Numerical studies of the flow around the slotted mechanized wing and morphing wing of a mainline aircraft in real flight conditions

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The results of numerical studies on the effect of gaps in wing mechanization during landing in icing conditions are presented. It is shown that a morphing wing, within the range of small angles of attack, is less susceptible to the negative influence of icing. Additionally, its ice accretions do not significantly alter the shape of the airfoil compared to a slotted mechanized wing. Numerical studies were conducted using a numerical code based on the Reynolds-averaged Navier–Stokes equations.

Keywords: aerodynamic characteristics, slotted mechanized wing, morphing wing, icing, CFD methods.

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Aviation equipment is being improved constantly. New approaches to improving the takeoff, landing, and cruise performance of aircraft are being proposed. Research into the design of a wing geometry with a continuous derivative in all flight modes (specifically, a morphing wing) is currently being conducted worldwide [1,2].

A code based on the Reynolds-averaged Navier–Stokes equations was used to perform a numerical study of a slotted mechanized wing and a morphing wing of a mainline aircraft under actual flight conditions: a landing approach from the „holding" mode. In the context of icing, this flight mode is risky in that the aircraft flies at a relatively low speed at a low altitude, where it may enter a region with a high concentration of supercooled water droplets at a negative temperature of its surface. The shape, size, and density of ice formed on the aircraft surface depend on meteorological and flight conditions.

The model is composed of a fuselage, a wing with its mechanization in the landing position (slat deflection angle $\delta_{slat} = 20^\circ$; flap deflection angle $\delta_{flap} = 36^\circ$), and a horizontal tail (Fig. 1). The half-total airfoil area is $S_{1/2\,wing} = 192\,\mathrm{m}^2$, the mean aerodynamic chord (MAC) of the wing is 7 m, and the wing span is 29.5 m. A morphing wing was constructed by covering the gaps on the original mechanized wing (Fig. 1, a) with a new surface tangent to the initial one (Fig. 1, b).

Numerical 3D modeling was carried out for the left half of the aircraft model with account for the plane of symmetry. A structured grid containing approximately $1.2 \cdot 10^7$ cells was constructed for calculations. A total of 155 of these cells were located along the wing chord, and 20 cells were located along the „O-grid" (a special grid type for correct calculations of the boundary layer) height. A realizable $k-\varepsilon$ turbulence model with improved modelling of turbulence parameters near the wall and with the pressure gradient taken into account was used in ANSYS FLUENT calculations. The $k-\varepsilon$ method relies on the simultaneous solution of the equations of kinetic energy k, dissipation rate ε of turbulent pulsations, and momentum transfer. A one-parameter turbulence model adapted to boundary layer flows was used in the near-wall region.

The effect of gaps on the aerodynamic characteristics of the wing was examined at angles of attack $-5 \leqslant \alpha \leqslant 25^\circ$ with Mach number $\mathrm{M} = 0.4$ and Reynolds number $\mathrm{Re} = 60 \cdot 10^6$. Calculations were performed both in dry air and in icing conditions.

The accumulation of ice on the aircraft surface was calculated in FENSAP-ICE [3] at angle of attack $\alpha = 2^\circ$, flight altitude $H = 500\,\mathrm{m}$, and ambient temperature $T = 268\,\mathrm{K}$. A constant arithmetic mean value of the droplet diameter ($20\,\mu\mathrm{m}$) was set in these icing calculations. The density of ice generated by FENSAP-ICE was taken to be constant ($\rho_{ice} = 917\,\mathrm{kg/m}^3$), and the liquid water content (LWC) in the air was set to $0.005\,\mathrm{kg/m}^3$. The shapes of ice in the MAC section of the wing are presented in Figs. 1, c, d.

The aerodynamic characteristics of the aircraft models were first calculated without ice in ANSYS FLUENT. The obtained results were then used by FENSAP-ICE to evaluate the wettability of the aircraft surface by water droplets and the accumulation of ice. Ice buildup is reproduced in this program by modeling the deposition of liquid from falling droplets in the form of a thin liquid film. The height of the liquid film is calculated at grid nodes on the solid surface [4].

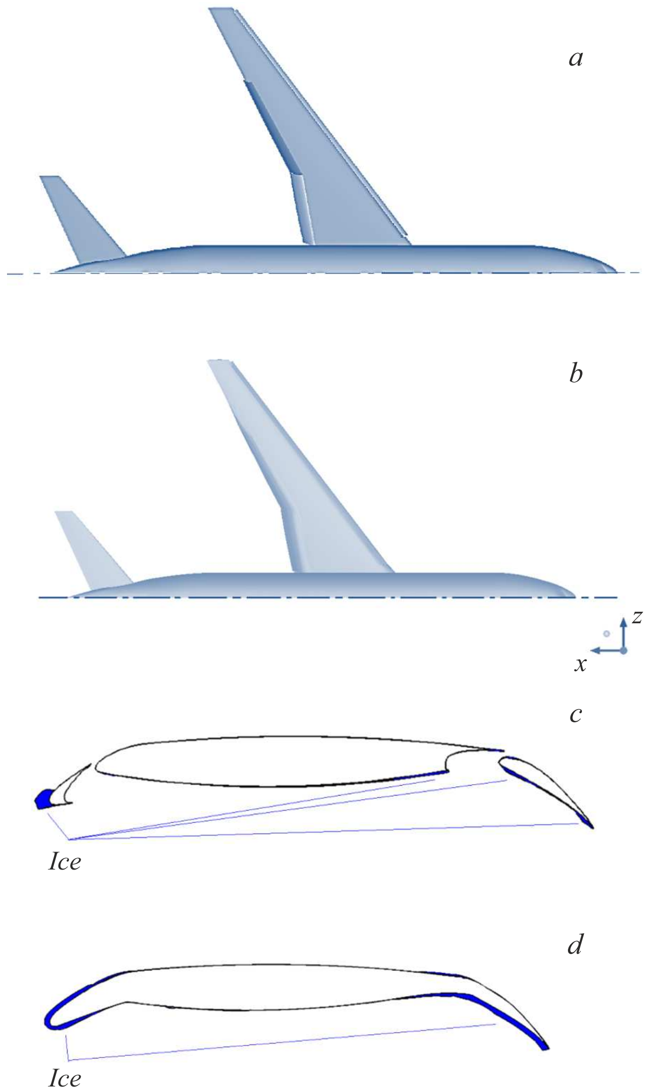

Figure 1. General view of the aircraft model. a — Top view of the calculation model with a slotted mechanized wing; b — top view of the calculation model with a morphing wing; c — MAC section of the slotted mechanized wing with ice; and d — MAC section of the morphing wing with ice.

The shape and height of ice accumulated on the wing vary depending on the presence of gaps, which affect the downwash and velocities of flow around the wing. The maximum ice height in the region of the mean aerodynamic chord of the slotted mechanized wing at its leading edge is 3% of MAC, and the same parameter for the morphing wing is close to 1.4% of MAC. However, a smaller amount of ice is accumulated on the lower surface of a deflected flap of the slotted mechanized wing (Figs. 1, c, d). This is attributable to the difference in velocity fields in the region of the lower surface of the flap. The flap shroud gap contributes to downwash in the region of the lower flap surface and alters the local angles of attack; it directs the air flow from the lower surface to the upper one, thereby increasing its velocity. Thus, a certain fraction of cooled droplets moving toward the lower surface of the flap are carried by this flow upward through the gap, while droplets on the morphing wing flap spread downstream and freeze uniformly on its lower surface.

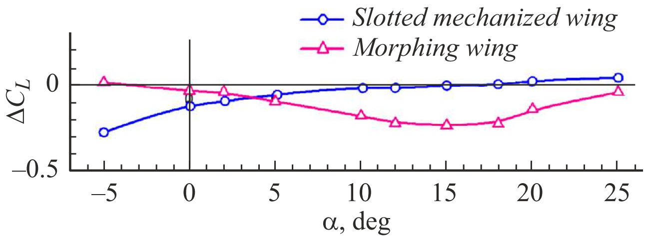

Figure 2. Increase in lift coefficient in the process of wing icing as a function of the angle of attack.

Following calculation of the ice shapes in FENSAP-ICE, they were transferred (in the form of a file with their geometric data) to the ANSYS ICEM CFD software, where new computational grids with ice were constructed. After this, the effect of icing on the aerodynamic characteristics of the model was calculated in FLUENT.

The increments of lift coefficient due to wing icing were determined as functions of the angle of attack by substituting the lift coefficient of the aircraft model without ice from the one with ice: $\Delta C_L = \Delta C_{L\ ice} - C_{L\ without\ ice}$ (Fig. 2). It was found that the effect of icing on the slotted mechanized wing in the deflected configuration at angles of attack $-5 \leqslant \alpha \leqslant 5°$ is stronger than that for the morphing wing, but the morphing wing with ice loses lift compared to the slotted mechanized wing at angles of attack $\alpha > 5°$. The pressure distribution in Fig. 3 reveals significant differences in flow around the airfoil leading edge in the region of the mean aerodynamic chord at angle of attack $\alpha = 2°$. Owing to the buildup of ice on the leading edge of the slotted mechanized wing, the pressure on it increases, while the pressure distribution for the morphing wing is not affected in any significant way by icing.

Numerical studies have demonstrated that the constructed morphing wing is less susceptible to the negative impact of icing (simulated at angle of attack $\alpha = 2°$) at small angles of attack $-5 \leqslant \alpha \leqslant 5°$ and, contrary to the case of the slotted mechanized wing, the process of ice buildup on it does not alter the airfoil shape in any significant way.

Conflict of interest

The authors declare that they have no conflict of interest.

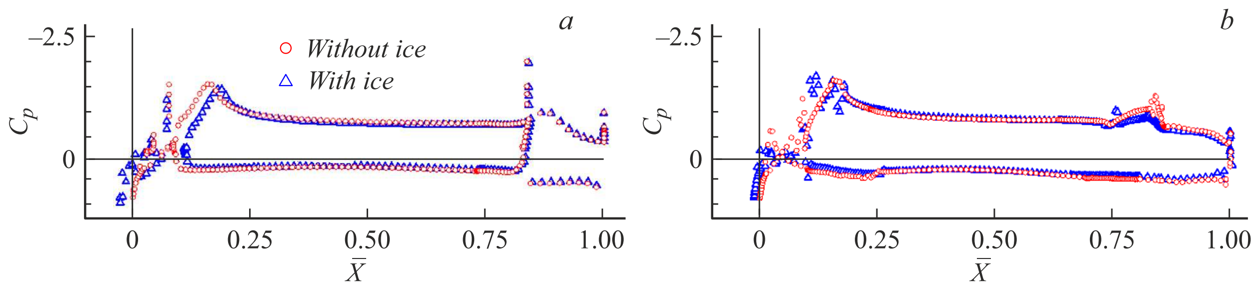

Figure 3. Distribution of the pressure coefficient in the MAC section for the slotted mechanized wing (a) and the morphing wing (b). $\alpha = 2^\circ$.

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