 Introduction

The Blended-Wing-Body configuration is a revolutionary concept for commercial transports, which is a potential choice to fulfill the desire to produce environmentally friendly transports [1]. By integrating wings, fuselage, and tails into a single lifting surface, BWB configuration achieves a substantial improvement in performance. Aviation industry shows interest in the ability of BWB configuration to efficiently fly over long ranges at reduced direct operating cost with large capacity. Investigations have been carried out with various purposes at Boeing Company [2, 3], NASA [5], ONERA and DLR [6] for many years. Advantages have been approved that BWB configuration has better aerodynamic characteristics, lower weight, lower fuel burn, lower emissions and lower noise, compared with the conventional tube and wing configuration.

Multidisciplinary design is necessary during the BWB transports conceptual design process. The most representative researches are as follows: Boeing Company employs wing multidisciplinary optimization design code (WingMOD) and obtains the remarkable work of BWB-450 aircraft [2]; Massachusetts Institute of Technology and Cambridge University utilize a quasi-3D airframe design methodology for Silent Aircraft eXperiment (SAX) design [8, 9]; the design methodology is further extended to make a first attempt towards the aggressive N+3 targets [10].

Due to its unique geometry and integrated nature, BWB transport conceptual design faces several difficulties. Attentions must be paid to the following aspects. Firstly, the combination of aerodynamic, structure, stability and control issues are highly connected. This feature requires a conceptual design platform to gain the ability to evaluate each of the issue and find a compromise among the different disciplines. Secondly, the accurate weight prediction remains a challenge, especially for the centerbody structural weight estimation. The centerbody of BWB aircraft functions as a lifting surface and a fuselage with internal pressure. Several structure estimation methodologies have been put forward to solve the complicated loading problem [11]. As no historical data is available, calibration or validation of the weight estimation is difficult. Besides, due to the high cruise speed and strong three dimensional effect of the centerbody, aerodynamic estimation results must be checked by the high-fidelity methods. Finally, the absence of tails emphasizes the importance of stability and control design of the BWB transports.

In order to explore the design space to get reasonable predicted results, BWB conceptual design platform should apply physically-based approaches that are time efficient with adequate accuracy. Advanced Aircraft Analysis (AAA) by DARcorp [12], RDS by Ramyer [13], and Torenbeek's handbook methods [14] are the representative traditional conceptual design platforms that provide quick and reasonable results towards conventional tube and wing aircrafts. Dommelen's study details the first step towards the implementation of traditional design methods to enable preliminary sizing of a BWB [15]. However, these methods depend on empirical data. Due to the lack in historical data, empirical methods are not reliable to evaluate the innovative configuration with advanced technology assumptions. Higher-fidelity methods, such as computational fluid dynamics and finite element analysis, are so time-consuming that is not suitable for conceptual design. Thus, it is desirable to promote the conceptual design platform with physically-based methods which have adequate accuracy and calculation speed.

The present work is based on the former work of Northwestern Polytechnical University, where the BWB aerodynamic design Methodology is established [16]. A 300-passenger BWB aerodynamic configuration is provided, whose maximum lift to drag ratio and pitch trim are achieved at cruise condition. The paper applies the aerodynamic design methodology and adds a physically-based weight estimation method to obtain a feasible conceptual design of BWB transport with lower weight and better aerodynamic performance.

The present objective is to construct a physically-based platform for the BWB conceptual design. Low-order physical models which implement fundamental structural, aerodynamic methods are used to predict the weight and aerodynamic performance. Historical correlations will be adopted in the estimation of the secondary structure and equipment similar to the conventional aircrafts.

In subsequent sections the structure of the conceptual design platform for BWB is described. Methodologies of Geometry module, weight module and aerodynamic module are presented in the following sections with validations. Then, the BWB conceptual design platform is utilized to MDO design whose objective is to find a BWB planform with best performance and minimum take-off weight. The characteristics of the optimized BWB aircraft are analyzed and discussed.

2 Methodologies and Modules

2.1 Structure of Conceptual Design Platform

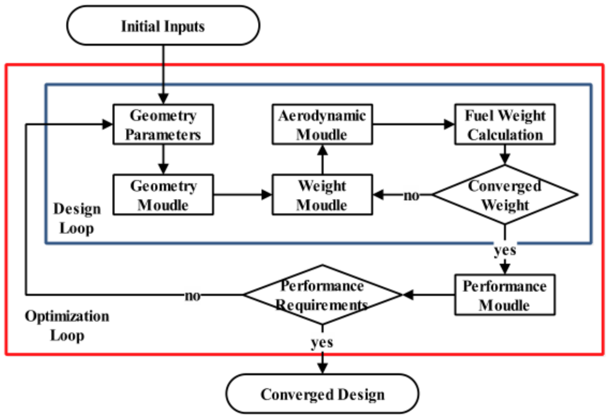


Fig.1. Conceptual Design Platform Program Structure

The overall structure of the conceptual design platform can be seen in

Fig.1 and is accomplished under MATLAB. The program structure can be divided into a design loop and an optimization loop. The modules within the blue box represent the design loop while all the modules together make up the optimization loop. This two-level structure enables the platform to act as either a quick evaluation tool or a MDO design tool.

The design loop begins with the definition of the input parameters that describe the design constraints and the geometry of a BWB aircraft. Then the geometry module translates parameters into geometric shape, which is the foundation for the following analysis module. 3D geometry is generated with the help of Open VSP, so that the geometry can be checked to reduce the potential mistakes in the input parameters. An integration process is applied to weight and aerodynamic analysis modules to ensure proper coupling of disciplines. After the convergence of both weight and aerodynamic, performance module is applied to evaluate the characteristics of the design.

The optimization loop utilizes the multi-objective genetic algorithm (GA) to perform the conceptual design of a BWB configuration. The optimization objective is to find a planform with best performance and minimum total gross weight. After defining the design space of each variable, Latin hypercube sampling is applied to ensure proper spatial distribution of first generation. Geometry limitations, static stability, payload and fuel capacity requirements are treated as optimization constraints to achieve a feasible design.

2.2 Geometry Module

Parametric method is applied in the geometry module to generate the geometry of BWB design. The geometry module provides both the outside aerodynamic shape and inside arrangements of cabin, cargo, fuel volume. The basic geometry is decomposed into planform and section airfoils.

As exhibited in Fig.2, the planform consists of 4 parts: cabin, rear cabin, trapezoidal wing and the outboard wing. The centerbody consists of cabin and rear cabin. And it is a distinguishing feature towards the conventional aircrafts. The cabin section is the pressurized bay, which is sized by the number of passengers and the amount of cargo. The rear cabin is the area attached with the engines and the trailing-edge elevon of centerbody. The outboard wings act just like the conventional wings. Trapezoidal wings provide smooth transition from the centerbody to the outboard wing sections. Fuel tanks are placed in the outboard and trapezoidal wings. It is a design constraint to make sure that the volume of fuel tanks is enough.

The planform is defined by 10 explicit physical parameters, which can be grouped in chord-wise length, span-wise length and sweep angle. These parameters lead to a linear planform shown in red dashed line. Then piecewise cubic splines are applied to generate smooth leading and trailing outlines of the centerbody and transition area of the aircraft. It is convenient and efficient to use these parameters to describe a reasonable planform and arrangement.

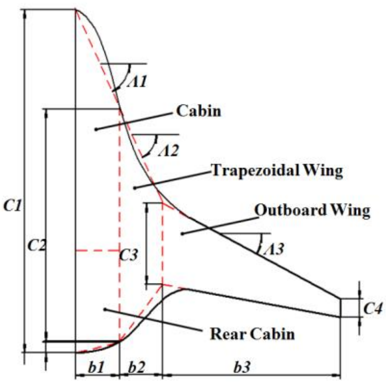


Fig.2. Planform Geometry Parametric Definition

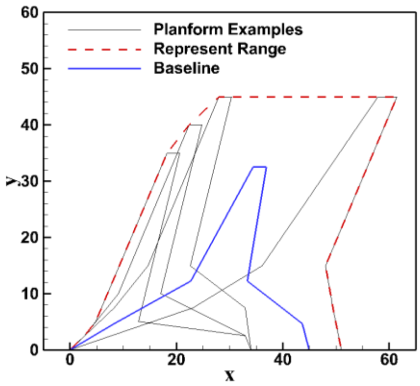


Fig.3. Range of Planform Representation (Down)

The representation capability of parametric geometry module for BWB planform is tested in a large initial design space, as shown in Fig.3. A variety of BWB-like planforms that differ in chords, widths and sweep angles are generated.

BWB configurations require special airfoils that differ from the ones applied in the traditional subsonic transports. With considerations of trim, stability requirements and cabin, cargo arrangement, thick reflexed airfoils are used in center-body section while typical super-critical airfoils are applied in the outboard wing.

Airfoils could also be described in parametric approaches. However, the present study will focus on the effects of the planform variation. Expressing the airfoils in parametric approaches will greatly increase the number of design variables and slowdown the speed of planform optimization. Thus, properly designed profiles in our earlier BWB study are used here as basic airfoils. The thicknesses of the airfoils are modified according to the capacity requirement during the conceptual design process.

The final three-dimensional geometry is obtained by interpolating section airfoils along the planform with the help of Open VSP.

2.3 Weight Module

The weight module estimates the weights of the major components, where physically-based methods are used to estimate the primary structure weight. The total take-off weight is decomposed into structure weight, fuel weight, propulsion weight, landing gear weight, fixed weight, payload and cargo weight.

Structure weight consists of four parts: cabin, rear cabin, trapezoidal wing and outboard wing, as shown in Fig.2. The former two centerbody weights are obtained by Bradley's regression equations based on the finite element analysis of BWB configuration [17]. These equations are suitable to the design and analysis of a 200- to 450-passenger BWB transport. The equations are shown as follows:

$$W_{cabin} = 0.316422 K_S (TOGW)^{0.166552} (S_{cabin})^{1.061158} \quad (1)$$

$$W_{aft} = 0.53(1+0.05NEng) S_{aft} TOGW^{0.2} (\lambda_{aft} + 0.5) \quad (2)$$

Where K_S =5.698865, is a scaling factor. *NEng* is the number of engines support by the centerbody, S_{aft} is the planform area of the aft centerbody, and λ_{aft} is the taper ratio. Equation 1 is applied for cabin weight while Equation 2 is applied for the rear cabin,

The latter two wing weights employ the physically-based method, which is promoted by Delra [18]. Modification has been made to use the wing loading calculated from the vortex lattice method instead of empirical loading factors. The wing is assumed to be cantilevered and the material gauges are sized to undertake the critical loading cases. The resulting wing-box volumes, together with specified material density, give the primary wing structural weight. The secondary structural weights are estimated via historical weight fractions.

The other component weight calculations are similar to the conventional aircrafts' and empirical relationships can be used appropriately. Payload and cargo weights are estimated according to the design requirements. Fuel weight is obtained using Breguet's range equation and weight fractions for other flight segments. Torenbeek's handbook method is utilized to evaluate the fixed weight. Propulsion weight is obtained by an empirical function of static trust and bypass ratio. The overall aircraft CG of weight moment is computed form component weights and their locations.

2.3 Aerodynamics Module

Aerodynamic methods are fundamental to evaluate the performance. To gain confidence about the final results, multilevel fidelity aerodynamic models are used in the platform. Low fidelity methods are applied during the optimization process, while high-fidelity calculations are employed to check the final result.

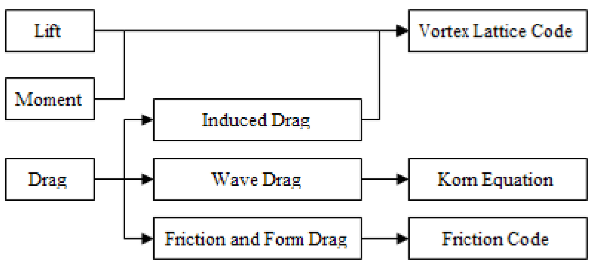


Fig.4. Aerodynamic Coefficients Breakdown and Analysis Methods

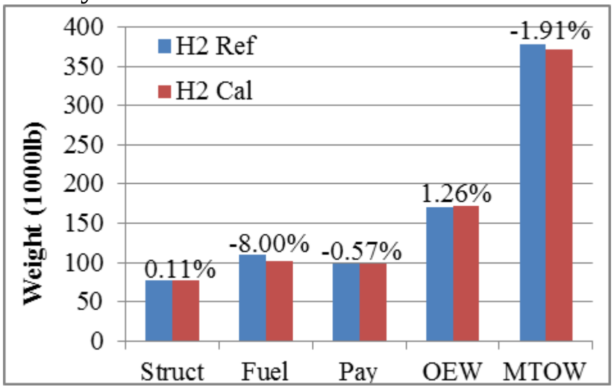
Low fidelity aerodynamic module is developed, which is efficient with adequate accuracy. The breakdown of the aerodynamic coefficients and the calculation methods are described in Fig.4. Lift coefficient and induced drag are estimated by a vortex lattice method. Friction drag is calculated using standard flat plate skin friction formulas with compressibility correction and form drag is estimated by the form factor. Wave drag is estimated by Korn equation in an easy and effective way. The details of this method can be found in Mason's lecture [19]. Besides, the twist angle distribution of section airfoils is integrated to obtain a desired lift distribution to minimize the induced drag at cruise. The vortex lattice method is also employed to evaluate the zero lift moment and the longitudinal stability. Positive zero lift moment with reasonable static longitudinal stability is essential for tailless configuration.

High fidelity aerodynamic module consists of a structural mesh generating code and CFD solver. High fidelity aerodynamic module is applied to evaluate the optimized planforms by conducting RANS calculations. In this way it predicts aerodynamic forces and reveals the details of flow phenomena.

3 Validations

Due to the complicate loading phenomenon and indeterminate structure of the centerbody, uncertainty remains in weight estimation. However, physically-based methods are examined and the results are reasonable by comparing the detail component weight data with the H-series aircrafts [20]. As shown in Fig.5, component weights show good agreement with H2 and H3.2 aircrafts. The histogram provides detailed component weights comparisons between calculation results and reference weights. Each bar stands for a component weight with relative errors on the top. Results show that the accuracy of operating empty weight (OEW) estimation is acceptable, while the relative errors of the Maximum-take-off weights (MTOW) are below 2%, which is adequate for conceptual design platform.

Aerodynamic module is tested by comparing the low fidelity estimation result with the high fidelity CFD result of the same geometry at cruise condition. A N2A-like geometry is constructed by simplifying the N2A planform [21] and applying the typical BWB airfoils for each section. Result proves that the low fidelity aerodynamic module provides reasonable sense of lift, drag, balance and stability in a time-saving way. Small differences still exist in aerodynamic coefficients, as shown in Fig.6. Because the applied Prandtl-Glauert compressibility correction rule underpredicts the compressible effect, the lift slope is smaller compared with the CFD result. The pith moment is also affected in this manner. Besides, drag prediction result is a little over-optimistic. These owe to the limitation of applied low fidelity methods.



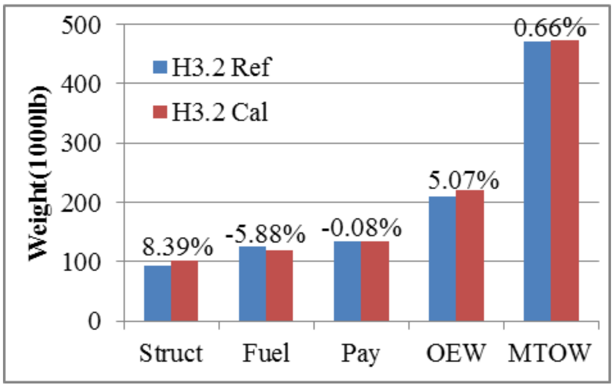


Fig.5. Weight Validation with H-Series Aircrafts

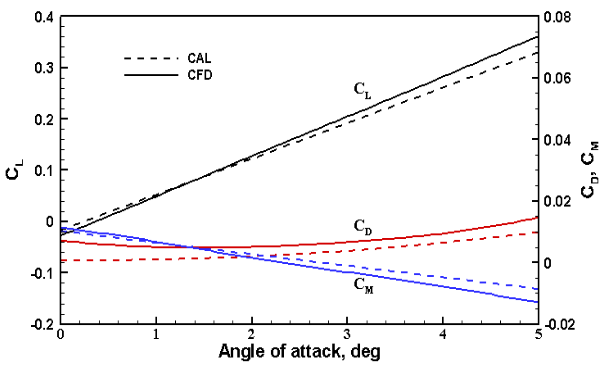


Fig.6. Aerodynamic Validation (Based on simplified N2A Planform)

Before conducting the multidisciplinary optimization design, sensitivity analysis of the MTOW and L/D with respect to the nondimensional planform parameters is conducted. The predicted results are generated from the combination of the conceptual design platform except for the optimization procedure. The ranges of parameters are provided in Table.1, and will be used to generate the initial design space of the conceptual design optimization.

Table.1. Parameter Design Space

Design Parameter	Units	Lower bound	Up Bound
C1	m	34	51
C2	m	24	36
C3	m	8	12
C4	m	2.4	3.6
B1	m	2.5	7.5
B2	m	2.5	7.5
B3	m	10	30
S1	Degree	48	72
S2	Degree	40	60
S3	Degree	24	40

This sensitivity analysis offers a first glance towards the variation of the objectives which is caused by the change of a single design parameter, as shown in Fig.7.The parameters are divided into three groups, according to their physical meanings. The sensitivities of different design parameters vary from each other towards a same goal, and trends of same parameter towards different goals are not the same.

Take the span length group for example. b_1 stands for the width of cabin area. A larger b_1 means that the aircraft has a larger centerbody which is heavy and less efficient in aerodynamics. The L/D will drop slowly due to the lower aspect ratio, and the gross weight will increase rapidly as the heavier cabin and more fuel burn. However, the trend of b_3 is the opposite. The outboard wing is the most aerodynamic efficient part of the aircraft. Benefits in aerodynamics will be received if the outboard wing span is increased. There will be less fuel burn but heavier outboard structure weight.

It is complicate to manually decide the parameters to achieve a reasonable design, let alone designing a BWB aircraft under several constraints on several disciplines. Thus, it is necessary to promote a conceptual design platform to perform the multi-disciplinary optimization design.

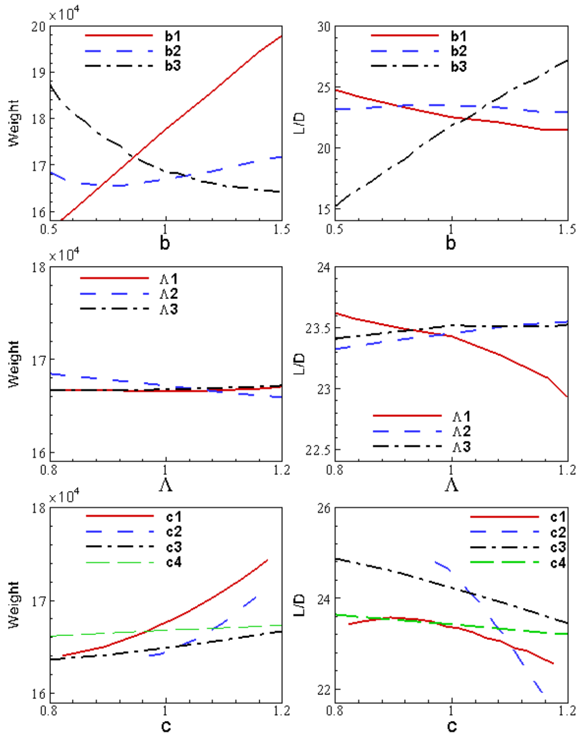


Fig. 7. Planform Parameters Sensitivity Study of L/D and MTOW

4 Multidisciplinary Optimization Design

4.1 Optimization Problem Statement

The constructed conceptual design platform is utilized to conduct a multi-disciplinary optimization design. The optimization objective is to minimize the total gross weight and to maximize the aerodynamic efficiency of a 300-passenger BWB transport with cruise speed of Ma 0.82. The design focuses on the performance of cruise period, with the design idea that cruise point, maximum lift to drag point and pitch trim point are in the same flight attitude.

The design requirements are summarized in Table.2. Design constraints of geometry, payload and fuel capacity are considered inherently within each module. The total span of the aircraft is further constrained less than 65 m which is the typical value of a conventional tube and wing aircraft. Balance and stability is regard as optimization constraints. It is generally believed that pitch moment approaching to zero is the ideal condition at cruise. Given the static stability and pitch trim considerations, zero lift pitch moment must be above zero to ensure the static stability.

Table. 2. Top Level Requirements

Requirement	Value	Unit
Number of pax	300	–
Freight weight	20,000	kg
Cruise range	13,000	km
Alternative destination range	500	km
Cruise Mach number	0.82	–
Cruise altitude	11,000	m
Loiter time	30	min

The multi-objective GA method is ultized to conduct the optimization. The corresponding objectives and constraints for the two-point optimization design are defined as follows:

$$\begin{aligned}
&\textit{Objective} \quad && \max L/D \\
& && \min MTOW \\
&\textit{Constraint} \quad && C_{M0}>0, \\
& && -0.005 \le \partial C_M / \partial C_L < 0 \\
& && b \le 65\,m \\
& && S_{cabin} \ge S_{required} \\
& && V_{fuel} \ge V_{required}
\end{aligned} \tag{3}$$

4.2 Optimization Result

After integrated for more than 70 generations, the optimization reaches convergence. The optimization results show that the optimized planforms meet the objective of lower MTOW and higher L/D, which and are satisfied with the design constraints.

The Pareto front points of the optimization are shown as black squares in Fig.8. A dashed line regression curve is provided as the ideal Pareto front. Each point represents a planform that is calculated during the optimization process. The blue points represent that the planforms succeed in meeting constraints defined in Equation (3), while the red ones fail to satisfy at least one of the constraints.

However, the optimization result shows that points of the Pareto front are unexpectedly congregated in a small area, which performs like a single-objective optimization. This is due to the tight correlation between the optimization objectives. As described in the Breguet’s range equation, higher lift to drag ratio reduce the fuel burn during cruise, reducing the max-take-off weight. Compared with the initial planform, the gross weight is reduced by 7%, while the lift to drag ratio is increased by 20%.

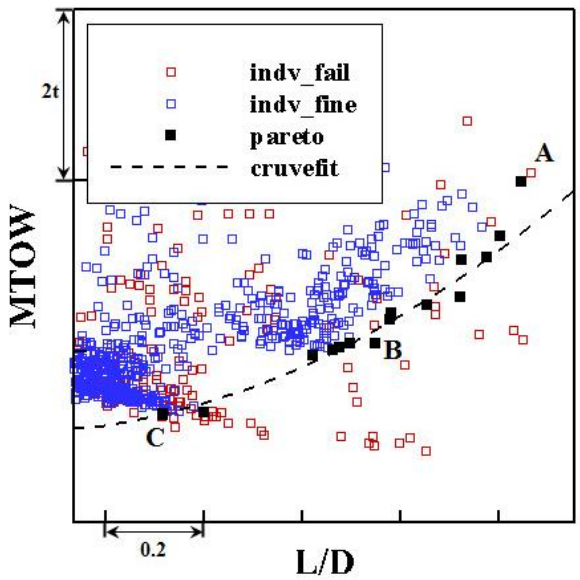


Fig.8. Pareto Front of the Optimization

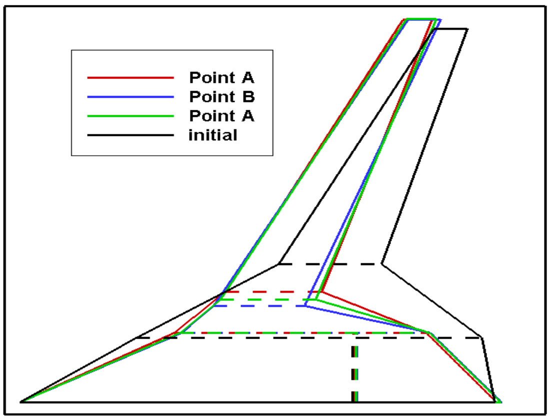


Fig.9. Comparison of optimization and initial planforms

The planforms of points of Pareto front follow the same variation trend compared with the initial planform. The optimized planforms have a slim centerbody and a larger outboard wing sections which greatly improve the aerodynamic efficiency. The heavy aft centerbody and transition area are tailored to reduce the weight and wetted area. However, the width of the centerbody is slightly increased to ensure the cabin area. The comparisons of optimized and initial planforms are provided in Fig.9.

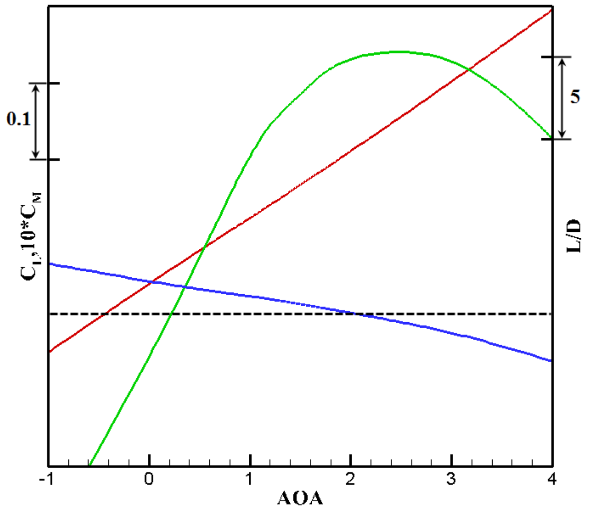


Fig.10. Aerodynamic Characteristic of the Optimazaion Result

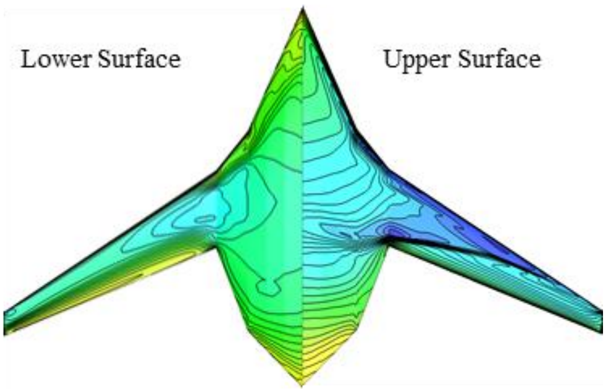


Fig.11. Pressure Counter of Optimized Configuration at Cruise

The Point B of the Pareto front is evaluated by high-fidelity aerodynamic method. The result approves that the design idea is achieved that cruise point, maximum lift to drag point and pitch trim point are in the same flight attitude as shown in Fig.11. The designed configuration is naturally trimmed at cruise condition with the highest efficiency.

Disadvantages of the optimized planform are also exposed. The pressure distribution among the surface is not desirable, and shock wave appears in the transition area. However, designing a desired pressure distribution or eliminating the shock wave for a transonic aircraft is difficult even for the high fidelity design or optimization methods. The conceptual design platform for BWB transports only provides an initial planform that meet the design requirement.

5 Conclusion

This paper develops a conceptual design platform for BWB transports which is applied to design a 300-passenger BWB configuration. Conclusions are presented as follows:

Low-order physical models based on fundamental structural, aerodynamic principles are illustrated. The validations of the methods show capabilities and give confidence to the conceptual design platform of BWB aircrafts.

The conceptual design platform is proved time-efficient to explore a large design space and to form the initial design of the aircraft from top-level requirements.

The optimized planform is evaluated by high-fidelity method. The results show the feasibility and reliability of the platform.

Further research is required to optimize the BWB configuration towards irrelevant objectives such as fuel consumption, noise and emissions.

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