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Numerical Simulation of Airfoil Ice Accretion Based on Parcel Concept

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Abstract: Based on the parcel concept, a modified numerical method for simulating ice accretion on aircraft wing is presented in this study, which obeys the fundamental assumption of Lagrangian and Euler method. The method overcomes the shortages of Lagrangian method, such as large amount of computation work, low efficiency and the matching between droplet space distribution and grid density. NACA0012 rime ice accretion, local droplet collection and local impingement efficiency at 0° and 4° AOA (Angle of Attack) is simulated to validate the method. The computation results show that the modified method based on parcel concept is feasible and robust.

Key words: Icing simulation, parcel concept, impingement property, aerodynamic performance

INTRODUCTION

Flying in the super cooling cloud or the raining zone, the aircraft often suffers ice accretion. It degrades the performance of aircraft and damages the flight safety, especially in taking off and landing. In past years, several deadly accidents occurred in China, which were attributed to ice accretion. The ice accretion on the leading edge of wing or airfoil not only reduces the lift, but also causes the stall at much lower angle of attack. Currently, numerical methods are widely used as a powerful assistant tool in icing research. And ice accretion prediction is one of the two most important fields of icing research. There are two types of methods used by researchers, Euler and Lagrangian methods. This study explained a modified ice accretion numerical method based on the droplet parcel concept, which obeys the fundamental assumption of Lagrangian and Euler methods.

Icing simulation generally adopts Lagrangian (Cebeci *et al*., 1991; Paraschivoiu *et al*., 1993; Saeed *et al*., 2005) or Euler (Scoot *et al*., 1998; Heloise *et al*., 2003; Zhang and Chen, 2004) method to gain the water collection coefficient on the surface of airfoil. Lagrangian method uses a large number of droplets in upstream before airfoil to simulate the droplet colliding on the airfoil. Lagrangian method costs a lot of CPU time and needs the aid of parallel computer sometimes (Caruso *et al*., 1993). In fact, some of these droplets that can not hit the surface of airfoil are not necessary to calculate. And the ice shape simulated with this method is pertinent with the airfoil surface grid distribution. Figure 1 gives

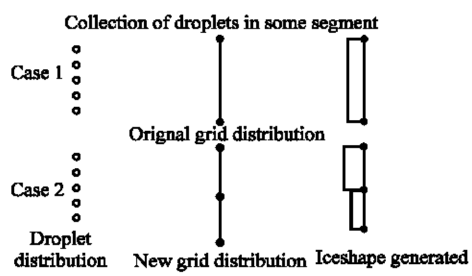

Fig. 1: Match problem between droplets distribution and grid points distribution

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a simple example about this problem. The same droplet distribution is used in case 1 and case 2, but the ice shapes generated may be different for the different grid distributions.

MATERIALS AND METHODS

Droplet Parcel Concept

To overcome the shortage of traditional Lagrangian method, the droplet parcel concept is used in this study. The droplet parcel concept is developed from the fluid parcel concept (Streeter *et al*., 1998) that is widely used in hydromechanics. Before developing the droplet parcel concept, a fundamental assumption used by both Lagrangian and Euler method is introduced:

- The droplets do not collide with each other in moving and the trajectories of droplet movements do not intersect either.

Based on the assumption above and the concepts of fluid parcel and stream tube, the droplet parcel concept is developed

- The droplet parcel is composed of a group of droplets, which move as a complete unit,
- There is no exchange of droplets between droplet parcels,
- The droplet parcel moves in a stream tube and can adjust its size with the change of cross section of the stream tube.

Based on the parcel concept, conclusion was drawn that the mass of droplet moving in a stream tube does not change wherever the droplet parcel is in the stream tube. Thus, the water collection on a segmental arc of airfoil is connected only with the inlet section of stream tube corresponding with this segment (Fig. 2).

After building the stream tube corresponding to a segmental arc, the mass flow of droplet and local impingement efficiency on the segment can be easily calculated through the following formula

$$\dot{m} = |Y_{su} - Y_{sd}| \cdot V_{\infty} \cdot LWC \qquad (1)$$

$$\beta = |(Y_{su} - Y_{sd})/(Y_{cu} - Y_{cd})| \qquad (2)$$

Where, $\dot{m}$ is the mass flow of the droplet on the segment, β is the local impingement efficiency on the segment, V_{∞} is the free stream velocity, LWC is the liquid water content in the air, Y_{su} and Y_{sd} are y coordinates of the initial location of stream tube, Y_{cu} and Y_{cd} are the end points corresponding to the lower and upper limitation of the segmental arc.

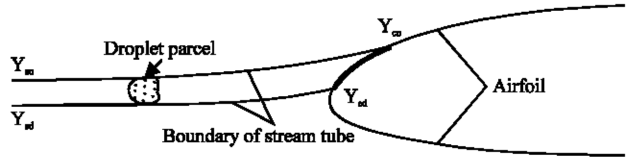

Fig. 2: Stream tube corresponding to a segment of airfoil

The Buildup of the Stream Tube

The most important point of this modified method is how to build the stream tube. In current study, the Lagrangian method is used to build the stream tube by tracing the droplet trajectory.

There are gravity, buoyancy and drag acting on a droplet. Based on the Newton law, the movement equation of droplet can be written in the following vector formula

$$M_d \frac{d^2 r}{dt^2} = (\rho_d - \rho_a) V_d g + \frac{1}{2} \rho_a A_d C_d \,|\, v_a - v_d \,|\, (v_a - v_d) \tag{3}$$

where, M_d is the mass of droplet, r is the droplet location vector, ρ_a is the density of air, ρ_d is the density of droplet, V_d is the volume of droplet, g is the gravity acceleration, A_d is the characteristic area of droplet, C_d is the drag coefficient of droplet, V_a is the local airflow velocity, V_d is the droplet velocity. A modified formula is used to calculate the drag coefficient (Snellen *et al*., 1997)

$$\frac{C_d \mathrm{Re}}{24} = 1.0 + 0.197 \mathrm{Re}^{0.63} + 2.6 \times 10^{-4} \mathrm{Re}^{1.38} \tag{4}$$

where, $\mathrm{Re} = \rho_a \,|\, v_a - v_d \,|\, D_{eq}/\mu_a$, μ_a is the viscosity of air, D_{eq} is the mean diameter of droplet. From Eq. 4, the movement equation of droplet can be written in the following formula

$$\frac{d^2 r}{dt^2} = \frac{\rho_d - \rho_a}{\rho_d} g + \frac{C_d \mathrm{Re}}{24} \frac{18 \mu_a}{D_{eq}^2 \rho_d} (v_a - v_d) \tag{5}$$

Equation 5 was solved using a 4-order Runge-Kutta scheme with airflow speed interpolated from the nodal points of the cell that contained the droplet. After the droplet impinged a segmental arc of airfoil, the boundary of stream tube is built by connecting all the locations that the droplet passed.

The point of impingement on the segmental arc of airfoil can be defined with the knowledge of droplet position P_1 (x_1, y_1) and P_2 (x_2, y_2) (Fig. 3).

The segmental arc of the airfoil can be considered as line L represented by equation, Ax+By+C = 0, P_1 and P_2 is the old position and new position of droplet, respectively and $I_1 = Ax_1+By_1+C$, $I_2 = Ax_2+By_2+C$. When $I_1 . I_2 \leq 0$ the impact takes place on the segmental arc and the impact point is calculated by solving the following two straight line equations

$$\left.\begin{aligned} Ax + By + C = 0 \\ (y_1 - y_2)x - (x_1 - x_2)y + (x_1 - x_2)y_2 - (y_1 - y_2)x_2 = 0 \end{aligned}\right\} \tag{6}$$

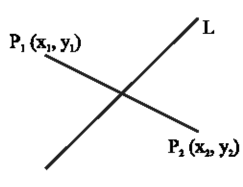

Fig. 3: Relationship of droplet trajectory and segment of airfoil

Improvement in Computational Efficiency

The calculation of droplet trajectories costs most of the CPU time in icing simulation. Generally, the global minimum time step, the ratio of minimum grid length to maximum airflow speed in the field, is used in the calculation. It leads a large workload. The concept of local minimum time step is used to improve the computational efficiency

$$\Delta t_i = \min(L_i)/\max(V_i) \text{ or } \Delta t_i = \min(L_i)/V_{di} \tag{7}$$

where, Δt_i is the local time step of cell i, min (L_i) is the minimum mean length of cell i, max (V_i) is the maximum airflow speed in cell i, V_{di} is the droplet speed at cell i. The usage of local minimum time step sharply reduces the calculation workload and keeps the calculation precision of global minimum time step. Figure 4 describes the calculated results using global minimum time step and local minimum time step. It is found that the droplet trajectories calculated in two distinct time step methods are basically the same.

RESULTS AND DISCUSSIONS

There are two methods to build the stream tube. The first method builds the stream tube corresponding to the grid point of airfoil. The second method builds the stream tube according to the request of user. The first method is used in this paper and the binary search method is used to find the limitation of impingement.

The flow field around the airfoil is gained by using a flow solver which uses JST method (Jameson *et al*., 1981). And the Sparalt-Allmaras (Spalart *et al*., 1992) one-equation turbulence model is implemented when solving the Navier-Stokes equations.

The simulation of rime ice at 0° and 4° AOA is carried out to validate the method and the results are compared with other simulation and experiment results. The results show the effect of various AOA on impingement characteristics.

In test case one, the angle of attack is 0°, the freestream velocity is 129 m sec^{-1}, the static pressure of freestream is 101300 Pascal, the liquid water content (LWC) is 0.5 g m^{-3}, the Mean Volumetric Diameter (MVD) of droplet is 20 μm and ice accretion time was 120 sec.

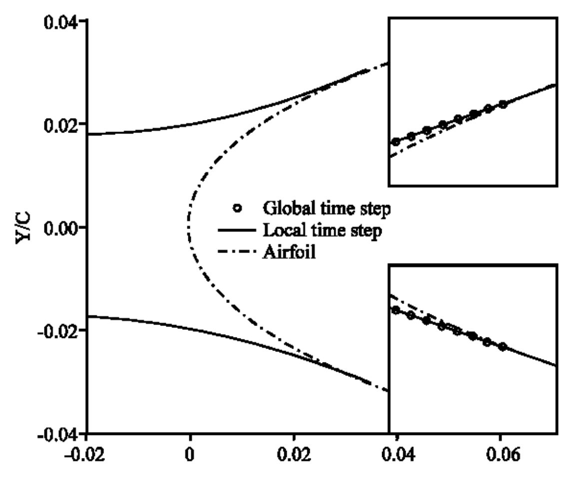

Fig. 4: Droplet trajectory calculation result using two time steps

The droplet trajectory at 0° AOA is described in Fig. 5 and the local impingement efficiency and liquid droplet collection are shown in Fig. 6 (Where S_x means the projection of airfoil curve coordinate on x axis).

Figure 7 describes the comparison of ice s hape of this method with previous results (Snellen *et al*., 1997). The results shows that the volume of ice is a little larger than the previous result but the range of ice on the airfoil is almost simmilar on both results.

In test case two, the angle of attack is 4 degree, the freestream velocity is 67.5 m sec^{-1}, the static pressure of freestream is 101300 Pascal, the liquid water content (LWC) is 1.0 g m^{-3}, the mean volumetric diameter (MVD) of droplet is 20 μm and ice accretion time was 360 sec.

The droplet trajectory at 4° AOA is shown in Fig. 8 and 9 describes the local impingement efficiency and liquid droplet collection at 4° AOA. The result shows that the location of max local impingement efficiency moves to the lower surface of airfoil because of the increase of angle of attack.

Figure 10 shows the simulated ice shape at 4° AOA. The result shows that the maximum thickness of ice shape moves to the lower surface of airfoil, which is agreement with the result of local impingement efficiency. The result shows that the ranges of ice region in previous study present are not fully agreed with experiment (Fortin *et al*., 2003). The ice region in previous study is larger than

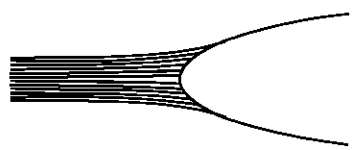

Fig. 5: Droplet trajectory at 0°AOA

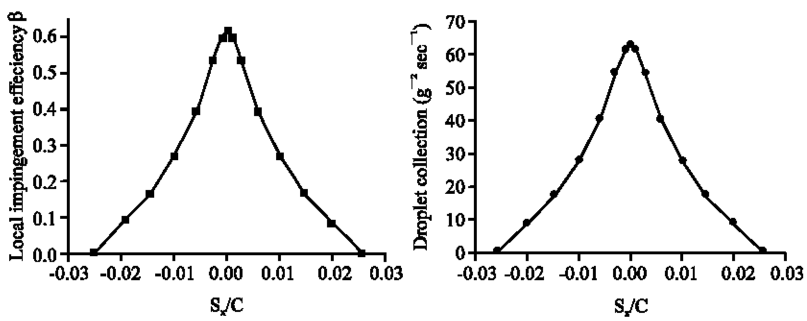

Fig. 6: Local impingement efficiency and liquid droplet collection at 0° AOA

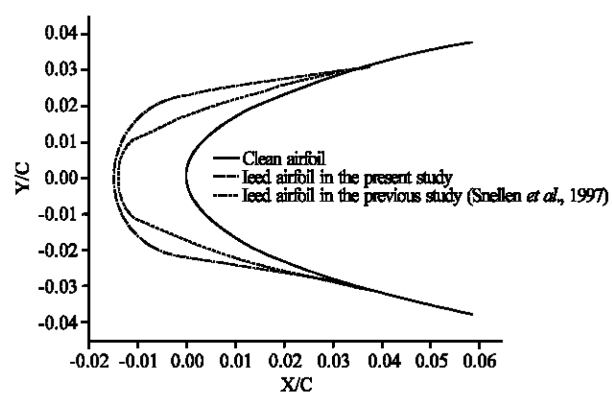

Fig. 7: Simulated iced airfoil of 0°AOA

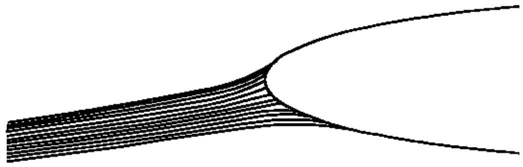

Fig. 8: Droplet trajectory at 4°AOA

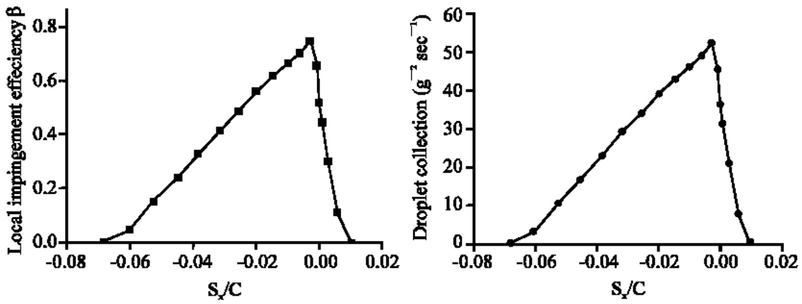

Fig. 9: Local impingement efficiency and liquid droplet collection at 4° AOA

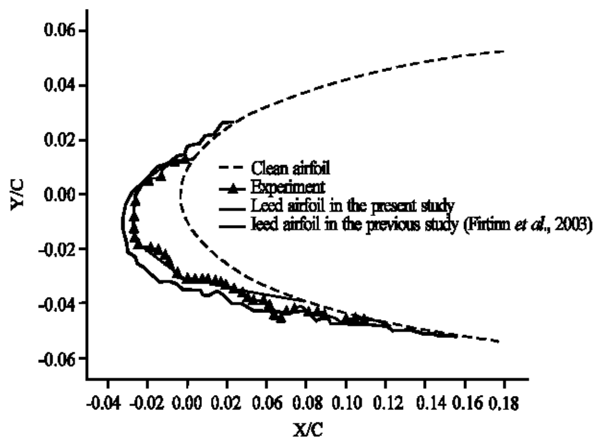

Fig. 10: Simulated iced airfoil of 4° AOA

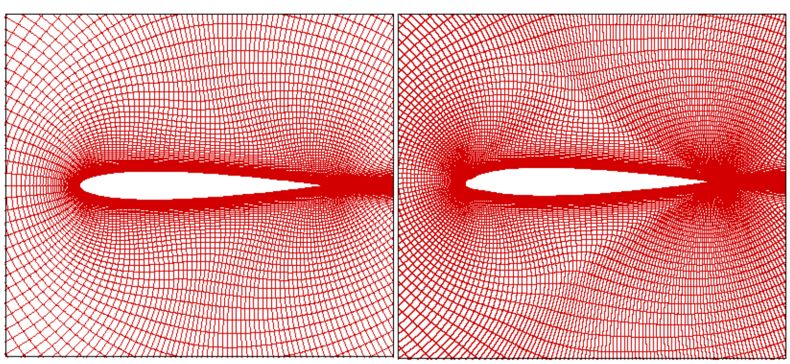

Fig. 11: Grid for CFD computation

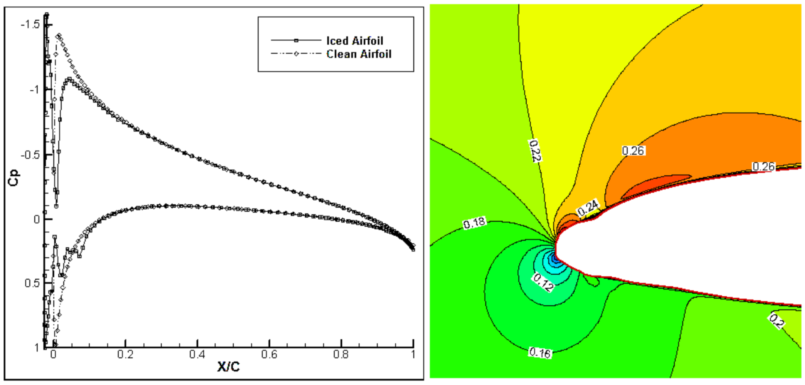

Fig. 12: Pressure and mach contour at 4°AOA

experimental result both on the lower and upper surface and the ice region of this study is less than the experimental result only on the lower surface.

The aerodynamic performance of NACA0012 airfoil with and without ice is compared at 4° AOA. Figure 11 presents the computational grids of clean and iced airfoil. The results presented in Fig. 12 show that the pressure coefficient oscillation occurs on upper and lower surface because of the ice accretion. A pressure loss occurs on the surface where the ice and clean surface joint together. It damages the aerodynamic performance of airfoil. And the pressure coefficient oscillation also damages the pitching characteristics.

CONCLUSIONS

This study presents a modified method based on the fundamental assumption of Lagrangian method. The paper presents the impingement result and ice shape prediction for a NACA0012 airfoil at 0° and 4°AOA. The results show that the modified method predicts the iced airfoil well. The use of local time step accelerates the calculation process and the use of parcel concept reduces the workload in tracing the droplet trajectory.

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