



Investigation of the aerodynamic characteristics of wings under icing conditions at various swept angles

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Abstract

An ice risk assessment model is developed to analyze the uncertainty in atmospheric circumstances and flying states throughout the aircraft icing process. The icing safety boundary is analyzed quantitatively by the model. The aerodynamic characteristics, such as lift, drag coefficient and moment, are calculated using numerical simulation to generate initial samples. This is done by slicing several swept-wing ice wind tunnel test models, based on the distribution characteristics of velocity, angle of attack, and pressure. The user inputs the geometric information, which includes the sweep angle and cross-section position. By utilizing the sensitivity analysis method and correlation analysis method, the study successfully determines the sensitivity of various icing parameters. Finally, a quantitative model is developed to assess the uncertainty of ice aerodynamics for the swept wing model.

Keywords: uncertainty, icing process, swept wing, correlation analysis, sensitivity analysis

1. Introduction

During the flight of an airplane, the atmospheric parameters such as pressure, temperature, and humidity undergo random and instantaneous changes within a particular range. It is necessary to have an efficient and credible method for making adjustments to the aircraft's aerodynamic characteristics while in motion, particularly while encountering icing conditions. Uncertainty analysis is essential in this process. The National Aeronautics and Space Administration (NASA) and Defense Advanced Research Projects Agency (DARPA) have carried out corresponding projects in the early stage of research[1,2], hoping to develop mathematical tools to quantitatively and effectively communicate and manage the impact of uncertainty. The icing phenomenon of aircraft is more significantly affected by uncertain conditions. The surface ice shape features of the aircraft will vary depending on the atmospheric temperature, size, and concentration of water droplets. These variations in ice shape have different effects on the safety of aircraft during flight. Hence, how to use the uncertainty propagation method to give high-confidence prediction results is one of the current research directions.

It is widely recognized that swept wings are a prevalent feature in both military and civilian aircraft currently in use. Simultaneously, numerous researches concentrate on icing and the forecasting of flat wings, typically choosing a portion of the flat wing's section as the ultimate ice configuration, disregarding the cross-flow ice formation resulting from the three-dimensional spanwise flow phenomenon[3,4]. The actual three-dimensional wing icing shape will change with the spanwise position. At the same time, the prediction methods of icing are relatively limited and mainly divided into two categories: experimental and numerical calculation. The cost of the experiment is that it needs to spend a lot of money and energy, and the low cost of numerical calculation has become the primary research method. Traditional CFD calculation usually introduces a large number of ideal parameters. The difference in the selection of turbulence models will bring new calculation errors, and the numerical calculation of icing is similar. At present, programs with a broad audience on the

market, such as FENSAP-ICE and LEWICE, are in the calculation process and make a lot of assumptions, such as the choice of surface roughness model. In the use of steady multi-period ice loose coupling to achieve the unsteady ice process, the prediction results are often based on the difference of several shape parameters as the accuracy judgment; in some cases, the predicted shape will be completely different from the real ice shape.

By using interval parameters instead of a single input, the envelope of aerodynamic characteristics change after icing is obtained by multiple numerical calculations based on the existing ice shape data of icing wind tunnel tests. The aerodynamic deterioration result caused by critical ice shape is given to reduce the influence of the accumulation of errors such as empirical parameters. Uncertainty analysis is employed to specifically describe the impact of swept angle changes on icing wings.

2. Analysis of ice shape characteristics

The current study employed the following ice form icing conditions: $T_s = -7^\circ\text{C}$, $MVD = 20\mu\text{m}$, $LWC = 1.0\text{g/m}^3$, $H = 457\text{m}$, $V = 67.1\text{m/s}$, $t = 29\text{min}$, and $\text{aoa} = 0^\circ$. $\eta = 0^\circ, 15^\circ$, and 30° are the relative sweep angles. The NACA 0012 swept wing icing model is the geometric model. The section is the NACA 0012 airfoil, with a chord length of 0.78 meters and a spread length of 1.75 meters. The China Aerodynamics Research and Development Center's 3 m x 2 m icing wind tunnel experiment produced a number of ice formations[5], as seen in Figure 1. In the icing wind tunnel, most of the icing meteorological conditions specified in the FAR25 appendix can be produced reliably and precisely. The present work is based on experimental ice shape data to build a prediction model of aerodynamic changes caused by uncertain inputs.



Figure 1 –The wing's leading edge's ice shape at a 30-degree sweep angle

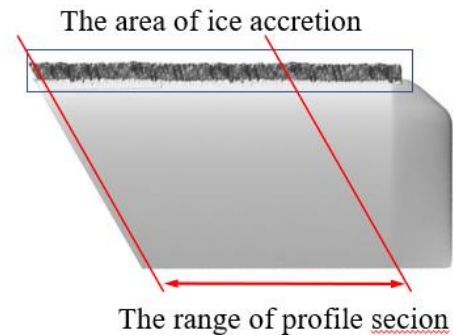


Figure 2 –The range of selected ice-shaped sections

Figure 2 exhibits ten segments of the ice wing, each characterized by unique sweep angles. In order to compensate for the absence of elongation in the wing tip caused by NACA 0012, a plane parallel to the wing root is used to split the wing of the interval of $d = 0.1\text{m}$. This method ensures that the rest of the airfoil is consistent with the initial airfoil except for the ice shape of the leading edge.

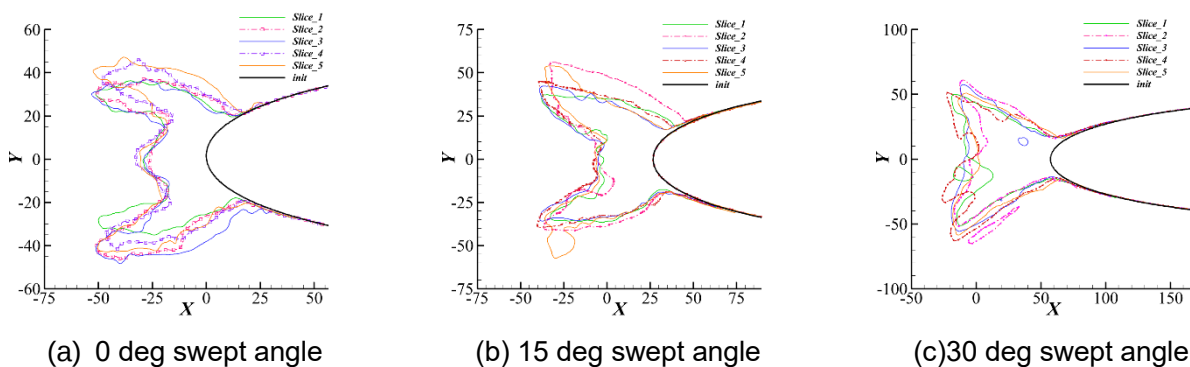


Figure 3 –The wing's leading edge's ice profile at different swept angle

Modifying the sweep angle results in variations in the ice shape, leading to distinct geometric properties. Figure 3 demonstrates that the sweep angle of 0 degrees remains constant along the longitudinal position. The ice structure, known as a lobster-tail ice shape, remains mostly unchanged and is still stacked around the X-axis. At a sweep angle of 15 degrees, a partially asymmetric structure starts to form, resulting in significant ice accretion on the lower surface of the leading edge of Slice_5. At a sweep angle of 30 degrees, the two-dimensional section displays a closed curve for the ice shape, with the exception of the outline. The outline is caused by the three-dimensional action of the air flowing across separate portions, resulting in spanwise ice formation.

Nevertheless, this particular aspect of geometry cannot be computed for the following aerodynamic properties. Therefore, in this case, the ice angle with a more substantial impact is calculated while disregarding the ice shape of the little hole. The difference in ice angle illustrates the uncertainty caused by the sweep angle. As stated in reference [6], the extent of ice can be measured using various parameters, including the upper ice angle θ_{upper} , lower ice angle θ_{lower} , upper ice height h_{upper} , lower ice height h_{lower} .

3. Uncertainty analysis of variables

The frequent stage of icing accidents is mainly concentrated in the takeoff and landing stage of aircraft, and the flight environment in low temperature and high humidity environment is easy to cause loss of control. According to the operation manual and flight envelope of civil aircraft, the takeoff and landing speed is generally 61.7m/s to 95.59m/s. The maximum speed below 10,000 feet is limited to 250 knots. Hence, the designated speed parameters are 60m/s to 90m/s. The angle of attack of the main wing is commonly within 10 degrees, but considering the current experimental conditions, the aircraft may have stalled entirely near 10 degrees. The analysis of aerodynamic characteristics near the angle of attack of stall requires an accurate turbulence model, which is outside the scope of the current work. The given angle of attack is 0 to 6deg. When considering icing threats, it is essential to not only focus on civil aircraft but also consider the flight altitude of propeller aircraft in order to improve overall applicability. Thus, the altitude of the flight ranges from 0 to 3 kilometers. The precise flight characteristics can typically be quantified to determine their probability density function, while there are inherent elements of randomness and unintentional ambiguity. The three input variables mentioned above are considered to be uniformly distributed interval variables. Ten samples were taken from each variable using Latin hypercube sampling to obtain a representative result. This results in a total of 30 input parameters.

The solver is verified using DLR-F6 common research model [7]. The initial grid layer's height in the calculation satisfies the condition $Y^+ < 1$. The computation was performed with $Ma=0.75$, $Re=3 \times 10^6$, $CL=0.5$, and the SST turbulence model was utilized [8]. The pressure distribution at two specific locations, $y/b=0.239$ and $y/b=0.514$, over the wing span is compared with the experimental data, as depicted in Figure 5. The black point represents the experimental data, while the blue line represents the estimated cross-section pressure distribution. The pressure distribution at various spanwise positions of the wing shows good agreement, confirming the high accuracy of the solver employed. Based on the above input variables, a total of 900 samples are created using aerodynamic calculation. The output is identified by measuring the difference in the lift and drag coefficient between the ice airfoil and the initial smooth airfoil.

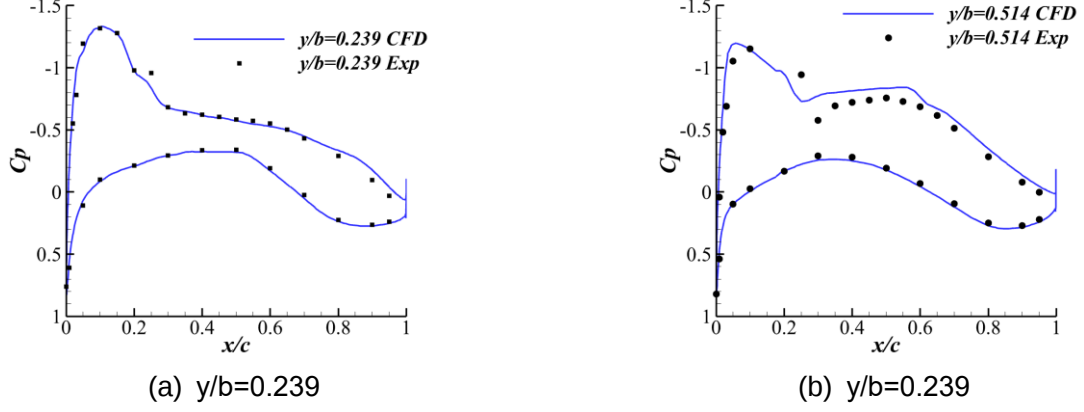


Figure 4 –Comparison of calculation results

The uncertainty investigation of diverse input parameters is conducted in conjunction with the correlation analysis approach, which is separated into multiple steps:

- 1) The dataset is comprised of ice shape characteristics, lift coefficient and drag coefficient increments, and flying conditions.
- 2) Standardized variable values across different scales to guarantee equitable initial weight distribution of variables in subsequent models.
- 3) Correlation analysis is employed to quantify the extent of correlation between two variables[9]. The Spearman correlation coefficient is utilized in this work, as it does not necessitate the assumption of variable distribution and exhibits less susceptibility to outliers resulting from errors introduced during the measurement of ice shape. The calculating formula is as follows:

$$\rho = 1 - \frac{6 \sum d^2}{n(n-1)^2} \quad (1)$$

The Spearman rank correlation coefficient, denoted as ρ , is calculated by taking the difference $d\rho$ between the ranks of the two variables and the number n of observations in the dataset.

- 4) The Sobol approach is employed to assess the impact of each input variable on the output[10]. It calculates the first-order Sobol index of input variance, disregarding the interaction between input variables. The expression can be generalized as follows:

$$S_j = \frac{V[E[Y | U^{(j)}]]}{V[Y]} = \frac{V_j}{V[Y]} \quad (2)$$

None of the input parameters show a clear association with the typical parameters of the ice shape. Additionally, most of these parameters are disordered and represented as discrete points. The primary focus of study is the unpredictable impact resulting from variations in flight conditions.

The link between the angle of attack and the lift drag coefficients remains heightened and is not weakened by an accumulation of ice on the wing's leading edge. The drag coefficients exhibit significant sensitivity to θ_{upper} , with ΔC_d is moderately correlated with θ_{upper} and h_{upper} . On the other hand, θ_{lower} and h_{lower} show weak correlation and sensitivity to ΔC_d , suggesting that the changes in form and friction resistance caused by them are minimal. The above analysis shows that the majority of the drag is still primarily influenced by the upper ice horn.

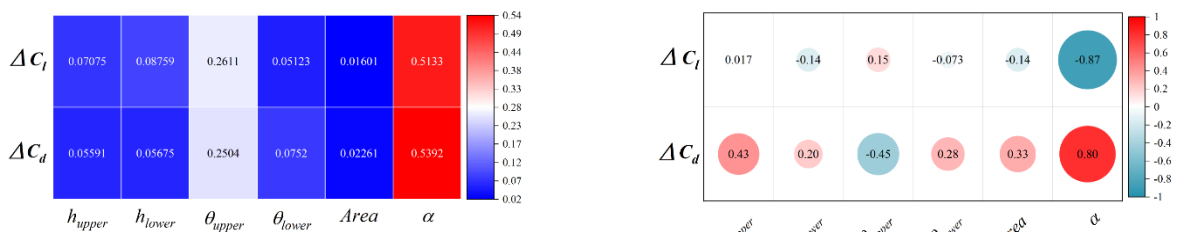


Figure 5 –Sensitivity and correlation map with varying angle of attack (left: sensitivity, right: correlation)

Reynolds number and temperature are the factors affected while altering altitude, while keeping the angle of attack constant. All of the other feature sensitivity indicators are less than 0.3, and the variations associated with altitude are almost negligible. The variable θ_{lower} exhibits a moderate positive connection with the ΔCl and a moderate negative correlation with the ΔCd .

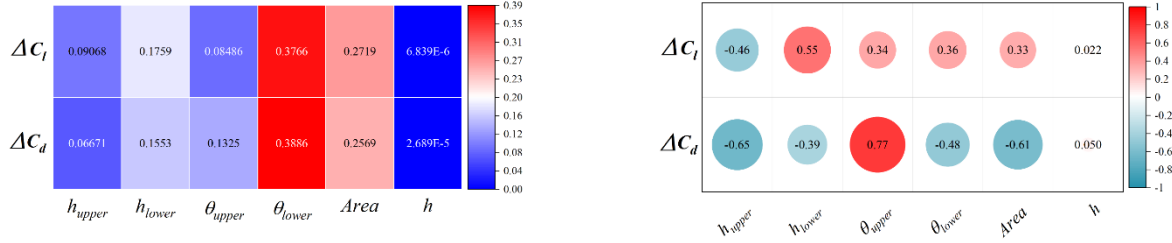


Figure 6 –Sensitivity and correlation map with varying altitude (left: sensitivity, right: correlation)

Comparable results can be observed with respect to sensitivity to variations in altitude and velocity. The θ_{lower} is more sensitive to ΔCl and ΔCd , which indicates that even as altitude and velocity vary, the proportion of contribution to the aerodynamic properties of the original ice shape remains unchanged. Consequently, the extent of the contribution continues to be dictated by the characteristics of the ice shape itself. The θ_{upper} and ΔCd have a strong negative correlation. Nevertheless, the sensitivity between the two variables is extremely limited. The θ_{lower} is the primary factor influencing the relationship

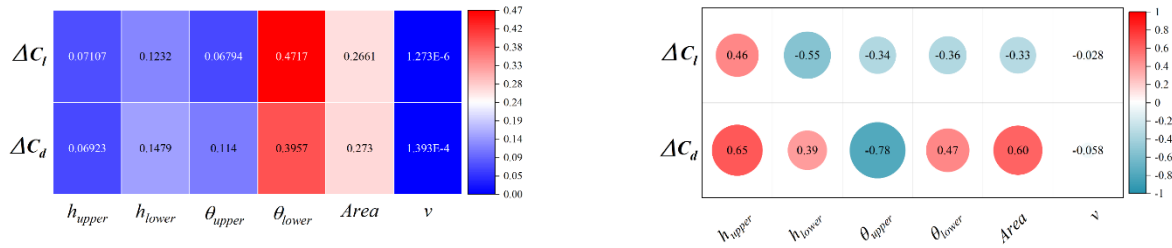


Figure 7 –Sensitivity and correlation map with varying velocity (left: sensitivity, right: correlation)

4. Conclusions

The present research focuses on investigating the impact of geometric attributes of ice formation on aerodynamic properties at varying sweep angles. The study examines the impact of three-dimensional effects on changes in ice shape by examining the differences in ice shape at various aspect points of wings with varying sweep angles. The majority of changes induced by sweep angles cannot be solely attributed to the icing of flat wings. The presented information provides the level of uncertainty for the variables of velocity, height, and angle of attack. The quantitative explanation of the relationship between ice shape properties and aerodynamic force is achieved by correlation analysis and Sobol sensitivity parameters.

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