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Multi-step ice accretion on complex three-dimensional geometries

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Abstract. This work presents the Politecnico di Milano Icing Research Group's contribution to developing new numerical tools and methodologies for simulating long-term in-flight icing over complex three-dimensional geometries. PoliMIce is an in-house ice accretion software that includes state-of-the-art solvers for the dispersed phase to compute the droplets' impact on the aircraft, and ice accretion models, including the exact local solution of the unsteady Stefan problem. PoliMIce has also been extensively developed for the simulation and robust design optimization of thermal ice protection systems. A crucial aspect that characterizes and makes numerical simulations challenging is the formation, and evolution in time of complex ice geometries, resulting from the ice accretion over the body surface and/or previously formed ice. A multi-step procedure is implemented since the aerodynamic flow field is coupled with ice accretion. The total icing exposure time is subdivided into smaller time steps. At each time step, a three-dimensional body-fitted mesh suitable for the computation of the aerodynamic flow field around the updated geometry is generated automatically. The novel remeshing procedure is based on an implicit domain representation of the ice-air interface through a level-set method and Delaunay triangulation to generate a new conformal body-fitted mesh. In this work, the unique capabilities of the PoliMIce suite are employed to perform automatic multi-step ice accretion simulations over a swept wing in glaze ice conditions. Numerical simulations are hence compared with the available experimental data.

Introduction

In-flight icing is a complex problem that involves various disciplines, including aerodynamics, multi-phase flows, thermodynamics, and meshing capabilities.

It is a critical safety issue in aeronautics since it disrupts the aircraft's aerodynamics. Computational fluid dynamics techniques are valuable for simulating different and potentially extreme conditions that complement experimental and in-flight campaigns, better understanding how ice accretion affects aerodynamic performances, and designing optimal ice protection systems [1].

For the numerical simulation of in-flight ice accretion, most of the icing tools, such as LEWICE [2], FENSAP-ICE [3], SIMBA-ICE [4], rely on a standard and well-established segregated approach as multi-step approach. Under a quasi-steady assumption, the total icing exposure time is divided into smaller time steps. The aerodynamic flow field, the amount and distribution of the cloud water droplets impinging on the selected surfaces, and the ice growth rate are computed sequentially at each step. Then, the new geometry and the corresponding surrounding mesh must be updated. This operation is usually the most critical phase of the multi-step loop, especially if a fully automated procedure is desired.

The following sections describe how the in-house code PoliMIce [5] computes the aerodynamic flow field, the amount and distribution of the cloud water droplets impinging on the selected surfaces, the ice growth rate, and the updating of the geometry and corresponding surrounding mesh.

Flow solver

Aerodynamic simulations of the external airflow are performed here using SU2 [6]. A node-centered finite volume method (FVM) is applied on arbitrary unstructured meshes using a standard edge-based data structure on a dual grid with median-dual control volumes. Convective fluxes are discretized at each edge mid-point using either centered or upwind schemes. The aerodynamic field is computed as a solution to the Reynolds-averaged Navier-Stokes (RANS) equations, used in this study in tandem with the Spalart–Allmaras (SA) turbulence model.

Collection efficiency solver

Due to the scales at play in ice accretion and the concentration of water droplets, their effects on the solution of the airflow field can usually be neglected so that the computation of the aerodynamics can be performed independently of the water droplets. This assumption leads to the so-called one-way coupled approach; only the airflow field can affect the motion of water droplets. The in-house particle tracking code is based on a Lagrangian framework and simulates clouds containing supercooled water droplets [7, 8].

The Lagrangian framework allows straightforward modeling of supercooled water droplets' effects, such as splashing, aerodynamic breakup, and deformation, and can deal with secondary particles. As the result depends on the particle resolution, a strategy was developed to automatically refine the seeding region by adding new particles where needed. Elements are incrementally split at each iteration, evolving the current cloud front, and computing the collection efficiency on the surface. The simulation stops when the difference in the L_2 norm between two consecutive collection efficiency calculations is below a user-supplied threshold.

Thermodynamic solver

The in-house code PoliMIce [5] is used for computing the ice accretion. Computing the thickness of the forming ice layer amounts to solving a phase change problem over the body surface. Typically surfaces are first discretized in computational cells, and a one-dimensional Stefan problem is solved for each control volume. Early icing tools rely on the approximate solution of the Stefan problem proposed by Messinger in 1953 [9] for aeronautical applications. In 2001 Myers [10] proposed an improved version of Messinger's model, obtaining a better representation of the transition between the rime and the glaze ice. A further modification to Myers' model, based on the exact local solution of the unsteady Stefan problem, is implemented in the current version of PoliMIce [11]. PoliMIce can also perform numerical simulation of Electro-Thermal Ice Protection Systems (ETIPS) [12], both in the anti-icing and de-icing mode, identifying six different icing conditions and the transition between one and the other, including accretion, melting of ice, and water evaporation.

The surface roughness is estimated a-priori with the empirical formula of Shin, as a function of liquid water content (LWC), static air temperature, and freestream velocity. It provides an equivalent sand-grain roughness, k_s, which is needed by the Spalart-Allmaras turbulence model.

In the multi-step procedure, the water film distribution and all the icing data are interpolated from the previous step through a nearest-neighbor search algorithm.

Updating geometry module

To avoid mesh entanglement and grid intersections typical of standard mesh deformation techniques, PoliMIce updating geometry module [13, 14] is based on an implicit domain remeshing strategy to obtain a robust and automatic remeshing procedure that permits long-term in-flight icing simulations without the user intervention.

At each step, the new ice-air interface is represented as the zero-contour level of a level-set function defined over the computational volume, such that $\varphi < 0$ in the portion of the domain occupied by material, $\varphi > 0$ in the portion of the domain not occupied by material, and $\varphi = 0$ at the interface. Keeping the clean body elements untouched, only the ice-air interface ones are then isotropically remeshed to obtain a body-fitted surface mesh with good-quality elements, which is finally used as a base for generating the volume grid required for the next time step computations.

Results

This section presents a 10 steps ice accretion simulation over a 30° degree swept NACA0012 wing in glaze ice conditions, taken from the 1st Ice Prediction Workshop. Numerical results are compared with the experimental results obtained at NASA Glenn Icing Research Tunnel (IRT).

Test conditions are reported in Table 1. The inputs to the problem are the angle of attack (AoA), the freestream velocity, temperature and pressure, the liquid water content (LWC) of the cloud, i.e. the grams of water contained in a cubic meter of air, the droplet median volume diameter (MVD) and the total icing exposure time.

Table 1: Icing test conditions.

Case	Sweep Angle [deg]	AoA [deg]	Vel [m/s]	Temp [K]	Pres [Kpa]	LWC [g/m^3]	MVD [μm]	Time [s]
362	30	0	103	266	92.32	0.5	34.7	1200

The simulated ice shape is characterized by high temperatures near the stagnation point, which result in thin ice layers at the leading edge, and runback water driven by shear stresses.
The length and the angle of the horns are well predicted, although there is an underprediction in the overall mass of ice accreted, particularly near the stagnation point.

The final ice shape and the evolution of the geometry represented through a slice perpendicular to the leading edge are represented in Figure 1 and Figure 2, respectively. Comparing the solution obtained with the single-step approach with the multi-step one, it is evident how the latter is fundamental to correctly capture the glaze ice shape, accounting for the progressive modification of the flow field around the wing.

Conclusions and future work

This paper briefly presented the PoliMIce toolkit, which can perform multi-step simulations of in-flight ice accretion over three-dimensional geometries, avoiding mesh entanglement and allowing for long-term simulations necessary to simulate full aircraft configurations and bringing the possibility of certification by simulation in the near future.

In the future, PoliMIce will be employed for multi-step simulations around other swept wings with different sweep angles, testing new roughness and density models to better understand ice accretion's physics and consequently improve its modeling. Finally, complex three-dimensional ice shapes, easily managed by the proposed methodology, will be adopted to evaluate the aerodynamic losses due to ice formation on commercial and military aircraft.

Figure 1: Glaze ice shape at t= 1200 s.

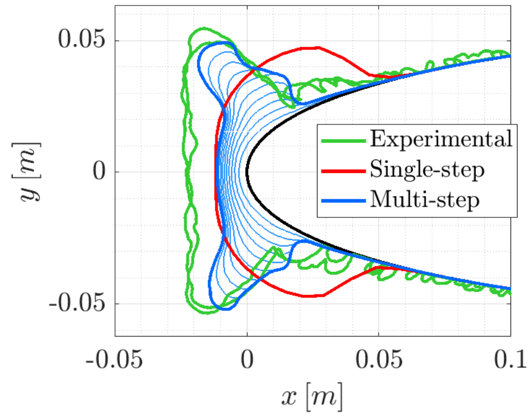

Figure 2: Ice shape evolution.

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