A HIERARCHICAL STRUCTURAL MODEL FOR CONCEPTUAL DESIGN OF TRANSPORT AIRCRAFT WING

Yukang Yin, Wenbin Song

School of Aeronautics and Astronautics
Shanghai Jiao Tong University, Shanghai, China

Abstract

The operating economics and environmental performance of transport aircraft are two main indicators of their competitiveness. As a key component of the aircraft, various characteristics of the wing have a major impact on the overall competitiveness of the aircraft. It is a significant challenge to reach a global optimization of aircraft aerodynamic, structural, and economic performance during the aircraft development cycle. Model-based multidisciplinary optimization has become an effective way to solve this problem. However, how to deal with the huge amount and consistency of information in early design stages is a problem that needs to be solved. Here a model-based approach is proposed to perform aerostructural design tasks within a CAD system, which provides basic parameters for the subsequent wing design. The focus of this work is to improve automation in the modeling process. The first and second level models can be automatically modeled using VB Scripts, and the third level model needs to be manually adjusted. Both CFD and structural simulations can be done using this same model. The aerodynamic load is applied to the wing surface to analyze the deformation of the wing structure, which preliminarily illustrates the application of the model in wing design.

Keywords: transport aircraft wing, structural model, parametric design, computational fluid dynamics, computational structural mechanics

1. Introduction

The pursuit of efficiency and economic competitiveness for transport aircraft continues to drive the development of new technologies. For conventional configuration, the wing provides most of the lift for the aircraft. To ensure aerodynamic performance, the size, shape, and structural layout of the wing should be optimized to achieve the required performance with minimum drag, thus less fuel consumption. Therefore, the various characteristics of the wing have to be considered in an integrated manner to improve the overall efficiency of the aircraft. For the near future, commercial transport aircraft is most likely to fly at transonic speed around 0.7 - 0.9, and therefore the design of transonic wing has become one of the main tasks in aircraft design.

The design of a transport wing is a complex task involving many aspects such as aerodynamics, structural analysis, manufacturability, and system integration, etc. Two primary aspects include aerodynamic design and structural design, and the two aspects are interrelated. For example, in the aerodynamic design, the wing needs to have a greater lift-to-drag ratio during take-off, cruise, and maximum lift at landing configurations. In the structural design, it is necessary to consider the strength condition and fatigue damage and to reduce the structural weight as much as possible to obtain better economics. To cope with different requirements at different design stages, different models of multi-fidelity are often required. In early design tasks, the ability to explore large numbers of vastly different designs with relatively low accuracy is a key feature. On the other hand, higher fidelity models with increased details are essential when the design progresses into later stages of development. It is also necessary to ensure the consistency of these models and to increase the design efficiency via the use of a CAD-based approach.

The main focus of this paper is the development of a multilevel structural model, integrated with a parametric wing geometry model for aerodynamic analysis. A method of hierarchical wing model is developed in CATIA based on a fully parameterized wing geometry. The model includes shape definitions and multilevel internal structure definitions, which can reduce manual operation as much as possible. The objective is to develop a CAD-based parametric model for multiple purposes including aerodynamic, and structural analysis.

2. Related Work

The aerodynamic design of the aircraft project development is critically important, in particular for components such as the wing. Wing design needs to seek a balanced optimum between aerodynamics and structural performance to deliver a competitive edge in terms of direct operating cost (DOC). This requires optimal aerodynamic load and weight distribution as well as meeting fuel capacity requirements. Many studies have been carried out on the aerostructural integrated modeling and analysis for transport aircraft. These studies are summarized below from different aspects.

2.1 Wing Structural Modeling Method

2.1.1 Knowledge Based Engineering Method

The German Aerospace Center has studied the ELWIS (Finite Element Wing Structure) model generator for the finite element model of the aircraft wing structure. The structural modeling was not limited to the main structure of the wing, but also could explore the effect of high lift devices in the early stage of design [1]. A knowledge based approach and a wide range of engineering rules were employed to enable aircraft designers to accurately analyze wing model in the early design phase. Van der Laan et al. [2] applied a Knowledge Based Engineering (KBE) approach to the design of a business jet empennage, reducing the lead time of the machined rib design by 40%. A knowledge based approach is to acquire knowledge from experts who had participated in the development process and use knowledge to create automation tools. Its advantage is that it significantly reduced the time it cost to design and manufacture. The disadvantage is that it cost more time to capture knowledge.

The significant advantage of a knowledge based modeling approach is that it reduces the time required for repetitive work and allows more time for creative work. However, the prerequisite for the application of KBE is that the number of components to be designed is sufficient, and the structural topology is similar but not completely consistent. There are a large number of such components in aircraft components, such as ribs, stringers, bulkheads. If the KBE method can be applied reasonably, the efficiency can be effectively improved. However, before the KBE is applied, it is necessary to analyze the structure of the component to be designed in detail, consult the design expert, determine the knowledge rules of the component design, and convert the knowledge rules into a form that the designer can recognize on the computer. The use of knowledge based methods is time-consuming in the early stage, but it can play a key role in the later stage. In general, the application of knowledge based approaches is a development trend. This idea is widely adopted in the structural models of this paper.

2.1.2 Parametric Method

Tarkian et al. [3] developed an aircraft parametric 3D modeling tool using a multidisciplinary analysis method with an easy to use interface. Parametric association modeling can realize top-down assembly design, and the parameter changes can be automatically passed to the associated parts after model modification. Bombardier Aerospace developed the CATIA V5-based parametric aircraft geometry modeler CATALIST [4]. It could re-model an aircraft by reading the parameters of the design table. It had the advantage of reducing the amount of manual operation during the conceptual and preliminary design stages of aircraft. A robust parametric structure can calculate a given structure in an efficient and automated manner and evaluate the advantages and disadvantages of different solutions [5]. Hürlimann et al. [6] broadened the design space of aircraft and wingbox geometry models by using the parametric associative modeling method.

Parameterization is a key feature of the wing modeling. The above-mentioned several papers have reduced the manual modeling work and improved the efficiency by adopting parametric modeling. On the one hand, the wing design is an iterative process, and some of the initial value of parameters need to be constantly adjusted during the optimization process to improve aircraft performance. On the other hand, there may be associations between parameters, and parameterization enables the automatic transfer of relationships between parameters.

In the preliminary stage of the wing design, the number of parameters should be appropriate, and the wing design should be fully represented with as few parameters as possible. The types of parameters should be classified, such as the global parameters of the wing planform and the local thickness of the spar web. Finally, the premise of multidisciplinary design optimization is to realize the parameterization of the wing model and seek the global optimal solution by iterative design. There exist requirements that when some parameters are varied in the design, other parameters should be able to adapt to provide valid designs.

2.1.3 Hierarchical Modeling Idea

Bindolino et al. [7] proposed a multilevel structural optimization system for wing structure and cross-section properties evaluation, which can estimate the wingbox weight of commercial aircraft. Dababneh et al. [8] described the wingbox structure using four models with gradually increasing structural details for structural weight prediction and made a trade-off between wingbox geometry description and computational resources to obtain the required accuracy.

The multilevel model has important significance in the preliminary design of the wing, and the details of the wing are different at different internal stages of the preliminary design phase. As the level of the model increases, the complexity of the model increases, and the corresponding fidelity is gradually increased. At the same time, the computational cost of the model is gradually increased. The core of the multilevel model is to match different level models and the required analysis needs in the preliminary design stage. The level of model detail is gradually improved, and the high level model is built based on the low level model.

2.2 Fluid-Structure Interaction

2.2.1 Aerodynamic Load Calculation and Transfer

With the development of computer technology, the flow field simulation based on Reynolds-Averaged Navier-Stokes (RANS) is widely used in aircraft design. Lyu et al. [9] carried out the aerodynamic shape optimization research of the NASA Common Research Model (CRM) wing, used the Spalart-Allmaras turbulence model to solve the RANS equation, and achieved an 8.5% drag reduction effect by single-point optimization. For the study of fluid-structure interaction, it is necessary to consider the transfer of aerodynamic load to the structure. Keye et al. [10] used a two-way interpolation procedure to map aerodynamic loads to structural nodes and transfer structural deformations to the CFD mesh and form a closed coupling loop. This paper focuses on the modeling method, so the one-way fluid-structure interaction is adopted, that is, only the aerodynamic load is transferred to the structure to observe the structural deformation.

2.2.2 Structural Finite Element Method

Tang et al. [11] constructed a knowledge-driven rapid finite element modeling system. Based on CATIA, the automatic meshing of the wing structure was carried out, and the finite element attribute was also automatically loaded onto the wing structure, which could eliminate lots of manual operations in finite element pre-processing. Benaouali et al. [12] used commercial software to perform multidisciplinary design optimization of an aircraft wing. In the structural analysis, PATRAN was used to carry out the finite element pre-processing, and NASTRAN was used to the structural sizing of the wing, and the range was increased by 8.9%.

The future wing design should realize the aerostructural integrated design, adopt multidisciplinary design optimization method, and can quickly achieve design iteration according to different requirements in the preliminary design stage. This paper focuses on the structural model of the transport aircraft wing and creates a parametric model in CATIA. The first two levels of the wing structural model are automatically created by the VB Scripts, and the third level model needs some manual operation from the user. And these models form a consistent, increasingly accurate representation of the wing. Using FLUENT to perform CFD calculation, the relevant aerodynamic load is obtained, which is transferred to the wing surface to simulate structural deformation.

The remainder of this paper is organized as follows. Section 3 describes the conceptual design of transport aircraft used for the wing design. Section 4 describes the wing modeling and CFD simulation methods. Section 5 presents the analysis results and discussions. Section 6 provides concluding remarks.

3. Conceptual Design of Transport Aircraft

3.1 Mission Specification

Design of an ultra-long-range transport aircraft with a range of up to 13,000 km is used as study aircraft. At present, wide-body transport aircraft generally cruise at an altitude of 11,000 m. This cruise altitude is adopted in this paper. The cruise speed is set to a Mach number of 0.85. According to the Top Level Aircraft Requirement (TLAR), the main technical specifications are set as shown in Table 1.

Table 1 – Top level aircraft technical specifications.

Item	Value
Seats (2-class)	280
Range / km	13,800
Cruise Mach	0.85
Initial cruise altitude / m	10,000
Maximum cruise altitude / m	12,000
Takeoff field length / m	2,800
Landing field length / m	1,600
Approach speed / knots	153

Referring to similar types of aircraft, the takeoff field length is set to 2,800 m, and the landing field length is set to 1,600 m. An important speed requirement is the approach speed, where V_A = 153 knots is set, which is the speed at which the aircraft approaches the runway.

3.2 Takeoff Weight Estimation

Weight has an important impact on the performance of aircraft. Accurate capture of weight characteristics in the early stage of design is conducive to making accurate judgments and achieving more benefits in aircraft operation economy. In this paper, the method of Raymer [13] is used to estimate the takeoff weight of the aircraft, and the corresponding results are used as a reference for the overall design of the aircraft.

The composition of aircraft takeoff weight can be divided into crew weight, payload weight, fuel weight, and aircraft empty weight. Empty weight includes structure, engine, landing gear, fixed equipment, avionics, and other components that are not part of crew members, payload, or fuel. Specifically, the takeoff weight can be expressed as follows:

$$W_0 = W_{crew} + W_{payload} + W_{fuel} + W_{empty} \tag{1}$$

The crew weight and payload weight can be considered to be known. It is set that the crews consist of 2 pilots, each with a total of 95 kg of luggage and 10 crew members with 85 kg of luggage. Payload refers to the weight of passengers and their luggage, which is set to contain 100 kg of luggage per person.

For fuel weight and aircraft empty weight, they all depend on the total weight of the aircraft, so the iterative calculation is needed in aircraft weight estimation. The fuel weight and aircraft empty weight are expressed as part of the total takeoff weight, and Eq. (1) can be rewritten as follows:

$$W_0 = \frac{W_{crew} + W_{payload}}{1 - \left(W_{fuel} / W_0\right) - \left(W_{empty} / W_0\right)} \tag{2}$$

For the empty weight ratio W_{empty}/W_0, it can be calculated according to the empirical formula. The fuel ratio W_{fuel}/W_0 needs to be determined in combination with the specific flight profile. In this case, according to Eq. (2), the new takeoff weight can be calculated by specifying the initial takeoff weight W_0. There may be differences between the calculated value and the initial value. The iterative calculation is carried out by increasing the initial value until the difference between the two meets the convergence criteria, and the relatively accurate estimation of aircraft takeoff weight is obtained.

4. Wing Modeling and CFD Simulation Methods

4.1 Technical Roadmap of Wing Structural Modeling

The wing design is divided into three levels to meet the requirements of different situations. With the increase in the complexity of the model, the time required for modeling increases. There are shared parameters and independent parameters among different levels of the model. The second level model is based on the first level model and the third level model is based on the second level model. The multilevel structural model starts from the aerodynamic shape of the transport aircraft wing, and various parameters are set in the initial model. The three-level model is integrated into a CATIA part. The selection of various parameters in the model has referred to the relevant contents of the aircraft structure design manual as much as possible so that the wing design can meet the actual engineering requirements as close as possible.

4.2 Wing Aerodynamic Shape

The initial aerodynamic shape of the wing was created in CATIA, as shown in Figure 1. First of all, the wing planform was built. Then the leading edge was created on the basis of the wing planform in combination with the dihedral angle. Different airfoils were arranged in the spanwise direction, and the initial aerodynamic shape of the wing was completed through the multi-section surface considering the twist angle of each airfoil. With the aerodynamic shape of the wing, the subsequent multilevel structural model was developed.

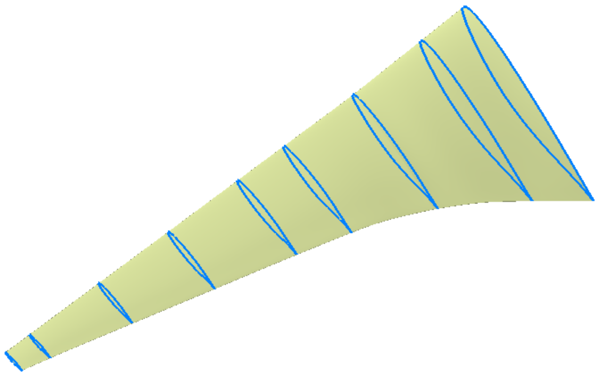


Figure 1 – The initial aerodynamic shape of the wing.

4.3 Wing Geometry Parameterization

Associative parameterization is at the core of the entire structural model, therefore parameters closely related to the wing design are integrated into the CATIA model. Parametric models enable flexible modification and rapid modeling goals. The aircraft takeoff weight estimation has been embedded in the model, and various parameters of the structural model to be built later are stored in the CATIA model. The parameters information can also be output to the EXCEL table as needed to achieve data output. In addition, the parameters of the model can be assigned by reading the data in the EXCEL table.

4.4 Hierarchical Structural Model

The wing structural model in this paper include spars, engine nacelle and pylon, landing gear, ribs, stringers, central wingbox, and fuel tank. Parameters used in the three-level model are different, forming an increasingly expanding three parameter sets. The changes in the parameters of the upper level will affect the geometry of the lower level, but the changes in the parameters of the lower level will not affect the geometry of the upper level. Within each level model, updates of parameters can realize geometric changes within the level and transfer changes to the lower level. The relations among these sets of parameters are given in Figure 2.

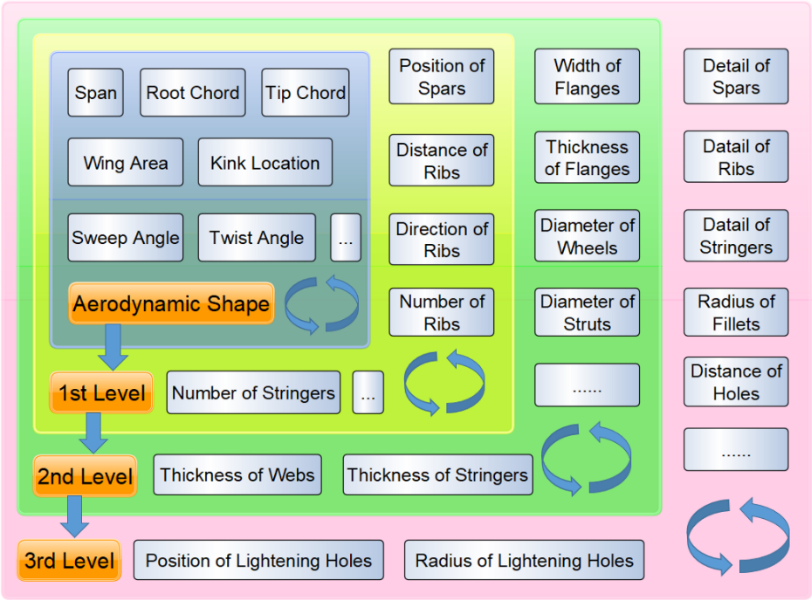


Figure 2 – The relations among sets of parameters.

4.4.1 The First Level Model

The first level model is a surface model and there is no thickness in the model. It serves as the basis for the wing layout. The spars include the front spar, the rear spar, and the main landing gear support spar. According to the given position, the modeling idea is to extrude the positioning line of the given spar and then cut it with the aerodynamic surface to obtain the planar shape of the spar. The planar shape will serve as a web for the second level wing spar. The nacelle model refers to the external model and matches the parameters in the overall model. When designing the main landing gear, the number of tires on the main landing gear is automatically adjusted for different takeoff weights due to the program-driven and knowledge based approach.

The ribs are divided into common ribs and stiffening ribs. According to the layout direction and distance parameters, the stringers can be automatically modeled after running the program. The structure of the central wingbox is basically the same as that of the wing, including ribs, stringers. And the modeling idea is similar to the wing. The fuel tank is divided into three parts: the central fuel tank, the main fuel tank, and the vent tank (the right fuel tank is symmetrical with the left side). Figure 3 shows that the completed first level model.

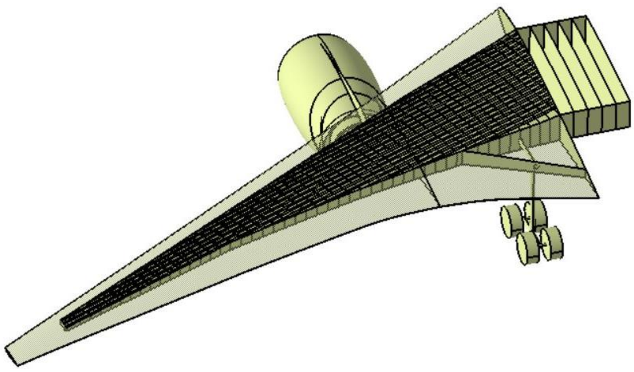


Figure 3 – The first level model.

4.4.2 The Second Level Model

The spar adopts a combination of traditional web and caps. The parameters that can be changed are web thickness, cap width and thickness. The engine pylon and stringers are obtained after thickening treatment, and the engine nacelle and landing gear are obtained by closing the surface. The rib structure is similar to the spar with a web and upper and lower cap. The web thickness, cap width, and thickness can be flexibly adjusted. The modeling idea of central wingbox is similar to the wing, and the completed second level model is shown in Figure 4.

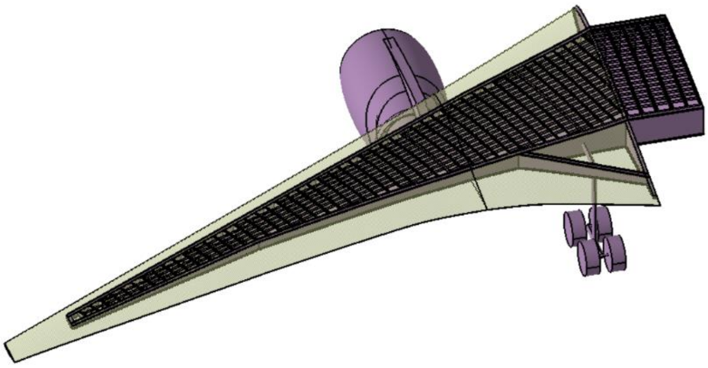


Figure 4 – The second level model.

4.4.3 The Third Level Model

On the basis of the second level model, the details of the model are strengthened, mainly by adding lightening holes and fillets in the ribs. The details of the third level model are shown in Figure 5.

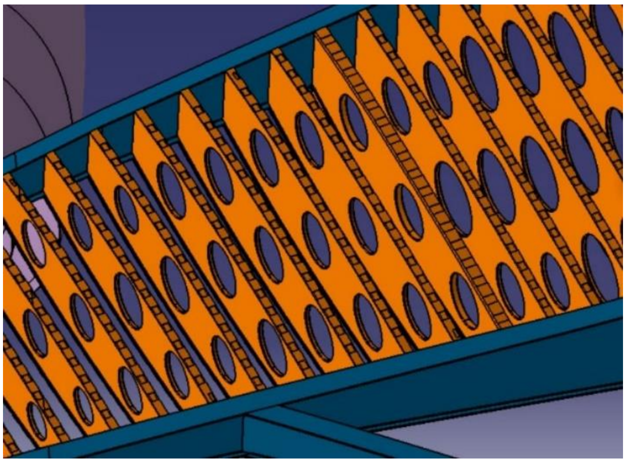


Figure 5 – The details of the third level model.

4.4.4 Program Driven Modeling

Record the modeling process for each stage using the macro recording function in CATIA. The recorded macros cannot be used directly and need to be modified. The VB Scripts are used to control the modeling process, and various parameters and related functions in CATIA automation are added. By running the program, the first and second levels of the model can be automatically created from the initial aerodynamic shape.

The parameters in the structural model can be easily modified, and then models of different sizes and topologies can be automatically modeled from the initial aerodynamic shape. Rib direction change, the variable distance, and the engine's spanwise location are shown in Figure 6. The first level model with the sweep angle changed is shown in Figure 7. The number of tires is automatically judged according to the takeoff weight of the aircraft, thereby realizing the different number of tires for different takeoff weight. The landing gear models are shown in Figure 8.

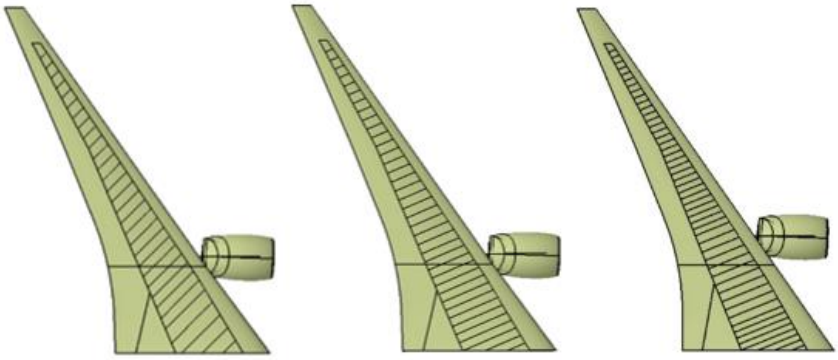


Figure 6 – Direction, distance change of ribs, and nacelle’s spanwise location change.

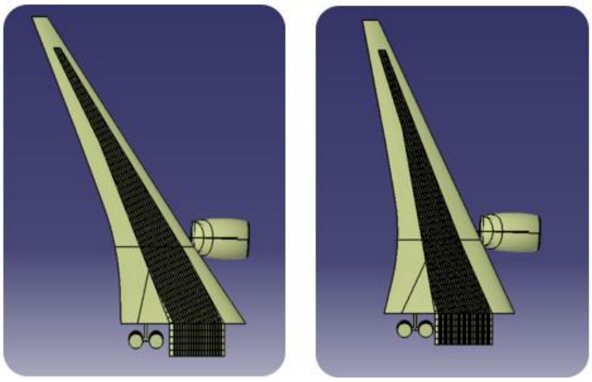


Figure 7 – Different sweep angle.

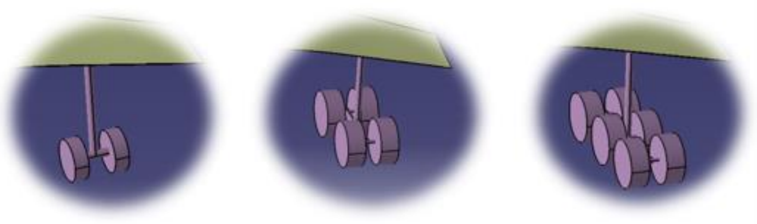


Figure 8 – Different number of tires for landing gear.

4.5 CFD Simulation and Validation

The application of RANS CFD in aerodynamic design has become more and more common. This paper attempts to implement the application of the RANS CFD into more aspects of aircraft design by creating a consistent fully parameterized wing model. To simplify flow field meshing, a hybrid mesh was used. The mesh was created as shown in Figure 9 and Figure 10.

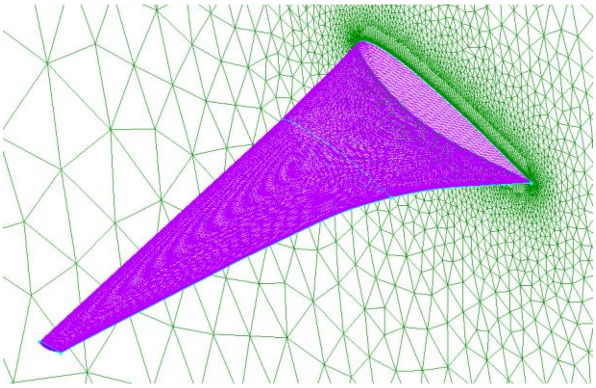


Figure 9 – Surface mesh of the wing.

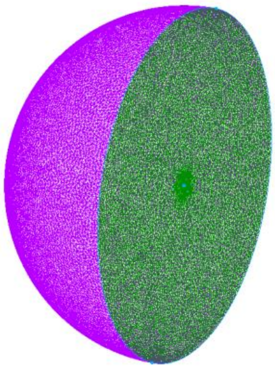


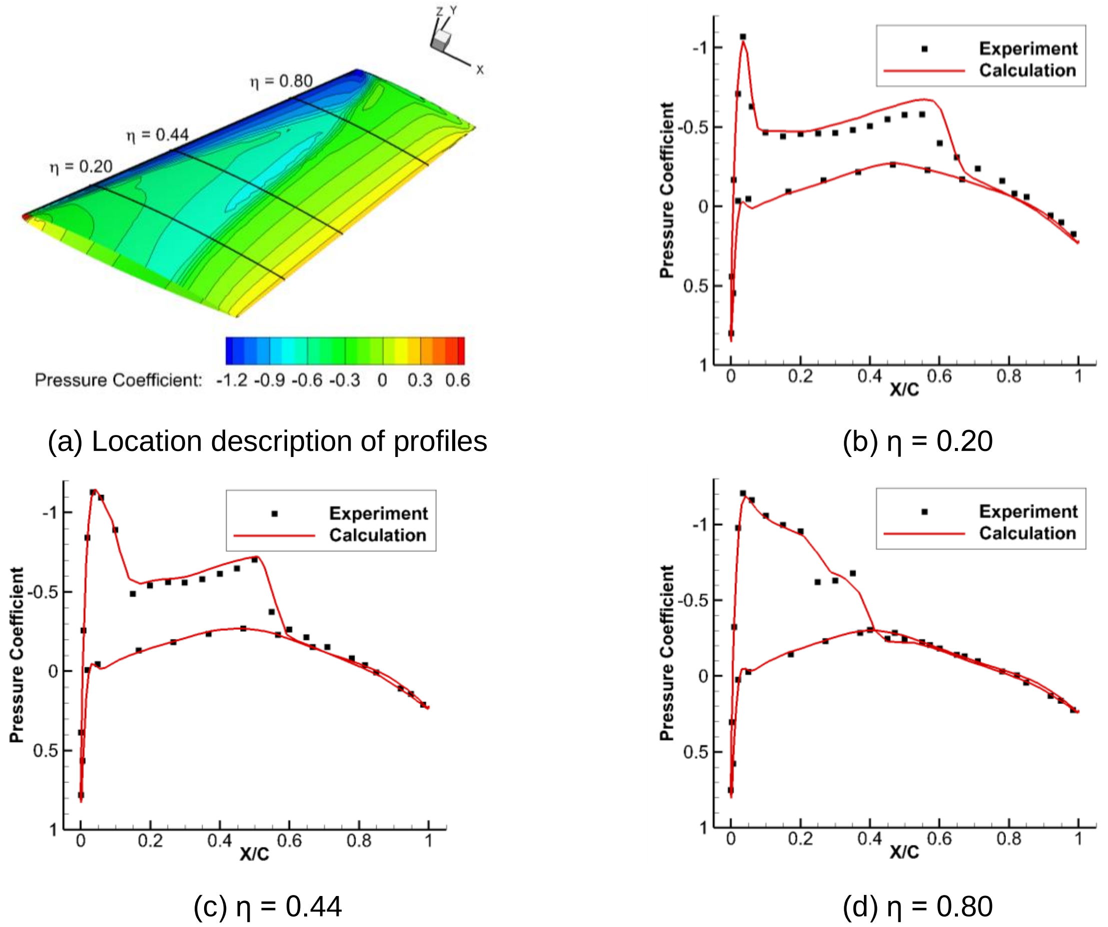
Figure 10 – Whole flow field of the wing.

In order to validate the accuracy of the flow field CFD simulation method, the ONERA M6 wing was used to validate. The ONERA M6 wing has been used as a validation case in many CFD fields, and the aerodynamic data obtained through experiments are widely used to validate the results of CFD calculations. The validation method is to use the same mesh form as described above and set the same flow conditions as the Test 2308 [14]. The specific parameters of the CFD simulation are shown in Table 2, which makes the Reynolds number based on the mean aerodynamic chord is about 11.72 million.

Table 2 – Parameter setting of ONERA M6 CFD simulation.

Parameter	Value
Freestream pressure / Pa	101,325
Freestream temperature / K	288.15
Freestream Mach number	0.8395
Angle of attack / deg	3.06

The distributions of pressure coefficient on the upper and lower surface of the wing at 0.20, 0.44, and 0.80 spanwise were compared. The results are shown in Figure 11. It can be seen that the pressure distributions of the lower surface are matched well, and the results of the upper surface are acceptable. This is because the shock wave of the upper surface is relatively stronger, and it is necessary to increase the quantity of flow field mesh of the shock wave position. It is possible to try to refine the mesh of the shock wave position to improve the pressure distribution matching, but the current results are deemed acceptable in the present work.



(a) Location description of profiles

(b) η = 0.20

(c) η = 0.44

(d) η = 0.80

Figure 11 – Comparison of surface pressure distributions of the experiment and calculation.

5. Results and Discussions

5.1 Structural Sizing

Taking the simplified model of the first level model (without nacelle, pylon and landing gear in aerodynamic calculation) as an example, the aerostructural analysis of the wing was performed. The preliminary wing structure layout was established according to the parameters. This model is a shell element model, and the structure thickness needs to be specified in the finite element analysis. First, it is necessary to size the structure at a 2.5g load case to obtain reasonable structural thickness. For simplification, all wing structures are made of aluminum alloy, whose properties are shown in Table 3.

Table 3 – Material properties of aluminum alloy.

Property	Value
Density / (kg/m^3)	2,770
Young's modulus / GPa	71
Poisson's ratio	0.33
Allowable yield strength / MPa	280

The boundary conditions were set referring the method used by Brooks et al. [15]. The rib at the symmetry plane is a fixed support constraint, and the rib at the wing-fuselage junction is a displacement constraint, which limits the displacement in flow direction and vertical direction. The loads include aerodynamic load, fuel load, structure mass, and engine mass. The complete boundary conditions and loads are shown in Figure 12. After completing the structural sizing, the equivalent stress contour of the wing is shown in Figure 13. The maximum stress is located at the wing-fuselage junction, and the maximum stress value does not exceed the allowable yield strength of the aluminum alloy, meeting the structural strength requirements.

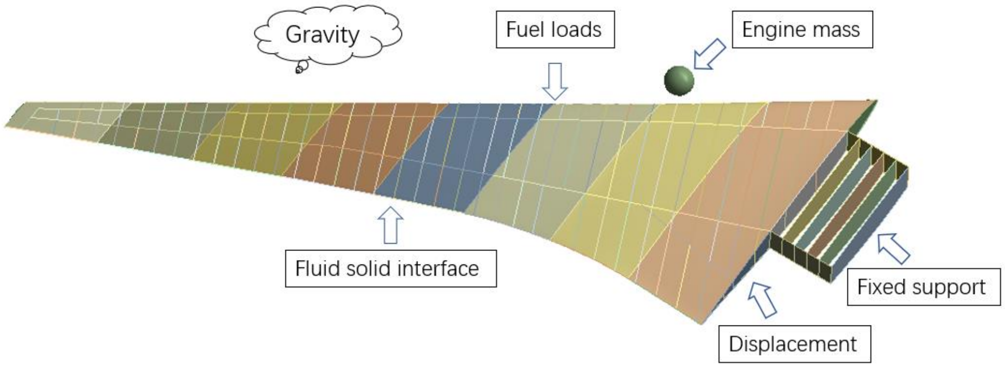


Figure 12 – Illustration of boundary conditions and loads.

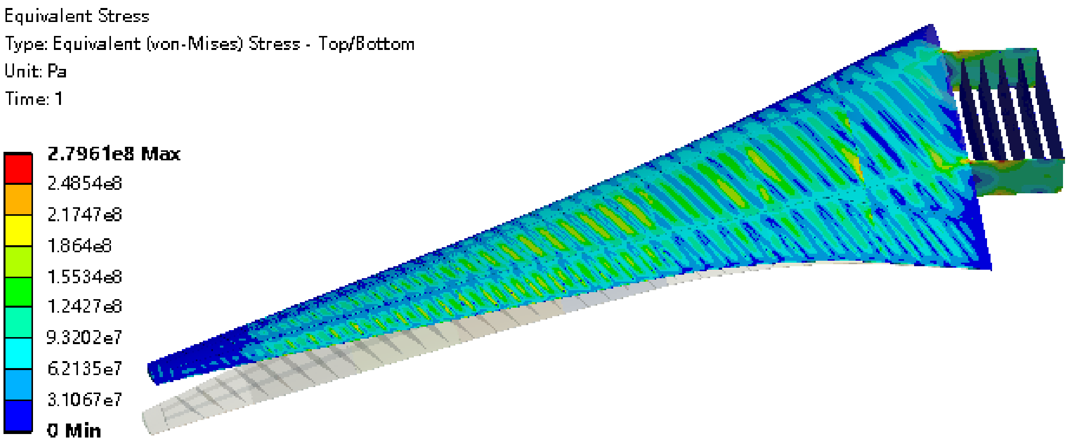
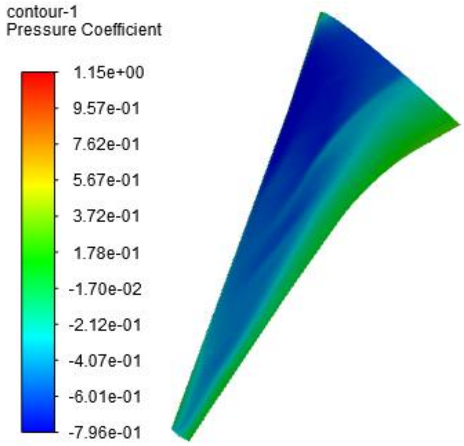


Figure 13 – Equivalent stress of wing structure at a 2.5g load case.

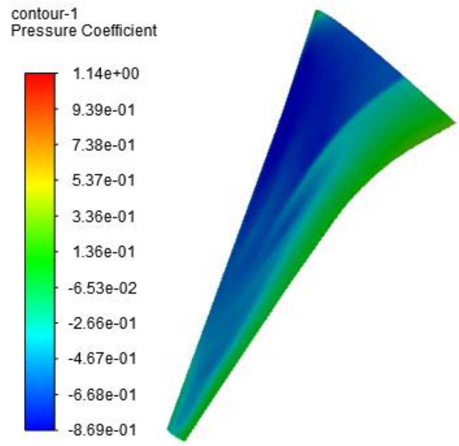
The preliminary estimation of wing weight can be carried out by using the above wing model. Firstly, the simplified model of the first level model is imported into the structural analysis module. Then, at a 2.5g load case, the thickness distribution of the spars, ribs, and skins is adjusted to make the total weight of each component lighter on the premise of meeting the material strength. Finally, the total volume of each component of the wing is measured, and the wing weight can be obtained according to the material density. After the aforementioned structural sizing, the total volume of the components is about 5.51 m^3, so that the wing weight is about 15262.7 kg. This weight estimation method is directly based on the physical model to estimate the wing weight. Compared with the traditional empirical estimation method, it can play a better role in the novel configuration.

5.2 Aerodynamic Analysis

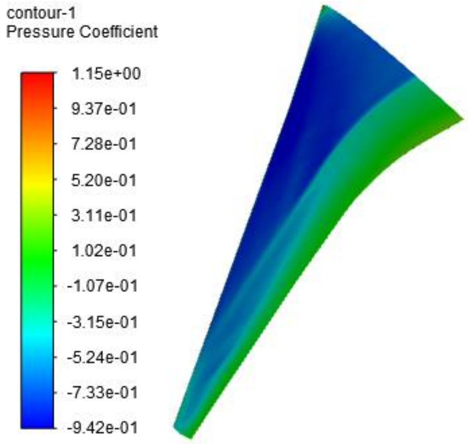
The angle of attack when the aircraft at cruise condition is generally about 2°. This paper simulated cruise condition and carried out the aerodynamic analysis of the aircraft for different angles of attack. The angles of attack were 1.5°, 2°, 2.5°, and 3°. The cruise altitude was 11,000 m and the temperature was 216.774 K, which was simulated using FLUENT. Figure 14 shows the pressure distribution on the wing surface at different angles of attack. With the increase of angle of attack, the peak value of negative pressure gradually increases. However, there is no major change in the peak value of positive pressure. The main reason is that the maximum pressure value has little relationship with the angle of attack. It is also noted that the pressure distribution on the upper wing surface is not ideal, because this wing is a jig shape and the control profile is not modified reasonably. The main purpose of aerodynamic analysis in this paper is to obtain the aerodynamic load for subsequent finite element analysis.



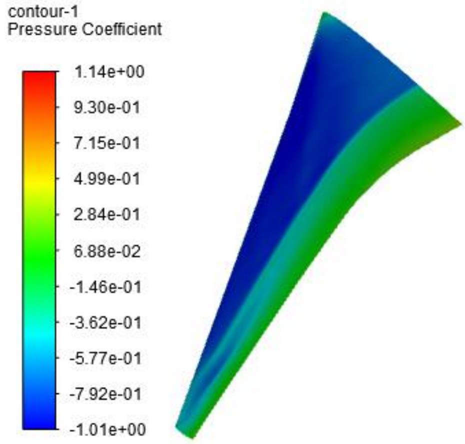
(a) AoA = 1.5 deg



(b) AoA = 2 deg



(c) AoA = 2.5 deg



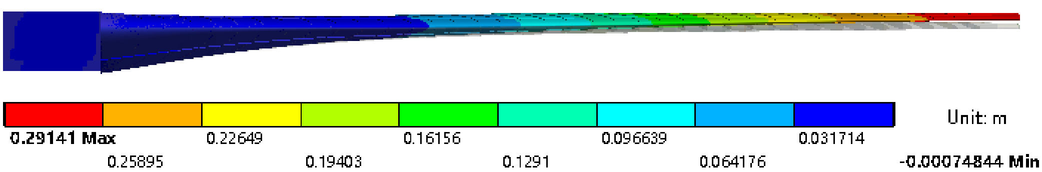
(d) AoA = 3 deg

Figure 14 – Wing surface pressure distributions at different angles of attack.

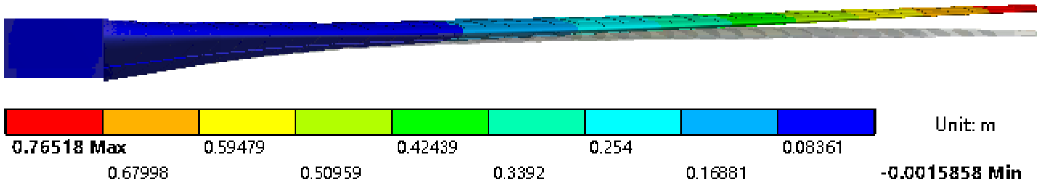
5.3 Structural Finite Element Analysis

After obtaining the aerodynamic load of the upper and lower surface of the wing, a simple finite element analysis of the structure of the wing could be performed, that is, a one-way transfer fluid-structure interaction was completed. The object of finite element analysis is the simplified model of the first level model, which includes spars, ribs, skins. In fact, the second and third level models can also be used in finite element analysis, which can obtain more accurate results and increase the calculation cost.

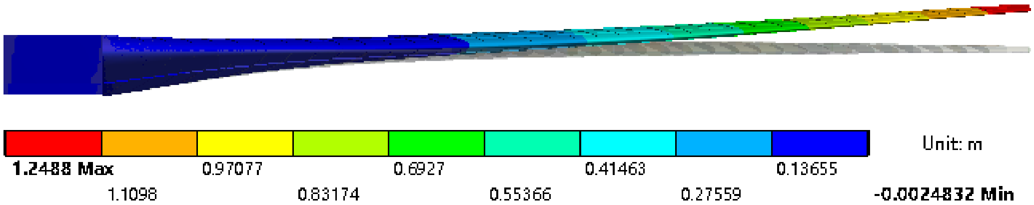
Figure 15 shows the vertical deformation of the wing at different angles of attack. The maximum deformation in the vertical direction is 0.29141 m when the angle of attack is 1.5°, and the maximum deformation in the vertical direction is 1.7477 m when the angle of attack is 3°. It can be seen that the deformation at the wingtip is the largest, and as the angle of attack increases, the maximum deformation in the vertical direction also increases. This is because as the angle of attack increases, the aerodynamic forces acting on the wing surface also increase, resulting in greater structural deformation of the wing.



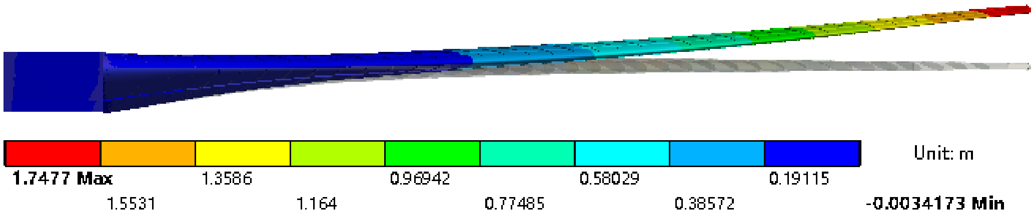
(a) AoA = 1.5 deg



(b) AoA = 2 deg



(c) AoA = 2.5 deg



(d) AoA = 3 deg

Figure 15 – Wing deformation at different angles of attack.

6. Conclusions

The core of this paper is the modeling method of the structure for a transport aircraft wing. In the preliminary design stage of the aircraft wing, the internal structure is not required to be too detailed, and the complicated structural model costs more time and delays the lead time. Therefore, it is necessary to use structural models with different complexity at different stages of the wing design. Models with different complexity must have different fidelity to meet the actual requirements of the engineering project.

Combining parameterization and program-driven modeling can achieve powerful functions. The modeling program is time-consuming to develop, but it is very convenient to rebuild the model after the program is completed, thus eliminating the repetitive and non-creative work, and embodying the advantages of the knowledge based engineering method.

In this paper, the automatic modeling of the first and second level models of the transport aircraft wing was realized by using the program, and the third level model was manually established. By changing initial parameters, different wing models can be generated, which indicates that the wing structure modeling method based on CATIA platform has good flexibility. In addition, taking the simplified model of the first level model as an example, the one-way aerostructural coupling calculations were carried out, which preliminarily illustrated the application of the model in wing design.

7. Contact Author Email Address

Prof. Wenbin Song

Mailto: swb@sjtu.edu.cn

8. Copyright Statement

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