Aerodynamic Effects of Load Deformation on Civil Aircraft Forward Fuselage

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Abstract. This paper investigates the aerodynamic effects of load deformation on the forward fuselage of civil aircraft. The study begins by analyzing the typical structural characteristics and load deformation distribution of the forward fuselage. Based on the finite element analysis results, the deformed shape of the forward fuselage under typical cruise conditions is simulated. The aerodynamic influence of local deformation is evaluated by using computational fluid dynamics (CFD) methods. The results show that the aerodynamic performance, including drag coefficient and pressure distribution, is sensitive to local shape changes, especially in the boarding gate area. Finally, two control strategies, passive control, and active control, are proposed to minimize the adverse aerodynamic effects caused by load deformation of the forward fuselage.

Keywords: aerodynamic effects, local deformation, aircraft

1 Introduction

At present, the research on the overall design and aerodynamic design of the forward fuselage of civil aircraft has been very extensive and in-depth [1][2], but it is limited to the theoretical shape of the jig state. While the cruise state is affected by cabin pressurization and aerodynamic load, fuselage deformation is inevitable. This paper analyzes the simulation of the forward fuselage deformation and aerodynamic influence after cabin pressurization in a typical cruise state, providing design ideas for the forward fuselage shape control.

2 Geometric Characteristics of Civil Aircraft Forward Fuselage

The forward fuselage shape is the difficulty of the shape design of civil aircraft, especially the geometric design. To minimize the resistance generated, the forward fuselage shape generally tends to be cone-like, because it also needs to meet the installation space requirements of weather radar, front-end, cockpit equipment, and other systems, and the final appearance of the forward fuselage shape looks full. At present, the typical forward fuselage shape of civil aircraft can be divided into two types: (1)

Traditional forward fuselage, such as B737 and A320. The shape of the lower edge of the windshield has a clear bend and a flat windshield; (2) A streamlined forward fuselage, such as B787 and C919, has a curved windshield without turning at the lower edge.

3 Typical Structure of Civil Aircraft Forward Fuselage

The main structure of the civil aircraft head adopts a typical semi-hard shell metal structure composed of a frame, girder, and skin, and is divided into a hatch cover, front lift, floor, wall girder, various types of frames, door frame reinforcement structure, transparent parts, radome, and other components according to different parts. There are many openings in the civil aircraft forward fuselage structure, including the windshield transparent part opening, the forward fuselage landing gear compartment, the boarding door, the service door, and other large openings, the EE cabin opening, the emergency door exit on the top of the cockpit, the wiper, the angle of attack sensor and other equipment small openings and maintenance covers, etc., which are locally strengthened.

4 Load Deformation on the Forward Fuselage

The internal and external pressure difference caused by the flight load and the pressurized cabin load leads to the deformation of the forward fuselage. Due to the curvature distribution characteristics of the forward fuselage and the structural design characteristics of the forward fuselage, the deformation varies from place to place. We take a research proposal as an example to analyze its macroscopic and microscopic deformation characteristics.

4.1 Macroscopic Characteristic Analysis

The finite element model mesh node is shown in Figure 1. The node displacement after loading is shown in Figure 2.

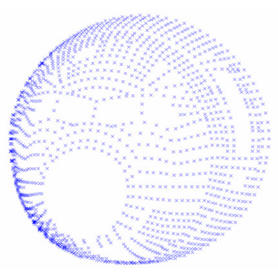

Fig. 1. Finite element mesh nodes.

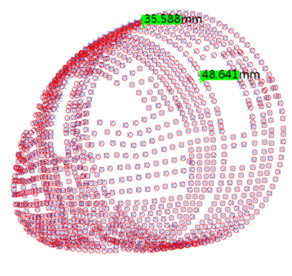

Fig. 2. Node before and after loading.

The macroscopic characteristics of the deformation distribution are as follows:

- Front service area overhead recessed.
- The boarding gate area is convex.
- Forward lifting is convex.
- In the windscreen front area, the main windscreen is recessed, and the side windscreen is convex.

4.2 Microscopic Feature Analysis

Based on the nodal displacement information of the finite element model, the shape of the machine head after loading is simulated (refer to Chapter 5 for the simulation method), and the surface quality is analyzed. Figure 3 is the result of Gaussian curvature analysis. There are obvious ripples (color-mottled area) in the local part, and the maximum amplitude is about 10 mm.

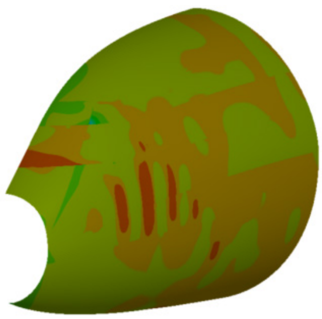

Fig. 3. Surface quality analysis.

5 Load Deformation on the Forward Fuselage

Based on the data from Chapter 3, we simulate the shape of the loaded forward fuselage. The shape of the deformed forward fuselage is reconstructed according to the finite element node loaded, which is close to the node while maintaining the original forming law of the theoretical shape, wherein the radome, the cockpit windshield, the boarding gate, the service gate, the front lifting cabin door and the like are missing in the finite element model, deforms with the adjacent nodes, and keeps tangent continuous with the straight segment of the fuselage.

The distance between the finite element node and the simulated shape loaded is shown in Figure 4, all of which are less than 1 mm, indicating that the deformation simulation method is accurate and reliable.

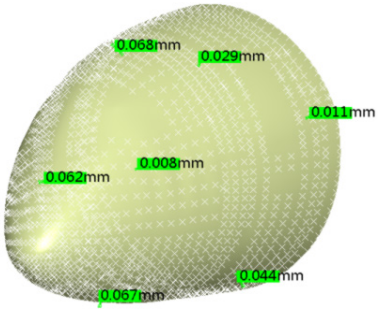

Fig. 4. Surface quality analysis.

6 Aerodynamic Analysis Method

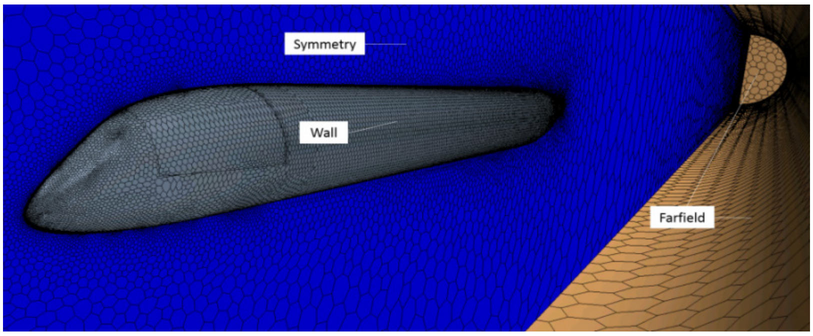

Fig. 5. Mesh and boundary condition settings.

Computational Fluid Dynamics (CFD) has emerged as a powerful tool for aerodynamic analysis in the aerospace industry [3][4][5]. CFD simulations allow engineers to predict and analyze the flow behavior around complex geometries, such as the forward fuselage, with high accuracy and efficiency. Considering the efficiency of calculation and the symmetry of the fuselage, the half-mold fuselage configuration is adopted. A convection field domain generates a non-structured body mesh, and defines a semi-cylinder far-field domain with a flight direction of 1, 300 m and a radial direction of 30 m, wherein the Reynolds number Re is 4.65×10^7, the first layer mesh ensures $y^+ = 1$, the thickness of the boundary layer is 0.005 mm, the total thickness of the boundary layer is 86 mm, and there are 45 layers of grid in total. Considering the curvature distribution of the forward fuselage shape, the mesh is sparsely treated, and the local transition of the mesh at the boundary layer and the flow field are adjusted to ensure the convergence of the calculation. The mesh and boundary condition settings are shown in Figure 5. Reynolds number average NS equation (RANS), high Reynolds number SA turbulence model, and steady implicit coupling solver were used to solve the flow field.

7 Aerodynamic Effect Analysis

Considering that the finite element calculation result corresponds to two times airtight load condition, and the aerodynamic effect analysis focuses on the typical cruise state, the deformation data in the finite element model is approximated by half, the deformation distribution factor contained in the finite element model is defined as 1, and the theoretical shape deformation distribution factor is defined as 0. Then, we focus on the forward fuselage shape with the deformation distribution factor of 0.5 and make a local sensitivity analysis for the boarding gate area with large deformation.

Based on the forward fuselage shape of the deformation factor 0.5, the design deformation factors of the boarding gate area are 0.3, 0.4, 0.6, and 0.7, respectively. Considering the large scale and large deformation here, the gentle transition around requires a large space.

In the typical cruise state, the resistance coefficient changes obviously in different degrees of deformation (see Table 1), and the pressure distribution pattern shows a worsening trend (see Figure 6 to Figure 10), indicating that this area is more sensitive to shape changes.

Table 1. Drag coefficient.

Factor	Resistance coefficient increment
0.3	-10.92%
0.4	0.57%
0.5	0
0.6	-10.34%
0.7	-11.90%

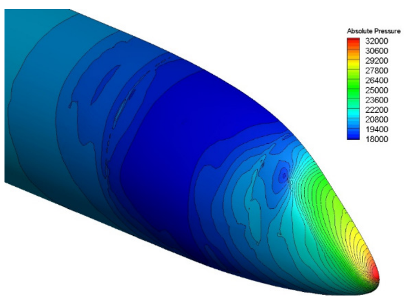

Fig. 6. Factor 0.3.

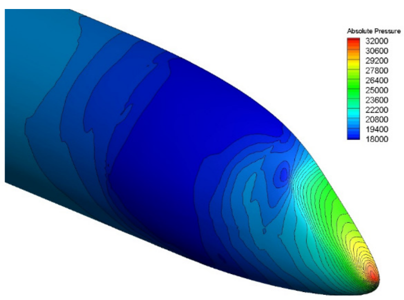

Fig. 7. Factor 0.4.

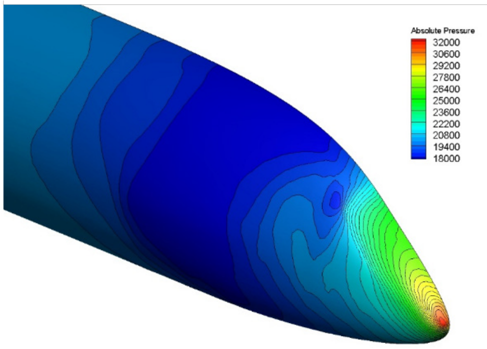

Fig. 8. Factor 0.5.

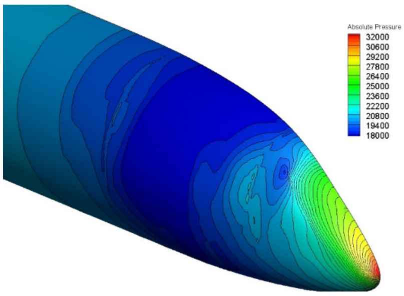

Fig. 9. Factor 0.6.

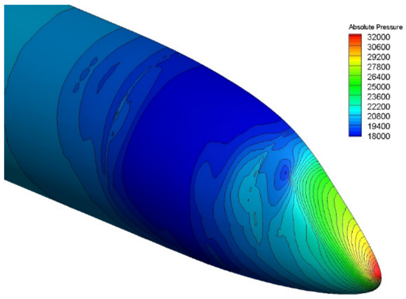

Fig. 10. Factor 0.7.

8 Conclusion and Recommendation

The aerodynamic influence of the load deformation of the forward fuselage cannot be ignored. The forward fuselage shape emphasizes overall coordination, and the drag coefficient and pressure distribution pattern have significant changes after local deformation.

Two ideas can be considered to realize the load deformation control of the forward fuselage shape of civil aircraft. The first idea, passive control, is to design the structure based on the theoretical shape, obtain the distribution of the load-deformation, conduct different deformation simulations and comprehensive evaluation, formulate the load deformation index of the forward fuselage shape, and locally optimize the structure design according to the deformation index. The second idea, active control, is to redesign the structure based on the theoretical shape, obtain the load deformation distribution, reversely modify the theoretical shape according to the load deformation distribution, and update the structural design and system layout based on the modified shape, to hope that the deformation after load returns to the original theoretical shape.

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