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Multi-physics simulation of in-flight ice shedding

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Abstract. In-flight ice accretion may possibly jeopardise the safety of fixed- and rotary-wing aircraft. Icing can possibly occur if supercooled water droplets in clouds impinge on the aircraft surfaces and freeze upon impact. A major issue related to ice accretion is the possibility of ice shedding from the main body and impacting other parts of the aircraft or being ingested by the engines. A multi-physics framework is presented to simulate ice accretion and shedding from wings and engine nacelles due to aerodynamic forces. The aerodynamics is computed using the open-source tool-kit SU2. Cloud droplet trajectories are computed using the arbitrary-precision Lagrangian in-house solver PoliDrop. Then, the in-house ice accretion tool-kit PoliMIce is used to determine the ice layer. A FEM structural analysis is performed on the accreted ice shape by means of the open-source code MoFEM. Internal stresses within the ice geometry due to aerodynamic forces are computed. The possibility of the occurrence of cracks in the ice layer is assessed and its propagation is determined numerically. Two-dimensional ice accretion simulations are performed to check the validity of the present approach and compare fairly well with available results.

1. Introduction

In-flight ice accretion is a safety concern in the operation of commercial and military flights. It can possibly occur if aircraft flight in clouds containing supercooled liquid droplets (SLD). These droplets remain in a liquid state even if their temperature is below 0 °C. Being in an unstable state, they freeze upon impact with the aircraft, thus leading to the formation of various kinds of ice including rime, glaze and mixed ice. The ice accreted over the aircraft surface can jeopardize the aircraft aerodynamics and the operation of probes and engines. Ice shapes can also break and detach from the main body. This is the so-called ice shedding, which affects both fixed- and rotary-wing aircraft. In the first case, the ice shapes can be broken by de-icing systems, by the action of the aerodynamic loads or by a combination of both.

Bennani et al. [1] studied the shedding of ice from a 2D surface equipped with an electrothermal de-icing system. Mechanical properties of natural ice were used and they assumed temperature-independence of these parameters. Their procedure starts by computing the 2D flow solution and the ice accretion. A portion of the ice at the leading edge is removed to imitate a parting strip. Then, a thermal simulation is performed to predict the melted regions at the ice-airfoil interface. Finally, aerodynamic loads are applied and predict crack propagation through an in-house software based on continuum damage theory.

Zhang and Habashi [2] developed a 2D Finite Element Analysis for in-flight ice break-up. Pressure obtained from the flow solution is set as Neumann boundary condition at the ice-flow interface. For the ice-airfoil interface, instead, a zero-displacement Dirichlet boundary condition was applied. A 2D crack propagation module was developed, in which a crack is introduced if

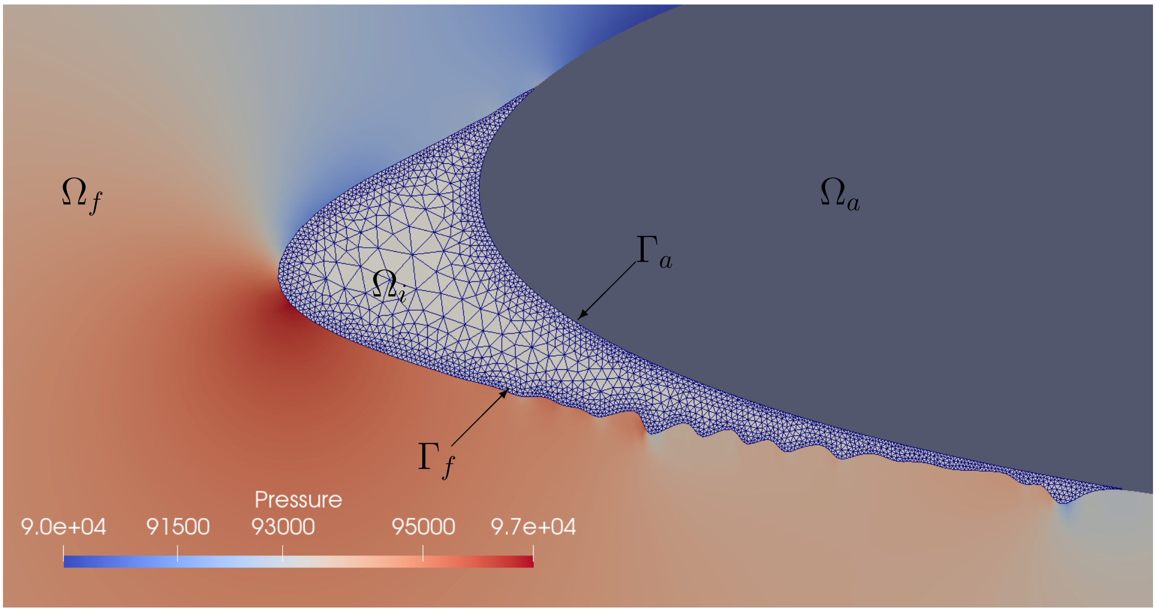


Figure 1: Domain definition

certain conditions are satisfied. The propagation of the crack is then checked at each step of the analysis and the shed-ice piece geometry is provided as output.

In the present work, ice shedding due to aerodynamic loads is studied via the coupling of the ice accretion framework PoliMIce [3] with the FEM structural analysis framework MoFEM [4].

2. Proposed Methodology

The ice shedding simulation is divided into three main steps: *Ice accretion*, *Structural analysis* and *Crack propagation* as follows.

2.1. Ice accretion

Ice accretion is a time dependent problem with a free boundary[3]: the shape of the surface changes as ice forms and therefore the aerodynamic flow field around the body is modified. This, in turn, modifies the droplet trajectories and the impingement points, thereby changing the ice accretion rate.

Since $\Delta t_{CFD} < \Delta t_{ICE}$, with Δt_{CFD} aerodynamic characteristic time scale and Δt_{ICE} the ice accretion scale, a quasi-steady approach is used to perform ice accretion. The computation is split in the following steps: *Aerodynamic flow field computation*: a CFD solver is used to compute the aerodynamic flow field around the body; *Particle Tracking*: a Lagrangian approach allows the computation of the trajectories of water droplets. Given the impingement positions, it is possible to determine the water mass distribution used for the definition of the collection efficiency parameter; *Ice accretion*: the ice accretion performed by PoliMIce defines the new body geometry; *Mesh update*: the new mesh is created to fit the new iced geometry. This mesh is then used as the input grid for a new iteration.

2.2. Structural analysis

Once the ice accretion is performed, a new CFD computation is necessary in order to obtain the aerodynamic loads acting on the ice shape, needed to compute the stresses internal to the ice shape. Internal stresses are computed using the linear elasticity module of MoFEM [4]. A comparison between linear and non-linear elasticity was already performed by Habashi et al. [2], showing no significant differences and thus confirming the hypothesis of linear elasticity holds. With reference to fig. 1, the computational domain is divided into three regions: *Flow Boundary* (Γ_f) as the interface between the domain where flow properties are computed (Ω_f, coloured region) and the ice shape; *Airfoil Boundary* (Γ_a) as the boundary of the airfoil (grey region, Ω_a) surface (or volume) that is in contact with the ice; *Ice region* as the surface (or volume) in between the boundaries described above (Ω_i) (meshed region).

The internal stresses computation is performed with a Finite Element Method (FEM) approach by solving the linear system obtained through the Principle of Virtual Works applied to the Newton's second law [5].

$$\mathbf{K}\mathbf{a} + \mathbf{f} = \mathbf{r} \tag{1}$$

where $\mathbf{a}$ is the vector containing the nodal displacements of the elements derived from FEM discretization, $\mathbf{K}$ is the stiffness matrix, related to the mechanical properties of the material like *Poisson ratio* and *Young Modulus* and is defined as

$$\mathbf{K} = \iiint_{\Omega_i} \mathbf{B}^T \mathbf{D} \mathbf{B} \, dV, \tag{2}$$

where $\mathbf{f}$ represents the vector containing the distributed loads on the boundary of the ice shape and within the geometry it self, defined as

$$\mathbf{f} = -\iiint_{\Omega_i} \mathbf{N}^T \mathbf{b} \, dV - \iint_{\Gamma_f} \mathbf{N}^T \bar{\mathbf{t}} \, dA - \iiint_{\Omega_i} \mathbf{B}^T \mathbf{D} \boldsymbol{\epsilon}_0 \, dV + \iiint_{\Omega_i} \mathbf{B}^T \boldsymbol{\sigma}_0 \, dV \tag{3}$$

and $\mathbf{r}$ is a vector that contains the loads concentrated on the single nodes of the FEM elements. The system of linear equations in eq. (1) is solved for the unknowns $\mathbf{a}$ by setting the appropriate boundary conditions.

Aerodynamic pressure is already taken into account in eq. (3) through the traction term $\bar{\mathbf{t}}$. In particular, the values of flow pressure computed by the CFD analysis and that acts on the boundary Γ_f are extracted from the flow solution. Flow shear stresses are not considered in the present work. Regarding the interface boundary, instead, a Dirichlet boundary conditions setting zero displacement is imposed, defined as $\mathbf{a} = 0$ on (Γ_i). This condition is enforced in order to remove rigid body motion as solution of the elastic problem. However, more complicated boundary conditions could be used to represent the adhesion constraint between ice and airfoil.

2.3. Crack propagation

Once the internal stresses distribution is reconstructed from the nodal displacements, the initial crack surface has to be initiated. Note that the strength of ice is lower when subjected to traction loads other than compressive ones [2]. One way to define the load state of the ice shape is to compute the *Principal Stresses*, defined as the maximum normal stresses acting on a plane on which no shear loads are applied. They are computed from the internal stresses distribution and are defined in a way in which the first principal stress, σ_1, is the largest one. Thus, if at a given point $\sigma_1 > 0$ then the ice shape is subjected to traction loads at that point.

The region with highest first principal stress is selected to initiate the crack surface. Then MoFEM is used to compute the crack propagation starting from the ice shape adjoined with the crack surface. The fracture module implemented in MoFEM is described in [6] and it represents a novel formulation for brittle fracture in elastic material.

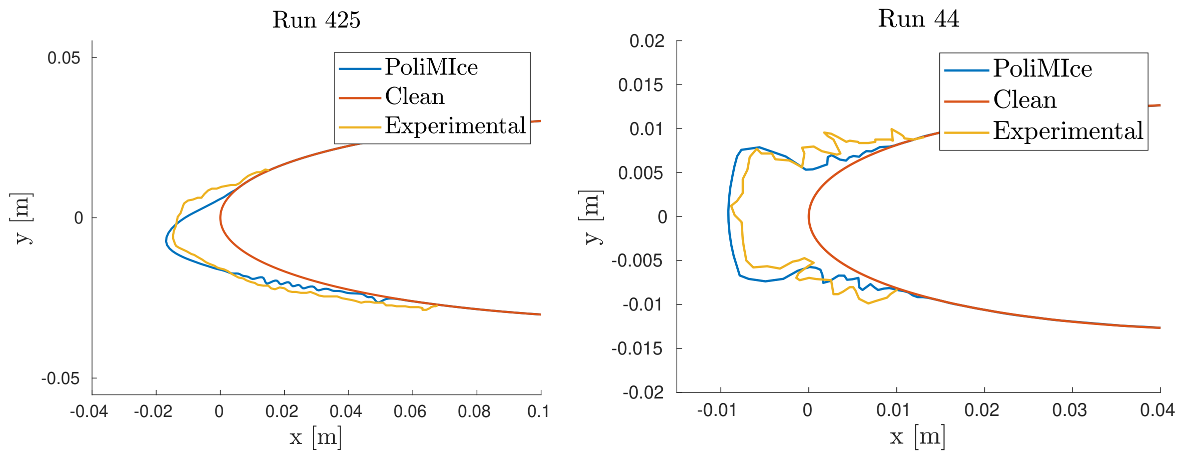
In the fracture model, the prediction of the direction of the crack extension is based on the principle of energy minimization in conjunction with a node-based Griffith-like crack criterion. An arc-length approach [7] has been used in order to compute the scale factor of the external loads which is required to extend the crack area by a certain amount. The arc length method is

Table 1: NASA - Run 425

Parameter	**Value**
Freestream Temperature [°C]	-28.64
MVD [μm]	20
LWC [gr/m^3]	1.0
AoA [°]	4
Air Speed [m/s]	67.1
Static Pressure [kPa]	101.325
Ice accretion time [s]	360

Table 2: AERTS - Run 44

Parameter	**Value**
Freestream Temperature [°C]	-10.1
MVD [μm]	15
LWC [gr/m^3]	1.45
AoA [°]	0.58
Air Speed [m/s]	66.73
Static Pressure [kPa]	101.325
Ice accretion time [s]	180



(a) (b)

Figure 2: Shape comparison: (a) NASA - Run 425, (b) AERTS - Run 44

used to find the scale of the external pressure needed to make this extension. This is repeated iteratively, and at each step this amount of crack area extension can be decreased to speed-up the convergence or increased if convergence is good. If the load factor exceeds unity the ice shape will not break under the aerodynamic loads provided by the CFD analysis.

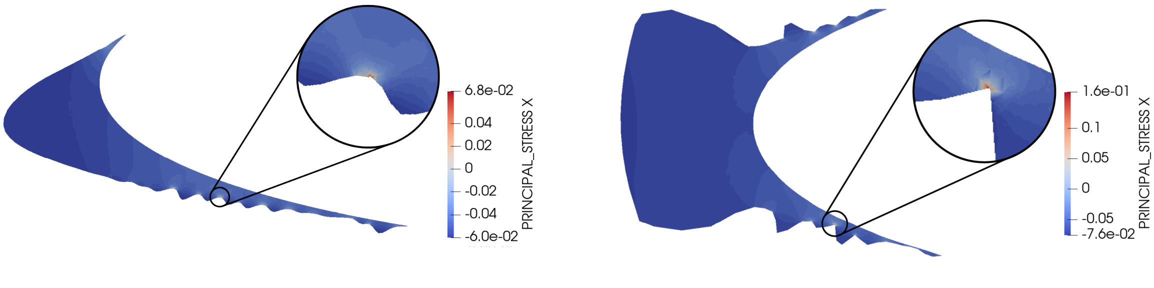
3. Results

The MoFEM framework was already validated [6] and thus no other results have been reported here to prove its effectiveness. Regarding the coupling with PoliMIce, experimental test cases are used in order to check the shape obtained and are taken from both NASA runs in their Icing Wind Tunnel [8] and AERTS experimental campaign [9]. For both experiments ice shedding did not occur. The test conditions are reported in table 1 and 2.

In fig. 2 are reported the ice shapes obtained both numerically and experimentally, showing good agreement between the two approaches.

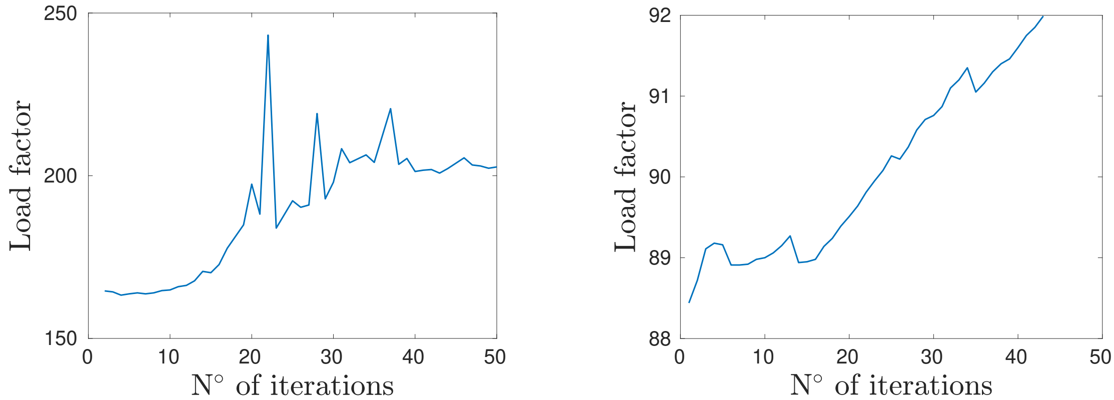
Once the ice shapes are obtained, the internal stresses are computed and the first principal stress distribution is extracted. The distributions for the considered cases is shown in fig. 3 for both test cases taken into account. As it can be noted, most of the ice shape is subjected to compressive loads, while traction load acts only on a limited portion of the ice shape. The regions in which the first principal stress is maximum and greater than zero are detailed in the same figure.

The crack is initiated from traction load regions and its propagation is computed. The load



(a) (b)

Figure 3: σ_1 distribution: (a) NASA - Run 425, (b) AERTS - Run 44



(a) (b)

Figure 4: Load factor versus iterations: (a) NASA - Run 425, (b) AERTS - Run 44

factor resulting at each step of the first iterations of this computation is reported in fig. 4 for both Run 44 and Run 425. As can be noted, it is much greater than 1. This suggests that the aerodynamic loads are not sufficient for a spontaneous crack propagation.

4. Conclusions

A multi-physics analysis tools for ice shedding was developed by coupling of the ice accretion framework PoliMIce with the FEM structural framework MoFEM. 2D ice accretion simulations were performed to validate the methodology. The values of flow pressure acting on the ice shape was used as forcing term for the elasticity analysis. The ice-airfoil interface was treated as a joint constraint in order to remove rigid body motions from the solution. Once the distribution of the stresses internal to the ice shape was obtained, the first principal stress distribution has been extracted. The region with highest first principal stress greater than zero is considered to initiate the crack surface. Crack propagation analysis is conducted through a thermodinamically consistent approach developed within the framework of MoFEM. The resulting load factor was studied to detect crack propagation. For both considered test cases, the load factor was far greater than 1, thus resulting in no shedding. This result is in agreement with the experimental evidences. Further developments could include the investigation of different boundary conditions applied to the ice-airfoil interface for a better simulation of the adhesion phenomenon. Due to the presence of non-smooth ice shapes, a not-steady CFD computation should be considered to assess the influence of an unsteady pressure distribution.

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