The Impact of Icing on the Airfoil on the Lift-Drag Characteristics and Maneuverability Characteristics

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Icing has now become an important factor endangering flight safety. This paper takes the icing data of the NACA 23012 airfoil as an example, establishes an icing influence model for real-time simulation based on icing time and aircraft angle of attack, and analyzes the influence of different icing geometry on aircraft characteristics. The two-dimensional interpolation method is used to improve the model of the aircraft’s stall area, which is mainly divided into the correction of the lift-drag coefficient linear area and the stall area and the correction of the aircraft stability derivative and the control derivative. The aerodynamic equation of the airplane after icing is established, and the modal analysis of the airplane under different icing conditions is completed through the linearization of the flight equation. The closed-loop simulation system of the altitude holding mode and roll attitude holding mode is used to calculate and analyze the flight quality changes of the aircraft after the wing surface is frozen. The analysis results show that, under icing conditions, in the range of small angles of attack, icing has no obvious influence on the aircraft mode. As the degree of icing increases, the throttleskewness and thenegativedeflectionangleoftheairplane’slevelflightrequirementscontinue to increase. The case of icing flight in altitude hold and roll hold modes shows that flying in the autopilot mode under severe icing conditions is very dangerous and is prone to cause the aircraft to stall.

1. Introduction

The main cause of flight accidents caused by airplane icing is the loss of control caused by the airplane stall. Under severe icing conditions, the stall angle of the aircraft decreases, and the stall speed increases. In 2001, Frank and Abdollah compared the stall angle of attack and the maximum lift coefficient of the wing and found that when the angle of attack of the wing is between 0° and 11°, the change in the maximum lift coefficient is in linear relationship with the lift coefficient after icing [1]. Since 1994, NASA had conducted research on tail icing for three years and pointed out that the flat tail icing is the cause of abnormal elevator efficiency. For a Twin Otter aircraft, when the flap deflects more than 30°, the flat tail stalls from the leading edge, causing the aircraft to be out of control. However, due to the complexity of the flat tail flow field and the influence of the wing flaps on the downwash of the flat tail, it is difficult to determine the boundary of the flat tail stall.

In terms of flight test, the aerodynamic data of the aircraft after icing are identified mainly through the aircraft icing test flight data. NASA has launched projects including the Tail Icing Project (TIP) [2, 3] and conducted a large number of flight tests with the Twin Otter aircraft (DHC-6), accumulating a large amount of aircraft icing flight data [4, 5]. Since 1999, Miller and Ribbens adopted identification methods such as SWR and OFFIT to obtain aerodynamic data [6, 7]. In 2000, Bragg et al. proposed a model with obvious physical meaning and simple structure to describe the effects of icing, which can be used to estimate the aerodynamic parameters of the aircraft after icing [8]. Dale simulated icing on the flat tail of the “Twin Otter” aircraft, and the response of the aircraft output was consistent with the test flight data [9]. Lampton and Valasek transformed the flight test results of the “Double Otter” aircraft into an icing influence factor model to simulate the longitudinal motion of the aircraft [10]. As discussed elsewhere [10, 11], an
asymmetric icing model was established, the lateral movement of the aircraft under icing was simulated, and the flight test on the Cessna 208B aircraft verified the reliability of the model. The model characteristics of the aircraft were analyzed.

Since it is currently impossible to eliminate the hazards of icing to flight safety, there is an urgent need for safety protection under icing conditions. In order to fully understand the effect of icing on the lift-drag characteristics and stability characteristics of aircraft flight, a real-time simulation icing influence model is established in this paper based on NACA 23012 airfoil icing data. Since icing will affect the stall characteristics of the aircraft and reduce the stall angle of attack, the model of the stall area of the aircraft is improved by modeling the aircraft in the linear phase and the stall phase. At the same time, two modes of autopilot are designed on the basis of the simulation model, namely, roll attitude hold (RAH) and altitude hold (ALH). The focus is on the analysis of the stability characteristics of the aircraft in the open loop and closed loop under icing conditions. Through open-loop simulation, the influence of icing on the longitudinal long- and short-period mode and the transverse mode is studied, and the influence of icing on the performance of autopilot is studied through closed-loop simulation.

2. Materials and Methods

2.1. The Influence of Airfoil Icing on Aircraft Aerodynamics and Model Establishment

2.1.1. The Influence of Airfoil Icing on Lift-Drag Characteristics. The selected wing of the aircraft is a trapezoidal wing with a large aspect ratio, and the aerodynamic layout is that the airfoil with a larger lift coefficient is arranged at the wing tip. The airfoil with a smaller lift coefficient is arranged at the wing root to ensure that the separation of aircraft airflow gradually spreads from the wing root to the wing tip. When an airplane wing tip stalls, the entire wing stalls. This paper selects NACA 23012 airfoil icing data which are close to the wing tip airfoil [12] for modeling.

Different shapes of ice determine different effects of icing on the aerodynamic characteristics of the airfoil. Taking the NACA 23012 airfoil as an example, the lift-drag characteristics of rime ice, glaze ice, and backface ice formed by different physical processes of ice accumulation are shown in Figure 1 [13].

The NACA 23012 airfoil is simulated under icing conditions with the airfoil surface at $Ma = 0.1$, $Re = 1.0 \times 10^6$, and angle of attack at 0°. The NASA Glenn Center has conducted wind tunnel icing experiments on it [13]. The flow field distribution of the NACA 23012 airfoil under nonicing conditions and severe frost and clear ice conditions is shown in Figure 2.

It can be seen from the NACA 23012 airfoil flow field distribution diagram that when the angle of attack is 0°, frost has little effect on the flow field distribution, and the airfoil pressure on the leading edge of the wing changes slightly. Clear ice has a great influence on the distribution of the flow field. The pressure on the upper and lower wing surfaces is reduced, and the pressure on the lower wing surface is greatly reduced. The pressure difference between the two wing surfaces is significantly reduced. Clear ice causes a significant drop in the lift coefficient of the airfoil.

According to the icing geometry classification, for the NACA 23012 airfoil, the lift-drag characteristics of four ice shapes, namely, roughness ice, horn ice, streamwise ice, and spanwise-ridge ice, are shown in Figure 3.

It can be seen from the figure that the ice ridge has the greatest influence on the aerodynamic characteristics of the airfoil. The maximum lift coefficient is reduced from 1.8 to 0.5, and the stall angle of attack is reduced from 18° to 6°. The resistance has increased significantly after the stall, as well as the pitching moment coefficient. The severity of other ice shapes is horn ice, roughness ice, and streamwise ice in a descending order.

The difference in the ice shape is closely related to the freezing time. Taking clear ice which has a serious impact on aerodynamic characteristics as an example, for the NACA 23012 airfoil [14], the NASA Glenn Center conducted an icing wind tunnel experiment under such conditions. The ice shape and lift-drag coefficient changes with time are shown in Figure 4.

As the freezing time increases, the shape of ice on the airfoil surface changes continuously. During the formation of clear ice, when ice freezes for 1 minute, streamwise ice that has a small impact on aerodynamics is formed. After 5 minutes of freezing, the ice shape develops into horn ice that has a serious impact on aerodynamic characteristics.

2.2. Effect Modeling of Icing on the Longitudinal Aerodynamic Coefficient. The effect of icing on the aerodynamic characteristics of the aircraft is mainly reflected in the reduction of lift, the increase of drag, and the reduction of control efficiency. Icing will also affect the stall characteristics of the aircraft and reduce the stall angle of attack. Therefore, it is necessary to improve the model of the stall area of the aircraft. Due to the difference in the icing time of the aircraft, the aerodynamic characteristics are different. This paper selects NASA’s clear ice icing data that have a serious impact on NACA 23012 airfoil icing data. The data change curve of the lift-drag coefficient with the angle of attack under different icing times is shown in Figure 5. Freezing for 5 minutes is considered as severely icing.

Due to the complicated changes in the longitudinal aerodynamic characteristics of the aircraft after icing, the modeling in this paper is divided into two phases: the linear phase and the stall phase. For the modeling of the stall zone affected by icing, it can be seen from Figure 6 that it is difficult to describe and model with a function. Therefore, this paper adopts the two-dimensional interpolation table. According to the NASA icing data, this paper standardizes the effect of icing on aerodynamic derivatives and takes nonicing as the standard to obtain the icing influence correction factor. In real-time simulation, the two-dimensional interpolation method is used to correct the
Figure 1: The aerodynamic characteristics of the NACA 23012 airfoil under different ice shapes: (a) lift coefficient and (b) drag coefficient.

Figure 2: Flow field distribution diagram of the NACA 23012 airfoil: (a) without icing, (b) under frost, and (c) under clear ice.

Figure 3: The lift-drag characteristic curve of the NACA 23012 airfoil under different ice shapes: (a) lift coefficient and (b) drag coefficient.
aerodynamic data of the aircraft stall area lift-drag coefficient. The influencing factors $K_{CL}$ of the two-dimensional interpolation data of lift coefficient after normalization are shown in Table 1, and the influencing factors $K_{CD}$ of resistance coefficient are shown in Table 2.

For the linear area of the pneumatic data of lift-drag coefficient, a correction formula is used for correction. The correction factors $k_L$ and $k_D$ for lift coefficient and drag coefficient are equations (1) and (2), respectively, which are functions of angle of attack and icing time:

$$k_L(\alpha, t) = -0.0015 \cdot t \cdot |\alpha|^{1.75} + 1, \quad (1)$$

$$k_D(\alpha, t) = 0.05 \cdot t \cdot |\alpha|^{1.7} + 0.275 \cdot t + 1. \quad (2)$$

According to the correction coefficient, taking the flight state of 0.2 Mach with the flap angle of the selected aircraft being 0° as an example, the curves of the change and lift-drag coefficient, with the angle of attack under different icing conditions are shown in Figure 7.

![Figure 4](image1)

**Figure 4:** Experimental results of the lift-drag coefficient of the NASA ice wind tunnel: (a) ice shape, (b) lift coefficient, and (c) drag coefficient.

![Figure 5](image2)

**Figure 5:** The data change curve of the lift-drag coefficient with the angle of attack under different icing times: (a) lift coefficient and (b) drag coefficient.
The effect of icing on the pitching moment coefficient of the aircraft in the linear region is expressed as a percentage of decrease. When the aircraft is approaching the stall angle of attack, its changes are also very complicated. This paper also uses the two-dimensional interpolation correction coefficient method for the stall area. The correction coefficient of the aerodynamic coefficient is shown in Table 3.

Taking the correction of lift coefficient after icing as an example, firstly, according to the lift coefficient and angle of attack when the aircraft is not icing, the linear zone correction equation coefficient and the two-dimensional lookup table interpolation coefficient are obtained. Then, the lift coefficient is revised. The correction of drag coefficient and pitching moment coefficient is similar to this.

This paper selects the air flight state of the airplane at 0.2 Mach when the flap angle is 0°. The lift coefficient and drag coefficient at different icing times are shown in Figure 8.

### 2.3. Model of the Influence of Airfoil Icing on Other Aerodynamic Derivatives.

The aircraft’s lift, drag, and pitching moment coefficients can be corrected by NASA data, and the icing effect mainly depends on the icing time and the aircraft’s angle of attack. However, NASA public data contain less for other aerodynamic derivatives of the aircraft. Detailed studies through flight tests were only carried out in NASA’s DHC-6 Twin Otter aircraft. Its aerodynamic data are given as a percentage increase or decrease. Lampton applied them to the Cessna aircraft and verified the rationality and usability of the data through flight tests. The changes of the aerodynamic derivative are also used in this paper, which are shown in Tables 4 and 5.

Assuming that these aerodynamic derivatives change linearly with time, taking $\Delta C_{Y\beta}$ as an example, when its value is reduced by 20%, it is regarded as a severe icing condition, that is, the condition reached after icing for 5 minutes. Therefore, the correction coefficient $k_{C_{Y\beta}}$ of the aerodynamic derivative $C_{Y\beta}$ under icing conditions is expressed as follows:

$$k_{C_{Y\beta}}(t) = 1 - \left(\frac{20\%}{5}\right) \times t,$$  \hspace{1cm} (3)

where $t$ represents the freezing time, and it is calculated in minutes. The aerodynamic derivative value after icing is

![Lift curve of the air condition of the whole aircraft.](image)

**Figure 6:** Lift curve of the air condition of the whole aircraft.

**Table 1:** Correction coefficients of the interpolation table of the stall zone lift coefficient.

| Angle of attack (degrees) | -1 | 1  | 3  | 5  | 7  | 9  | 11 | 13 | 15 | 17 | 18 |
|---------------------------|----|----|----|----|----|----|----|----|----|----|----|
| Not frozen                | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |    |
| Freeze for 1 min          | 1  | 1  | 0.9959 | 0.9700 | 0.9887 | 0.9592 | 0.8695 | 0.6703 | —  | —  |
| Freeze for 2.5 min        | 1  | 1  | 0.9312 | 0.9013 | 0.9469 | 0.8528 | 0.7953 | 0.6541 | 0.5040 | —  | —  |
| Freeze for 5 min          | 1  | 1  | 0.7993 | 0.8061 | 0.6494 | 0.6188 | 0.6883 | 0.5641 | 0.4152 | —  | —  |

**Table 2:** Modification coefficient of the interpolation table of the stall zone drag coefficient.

| Angle of attack (degrees) | 1  | 2  | 3  | 4  | 5  | 6  |
|---------------------------|----|----|----|----|----|----|
| Not frozen                | 1  | 1  | 1  | 1  | 1  | 1  |
| Freeze for 1 min          | 1.600 | 1.700 | 1.800 | 2.000 | 2.100 | 2.200 |
| Freeze for 2.5 min        | 1.625 | 1.765 | 1.944 | 2.000 | 2.143 | 2.273 |
| Freeze for 5 min          | 1.731 | 1.667 | 1.571 | 1.325 | 1.556 | 1.940 |
Figure 7: The modified curve of the lift-drag coefficient in the linear region: (a) lift coefficient and (b) drag coefficient.

Table 3: Stall zone interpolation table of pitching moment versus angle of attack derivative.

| Angle of attack | Not frozen | Freeze for 1 min | Freeze for 2.5 min | Freeze for 5 min |
|-----------------|------------|------------------|--------------------|------------------|
| 0               | 1          | 1                | 1                  | 1                |
| 6               | 1          | 1                | 0.95               | 0.95             |
| 7               | 1          | 0.95             | 0.85               | 0.75             |
| 8               | 1          | 0.95             | 0.85               | 0.75             |
| 9               | 1          | 0.95             | 0.75               | 0.75             |
| 10              | 1          | 0.95             | 0.75               | 0.75             |
| 12              | 1          | 0.95             | 0.75               | 0.75             |
| 16              | 0.95       | 0.75             | 0.75               | 0.75             |
| 30              | 0.75       | 0.75             | 0.75               | 0.75             |

Figure 8: The modified curve of the lift-drag coefficient: (a) lift coefficient and (b) drag coefficient.

Table 4: The influence of icing on the stable derivative.

| Stable derivative | Variation % |
|-------------------|-------------|
| ΔCLa              | −1.20       |
| ΔCmb              | −10         |
| ΔCmq              | −3.50       |
| ΔCyl              | −20         |
| ΔCbg              | −10         |
| ΔClb              | 0           |
| ΔCn              | −20         |
| ΔClng            | −6.10       |

Table 5: The influence of icing on the manipulation derivative.

| Manipulation derivative | Variation % |
|------------------------|-------------|
| ΔCld                 | −9.50       |
| ΔCmb                 | −10         |
| ΔCyl                 | −8          |
| ΔClb                 | −10         |
| ΔCn                 | −8          |
| ΔClng               | −8.30       |
3. Icing Aerodynamic Model and Autopilot Design

3.1. Aerodynamic Equation of the Airplane after Icing

Icing mainly causes the changes in aerodynamic parameters of the aircraft. Its modeling adopts the form of correction factor. Regarding the aircraft body shafting, the linear models of aerodynamic forces and aerodynamic moment coefficients can be divided into longitudinal and transverse models. The aerodynamic parameter models after icing are expressed as follows:

$$\begin{align*}
C_L &= k_{CL}(t, \alpha)C_{L0} + k_{C_{\delta\alpha}}(t, \alpha)C_{La} \alpha + k_{C_{\delta\beta}}(t)C_{La} \delta_e + k_{C_{\delta\alpha}}(t)C_{La} \delta_r \frac{\bar{\bar{C}}}{2V} + 2\% \\
C_D &= k_{CD}(t, \alpha)C_{D0} + k_{C_{\alpha\alpha}}(t, \alpha)(C_{Da} \alpha + C_{Da: \alpha^2}) \\
C_Y &= k_{C_{\beta\beta}}(t)\beta + k_{C_{\delta\alpha}}(t)C_{Y}\delta_e + k_{C_{\delta\beta}}(t)C_{Y}\delta_r + C_{Y\beta}p \frac{\bar{\bar{C}}}{2V} + C_{Yr}r \frac{\bar{\bar{C}}}{2V} \\
C_m &= C_{m0} + C_{m}(t, \alpha)\left[k_{C_{\alpha\alpha}}(t)C_{ma} \alpha + k_{C_{\delta\alpha}}(t)C_{ma} \delta_e + k_{C_{\delta\beta}}(t)C_{ma} \delta_r \frac{\bar{\bar{C}}}{2V}\right] \\
C_i &= k_{Ci}(t)C_{ib} + k_{C_{\delta\alpha}}(t)C_{ib} \delta_e + k_{C_{\delta\beta}}(t)C_{ib} \delta_r + k_{C_{\alpha\alpha}}(t)C_{ib}p \frac{b}{2V} + k_{C_{\alpha\alpha}}(t)C_{ib}r \frac{b}{2V} \\
C_n &= k_{Cn}(t)C_{in} + C_{n}(t, \alpha)\left[k_{C_{\beta\beta}}(t)C_{n\beta} + C_{n}(t, \alpha)C_{n\beta} \delta_e + C_{n}(t, \alpha)C_{n\beta} \delta_r + C_{np}p \frac{b}{2V} + k_{C_{\alpha\alpha}}(t)C_{n\beta}r \frac{b}{2V}\right].
\end{align*}$$

where $C_L$, $C_D$, $C_Y$, $C_m$, $C_i$, $C_n$ are the lift, drag, and side force coefficients of the aircraft in the shaft system, respectively, $C_{m0}$, $C_{i0}$, $C_{n0}$ are the pitch, roll, and yaw moment coefficients of the aircraft, $\delta_e, \delta_r, \delta_a$ are the elevator, rudder, and aileron deflection angles, $\alpha, \beta$ are the aircraft’s angle of attack and sideslip angle, $V$ is the airspeed, $b$ is the wingspan, $\bar{\bar{C}}$ is the average aerodynamic chord length of the aircraft wing, $k_{\cdot\cdot}$ represents the aircraft icing correction coefficient, which is a function of time, where $k_{C_{\cdot\cdot}}, k_{C_{\cdot\cdot\cdot}}, k_{C_{\cdot\cdot\cdot\cdot}}$ are the correction coefficient close to the stall angle of attack and are given in the form of two-dimensional interpolation, and $C_{\cdot\cdot}$ represents each aerodynamic derivative. The aerodynamic data used in this paper come from the wind tunnel test of the whole machine. Lift and polar curves of the air condition of the whole aircraft are shown in Figures 6 and 9.

3.2. Altitude Hold Mode. It is necessary to maintain altitude stability during the initial stages of aircraft climb, cruise, and landing. In the airplane altitude hold mode, the airplane can automatically maintain at a certain fixed altitude. By directly introducing the desired altitude, through the altitude difference signal, and the pitch attitude hold mode inner loop, the aircraft attitude change is controlled to realize the control of the aircraft altitude. Its structure principle is shown in Figure 10.
Its control law can be expressed as follows:

\[
\theta_{\text{ref}} = k_{\text{HP}} \Delta H + k_{\text{HI}} \int \Delta H dt - k_{\text{H}} \Delta H,
\]

(6)

where \( \Delta H \) is the altitude difference between the aircraft altitude command and the aircraft’s current altitude, that is, \( \Delta H = H_{\text{ref}} - H \). In the figure, the longitudinal inner loop of the aircraft after icing is the pitch hold loop after icing.

3.3. Roll Attitude Angle Hold Mode. In the airplane roll angle hold mode, the airplane can track the expected roll angle by controlling the ailerons. Maintaining the aircraft’s roll attitude is mainly based on the aircraft’s full-state feedback to increase the aircraft’s roll damping and stability so that the aircraft can track the roll attitude angle. Due to the coupling of the aircraft’s lateral and heading direction, the aircraft’s roll attitude must be adjusted through two channels: the lateral channel and the heading channel. In the lateral automatic control mode, the sideslip angle of the course is generally set to 0. Due to the roll attitude angle of the aircraft, it is necessary to ensure that the lift component in the vertical direction of the aircraft is balanced with gravity, and the component in the horizontal direction is balanced with the centrifugal force of the aircraft during coordinated turns. The basic structure is shown in Figure 11.

Its control law can be expressed as follows:

\[
\Delta \delta_a = G(s) \left[ k_{\phi \psi} \Delta \phi + k_{\phi} \int \Delta \phi dt + k_p \phi \right],
\]

\[
\Delta \delta_r = G(s) \left[ k_{\gamma \psi} \left( \frac{\psi}{V} \tan \phi \right) + k_r - k_{\beta} \int \beta dt \right].
\]

(7)

4. Results and Discussion

4.1. The Influence of Airfoil Icing on the Airplane Mode. The longitudinal motion of the aircraft can be divided into the short-period mode and long-period mode, and the lateral motion of the aircraft can be divided into the roll mode, Dutch roll mode, and spiral mode. The mode characteristic parameters with the aircraft in the state of level flight at an altitude of 3000 m and a speed of 120 m/s are analyzed, at which the trim angle of attack \( \alpha = 1.47 \) deg. They are linearized into a small disturbance equation, and the characteristic roots are obtained by solving the longitudinal fourth-order equation of the aircraft:

\[
\lambda_{1,2} = -0.8989 \pm 1.6257, \lambda_{3,4} = -0.0084 \pm 0.1015.
\]

(8)

The natural frequency and damping ratio of the short-period mode are calculated as

\[
\omega_s = 1.8577, \zeta_s = 0.4839.
\]

(9)

The natural frequency and damping ratio of the long-period mode are

\[
\omega_p = 0.1018, \zeta_p = 0.0825.
\]

(10)

The characteristic roots are obtained by solving the fourth-order equation of the aircraft’s lateral heading:
\lambda_1 = -2.9249, \lambda_2 = 0.0024, \lambda_3,4 = -0.2131 \pm 1.1062i. 

(11)

The calculated roll mode time constant to the aircraft is

\[ \tau_r = 0.3419 \text{s}. \]

(12)

The natural frequency and damping ratio of the aircraft in the Dutch roll mode are

\[ \omega_d = 1.1265, \zeta_d = 0.1892. \]

(13)

The spiral mode time constant of the aircraft is

\[ \tau_s = 416.67 \text{s}. \]

(14)

Select the flight at an altitude of 3000 m, level flight at 90 m/s, and trim angle of attack \( \alpha = 5.33 \text{ deg} \) as the comparison of the icing situation at a higher angle of attack. The aircraft longitudinal modal characteristics are analyzed under different icing conditions. Choose from nonicing to icing for 10 minutes for calculation, and obtain the time-varying curve of aircraft longitudinal modal parameters as shown in Figures 12 and 13.

It can be seen from the figure that, as the severity of icing increases, the natural frequency of the aircraft’s short-period mode remains basically unchanged, and the damping ratio increases. The time constant of the rolling mode does not change much, indicating that, under the condition of symmetrical icing on the wing of the aircraft, when the angle of attack is small, it has little effect on the roll mode of the lateral heading and the Dutch roll mode, but with the change of freezing time, the spiral time constant of the aircraft is subjected to great impact. Because the aircraft itself is relatively stable, its spiral time constant still meets the first-class flight quality. Generally speaking, the change of icing time will have an impact on various modal parameters of the aircraft. However, since the angle of attack is small when the aircraft is in level flight, icing has little effect on the aerodynamics of the aircraft, so icing has little effect on the flight quality modal parameters at low angles of attack. When the aircraft is flying at low speed and high angle of attack, icing has a significant impact on the quality of the aircraft.

4.2. Case Analysis of Flight Simulation after Icing in the Altitude Hold Mode. The flight in the aircraft altitude maintaining mode is taken as an example, and the influence of the aircraft’s icing conditions on the aircraft’s longitudinal dynamic response is studied. Through the design of the aircraft altitude hold mode, the aircraft is analyzed in the nonicing condition and the icing condition. The data of the airplane flying horizontally at an altitude of 4000 m at a speed of 120 m/s are selected, the flight without freezing and freezing for 2 min and 5 min is simulated, and the set altitude is maintained at 4100 m. The icing and nonicing simulation curves are shown in Figure 16.

Comparing the nonicing and icing states, the aircraft can still maintain normal flight after 2 minutes of freezing. Due to the influence of icing, the drag on the aircraft increases, the speed decreases, and the elevator efficiency decreases due to icing. The negative deflection angle of the elevator needs to be increased. The angle of attack of the aircraft increases, but the overall change is not significant. After 5 minutes of freezing, the aircraft cannot maintain altitude and fly
normally. As can be seen from the figure, before 30 s, the aircraft can still climb normally, the speed decreases, the pitch angle increases, and the negative deflection angle of the elevator increases. As the angle of attack of the aircraft increases significantly, the aerodynamic characteristics of the aircraft deteriorate further due to the influence of icing, which causes the aircraft to stall and the aircraft’s altitude to drop sharply. Therefore, when the aircraft is in severe icing conditions, the aircraft is likely to stall due to the reduced angle of attack of the aircraft in the aircraft altitude maintaining mode.

4.3. Case Analysis of Flight Simulation after Icing in the Roll Attitude Hold Mode. The flight in the roll attitude hold mode is taken as an example to study the influence of the aircraft in icing conditions on the aircraft’s lateral dynamic response. Through the design of the airplane roll angle hold mode, the airplane is analyzed in the nonicing condition and the icing condition. The airplane flies horizontally at an altitude of 4000 m at a speed of 120 m/s and enters the clouds. Under icing conditions, a coordinated turn is made with a 20° roll angle after flying for 200 s. The simulation curves are shown in Figure 17.
When the aircraft maintains a roll attitude without sideslip, as the freezing time increases, the aerodynamic characteristics of the aircraft further deteriorate. In order to maintain the flight altitude, the deflection angle of the aircraft’s elevator is increased, as well as the angle of attack and pitch of the aircraft. Under severe icing conditions, that is, icing for 5 minutes, the aircraft cannot maintain the normal flight altitude, and the flight speed is significantly reduced, indicating that the drag experienced by the aircraft has increased significantly. Compared with the nonicing state, the aircraft’s angle of attack has increased significantly. At the same time, the aircraft’s stall angle of attack has decreased due to the icing of the aircraft, which makes the aircraft extremely prone to stall and to lose control, resulting in accidents. Therefore, in the case of severe icing, the roll attitude maintenance mode cannot work normally, which can easily cause the aircraft to stall.

Figure 14: Change curves of natural frequency and damping ratio with icing time in the Dutch rolling mode.

Figure 15: Change curves of time constant with icing time in the rolling mode and spiral mode.
Figure 16: Continued.
Figure 16: Aircraft state curves under different icing conditions in the altitude hold mode: (a) curves of height and speed, (b) curves of pitch angle and elevator deflection angle, and (c) curves of angle of attack and pitch speed.

Figure 17: Continued.
Figure 17: Continued.
5. Conclusions

(1) An icing influence model for real-time simulation based on icing time and aircraft angle of attack is established. According to the classification of icing geometry, it is concluded that spanwise-ridge ice has the greatest influence on the aerodynamic characteristics of the airfoil.

(2) This paper selects NASA’s clear ice icing data with serious icing influence from the NACA 23012 airfoil icing data. The linear phase and the stall phase are modeled separately, and the two-dimensional interpolation method is used for correction, which is mainly divided into the correction of the lift-drag coefficient of the linear zone and the stall zone and the correction of the aircraft stability derivative and
the control derivative. The correction results turn out to be good.

(3) Airplane modes under different icing conditions were analyzed, the results of which showed that, under icing conditions, in the range of small angles of attack, icing has no obvious influence on the aircraft mode. As the degree of icing increases, the throttle skewness and the negative deflection angle of the aircraft for level flight continue to increase. The icing flight case in altitude hold and roll hold modes shows that flying in severe icing and in the autopilot mode is very dangerous and prone to cause the aircraft to stall.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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