3D modeling of in-flight ice break-up

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Abstract In order to reduce the danger of impact, ingestion, or vibrations caused by the break-up of ice accreted in-flight, it is important to analyze the conditions for cracking and eventual break-up, the shape of shed ice and its trajectories In this paper, we will present a 3D finite element method (FEM) to predict the shed ice shape, by using a fluid-solid interaction (FSI) approach to determine the loads and linear fracture mechanics to track crack propagation. A multiscale method is used to predict the crack's initiation. Various icing scenarios for helicopters are analyzed, and the possibility of ice break-up is investigated.

INTRODUCTION

With greatly expanded operations and increasingly broad range of tasks for modern helicopters, awareness of the hazards associated with in-flight icing has become important. Traditionally, researchers have focused their attention on icing effects on lift, drag, weight and thrust, while the hazards of in-flight ice break-up shedding is rarely addressed analytically. In-flight ice shedding is extremely important for helicopters, as ice break-up and shedding could create extremely severe vibrations of the rotor blades due to asymmetry, strike the fuselage and tail rotor or, worse, find its way into the engine. Hence, research on ice shedding is vital to the safety of helicopters.

Figure 1. In-flight icing: phenomenology

Ice shedding from helicopters involves four phases: ice detachment from the blade surface, rotor blade imbalance and vibration after ice release, tracking of the piece of ice as it is carried through the flow field, and the subsequent impact forces on solid surfaces. The first phase actually provides the initial conditions for the tracking phase. The impact phase obviously results from the terminal conditions of the tracking phase. However, each phase can be treated separately. This study is aimed at modelling ice-breakup under the influence of aerodynamic forces and two body forces, namely centrifugal force and gravity. Advances in FEM and fracture mechanics now allow analyzing crack generation and growth. While the fundamental rules for crack propagation come from fracture mechanics, FEM modelling makes it possible to handle complicated three-dimensional geometries.

In this study, ice is generated from the state-of-the-art icing code FENSAP-ICE [1, 2], based on typical icing conditions. The interaction of ice and flow field is considered as a fluid-structure interaction (FSI) problem and the pressure of the flow field is considered as a Neumann boundary condition, as shown in figure 2. The centrifugal force is calculated from the rotor blade's rotational speed and a three-dimensional fracture mechanics FEM code is developed to analyze crack propagation inside the ice. In this fracture mechanics code, quarter-point elements are used to capture the singularity around the crack tip and the stress intensity factor is obtained by a displacement correlation method. Anisotropic mesh adaptation is employed to adjust the mesh in the domain for a better resolution of the stress distribution in the vicinity of cracks. In order to capture the effect of microstructure of ice to crack initiation, a predictive multiscale framework for modelling the behaviour of ice is used.

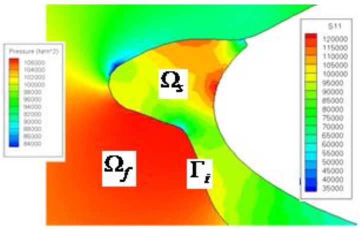

Figure 2. Fluid pressure and the induced stress in ice

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THEORY AND METHODOLOGY

Employing linear elasticity equations, along with the appropriate boundary conditions, performs stress analysis. According to mechanical properties of ice, the region with the highest principle tensile stress and highest Von-Mises stress are vulnerable to crack initiation. Ice is regarded as a polycrystalline material and the micro-cracks between grain boundaries plays a major role in crack initiation. Hence, a multiscale modelling approach based on a two-scale decomposition of the displacements has been employed to obtain the initial crack. For crack propagation, the direction is based on the Maximum Hoop Stress Criterion [3]:

$$\sigma_{r\theta} = \frac{K_I}{\sqrt{2\pi r}} \sin\frac{\theta}{2}\cos^2\frac{\theta}{2} + \frac{K_{II}}{\sqrt{2\pi r}}\left(\frac{1}{4}\cos\frac{\theta}{2} + \frac{3}{4}\cos\frac{3\theta}{2}\right) \tag{1}$$

The value of $\sigma_{r\theta} = 0$ when the Hoop Stress is maximum. According to the theory, a crack will kink into the direction normal to the maximum hoop stress. So the crack tip propagates in the direction where $\sigma_{r\theta}$ is zero. Substituting $\sigma_{r\theta} = 0$ into Eq. 1 we get:

$$\theta = 2\arctan\frac{1}{4}\left[\frac{K_I}{K_{II}} - sign(K_{II})\sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8}\right] \tag{2}$$

The quarter point elements are used around the crack tip. Using the displacement correlation method, the stress intensity factors are then calculated.

NUMERICAL RESULTS

2D analysis reveals that ice could break under the influence of aerodynamic forces, as shown in figure 3.

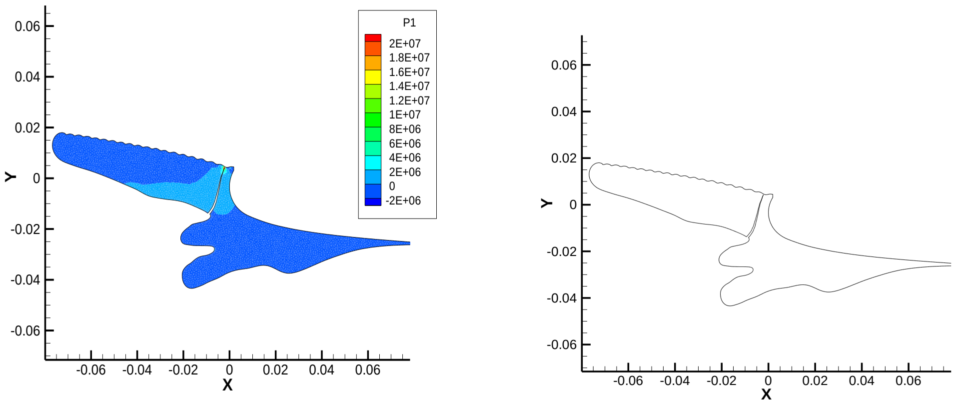

Figure 3. Solid (ice) domain: principal stress 1 (left) and cracked ice (right)

We are incorporating the effects of centrifugal force and gravity, along with the aerodynamic forces, into the 3D ice break-up model, and the results for the helicopter blades are considered work in progress.

CONCLUSIONS

Employing a fracture mechanics approach, a three-dimensional FEM code is developed for in-flight ice break-up. Ice on 3D helicopter blades is analyzed under various flow and icing conditions. By virtue of these analyses, the exact location of ice initial cracking, the crack propagation and the shedding ice shape and mass are obtained. In our future work, the ice break-up methodology will be coupled with rotor blade vibration analysis, and ice shedding trajectory and impact simulations.

References

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