FENSAP-ICE: Numerical Simulation of Rotor Blade Icing

Isik A. Ozcer,* Guido S. Baruzzi,* Thomas Reid,* Habib Fouladi ** & Wagdi G. Habashi **
*Newmerical Technologies International, Montreal, Canada, H3A 2M7
**Department of Mechanical Engineering, McGill University, Montreal, Canada, H3A 2T5

Summary In-flight icing on rotating components is a challenging problem that requires modeling of additional physical phenomena that are usually negligible for fixed wing applications, as well as strong radial gradients of velocity, shear stresses and stagnation temperature, which can range from sub-freezing to above freezing. This article will demonstrate the application of the FENSAP-ICE system to the numerical simulation of rotor blade icing on a two-blade rotor in hover. The Navier-Stokes equations are solved in the rotating frame of reference, with source terms for the centripetal and Coriolis acceleration. The stagnation temperature gradient effect is modeled with the Extended Icing Data approach. Furthermore, the solution-based, unstructured, anisotropic mesh adaptation module OptiGrid is applied to show that the accuracy of the solution obtained on the initial, manually-clustered mesh can be greatly improved without increasing the number of mesh nodes. The computed ice shapes are compared with available experimental data.

INTRODUCTION

Due to the lack of pressurization, most helicopters are limited to flight at low-to-moderate altitudes where they are particularly vulnerable to in-flight icing. Certification for helicopter icing is a complex, difficult and very expensive task and therefore most helicopters are not certified to fly in icing conditions; they must either exit the icing environment or land immediately. In-flight helicopter ice accretion simulations using tankers equipped with spray nozzles and ground icing facilities studies of full-scale helicopters have not been very successful in reproducing natural icing encounters [1]. The numerical simulation of ice accretion on rotating blades is a challenging problem that requires modeling of the centripetal and Coriolis forces, which are not relevant to fixed-wing aircraft, as well as strong radial gradients of stagnation temperature, which can range from sub-freezing to above freezing and require careful treatment. Additional effects, such as the strong radial gradients of velocity and shear stresses, and the contraction of the streamtube of the rotor contribute to the challenges of simulating airflow, droplet flow and ice accretion on rotor blades. These phenomena are strongly three-dimensional and hence cannot be accurately modeled with a simplified approach based on 2D icing codes.

METHODOLOGY AND RESULTS

The typical numerical ice accretion simulation consists of the airflow calculation, water impingement calculation and ice accretion for a specified duration. The accuracy of the resultant ice shape can be improved by subdividing the icing simulation into a sequence of shorter periods, or multi-shot approach, in which the mesh is displaced at the end of each period to conform to the surface of the accreted ice. The FENSAP-ICE system can compute ice accretion on rotating blades. The system is modular, and for the purpose of this study the modules used are FENSAP, DROP3D, ICE3D and optiGrid. FENSAP is the Finite Element Navier-Stokes solver, which produces high-quality turbulent airflow and heat transfer solutions. In particular, FENSAP can produce accurate results for surfaces with non-uniform roughness, which are typical of ice formations. Flows where the stagnation temperature changes from sub-freezing to above-freezing require the use of the Extended Icing Data (EID) option to post-process the solution and extract additional information relevant to icing. DROP3D is the Eulerian supercooled droplet module which computes the droplet flow and water impingement solution. DROP3D can simulate droplets of various diameters, from very small, of the order of a few micrometers, to the large ones found in SLD conditions, of the order of millimeters, and automatically provides a continuous distribution of the water impacts and catch efficiency on all wetted surfaces. ICE3D is the Shallow Water Icing Model (SWIM), based on the Messinger model. It computes water film flow over all wetted surfaces and the local rate of ice accretion, taking into consideration the incoming water droplets, evaporation, sublimation, convective heat transfer, radiation and film transport phenomena. All modules can easily handle fixed- and rotating-frame geometries.

In order to assess the capability of the FENSAP-ICE system to simulate ice accretion on rotating blades, the simple two-blade helicopter rotor proposed by Caradonna was considered [2]. The rectangular, untapered, untwisted rotor blades have an aspect ratio of 6 and a NACA 0012 airfoil cross-section, set to an 8º pitch angle. The rotor has a diameter of 2.286 m and rotates at 1,250 rpm. The farfield for the numerical calculations is cylindrical. Inlet, exit and sides are placed at a distance of 8, 28, and 7 meters from the center of rotation, respectively. A non-zero but very low value of inflow velocity (Mach 0.01) is specified at the inlet to simulate hover.

The Navier-Stokes equations are solved in the rotating frame of reference, with source terms for the centripetal and Coriolis acceleration, and the Spalart-Allmaras turbulence model. The accuracy of the surface heat fluxes is paramount in ice accretion simulations, therefore the Extended Icing Data (EID) option has been enabled in this FENSAP airflow calculation. The initial unstructured hybrid grid is clustered to better capture the wake of the blades. The FENSAP-ICE automatic, solution-based anisotropic mesh adaptation module optiGrid was applied for two cycles of mesh adaptation to capture the complex interactions occurring in the wake and vortex sheet in vivid detail and significantly enhance the accuracy of the airflow solution, allowing it to propagate further downstream before dissipating. The edges of the elements are coarsened, refined, swapped, and re-aligned in such a way as to minimize an error metric based on the Hessian of the second derivatives of the solution. Even though the size of the grid is kept nearly constant during adaptation, the solution on the initial grid, even with manual clustering, cannot compare with the very high resolution obtained after adaptation. Figure 1 shows a detail of the mesh which reflects the complex wake structure of the rotor. Figure 2 shows the helical vortex sheets and the tip vortices colored by turbulence intensity. Accurate heat flux computations are indispensable for ice accretion simulations. Due to the linearly increasing blade velocity along the span, the stagnation temperature should increase quadratically with radius, however the tip vortices cause a deviation from this behavior, and the effect can be clearly seen in the 3D heat flux distribution shown in Figure 3.

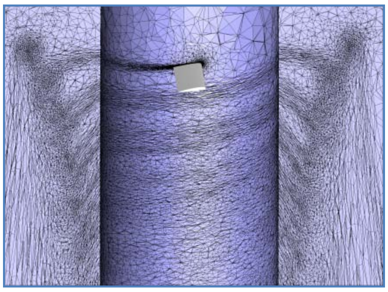
Figure 1. Second adapted mesh

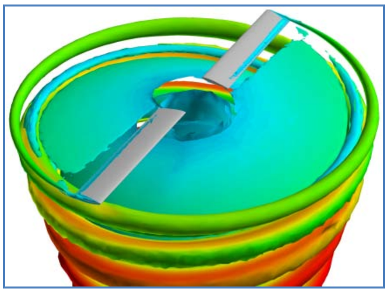
Figure 2. Vortex sheet and tip vortices

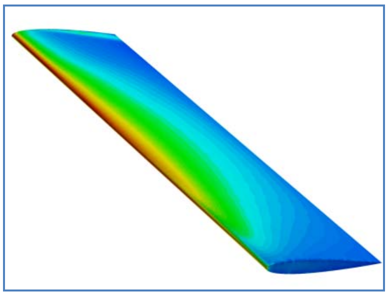
Figure 3. Heat flux distribution

After the flow solution has been computed on the last adapted grid, the Eulerian droplet equations are then solved to determine the water impact distribution on the blades. For this case the free stream Liquid Water Content (LWC) has been set to 1 g/m^3 and the droplet size to 20 microns. Figure 4 shows the LWC on a conical surface that passes through the vortex cores. The helical, droplet-free shadow zones (blue regions) in the wake of the blade are clearly visible. The tip vortex cores are also free of any droplets. The ICE3D module computes the film runback and ice accretion on the blades based on the airflow and droplet solutions. Figure 5 shows the film coverage on one of the blades. The droplet collection efficiency increases towards the tip due to the increasing tangential velocity. Since more water is caught near the tip, runback also increases in this region, compared to the runback at the root. Furthermore the ice accretion rate is greatly affected by the strong dependence of stagnation temperatures on radius, hence the nature of the accreting ice can change from rime to glaze [3]. Also, as radius increases, the centripetal and Coriolis forces begin to dominate over the shear stress as the main film driving mechanism. Figure 6 shows the ice shape obtained after an exposure of 60 seconds. It can be clearly seen that the ice shape is truly 3D and the ice coverage of the leading edge is not complete due to the increasing stagnation temperature at the tip.

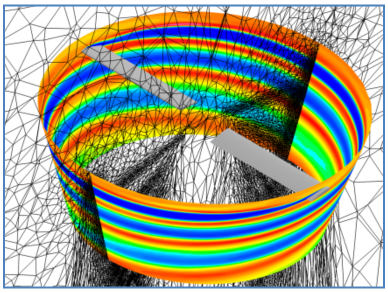
Figure 4. LWC on a conical cut

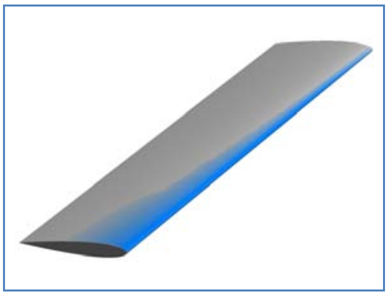
Figure 5. Water film distribution

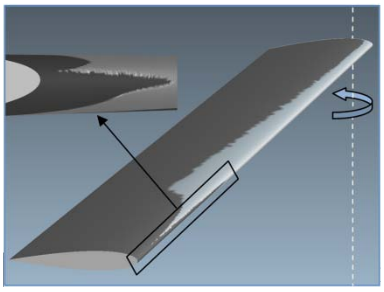
Figure 6. Ice shape after 60 seconds

CONCLUSIONS

Helicopters are particularly vulnerable to in-flight icing. Due to the difficulty and expense of the testing required for certification, most helicopters are not protected against in-flight icing and therefore are not allowed to operate in severe weather conditions. There is a constant push in the industry to develop the methodology to make the icing certification of rotorcraft more affordable and more complete. FENSAP-ICE can be a powerful tool in the arsenal of the blade designers to reduce the cost of certification. An example of its capabilities has been shown for a simple two-blade rotor, and in the final publication more rigorous comparisons with available experimental data will be presented.

References

[1] Flemming, R.J. Bond, T.H. and Britton, R.K.: Results of a Sub-Scale Model Rotor Icing Test. AIAA Paper 91-0660, AIAA 29th Aerospace Sciences Meeting, Reno, NV, 1991.

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