Thermal Assessment of Aircraft Fixed Leading Edge Compartment with Simulink and CFD Simulation

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Abstract. Fixed leading edge is an important part of aircraft wing, and its design should consider the influence of temperature. The temperature of the fixed leading edge compartment is affected by the high temperature and high pressure gas inside the bleed air duct and the ambient temperature outside the skin. The temperature, pressure and velocity of the gas inside and outside the compartment are quite different, so it is difficult to converge by computational fluid dynamics (CFD) analysis directly. In this study, the method of combining Simulink with CFD is proposed to solve the temperature of fixed leading edge compartment in a certain civil aircraft. The calculation method is easy to converge, and the obtained temperature can be directly used in the design of fixed leading edge structures to ensure aircraft safety.

Keywords: Fixed leading edge compartment, Bleed air duct, Temperature field.

1. Introduction

Large civil aircraft will encounter various environmental conditions during operation, among which the influence of extreme temperature on aircraft structure and system has always been an important factor that must be considered in the process of aircraft design and airworthiness certification [1-3]. If the temperature of aircraft is unreasonable, serious consequences will be caused. With the extensive use of composite materials in new civil aircraft [4], aircraft temperature and thermal management problems are more serious [5].

The fixed leading edge of the wing is an important part of the aircraft wing, which is located in the front side of the wing front beam and the rear side of the leading edge slat. The fixed leading edge not only supports the leading edge slat, but also plays an important role in resisting bird strike and installing various systems. However, there is usually a bleed pipe near the fixed leading edge compartment of civil aircraft, and high temperature and high pressure gas (usually more than 200 °C) is in the inside of the bleed duct, which will have a great impact on the temperature in the fixed leading edge compartment.

The main structures of a certain civil aircraft in the fixed leading edge compartment include fixed leading edge stiffener, fixed leading edge skin, slide rail, roller, bleed air duct, etc. Among them, the slide rail and roller are made of high temperature resistant titanium alloy, stainless steel and other materials. The fixed leading edge skin and rib plate are made of aluminum alloy. When the temperature exceeds 140°C to 150 °C, the performance of the that certain aluminum alloy will decrease obviously, which needs to be evaluated.
The purpose of this paper is to evaluate the temperature in the fixed leading edge compartment of a certain civil aircraft. Because the temperature and pressure of the air inside the bleed air duct are quite high, which is very different from the air in fixed leading edge compartment the air outside the wing skin. So it is difficult to converge directly by computational fluid dynamics (CFD) calculation. In this paper, the method of combining Simulink simulation with CFD calculation is proposed to analyze the influence of high temperature and high pressure gas in the bleed air duct and external ambient on the temperature in the fixed leading edge compartment. The results of the temperature evaluation will be used as the input of the strength analysis of the fixed leading edge structure, and on this basis, the appropriate structural design scheme will be adopted to avoid the performance failure caused by high temperature, so as to ensure the safety of the aircraft.

2. Description of the evaluation case

2.1. Geometric model
Figure 1 shows the simplified geometric structure of the fixed leading edge compartment, which mainly includes the upper and lower wing skin, bleed air duct, diaphragm, rib plate, slide rail and other structures.

![Figure 1. The simplified geometric model of a certain civil fixed leading edge compartment](image)

2.2. Qualitative analysis of internal heat transfer in fixed leading edge compartment
The internal temperature in the fixed leading edge compartment is influenced by the internal heat source (mainly the bleed air duct), the structure of the fixed leading edge, the air in the compartment and outside the wing skin. The main heat transfer features in fixed leading edge compartment are as follows:

a) The fixed leading edge compartment is a closed space, and the heat transfer form of the internal air is mainly natural convection;

b) The high-temperature bleed air duct is the mainly internal heat source, which continuously dissipate heat to the air in fixed leading edge compartment, and has radiation heat exchange with surrounding structures;

c) The parameters such as temperature and flow rate inside the bleed air duct are basically stable, and the external ambient will not change much, Therefore, the heat transfer process can be considered as steady state.

2.3. Work conditions
In this study, the aircraft systems and equipment are assumed in normal working condition. As the rib plate in fixed leading edge compartment is sensitive to high temperature environment, this paper will focus on the analysis of the internal environment temperature of the fixed leading edge compartment on
extreme high temperature condition, so as to provide reference data for the design of the aircraft internal fixed leading edge compartment.

In the whole flight process of the aircraft, the highest temperature condition is the hot day condition on ground. Generally, the maximum ground ambient temperature specified by the civil aircraft temperature envelope is 55 °C. Therefore, the ground ambient temperature of 55 °C is adopted in this study.

Besides, the maximum air temperature inside the bleed air duct is about 232 °C, which will be used as the input condition for calculating the surface temperature of the duct.

3. Simulation model

3.1. Overview of the method
The high temperature bleed air duct is the largest heat source in the fixed leading edge compartment, which has an important influence on the compartment temperature. However, the temperature or heating power of the bleed air duct is not clear in advance, because it is affected by the internal gas temperature of the duct, the air temperature in the fixed leading edge compartment and the material properties of the duct itself.

To solve this problem, the gas inside the duct, the duct itself and the air in the fixed leading edge compartment can be coupled together for CFD calculation. However, the direct calculation is difficult to converge because of the huge difference of temperature and pressure between the gas inside and outside the duct. This paper presents a method of combining Simulink simulation with CFD calculation, and the specific ideas are as follows:

a) According to the initial assumptions, the external surface temperature of the bleed air duct is calculated by using the Simulink model;
b) The external surface temperature of the duct calculated in a) is taken as the boundary condition to calculate the ambient temperature in the fixed leading edge compartment;
c) Compare the ambient temperature calculated in b) with the assumption in a), if not consistent, adjust the assumption in a) and recalculate.;
d) The above calculation will continuously iterate until the difference is reduced to an acceptable level.

3.2. Simulink model
The temperature of the bleed air duct is calculated by the Simulink model. The inside of the duct is high-temperature and high-pressure air, the outside is covered with insulation layer, and the outside is the fixed leading edge compartment. The heat transfer principle on the duct is shown in Figure 2.

![Figure 2. Schematic diagram of heat transfer form on the bleed air duct](image-url)
According to the heat balance equation, the heat transferred from the duct to the insulation layer is equal to the heat transferred from the insulation layer to the external environment, that is the fixed leading edge compartment. To be more specific, the heat transferred from the duct to the insulation layer includes the heat radiation from the duct to the insulation shell as well as the heat conduction between the duct and the insulation shell. Similarly, the heat transferred from the insulation shell to the external environment includes the heat radiation from the insulation layer to the environment as well as the convective heat transfer between the insulation layer and the compartment. Therefore, the heat balance equation is established as Eq. (1).

$$\pi d_1 \left[ \frac{\sigma}{\varepsilon_{duct}} \left( T_{hc}^4 - (T_{cs})^4 \right) \right] + \frac{2\pi k_{eff} (T_{hc} - T_{cs})}{\ln \left( \frac{d_2}{d_1} \right)} = \pi d_2 \varepsilon_{cover} \sigma \left( T_{cs}^4 - (T_{amb})^4 \right) + \pi d_2 h_{conv} (T_{cs} - T_{amb}) \quad (1)$$

Where,
- $d_1$ is the diameter of the duct;
- $d_2$ is the diameter of the insulation layer;
- $T_{hc}$ is the internal surface temperature of the duct, which is almost equal to the temperature of the air in the bleed air duct;
- $T_{cs}$ is the outer surface temperature of the insulation layer;
- $T_{amb}$ is the temperature in the fixed leading edge compartment;
- $\varepsilon_{duct}$ is the emissivity of the duct;
- $\varepsilon_{cover}$ is the internal surface emissivity of the insulation layer;
- $k_{eff}$ is the thermal conductivity of the duct;
- $h_{conv}$ is the convective heat transfer coefficient;
- $\sigma$ is the Boltzmann constant, which is $5.67 \times 10^{-8} \text{W} / (\text{m}^2 \cdot \text{K}^4)$.

### 3.3. CFD model

The field distributions of air velocity and temperature are obtained by computational fluid dynamics (CFD) calculation. The basis of CFD can be summarized as Eq. (2).

$$\frac{\partial}{\partial t} \left( \rho \phi \right) + \frac{\partial}{\partial x_j} \left( \rho u_j \phi \right) = \frac{\partial}{\partial x_j} \left( \Gamma_\phi \frac{\partial \phi}{\partial x_j} \right) + S_\phi \quad (2)$$

Where $\rho$, $t$, $\Gamma_\phi$, $S_\phi$ are air density, time, diffusion coefficient and source term respectively, $u_j$ is velocity component in three directions ($x_j$, $j = 1, 2, 3$). When $\phi$ stand for different values, equation (1) can represent continuity, momentum and energy equations.

In this study, the numerical simulations are conducted by using the CFD software Star-CCM+. The basic mesh size is 0.01m, and the mesh is densified near the rib and other local positions, and the final generated meshes are shown in Figure 3.
4. Results and discussion

Through iterative calculation of the Simulink model and the CFD model, the temperature of the duct is confirmed to be about 146 °C, and the average temperature of the air in the compartment is about 91.7 °C. Detailed temperature data are as follows.

4.1. Overall temperature distribution

The overall distribution of ambient temperature in the fixed leading edge compartment is shown in Figure 4, and the ambient temperature near the main internal structure is shown in Figure 5. It can be seen from Fig. 4 and Fig. 5 that the ambient temperature in the compartment changes with the distance from the duct. In most areas far away from the duct, the temperature does not exceed 105 °C, which is lower than the sensitive temperature of the rib plate, while the temperature is slightly higher in small areas near the high temperature duct, and this will be discussed in the following.
Figure 5. The ambient temperature near the main internal structure

4.2. Temperature field near the rib plate

Figure 6 shows the temperature near the rib plate. It can be seen that the temperature distribution near the rib plate is consistent with the overall temperature distribution in the compartment, that is, the temperature in most areas does not exceed 105 °C, and the temperature near the high temperature duct is slightly higher. In Fig. 6, the temperature of the small upper area on rib plate is more than 120 °C (orange temperature in the figure), but the proportion of this area is small, and the maximum temperature is about 130.73 °C, which is still lower than sensitive temperature, which is about above 140°C to 150 °C.

Figure 6. Temperature distribution near the rib plate

Figure 7 shows a enlarged local view of the high temperature area of the rib plate. The highest temperature is about 130.73 °C, which is lower than the sensitive temperature. Moreover, this high temperature only occurs at the point closest to the high temperature duct, which accounts for a very small proportion of the rib plate area.
5. Conclusions

In this study, the temperature distribution of the fixed leading edge compartment of a certain civil aircraft in extremely hot day (55 °C) is obtained by using the method of combining Simulink simulation and CFD calculation. The method proposed in this paper avoids the difficulty of convergence caused by the huge difference of gas temperature and pressure inside and outside the bleed air duct.

The results show that the average air temperature in the fixed leading edge compartment is about 91.7 °C, and the ambient temperature in most areas is less than 105 °C. In the local area near the high temperature duct, the temperature is slightly higher, but the maximum temperature is still lower than the sensitive temperature of rib plate.

For the rib plate, the temperature distribution is consistent with that in the compartment, and the highest temperature is about 130.73 °C, which is lower than the sensitive temperature and occurs only at the position near the high temperature duct.

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