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Research Paper

Reliability analysis of bleed air anti-icing system based on subset simulation method

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ABSTRACT

Based on subset simulation method, this paper analyzes the temperature control failure of the aircraft bleed air system. Firstly, a deterministic simulation model of the aircraft bleed air system is created in AMESim software. Secondly, the relationship between parameters of the bleed air system and the outlet temperature is built using the quadratic response surface method. Functional reliability analysis model under the temperature failure of the bleed air system is established with the consideration of the bleed air system parameters dispersion. The calculation procedure of the bleed air system failure probability is derived based on subset simulation method. By introducing reasonable middle failure events, a small probability is transformed into a product of a series of large conditional probabilities so that the computation efficiency can be improved. Results show that the subset simulation method has higher degree of accuracy and less calculation in the functional reliability assessment of bleed air system. The reliability analysis results provide reference values for the bleed air system design.

1. Introduction

When aircrafts fly in critical weather condition, the icing phenomenon often occurs on the leading edge of the wings [1]. The wing-icing problem deteriorates the aircraft's aerodynamic performance, causing the problem of lift-to-drag ratio decrease, loss rate increase and other issues, which affect the aircraft's maneuverability and stability from the failure of mission to the tragedy of severe plane crash [2,3]. Currently, most civilian airliners and military transport aircrafts have installed the anti-icing system to solve the wing-icing problem [4,5]. The bleed air anti-icing system drives heat from the engine, and assign it to each segment within the slats through supply line, then ejects from the sprout of flute-shaped tube within the slats to heat the leading edge skin of the wing, finally achieving the goal of anti-icing.

Bleed air system is an important part of the aircraft anti-icing system, which provides temperature-suitable heat for anti-icing chamber to meet the need of de-icing [6,7]. Statistics show that the bleed air system failure modes are multiple, repetitive and complex. Typically, the high-temperature failure and low-temperature failure are dominated [8]. The reason is that the bleed air system is generally designed by employing the safety factor method. This extensive design concept performs large human subjectivity, making the failure probability of the bleed air system given not in a quantitative way. In the recent years, a great deal of interest for bleed air system analysis has been given in the research programs and the open scientific literature. For example, Claudio and Luca [9] developed a complete model of an anti-ice system to study the behavior of anti-ice system at high bleed temperature, and found that with the increase of the bleed air temperature the air bled from the engine by the anti-ice system decreases since the valves regulating point shift down with temperature increase. Yu et al. [10] developed a three-dimensional numerical simulation method with internal-external tight coupled heat transfer to analyze the performance of an engine nacelle hot-air anti-icing system. Zheng et al. [11] studied the effect of free stream velocity on the runback water flow and heat transfer on the anti-icing surface. Guo et al. [12] established a simulation model for the hot air anti-icing system based on the principle of conjugate heat transfer between the external and internal chamber, which results can be provided as a reference to design, analysis and optimization on hot air anti-icing system. Zhu et al. [13] introduced the structure and theory of engine nacelle anti-icing system, and determined the critical design point and required flows of nacelle anti-icing system by calculating the required bleed air at complete evaporation and running wet station.

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Therefore, this paper established functional reliability model for the temperature on the basis of bleed air system simulation analysis, and combined the response surface method with subset simulation method to estimate the probability of system failure, enabling the quantitative assessment of bleed air system.

This paper is organized as follows. Bleed air system simulation model is established in Section 2. Functional reliability analysis of the bleed air system is carried out in Section 3. Conclusions are presented in Section 4.

2. Bleed air system simulation

2.1. Simulation model based on AMESim software

An example of an aircraft bleed air system is shown in Fig. 1. The system is composed of one-way valve, high pressure valve, high pressure regulator, pressure regulator, shut-off valve, overheating switch and precooler [14]. Normally the system drives heat from middle-pressure stage of engine. But the high-pressure stage of engine will be employed when the air pressure is too low. The AMESim software aims at the modeling, simulation and dynamic analysis of hydraulic/mechanical system, which provide a comprehensive, superior simulation environment and flexible solutions for fluid dynamic (liquids and gases), thermal fluid and control systems [12]. This paper introduced AMESim software to establish the simulation model of the bleed air system, as shown in Fig. 2, and conducted simulation analysis to get the outlet temperature response of system.

2.2. Outlet temperature simulation of bleed air system based on the response surface method

From the simulation of the bleed air system, we can see that outlet temperature of the system is related to system piping parameters, inlet gas parameters and others. By using AMESim software to conduct the simulation analysis of system outlet temperature, we can conclude that the outlet temperature T is the implicit function of inlet temperature T_0, inlet pressure P_0, pipe diameter D, thickness d, length l, relative roughness f. These parameters are random variables, obeying normal distribution, and their mean, standard deviation and coefficient of variation are given in Table 1.

Make $\boldsymbol{x} = (T_0, P_0, D, d, l, f)$, then the outlet temperature can be expressed as $T(\boldsymbol{x})$. Because of the complexity of simulation model, it's hard to directly get an explicit expression of the system outlet temperature $T(\boldsymbol{x})$. Response surface methodology is a combination of mathematical and statistical method, aiming at constructing the conversion relations between input and output of complex systems [15–19]. Based on limited experimental data, it uses analytical expression $\hat{T}(\boldsymbol{x})$ to fit the real $T(\boldsymbol{x})$ by polynomial regression [20,21]. This paper adopted the response surface method without cross terms to get the fitting expression of $\hat{T}(\boldsymbol{x})$ on the basis of AMESim's virtual simulation experiments, finally to characterize the function between the outlet temperature and system parameters. Fig. 3 verified the accuracy of the fitting expression. From the residual analysis for 20 groups of simulation value $T(\boldsymbol{x})$ and fitted value $\hat{T}(\boldsymbol{x})$, the average relative error is less than 3% which can meet the accuracy requirements. Therefore, we can use $\hat{T}(\boldsymbol{x})$ to replace $T(\boldsymbol{x})$ to conduct the analysis of system functional reliability.

3. Functional reliability analysis of bleed air system

3.1. Functional reliability analysis model under temperature failure

In Table 1, there exists random uncertainty in bleed air system parameters. Therefore, the system's outlet temperature $\hat{T}(\boldsymbol{x})$ is also a random variable. Too high outlet temperature will cause the structural damage of anti-icing chamber, and too low may fail the function of anti-icing. So the system outlet temperature $\hat{T}(\boldsymbol{x})$ should be in a predetermined range. If the outlet temperature $\hat{T}(\boldsymbol{x})$ deviates from the predetermined range, either the high or low temperature failure will occur. Therefore, this paper established the performance function $g_{(up)}$ and $g_{(low)}$ based on high and low temperature, as in

$$g_{(up)} = T_{(up)} - \hat{T}(\boldsymbol{x}) \quad \text{for high temperature} \tag{1}$$

$$g_{(low)} = \hat{T}(\boldsymbol{x}) - T_{(low)} \quad \text{for low temperature} \tag{2}$$

where $T_{(up)}$ and $T_{(low)}$ are the tolerant upper limit and lower limit of the outlet temperature of the bleed air system.

The failure domains of performance function $g_{(up)}$ and $g_{(low)}$ are expressed as $F_{(up)}$ and $F_{(low)}$, as in,

$$F_{(up)} = \{\boldsymbol{x} : \ T_{(up)} - \hat{T}(\boldsymbol{x}) < 0\} \tag{3}$$

$$F_{(low)} = \{\boldsymbol{x} : \ \hat{T}(\boldsymbol{x}) - T_{(low)} < 0\} \tag{4}$$

Assuming the failure probability of high and low temperature failure as $P_{f(up)}$ and $P_{f(low)}$, the solving equations can be written as

$$P_{f(up)} = \int \cdots \int_{g_{(up)}(\boldsymbol{x})<0} f_{\boldsymbol{x}}(\boldsymbol{x}) d\boldsymbol{x} \tag{5}$$

$$P_{f(low)} = \int \cdots \int_{g_{(low)}(\boldsymbol{x})<0} f_{\boldsymbol{x}}(\boldsymbol{x}) d\boldsymbol{x} \tag{6}$$

From Eqs. (5) and (6), we can see that the high and low temperature failure domains have no intersection. The total failure domain is the sum of them, i.e.,

$$F = F_{(up)} \cup F_{(low)} = F_{(up)} + F_{(low)} \tag{7}$$

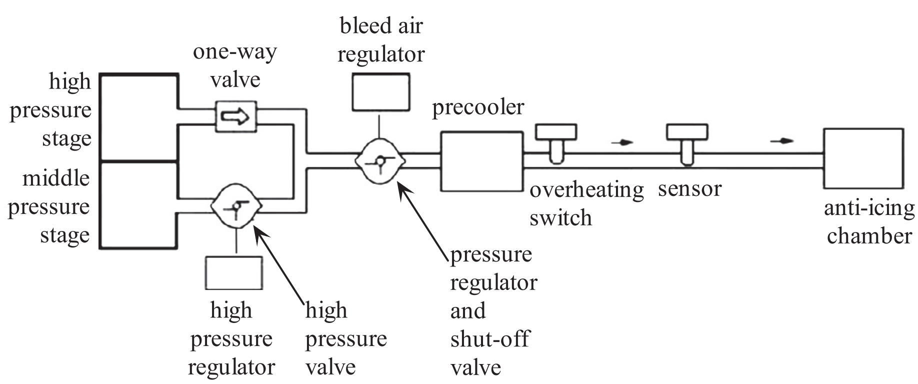

Fig. 1. A schematic diagram of the aircraft bleed air system.