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Numerical simulation and modeling of ice shedding: Process initiation

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ABSTRACT

In aeronautics, the issue of ice shedding prediction is of prime importance in the assessment of electro-thermal ice protection systems. In this paper, an ice shedding mechanism based on pressure redistribution in the water film formed at the ice/airfoil interface is proposed. This pressure distribution induces a stress concentration that leads to crack propagation in the ice. To determine whether this mechanism is relevant or not, two numerical experiments are performed. The results of these numerical experiments and the influence of a few material parameters are discussed, as well as their limitations and possible consequences arising from some of the hypotheses.

The numerical modeling is based on recent works on damage/fracture mechanics which provide a general framework for fracture mechanics computation. The effects of numerical parameters and mesh size are discussed. A mixed mode test case based on experimental data is also performed. This test case had not been attempted before on this particular numerical method, which therefore serves as further validation.

1. Introduction

In typical flight icing conditions, the water droplets contained in clouds are in a supercooled state. When an aircraft encounters such conditions, those droplets freeze upon impacting its surface, therefore leading to ice build-up. In the aeronautical world, icing is one of the most serious threats that can be encountered. Not only does it increase mass but it may also lead to a degradation of aerodynamic performances, blocked air intakes (among other undesirable consequences).

Aircraft manufacturers must therefore comply with certifications and regulations regarding flight safety in icing conditions. In order to achieve that goal, several ice protection technologies may be used. One commonly used is the "bleed-air" system: hot air is taken from the engines and blown onto the protected surface, as shown in Fig. 1.

However, this system is energy-greedy, and in the context of "more electric" aircraft and reduction of fuel consumption, new systems are being investigated. One of these systems is the electro-thermal ice protection system (ETIPS). This system is composed of heater mats installed within a multi-layered material and can be used in anti-icing or deicing configurations [2,3].

The nominal functioning of an ETIPS in de-icing mode is as follows (illustrated in Fig. 2): A region called the parting strip, usually located around the leading edge (for example the region corresponding to heater C), is constantly protected from ice accretion. More precisely, the corresponding heater mat is in anti-icing mode. The other heaters are activated according to a given cycle. Thus ice accretion is permitted in regions other than the parting strip. When a heater mat is activated, it melts a part of the ice in contact with the surface, creating a liquid water film and therefore lowering ability of the ice block to adhere to the surface. The aerodynamic forces are then able to detach the ice block (or part of it) from the surface.

In order to assess the performance of such a system, it is essential to understand the mechanisms by which the aerodynamic forces manage to detach the ice. The current state of the art in icing codes is an empirical criterion. It states that, if the length of the liquid water film has a sufficient length (typically 80% of the whole contact length), then the ice block detaches [2]. However such an empirical criterion is unsatisfactory. Therefore, to obtain more physical ice shedding models, a better understanding of the detachment process is needed.

In this paper a mechanism that could play a crucial role in the process of detachment of the ice block (from the protected surface)

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Nomenclature

α	angle of attack (°)
ϵ	strain
λ, μ	Lamé coefficients (Pa)
$\mathcal{H}$	history function (J m^{-3})
ν	Poisson's ratio
ϕ	porosity
d	damage variable
d_{grain}	grain size (m)
E	Young's modulus (Pa)
E_{crack}	crack energy (J)
E_{el}	elastic energy (J)
g_c	energy release rate (J m^{-2})
h	mesh element characteristic size (m)
h_{fp}	thickness of the flat plate (m)
K_{IC}	fracture toughness (Pa $\sqrt{m}$)
L_{fp}	length of the flat plate (m)
L_f	length of melted region between ice and protected surface (m)
L_t	total contact length between ice and protected surface (m)
P_∞	freestream pressure (Pa)
P_c	contact point between melted region and airflow (m)
$p_{exterior}$	exterior pressure distribution (Pa)
$p_{redistributed}$	redistributed pressure (Pa)
T	temperature (K or °C)
T_∞	freestream static temperature (K)
u	displacement (m)

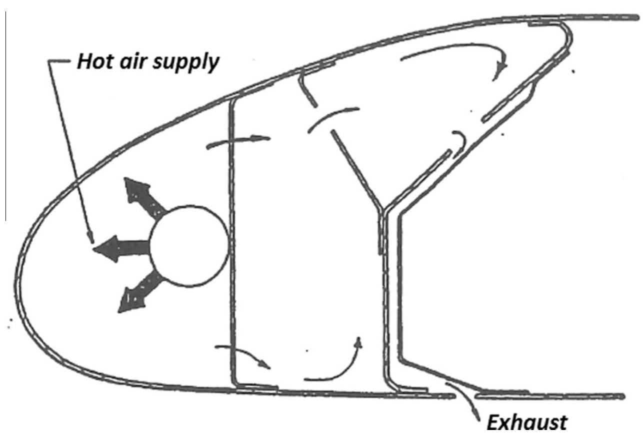

Fig. 1. Illustration of a bleed air system [1].

is presented. First, the proposed detachment mechanism is presented. Then, the modeling and numerical techniques used in this study are introduced. This will be followed by a parameter identification and validation against experimental data. After that numerical experiments are presented and performed. Finally the results are discussed.

2. Proposed mechanism

Let us consider a situation as depicted Fig. 3, where ice has accreted just after the parting strip. The contact zone between the ice and the surface extends over a curvilinear distance, say L_t. The proposed mechanism is based on two observations. Firstly, the flow over such a shape will induce pressure variations over the lump. Fig. 4 depicts a typical pressure distribution. Secondly, due to the ETIPS, a certain amount of ice in contact with the surface has melted. This leads to the creation of a thin film of liquid water extending over a distance L_f. A contact point, P_c, exists between the external flow and the film. The pressure at this point will be entirely redistributed by the film over the length L_f due to the absence of motion in the liquid water film[1] (hydrostatic pressure equilibrium). The presence of the ice shape will cause an acceleration of the flow when passing over it, which decreases pressure at the same time. This means the pressure recovered in the film will be higher than that acting on the external surface.

This pressure distribution creates a lifting force. To this force, one has to add the viscous forces, which are tangential. Thanks to these forces several outcomes may be possible:

- The whole length is melted ($L_f = L_t$) in which case the ice no longer adheres to the surface (or only by means of surface tension effects).
- *Adhesive break*: part of the length $L_f = x\%L_t$ is melted and the adhesion forces that maintain ice on the surface are no longer strong enough.
- *Brittle failure*: part of the length $L_f = x\%L_t$ is melted, ice can still adhere, but a crack may nucleate due to stress concentration and propagate through the ice, therefore tearing off a part of it.
- *Cohesive break*: part of the length $L_f = x\%L_t$ is melted, ice can still adhere, but a crack may nucleate due to stress concentration and propagate along the ice/protected surface interface.
- Ice shedding is due to a combination of the above possibilities.

The mechanisms leading to ice shedding are to this day not well understood. Experimental observation shows that brittle failure plays a crucial role. Hence, as a first approach to the problem, the present study is confined to the third possibility presented above, concerning brittle failure. To do so, a crack nucleation and propagation model is required. This implies knowledge about the mechanical properties of atmospheric ice.

3. Properties of atmospheric ice

One of the main problems that arises is to determine what mechanical properties are going to be used in order to characterize atmospheric ice. Unfortunately, very few studies on the subject exist. Most studies are interested in the tensile or compressive strength but do not provide many information on mechanical characteristics in the form of well defined laws [4–6]. These experiments are very difficult to conduct due to the vast number of parameters on which those properties depend, making the issue all the more complicated. For example, Eskandarian [7] reports a determination of Young's modulus and Poisson's ratio for porous ice.

Therefore, as a first approach, data and empirical laws given by experiments for natural ice are used as a starting point. These laws are more precise, and more widely studied. Nevertheless, they

[1] In fact, as liquid water takes up less volume than ice, a gap may form in the melted region. That is to say, the water film may not entirely occupy the volume formerly made out of ice and air may be allowed to fill in the gap. However, we would still be in a case of hydrostatic pressure equilibrium. Therefore pressure redistribution would still occur as described.