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Icing aircraft safety analysis based on optimal control of reachable set

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Abstract: Aiming at the problem that icing leads to poor aerodynamic characteristics and affects the safe flight of aircraft. This paper takes the simplified model of NASA's Civil Aircraft Research Model (CARM) as the research object ,establishing longitudinal dynamics model and icing effects model. Based on the optimal control theory of reachable set, the backward reachable set is proposed as the safe flight envelope, which used to analyze the influence of icing on flight safety. It is shown that with the increase of icing degree, the control range of key flight parameters is narrowed, and the possibility of aircraft stall is increasing. The evaluation results are consistent with the actual situation, which can provide some reference for the pilot control.

1.Introduction

Aircraft icing is a physical process in which liquid water in the atmosphere freezes on the surface of components and accumulates into ice when the aircraft is flying under frozen meteorological conditions which is a widespread phenomenon in flight. Icing will damage the normal dynamic characteristics, reduce the flight performance, maneuvering quality, and even make the aircraft loss of control, resulting in flight accidents[1].Although significant efforts have been made to prevent incidents and accidents caused by in-flight icing since 1920s, aircraft icing remains a major concern for aviation. According to incomplete statistics, there were 50 ice-related accidents in the United States alone, more than 800 people lost their life between 1992 and 2000[2]. China's famous 6.3 air disaster was caused by the loss of control of the aircraft due to icing on the wing, resulting in the crash of the aircraft caused by the tragedy of more than 40 people. When the aircraft freezes, the traditional flight safety envelope will seriously shrink due to the reduction of lift and stall angle of attack, increase of drag ,which will no longer be applicable and even provide wrong operation instructions for the flight control system, therefore, it is necessary to establish the flight safety envelope of the aircraft under the influence of icing.

In recent years, because of the frequent occurrence of flight accidents, extensive studies have been conducted on the determination methods of flight safety envelope. Moreover many nonliner methods based on Lyapunov's stability theory have been proposed as a region of attraction (ROA) prediction tool[3]. The ROA method is designed to predict a stable set in the vicinity of a given equilibrium point, however, the method itself is conservative. Based on manifold theory, Zheng et al. proposed to take the stability region of the aircraft in a specific flight state as the flight safety envelope [5]. Although this method can obtain the flight safety envelope more accurately, it's mainly dependent on the aircraft dynamics characteristics, which requires accurate model and has great limitations in

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engineering applications.

Based on the reachable set theory, this paper takes the backward reachable set as the safe flight envelope, first establishes the aircraft longitudinal dynamics model, obtains the corresponding aerodynamic parameters by using the flight data fitting, and then establishes the icing effects model. This paper study the flight safety envelope of the aircraft under the conditions of no icing ($\eta = 0$), slight icing ($\eta = 0.1$) and severe icing ($\eta = 0.2$), and then compare the result to determine the impact of icing on flight safety.

2. nonlinear model of icing aircraft

2.1 longitudinal dynamics of the aircraft

In this paper, we consider the aircraft longitudinal channel model, and neglect the couple relationship between transverse and longitudinal channels. In order to simplify the model, select the velocity *V* and the flight-path Angle γ as the state of longitudinal channel [6]. Although the pilot has control over elevator deflection, the model assumes that it can control α directly, and another inputs is the engine thrust *T*.

To illustrate the model of aircraft ,we consider a continuous dynamic system,

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u}) \tag{1}$$

$$x = \{V, \gamma\}, u = \{T, \alpha\}$$
 (2)

The longitudinal dynamic model of the simulated aircraft is presented below:

$$\begin{bmatrix} \dot{V} \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} \frac{1}{m} (T \cos \alpha - D(\alpha, V) - mg \sin \gamma) \\ \frac{1}{mV} (T \sin \alpha + L(\alpha, V) - mg \cos \gamma) \end{bmatrix}$$
(3)

With *m* is the mass of the aircraft, L,D respectively represents the lift and drag of the aircraft, can be expressed as follows:

$$\begin{cases} D(\alpha, \mathbf{V}) = \overline{q}S(\mathbf{C}_{D_0} + C_{D_\alpha}\alpha + \mathbf{C}_{D_{\alpha^2}}\alpha^2) \\ L(\alpha, \mathbf{V}) = \overline{q}S(\mathbf{C}_{L_0} + \mathbf{C}_{L_\alpha}\alpha) \end{cases}$$
(4)

Where the dynamic pressure $\bar{q} = 0.5\rho V^2$, *S* is reference area of aircraft. C_D is the drag coefficient and the C_L is lift coefficient, the lift and drag depend on two flight parameters α and *V* as well as on characteristics of the aircraft. It's obtained mainly through parameter fitting of wind tunnel test data.

2.2 icing effects model

Icing is the phenomenon that ice accumulates on some parts of the aircraft body surface, which will worsen the flight dynamics of the aircraft, leading to changes in the lift and drag coefficients, thus reducing the lift, and at the same time reducing α_{max} , which makes the pilot control easy to cause the overlimit of the key parameters of flight safety and lead to the accident of flight safety.



Figure 1 the map of lift coefficient of aircraft changes in clean and iced Bragg et al.[8] developed a simple but physically representative model to analyse the flight dynamics of an iced aircraft. The equation can be shown as follows:

$$C_{(A)iced} = (1 + \eta k_{C_{(A)}})C_{(A)}$$
(5)

Where $C_{(A)}$ is any arbitrary performance, stability or control parameter or aerodynamic derivative affected by ice. The $k_{C_{(A)}}$, which is constant for a given aircraft ,represents the change in an aircraft parameter, it's usually determined by the structure of the aircraft itself and obtained by wind tunnel test or flight simulation. The aircraft icing parameter η represents the severity of ice, when the aircraft is clean $\eta = 0$. the higher the value, the more severe the ice formation on the aircraft.

3. Safe flight envelope analysis

Safe flight envelope represents the maneuverable boundary of an aircraft under different flight conditions. The determination of traditional safe flight envelope is mainly to limit the key parameters and it's believed that the aircraft can fly safely as long as in the restricted range. However, the traditional safety envelope has certain conservativeness, which reduces the maneuverability of the aircraft. Based on the reachable set, this paper presents the maximum safe flight envelope of an iced aircraft and takes it as the safety set .

3.1 definition of flight safety envelope

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The reachability analysis seeks to decide whether the trajectories of a system model can reach a certain target set from an initial set within given time and input constrain[9].Considering a continuous dynamic system:

$$\hat{x} = f(x, t, u) \tag{6}$$

Where $x \in \mathbb{R}^n, u \in U \subseteq \mathbb{R}^m$, $f(\cdot, \cdot) : \mathbb{R}^n \times U \to \mathbb{R}^n$, a bounded and Lipschize continuous function, $l(\cdot): \mathbb{R}^n \to R$. And an arbitrary time horizon *T*. Let $U_{[t,t']}$ denote the set of Lebesgue measurable functions from the interval $U_{[t,t']}$ to U, then for every $x \in \mathbb{R}^n, \tau \in [t,T]$ and $u \in U_{[t,T']}$, the system admits a unique solution or trajectory ϕ , with $\phi(\tau, t, x, u(\cdot)) = x$.

Define a target set for the problem and it can be represented by zero level set of the functionas :

$$K = \{x \in \mathbb{R}^n \, | \, l(x) > 0\} \tag{7}$$

Then the backward reachable set is:

$$\{x \in \mathbb{R}^n \mid \exists u \in U_{[t,T]}, \ \exists \tau \in [t,T], \phi(\tau,t,x,u(\cdot)) \in K\}$$
(8)

The purpose is to determine the maximum range of safe operation of the aircraft in the iced state, Which includes the states that have the potential of returning to the safe boundary .According to the definition of the backward reachable set, it represents the set of all points that may reach the safe state. Therefore, the backward reachable set is adopted as the maximum safe flight envelope of the iced

aircraft.

3.2 computation of the reachable set

At present, the most commonly used method for computing reachable sets is the level set method, which is to take the low-dimensional dynamic curve as the zero level set, and then extend it to the higher-dimensional level set function. By solving the development equation satisfying the level set function, the evolution of the level set is promoted, and the shape of the interface is obtained when the evolution tends to be stable[10].

Based on the definitions in the previous section ,let $l(\phi(\tau, t, x, u(\cdot)))$ be the cost function of the state trajectory over time horizen [t,T], Then control problem can be formulated with SUPMIN optimal control problem.

$$V(t,K) = \{x \in \mathbb{R}^n \mid V_1(x,t) = \sup_{u(\cdot) \in U_{[t,T]}} \min_{\tau \in [t,T]} l(\phi(\tau,t,x,u(\cdot))) > 0\}$$
(9)

The boundary of reachable set can be determined by solving the valued function V and obtaining its zero level set. While computing reachability for a continuous system is much more difficult, an algorithm for computing the reachable sets of continuous system with nonlinar dyanmics was developed based on time-dependent HJ PDE[11].

$$\frac{\partial V_1}{\partial t} + \min\{0, \sup_{u \in U} \frac{\partial V_1}{\partial x}(x, t) f(x, u)\} = 0$$

$$V_1(x, T) = l(x) \quad for(x, t) \in \mathbb{R}^n \times [0, T]$$
(10)

With

$$H(x,p) = \max_{u \in U} p^T \cdot f(x,u) \tag{11}$$

Where $p = \frac{\partial V_1(x,t)}{\partial x}$ represent Hamilton state, the set-valued control synthesized from the

computations is

$$u^*(x,p) = \arg\max_{u \in U} p^T \cdot f(x,u) \tag{12}$$

3.3 Calculation of the optimal control

The optimal input $u^*(x)$ at state x represents a choice of u that will maximize the Hamiltonian at point x. The computation of the optimal inputs $u^*(x)$ is extremely expensive because it is nonconvex optimization problem, which requires exhaustuve search on domain of the interest. In the present case it would require maximizing H over (α, T) the space. For this model ,the optimization problem can be simplified. According to (3), the Hamilton function of the dynamic model is:

$$H(x,p) = \frac{p_1}{m} (T\cos\alpha - D - mg\sin\gamma) + \frac{p_2}{mV} (T\sin\alpha + L - mg\cos\gamma)$$
(13)

Take the partial derivatives at the angle of attack α and the thrust T respectively:

$$\begin{cases} \frac{\partial H}{\partial \alpha} = -\frac{p_1}{m} (T \sin \alpha + \frac{\partial D}{\partial \alpha}) + \frac{p_2}{mV} (T \cos \alpha + \frac{\partial L}{\partial \alpha}) \\ \frac{\partial H}{\partial T} = \frac{p_1 \cos \alpha}{m} + \frac{p_2 \sin \alpha}{mV} \end{cases}$$
(14)

analyze(14)can obtain the optimal control input (α^*, T^*) .

4.Application example

We present a example based on a nonlinear RCAM(Research Civil Aircraft Model), and take the backward reachable set as the safe envelope of aircraft. The primary states of interest are airspeed V and flight path angle γ . The virtual inputs for the dynamics are angle of attack α , and the thrust T. The trim set is the normal speed and flight path angle, the reachable set is extended from the trim set. When the state of the aircraft is beyond the safe flight envelope, no matter how the pilot controls, it

will not be able to enter the safe flight state range.

The values of the numerical parameters used for RCAM are: m=120000kg, $S=260 m^2$, $\rho=1.225 kg / m^3$,

 $g = 9.81m/s^2$. The allowed ranges of the virtual inputs are : $T_{\min} = 20546N$, $T_{\max} = 410920N$, $\alpha_{\min} = 0^\circ \alpha_{\max} = 14.5^\circ$. The safe trim envelpoe K is defined as the area between the boundaries $V_{\min} = 60m/s$, $V_{\max} = 100m/s$, $\gamma_{\min} = -10^\circ$, $\gamma_{\max} = +10^\circ$. According to the above parameters, the safe light envelope in normal flight is simulated, as shown in figure 2:



The rectangle in the figure 2 is the boundary of the target set, representing the range of normal parameter of the aircraft without icing. The curve is the boundary of the backward reachable set, which is the safe flight envelope.All points in the curve, there is a certain control that makes the aircraft return to the target set within a certain time.

When the aircraft iced, the safe flight envelope is shown in figure 3 and figure 4, green, pink and red respectively represent the flight safety envelope when the degree of icing is 0, 0.1 and 0.2. As we can see in figure 4, as the degree of icing increases, the contraction of the safe flight envelope becomes more and more serious. In the velocity axis, because of the severe icing ($\eta = 0.2$), the minimum flight speed is increased to 61.3m/s, maximum speed reduced to 94.6m /s. The safe speed range has been reduced by about 40%. In the flight path angle axis, due to icing, the lift decrease while drag increase, the safe flight envelope moves downward which cause an airplane to bow.

In a word, icing reduces the maneuverability boundary of aircraft and increases the possibility of

loss of control, which is a major hidden danger to the normal flight of the aircraft.

4.conclusion

The model of the longitudinal dynamics of a RCAM and icing effects presented in this paper were used to compute safety envelope of the aircraft in different icing degrees. Through the simulation, it illustrates the effect of icing on safe flight envelope. With the increase of the degree of icing, the safe flight envelope keeps shrinking and the controllable set keeps decreasing, making the pilot more difficult to operate and raising the possibility of risk.

In the future, computation resources will allow the treatment of higher dimensional models which would incorporate more parameters and features of the systems. On the other hand, it would take a date-driven approach to solve the problem of online safe flight envelope prediction for aircraft flight under iced condiction.

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