39th European Rotorcraft Forum
3-6 September, 2013, Moscow, Russia
Session: Aerodynamics

ICE BREAK-UP, SHEDDING, AND IMPACT ANALYSIS FOR HELICOPTERS

[1]Rooh A. Khurram and [2]Naeem-Ur-Rehman Minhas

1: Supercomputing Laboratory, King Abdullah University of Science and Technology (KAUST) Thuwal, Saudi Arabia
2: Physical Sciences and Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia

A fluid-structure interaction (FSI) problem of interest is the break-up of ice accreted on the rotor blades of helicopter. Interest in ice shedding involves its three phases: ice detachment from the surface, tracking of the piece of ice as it is carried through the flowfield, and the subsequent impact forces if it hits a solid surface. We present a 3D finite element method (FEM) to predict the shed ice shape by using an FSI approach to determine the loads and linear fracture mechanics to track crack propagation. The mass and shape of shed ice is calculated for a typical icing condition. Furthermore, results of the trajectories of the ice shed are also presented. These calculations provide initial conditions for the subsequent impact analysis. Qualitative and quantitative impact analysis of shed ice on target consisting of aluminum, carbon fiber reinforced plastic (CFRP), glass, and human skull are performed. The results show that the shed ice will cause: significant damage to aluminum and CFRP, shattering of glass windows, and fatal trauma to human skull.

1. INTRODUCTION

In recent years, several helicopter accidents have been caused by ice accretion on helicopter structural components. On Dec. 10, 2012, a 1992 BK117A3 operated by Air Methods for React crashed near Rochelle, Illinois, en route to a patient pick-up after encountering instrument meteorological conditions (IMC). Then, on January 2, 2013, a Bell 407 flying for Mercy Air and operated by Med-Trans crashed while flying visual flight rules (VFR) near Mason City, Iowa, en route to a patient pick-up, killing the pilot and two flight paramedics aboard. Conditions at the time of the evening crash were reported as overcast with a temperature of 27°F.

The formation of ice over the rotor of helicopter deteriorates aerodynamic performance and can result in shedding chunks of ice that could impact the helicopter or, worse, impact nearby buildings and personnel during any low flying operations. The overall process of ice accretion, break-up, shedding, and impact, is shown in Figure 1.

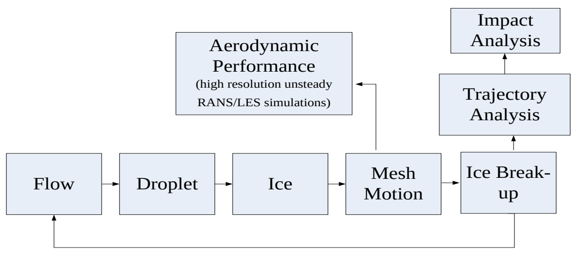

Figure 1: In-Flight icing procedure

In-flight ice accretion is performed using FENSAPICE[1]. Ice break-up analysis is conducted by employing linear elastic fracture mechanics (LEFM) approach[2,3]. Trajectory analysis can be performed by: conventional Arbitrary Lagrangian-Eulerian (ALE) approach[4], overlapping grid strategy - boundary-fitted grids are used near the boundaries while background Cartesian grids are used to handle the bulk of the domain[5], level set approach[6,7], Monte Carlo based technique[8], or 6-dof equation of motion[9].

Various attempts have been made to analyze the effects of ice impact on different materials. Both experimental and numerical results can be found in the literature. Carney et al.[10] developed and tested a phenomenological failure model for simulation of a high velocity impact of ice. They found that the load exerted on a steel plate by an ice piece travelling at 213 m/s was 11 kN. Combescure et al.[11] analyzed the high velocity impact of ice on aluminum (Al) plates. Their results showed that maximum damage was caused by a cone shaped projectile hitting the Al-plate head-on whereas a projectile hitting the plate at an angle had cracks that penetrated through the ice cylinder starting from the point of contact. This proves that the shape of projectile is indeed important. They measured the penetration of projectiles into Al-plates. They found that a cylinder travelling at 60 m/s will cause a dimple of 6mm in the Al plate.

Rymer et al.[12] looked at the effects of hail ice impact on (Carbon Fibre Reinforced Plastic) CFRP. They analyzed the damage caused by hail ice of various diameters and velocities on the CFRP panels of different thicknesses. They found that a 50.8 mm diameter hail of ice will have sufficient energy (400 J) to cause damage to a 16 layered (3.11mm thick) panel of CFRP.

The main objective of the paper is to describe the mathematical and numerical framework of the full process, from the ice accretion to the impact analysis, thus directly linking atmospheric conditions during flight, such as: ambient temperature, liquid water content (LWC), and droplet mean value diameter (MVD); to the damage caused by the detached ice pieces onto various objects in the vicinity of the helicopter.

2. IN-FLIGHT ICING

The simulation of in-flight icing is performed using FENSAP-ICE[1,2]. It is a CFD package that solves the Navier-Stokes equations, the droplet impingement equations and the ice accretion model, in sequence. The icing simulation consists of three main parts. The flow around the blades is first determined using CFD; supercooled droplets impact is then evaluated to obtain the distribution of water impinging on the surface; finally, a thermal analysis of the air-water-body system is performed to determine ice growth.

Caradonna hover test[13] case has been used for the flow solution. The rotor has two untwisted and untapered blades consisting of the NACA 0012 airfoil section with a rotor radius of 1.143 m and an aspect ratio of 6. The flow and droplet solutions are computed in rotational reference for the rotor speed of 400 rpm and collective pitch angle of 8 degree. Ice accretion also modeled in rotational reference at ambient temperature of -19°C, liquid water content (LWC) of 1 g/m3 and droplet mean value diameter (MVD) of 20 microns. The turbulence model is the one-equation Spalart-Allmaras model and the total ice accretion time is 120 seconds. Figure 2 shows the ice accumulation on the blades. For further information of this simulation the readers are referred to our earlier work[2].

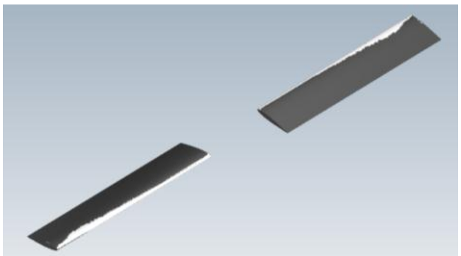

Figure 2: Ice accretion of helicopter blades[2]

3. ICE BREAK-UP

The interaction of ice and flow field is considered as FSI and the pressure of the flow field is considered as a Newman boundary condition. Centrifugal force is calculated from the rotor blade's rotational speed and a three-dimensional fracture mechanics code based on FEM is employed to analyze crack propagation inside the ice. Detailed description of the break-up analysis can be found from earlier work[2,3]. The cracked ice shape is shown in Figure 3.

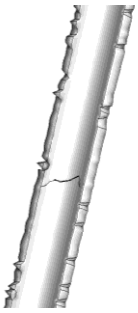

Figure 3: Ice break-up[2]

The output of this step is the shape and size of the shed ice. It should be noticed that the abovementioned analysis were conducted on a scaled model[2]. Considering the rotor blade length to be 7m, the scaled mass and velocity of the broken-off ice piece are 7.68 Kg and 245 m/s, respectively. However, during the detachment of big chunk of ice, it is likely that it will break into several arbitrary shaped and sized pieces. For simplicity the mass of a single ice chunk is assumed to be 1 Kg for all subsequent calculations.

4. TRAJECTORY OF BROKEN-OFF ICE

Trajectory of shed ice can be simulated by employing various numerical strategies by considering two-way coupling of ice pieces and the flow around the helicopter. Arbitrary Lagrangian-Eulerian[4] approach can be used for such analysis. Overlapping grid based techniques[5] can be more effective in simulating ice motion in the flow. In the current analysis, point of impact is not of much significance; rather the incident energy of impact is required for the subsequent damage analysis. Therefore a simple 1D equation of motion is considered for the calculation of the initial conditions for damage analysis. The effect of shape is implicitly taken into account by varying the drag coefficients (Cd). This has to be noted that these simplifications will not be valid for ice trajectory analysis of ice detached from the wings of an aero plane, where the engine ingestion is investigated.

The forces acting on the shed ice include the momentum of the ice piece, aerodynamic forces, and gravity. For simplicity, only drag force is considered. The variation of shape of ice is taken into account by varying the drag coefficient, which varies from 0.5 to 1.5 for 3D arbitrary shaped bodies[9]. The drag force is calculated using the equation given in (1).

(1) $$c_d = \frac{2F_d}{\rho v^2 A}$$

where F_d is the drag force, ρ is the density of air which is 1.29 Kg m^{-3} at 0°C, v is the free stream velocity of the air relative to the ice, and A is the reference area of the object. Reference area of the shed ice piece is calculated as 0.01 m^2, based on a cylindrical shape of ice with the mass of 1Kg with length to diameter ratio (L/D) of 1.

The contour plot in Figure 4 shows how the velocity of the ice piece varies with the distance travelled as the drag coefficient, Cd and distance between rotor tip and target varies. As predicted, it slows down with distance however a piece of ice with the drag coefficient of 1.5, still travels with the velocity of around 37 m/s, even 50 meters away from the rotor blade tip.

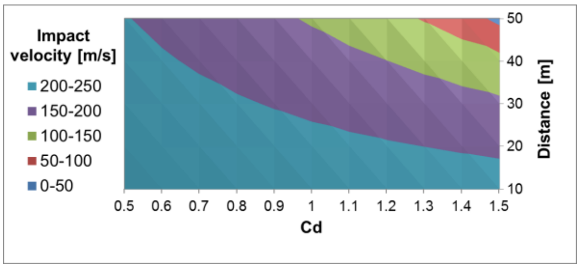

Figure 4: Impact velocities as a function of distance from the detachment point and Cd.

5. IMPACT ANALYSIS

5.1Qualitative analysis

This broken-off ice travelling at high velocities has the potential to cause damage to the property and humans. The severity of the damage depends on the velocity, impact energy, and the properties of ice as well as the properties of the target material.

The contour plot in Figure 5 shows the kinetic energies of the incident projectiles at the point of impact with the target as a function of distance and Cd.

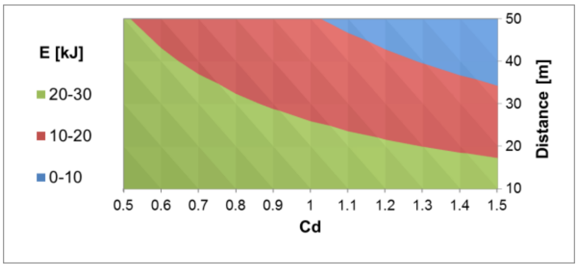

Figure 5: Kinetic energy of the projectile as a function of distance from the rotor blade and drag coefficients.

The effect of impact of ice on window glass, aluminium, Carbon fibre/epoxy, and human skull are analysed.

Combescure et al.[11] demonstrated that a small 7 gram cylindrical ice “bullet” travelling at around 60 m/s with the total kinetic energy of around 12.6 Joules caused a dimple in the aluminum plate. The ice piece with the range of energies (up to 30kJ) considered in this study will cause serious damage to the aluminum structures.

Rhymer et al.[12] looked at the damage caused by hails on a carbon/epoxy composite. They employed both experimental techniques as well the modeling approach to analyze the damage caused by hails. They used a vacuum gun to shoot hails onto composites and then recorded the impact with high-speed camera. They analyzed the damage in the composites using various non-destructive imaging and analysis techniques. They found that a 24-layered carbon/epoxy panel suffered serious damage when the energy of an impacting hail ice was around 1 kJ. Again, the energies carried by the shed ice from the helicopter blade are a lot more than the energy that caused damage in the hail conditions.

Zhang et al.[14] found that a 3mm thick sheet of glass plies laminated by 1.88 mm PVB interlayer will fracture if the impact energy is above 400 J. In our case, with energies in the kJ range, ice will certainly shatter glass windows.

Delye et al.[15] investigated effect of impact on human skull. Their work suggested that the frontal loading failure energy of a human skull is in the range of 22-24 J. Again, ice shed from typical helicopter blade will cause fracture to human skull.

5.2 Quantitative Analysis

Various models[16,17] have been proposed to establish whether a particular material travelling with a particular amount of velocity will cause failure or not. In our analysis we adopt the methodology proposed by Rubin and Yarin[16]. They proposed a two-staged mathematical model for calculating penetration depths of projectiles into the targets with infinite thickness. There assumption was that in the first stage, the projectile gets eroded away where some rigid tale survives. This surviving tale penetrates further into the target in the second stage of penetration. In the present case the second stage is neglected. The formula given in (2) describes the single stage penetration:

(2) $$P = \left[\frac{U}{V_0 - U}\right] L_{er}$$

where P is the penetration depth, U is the velocity of the front end of the projectile during penetration, V_0 is the initial impact velocity of the projectile which is calculated in the trajectory analysis (Figure 4) and L_{er} is the size of projectile eroded away during the penetration process.

(3) $$L_{er} = (L_0 - \ell_0)\left[1 - exp\left\{-\frac{\rho_{P(V_0-U)^2}}{2Y_P}\right\}\right]$$

Where L_0 (0.113 m), ρ_P (874 kg m^{-3}), and Y_P (1MPa) are total length of projectile, density and Yield stress of ice, respectively. ℓ_0 is a constant which is given as:

(4) $$\ell_0 = \frac{\sqrt{3}(\sqrt{2}-1)d_0}{2}$$

Where d_0 is the diameter of the projectile, which in this case is 0.113 m. U can be calculated by solving Bernoulli's equations which depends on the initial impact velocity and the densities of both projectile and target materials.

(5) $$U = \frac{V_0}{1+\alpha}$$

(6) $$\alpha = \left[\frac{\rho_T}{\rho_P}\right]^{1/2}$$

where ρ_T is the density of the target material which were taken as 2700, 2400, 1600, and 1200 Kg m^{-3} for aluminum, glass, carbon/epoxy and bone of skull respectively.

The model is verified by using the experimental data from Combescure et al.[11] The results of experiments and the numerical model are compared. The data from their experiment (case YEP03) is taken and experimentally measured penetration depth is compared with the calculated penetration depth. The penetration depths turned out to be around 5mm, which is very close to the experimentally measured penetration depth of 5.94 mm for a 25.5 mm cylinder with the initial contact velocity of $60ms^{-1}$. The densities of ice and aluminum plate were taken to be 0.874 g cm^{-3} and 2.4 g cm^{-3} respectively. This model was then applied to aluminum, window glass, CFRP, and human skull. The penetration depths are calculated at different velocities. The effects of shape are also considered by varying the Cd between 0.5 and 1.5. Figures 6-9 show the penetration depths of ice in Aluminum, Glass, CFRP and human skull as a function of distance from the rotor blade of helicopter and drag coefficients, respectively. The penetration depth increases with reduction in distance from the rotor blade and Cd. The highest penetration is calculated for human skull and the lowest penetration depth is for aluminum. The minimum penetration of ice into an Al plate with the Cd of 1.5 at 50 m distance is 9.2 mm whereas it is 10.2 mm for human skull.

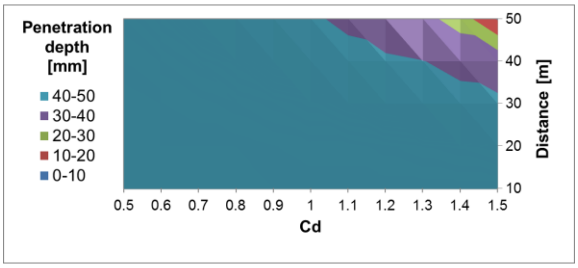

Figure 6: Penetration depth in aluminum as a function of distance from rotor blade and drag coefficient.

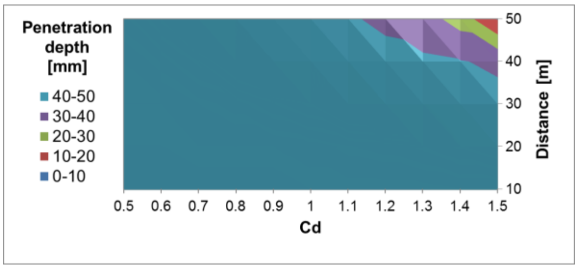

Figure 7: Penetration depth in glass as a function of distance from rotor blade and drag coefficient.

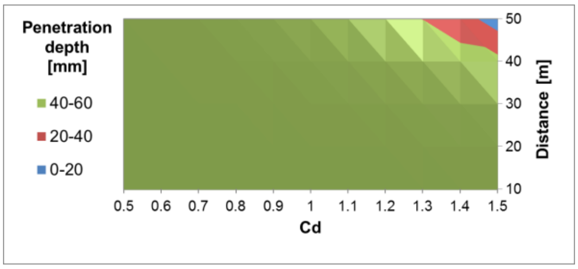

Figure 8: Penetration depth in Carbon/Epoxy as a function of distance from rotor blade and drag coefficient.

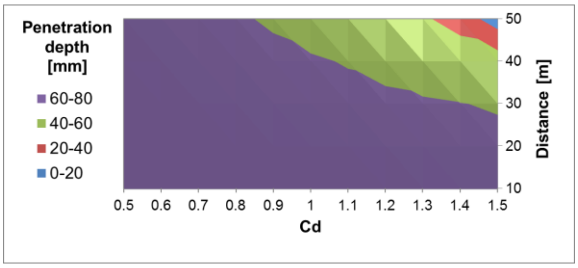

Figure 9: Penetration depth in human skull as a function of distance from rotor blade and drag coefficient.

The differences in the penetration depths in these four materials are minor however; the effects of this penetration will be different depending on the yield stress, fracture toughness, and modulus of these materials. Aluminum, for example, is more likely to deform plastically as a result of this impact whereas glass is more likely to shatter.

It can be seen from Figure 10 that the penetration depth of various materials drops mildly with increasing distance from the rotor blade of helicopter.

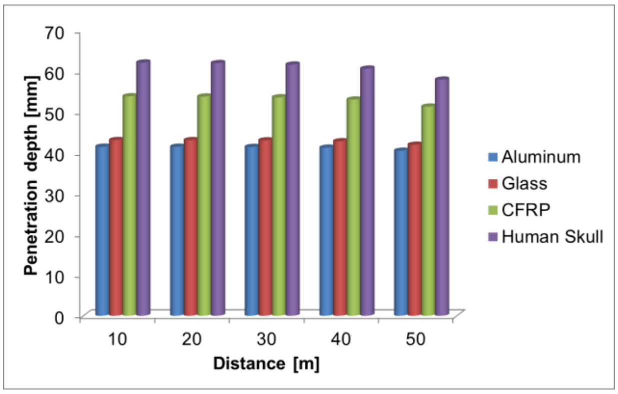

Figure 10: Penetration depths of ice cylinder in various materials as a function of distance. The data is taken for a Cd of 1.

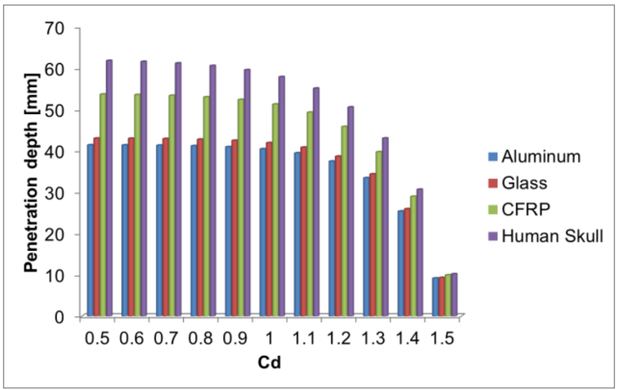

Figure 11: Effect of shape of ice on the penetration depths in various materials. Blunt shapes have lower penetration depths 50 meters away from the tip of rotor blade tip as compared to stream lined shapes.

However, the effects of shape on the penetration depth in various materials as seen in Figure 11 are much more profound. This again shows the importance of determining the correct shape of the shed ice. This is the topic for further investigation.

6. CONCLUSIONS

A 3D finite element method (FEM) is employed to predict the shed ice shape by using LEFM approach. The mass and shape of ice detached from the helicopter blades is calculated. By passing more computationally intensive two-way couple trajectory analysis, simple trajectory calculations are presented for the evaluation of correct initial conditions for the impact analysis. It is concluded that the detached ice from the rotor blade pose serious threat to the structural components of helicopter. In a low flying operations under icing conditions, shed ice can cause structural damage to the civil infrastructure and fatal trauma to humans.

The trajectory and impact analysis are based on numerous assumptions. The main scope of the present study is to perform preliminary evaluation of the merits in conducting an in-depth mathematical and numerical study. In the future study we will attempt to provide the answer to the key questions: how far we are from a full scale coupled 3D simulation of ice accretion, high resolution unsteady RANS/LES simulation for aerodynamic performance degradation analysis, ice break-up, ice shedding, and the damage caused by the impact of ice on the various targets?

Acknowledgements

Authors would like to acknowledge the encouragement and financial support of Professor Talaat Al-Kassab, Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, Saudi Arabia.

REFERENCES

[1] W.G. Habashi, Advances in CFD for in-flight icing simulation, Journal of Japan Society of Fluid Mechanics, Vol. 28, No. 2, pp. 99-118, 2009

[2] Z. Shiping, O. Kerdi, R. A. Khurram, W. G. Habashi, Finite element method for ice break-up during in-flight icing on aircraft wings, Finite Elements in Analysis and Design, Volume 57, Pages: 55–66, 2012

[3] Z. Shiping, R. A. Khurram, H. Fouladi, W. G. Habashi, Computational modeling of ice cracking and break-up from helicopter blades, AIAA 2012-2675, 42nd AIAA Fluid Dynamics and Co-located Conferences and Exhibit, New Orleans, 25 - 28 June 2012

[4] A. Masud, M. Bhanabhagvanwala, R. A. Khurram, An adaptive mesh rezoning scheme for moving boundary flows and fluid–structure interaction, Computers & Fluids 36 (2007) 77–91

[5] D. Appelo, J. W. Banks, W. D. Henshaw, D. W. Schwendemanc, Numerical methods for solid mechanics on overlapping grids: linear elasticity, J. Comput. Phys., (231):6012-6050, 2012

[6] R. Yapalparvi, H. Beaugendre, F. Morency, Calculation of ice chunk trajectory using proper orthogonal decomposition, 4th AIAA Atmospheric and Space Environments Conference AIAA 2012-2676, 2012

[7] F. Morency, H. Beaugendre, F. Gallizio, Aerodynamic force evaluation for ice shedding phenomenon using vortex in cell scheme, penalisation and level set approaches, International Journal of Computational Fluid Dynamics, Vol. 26, Iss. 9-10, 2012

[8] Deschenes, J., Baruzzi, G., Lagace, P., and Habashi, W., FENSAP-ICE: A CFD Monte Carlo approach to shed-ice trajectory and impact, SAE Technical Paper 2011-38-0089, 2011

[9] J. Jacob, Experimental and computational aerodynamic analysis of ice fragments shed from aircraft surfaces, Ph.D. thesis, University of Mysore, India, 2001

[10] K. S. Carney, D. J. Benson, P. DuBois, R. Lee, A phenomenological high strain rate model with failure for ice, International Journal of Solids and Structure, Vol. 43, pp. 7820-7839, 2006.

[11] A. Combescure, Y. Chuzel-Marmot, J. Fabis, Experimental study of high-velocity impact and fracture of ice, International Journal of Solids and Structures, Vol. 48, pp. 2779-2790, 201

[12] J. Rhymer, H. Kim, D. Roach, The damage resistance of quasi-isotropic carbon/epoxy composite tape laminates impacted by high velocity ice, Composites: Part A 43, pp. 1134-1144, 2012

[13] Caradonna, F. X., and Tung, C., Experimental and analytical studies of a model helicopter rotor in hover, NASA TM-81232, 1981

[14] X. Zhang, H. Hao, G. Ma, Laboratory test and numerical simulation of laminated glass window vulnerability to debris impact, International Journal of Impact Engineering, Vol. 55, pp. 49-62, 2013

[15] H. Delye, P. Verschueren, B. Depreitere, I. Verpoest, D. Berchkams, J. V. Sloten, G. Van der Perre, J. Goffin, Biomechanics of frontal skull fracture, Journal of Neurotrauma. Vol. 24, pp. 1576-1586, 2007

[16] M. B. Rubin, A. L. Yarin, A generalized formula for the penetration depth of a deformable projectile, International journal of impact engineering, Vol. 27, pp. 387-398, 2002

[17] M. J. Forrestal, B. S. Altman, J. D. Cardile, S. J. Hanchak, An empirical equation for penetration depth of ogive-nose projectiles into concrete targets, International Journal of Impact Engineering, Vol. 15, No. 4, pp. 395-405, 1994