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Improved Ice Accretion Prediction Code

B. Hoření[1], V. Horák[2*] and Z. Chára[3]

[1] *Institute of Hydrodynamics, Academy of Sciences of the Czech Republic*
[2] *Department of Mechanical Engineering, University of Defence, Brno, Czech Republic*
[3] *Institute of Hydrodynamics, Academy of Sciences of the Czech Republic*

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Abstract:

The paper deals with the further development of the computational wing airfoil ice accretion prediction code ICE. Presented version enables computational rime ice and glaze ice accretion prediction on single and multi-element airfoils in acceptable time of solution. Mathematical model has been modified for variable wall temperature along the airfoil surface. The code was also improved for the better approximation of transition boundary layer location. There are shown results ice accretion prediction of the wing airfoil with a slotted flap and various cases of predicted ice shapes in dependence of air temperature.

Keywords:

Aircraft icing, ice accretion simulation, icing code

1. Introduction

The phenomenon of in-flight icing may affect all types of aircraft and continues to be an important flight safety issue. The evaluation of both military and commercial aircraft systems in icing conditions continues to be important during both design and certification. Although some representative flight tests under natural icing conditions are required, a great saving in time and cost can be achieved by exploiting of a computation of ice-accretion-shape predictions. Computational simulation of ice accretion is an essential tool in design, development, and certification of aircraft for flight into icing conditions. In conjunction with the project of the Czech Ministry of Industry and Trade, was developed the tool for simulating flight into icing conditions. ICE is an ice accretion prediction code [1] that applies a time-stepping procedure to calculate the shape of an ice accretion.

* *Corresponding author: Department of Mechanical Engineering, University of Defence, Kounicova 65, 612 00 Brno, tel.: +420 973 442 616, E-mail: vladimir.horak@unob.cz*

Mentioned software enables to simulate both basic kinds of ice that can be formed on the wing surface:

- The ***rime ice*** if all the impinging super-cooled water droplets freeze immediately upon impact. It tends to form at combinations of low ambient temperature, low speed and a low value of cloud water content.
- The ***glaze ice***, which creates at combinations of temperature close to freezing, high speed or high cloud liquid water content. In that case, not all of the impinging water freezes on impact, the thin layer of remainder water is flowing along the surface and freeze at other locations. The process is strongly influenced by the heat transfer.

The ice accretion prediction code ICE was currently modified in regard of demanding solution of more complicated icing simulation cases, e.g. airfoil with slotted flap, wing slot, etc. The latest code version enables solution of multi-element airfoils, when the mutual flow overlap of circumfluent bodies can occur.

2. Trajectory of Water Droplets

The potential flow field is calculated in the ICE code using 2-D panel method [1]. This potential flow field $\boldsymbol{v}_f\,(\boldsymbol{r})$ is then used to calculate the trajectories of water droplets and the impingement points on the body.

The water droplet is considered as a mass point with a mass m on that the resultant force $\boldsymbol{F}$ is acting. Its acceleration and position vector $\boldsymbol{r}$ are given by relations

$$\frac{\mathrm{d}\boldsymbol{v}_p}{\mathrm{d}t} = \frac{\boldsymbol{F}}{m} \quad \text{and} \quad \frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}t} = \boldsymbol{v}_p\,. \tag{1}$$

Currently droplets passing through the atmosphere are considered as spherical elements (diameter $\boldsymbol{d}$) on that the surrounding fluid forces (aerodynamic and aerostatic) and gravitation act.

Considering the relative velocity $\boldsymbol{v}$ between surrounding fluid and droplets velocities

$$\boldsymbol{v} = \boldsymbol{v}_f - \boldsymbol{v}_p\,, \tag{2}$$

the vector of droplet drag is given by the expression

$$\boldsymbol{D} = c_D \frac{1}{2} r \left(\boldsymbol{v}_f - \boldsymbol{v}_p\right)\left|\boldsymbol{v}_f - \boldsymbol{v}_p\right| \frac{p\,d^2}{4}\,, \tag{3}$$

where c_D is a sphere drag coefficient and ρ is density of surrounding air.

Vector sum of the gravitation force $\boldsymbol{W}$ and aerostatic lift $\boldsymbol{L}_s$ is given by

$$\boldsymbol{W} + \boldsymbol{L}_s = \frac{p\,d^3}{6} r_p \left(1 - \frac{r}{r_p}\right)\boldsymbol{g}\,, \tag{4}$$

where ρ_p is droplet (water) density.

Rearranging the above equations we can obtain the droplet acceleration in form

$$\frac{\mathrm{d}\boldsymbol{v}_p}{\mathrm{d}t} = \frac{3}{4}\frac{c_D}{d}\frac{\frac{r}{r_p}}{1+\frac{1}{2}\frac{r}{r_p}}\left(\boldsymbol{v}_f - \boldsymbol{v}_p\right)\left|\boldsymbol{v}_f - \boldsymbol{v}_p\right| + \frac{1-\frac{r}{r_p}}{1+\frac{1}{2}\frac{r}{r_p}}\boldsymbol{g}\,. \tag{5}$$

Specifying equations (1) and (5) into components create the set of six ordinary differential equations for the droplets trajectory ***r*** (*t*) solution. That equation system can be solved numerically.

The improved ICE code version enables to solve system of several airfoils, by default, up to eight separate parts. Model algorithms have been extended to involve mutual flow overlap of multi-element airfoils (e.g. overlap between the airfoil and flap). The typical results of air streamlines of droplet trajectories around an airfoil with a slotted flap are presented in Fig. 1. There are seen droplet trajectories and impact locations near the airfoil leading edge. Trajectories of droplets impacting an airfoil surface are depicted by a black square. There is also obviously seen a portion of the overlap region between the airfoil and flap.

The impact locations where droplet trajectories intersect an airfoil surface may be divided into several separated subsections. It can be seen – for the case of airfoil with the slotted flap in landing position – in Fig. 2. The flap is not fully overlapped in this case. Then black squares of impinging droplets trajectories are divided on one impacting the airfoil and another one impacting the flap surface.

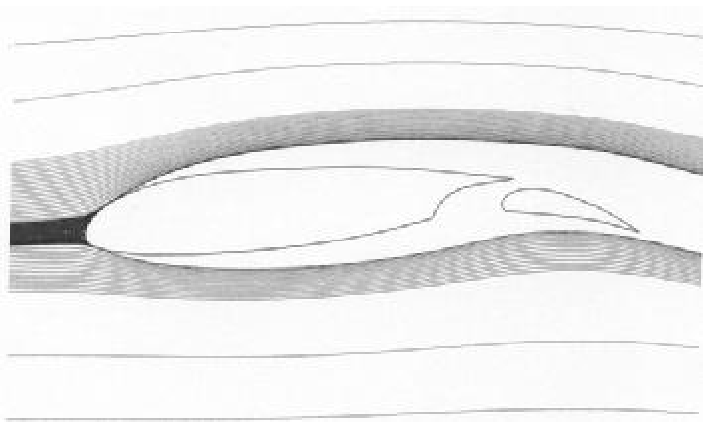


Fig. 1 Droplet trajectories near an airfoil with a slotted flap

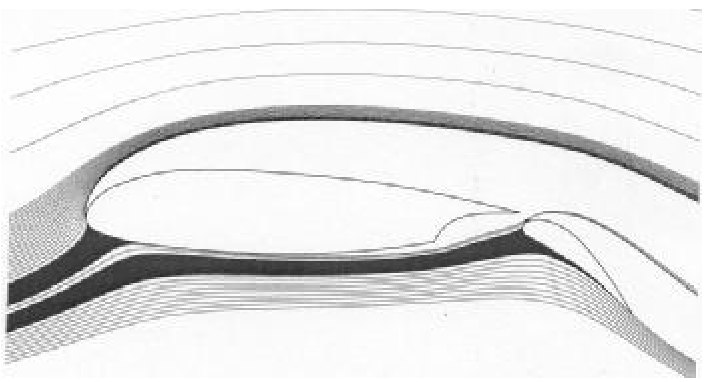


Fig. 2 Droplet trajectories near an airfoil with a slotted flap in landing position

3. Thin Liquid Layer Flow With Heat Transfer and Phase Changes

Theoretical solution of the flow of a thin water layer on a cold surface and gradual freezing is realized by the theoretical approach which is called as a shallow water theory. In compare to standard methods, we moreover try to include approximate influence of a velocity profile shape on the momentum equation. There are formally arranged the conservative equations using for the solution of water flow in open channels. The flux terms are evaluated using a discontinuous Galerkin method based finite-volume formulation [2]. For the full discretization of the problem, the basis set contains as spatial functions as functions of time. The problem leads to the solution of the system of ordinary differential equations in the final phase. Principles of the solution of glaze ice accretion prediction and applying the Galerkin method are closely explained in [3].

Thus detailed solution of thin water layer flow on the airfoil surface was very time-consuming procedure. Therefore, it was necessary to accept a simplification of mathematical model to reach in practice acceptable time of solution.

Evaluation of testing examples by discontinues Galerkin method acknowledged typical properties of water layer on the plane wing surface:

- The water flow layer on the wing surface is very thin, in the order of microns or tens of microns.
- Water flow velocity is very small, in the order of "millimeters per second".
- The water layer momentum is highly influenced by the shear stresses on the water surface and on the wall. The other effects are substantially smaller (change of layer thickness along the profile, gravitation forces, momentum of impacting droplets).
- Practically linear water layer velocity profile is reached very soon.

Using experiences obtained from the detailed solution [3], in the first approach we can at the steady state solution omit momentum equation and replace it by the relationship $Q\ (h,\ \tau_e)$, where Q is the flow volume, h is the thickness of water layer, and τ_e is the shear stress on the liquid surface (result of the boundary layer solution on the airfoil).

The precedent code version presumed constant surface temperature $T_w = const.$ This rather restrictive assumption was modified to the general form $T_w = T_w(s)$, where s is the coordinate measured along the airfoil surface.

Tests showed that the temperature distribution along the surface has a fundamental influence on the ice accretion process at temperatures close to freezing. The thin water layer reacts promptly even on small changes in surface temperature.

Determination of the temperature distribution along an airplane surface at given flight conditions represents an extremely complicated task. The result depends not only on the state of the surrounding atmosphere and flight mode, but also on the detailed wing design. Particular structure parts are manufactured from various materials and very different dimensions. Consequently there are large differences in thermal conductivity. There may be located heat sources (e.g. propulsion units) in a structure as well. The heat transfer solution can also be unsteady state, with time constants comparable to the duration of flight in icing conditions.

The "exact" solution of the surface temperature distribution as a part of the ice accretion prediction code is practically unfeasible. Therefore, it was necessary to choose a simplified version, which would be preferably definite and so as provide for reproducibility of results.

The chosen procedure follows from the adiabatic wall temperature $T_{ad}(s)$, which is entirely given by the solution of the stationary flow field. Otherwise, the adiabatic wall temperature can be expressed from the difference $T_{ad}(s) - T_{ext}$ with regard to free stream temperature T_{ext} and reference temperature T_{w0} by means of expression

$$T_w(s) = T_{w0} + a\,[T_{ad}(s) - T_{ext}], \tag{6}$$

where α is a constant allowing to create, together with T_{w0}, two-parametric set of temperature profiles.

For $\alpha = 0$, we will receive wall of constant temperature T_{w0}. For $\alpha = 1$ and $T_{w0} = T_{ext}$, is the adiabatic wall temperature $T_{ad}(s)$, respectively. It is possible, by the choice of $0 < \alpha < 1$, to approximate roughly a conversion between "intimate heat conductive" and "heat nonconductive" structure.

It proved that the ice accretion with the thin water layer on the airfoil surface can be substantially affected by the transition to turbulence of surrounding air flow. Namely, after the transition to turbulence, the heat transfer rate on the liquid level substantially increases.

Therefore, the mathematical model was modified for the better approximation of transition boundary layer location. There was used a practically well-tried method for predicting the onset of transition location based on empirical correlations [4], which follows from the relation between Reynolds numbers related to a length Θ and x, as

$$R_\Theta = \frac{u_e\,\Theta}{n} \qquad \text{and} \qquad R_x = \frac{u_e\,x}{n}. \tag{7}$$

Where Θ is the boundary layer momentum thickness, x is the distance from the leading edge along the airfoil surface, u_e is the free-stream velocity at boundary-layer edge, and v is the kinematics viscosity.

Both Reynolds numbers are continually evaluated at each point x during the solution of laminar boundary layer.

By introducing into equation

$$\Delta = R_\Theta - 1.174\left(1 + \frac{22\ 400}{R_x}\right)R_x^{0.46} \tag{8}$$

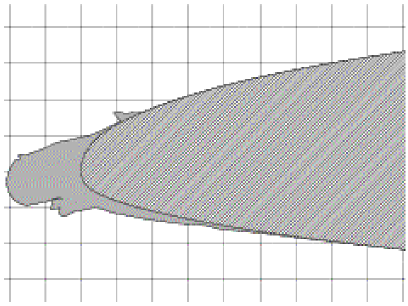
we can determine the transition location x_{tr} qualitatively, when Δ is zero, as the starting point of transition to turbulence.

4. Influence of Air Temperature on Ice Shapes

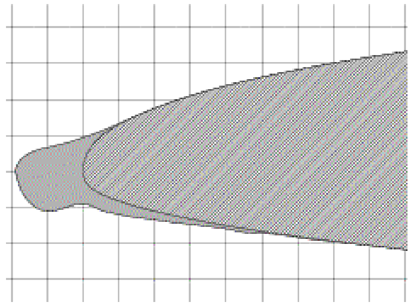
The glaze ice accretion process is strongly dependent on temperature, besides other icing parameters like the cloud liquid water content (*LWC*) and water median volume droplets diameter (*MVD*). Influence of the ambient air temperature *T* on iced airfoil shapes – predicted by the ICE code, version 3.1 – is shown in Fig. 3.

The *rime ice* (a) forms at low temperature when water droplets freeze instantly upon impact. Therefore the rime ice shapes are not dependent on air temperature, if is sufficiently low.

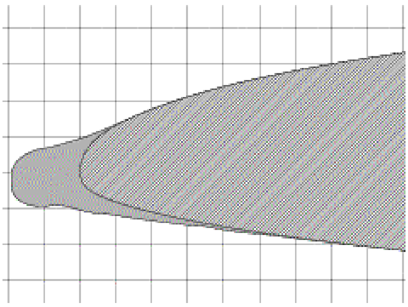
The *glaze ice* creates at combinations of temperature close to freezing, high speed or high cloud liquid water content, when the thin layer water is flowing along the airfoil surface and freezes subsequently at other locations from the points of droplets impact.



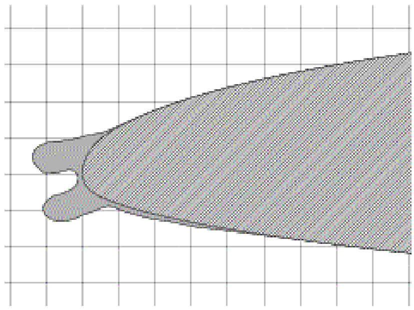
(a) Rime ice



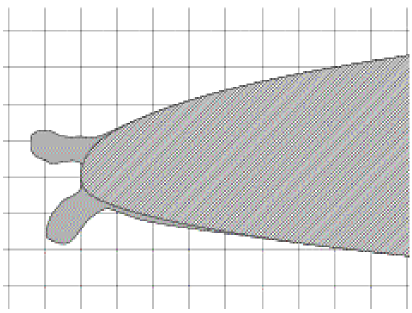
(b) Glaze ice: T = 269.65 K



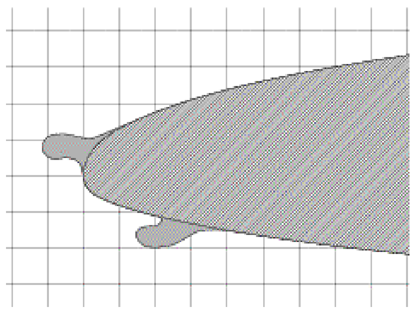
(c) Glaze ice: T = 270.15 K



(d) Glaze ice: T = 270.65 K



(e) Glaze ice: T = 271.65 K



(f) Glaze ice: T = 272.65 K

Fig. 3 ICE code simulation of air temperature influence on iced airfoil shape. Airfoil NFL0414, airfoil chord 0.45 m, angle of attack α = 0°, free stream velocity v_∞ = 77.2 m s^{-1}, MVD = 18 μm, LWC = 0.32 g m^{-3}, atmospheric pressure 100 kPa, icing duration time 900 seconds.

Process of glaze ice accretion is strongly related to the heat transfer between water layer and wing surface. Results of solution are therefore substantially influenced by both ambient and surface temperatures.

In Fig. 3, we can see various cases of glaze ice shapes predicted by ICE code:

- Stream-wise shape (b), (c)
- Double-horn shape (d)
- Span-wise ridge shape (e), (f)

There is vividly demonstrated the air temperature influence on iced airfoils shapes for $T = T_w$.

It is evident how small changes in temperature, in a few tenth degrees centigrade, implicate changes of rime ice predicted shapes, which can have a very negative effect on the aerodynamics. From the viewpoint of aerodynamics, when compared to wings without ice, wings with ice indicate decreased maximum lift, increased drag, changes in pressure distribution, stall occurring at markedly lower angles of attack, increased stall speed, and reduced controllability.

5. Example of Flapped Airfoil Icing

The ability of the improved ICE code version to predict ice accretion of flapped airfoils is presented on the case of the wing airfoil with a slotted flap. Example of the rime ice shape on the wing airfoil with the slotted flap in landing position is shown in Fig. 4.

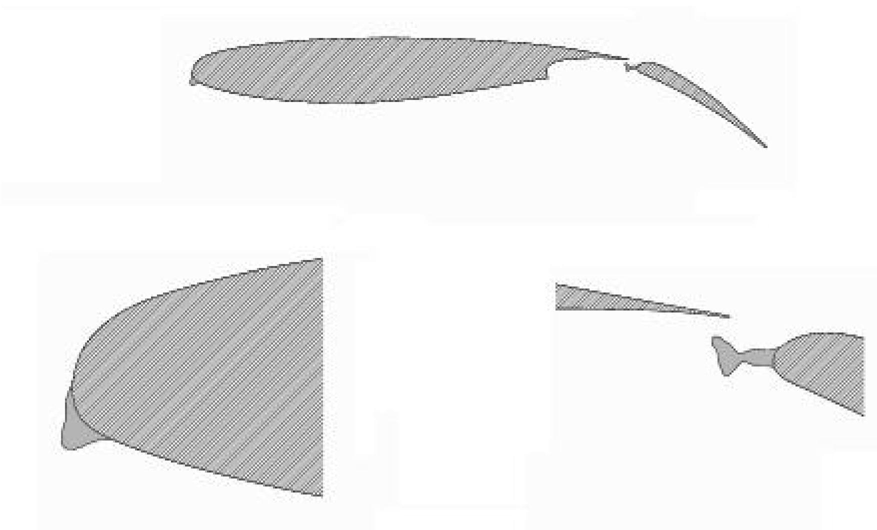


Fig. 4 Example of the rime ice prediction on the wing airfoil with a slotted flap in landing position

Mentioned ice accretion on the flap causes the reduction of the gap size between main element and flap. Consequently, it can have a large impact on the performance degradation of iced multi-element airfoils. Lastly, there is a potential mechanical problem in the elevator mechanism itself.

6. Closing Remarks

Improved ICE code version [1] enables computational rime ice and glaze ice accretion prediction on single and multi-element airfoils in acceptable time of solution. Mathematical model has been modified for variable wall temperature along the airfoil surface. The code was also improved for the better approximation of transition boundary layer location.

The software was currently used for icing simulation as an aid to the certification process of small transport aircraft for flight in icing conditions according to international aircraft standards, where maximum and intermittent maximum icing conditions are specified.

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