A Methodology for Modeling the Effects of Icing on Rotary Wing Aerodynamics

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Abstract

A computational methodology has been developed for modeling the effects of ice accretion on a helicopter rotor in forward flight. The mythology is modular to allow for independent update of the individual modules as improvements to the underlying methodologies are made. This process requires software specialized for ice accretion, computational aerodynamics, grid generation, and rotor aeroelasticity. This methodology is exercised on three flights of the UH-60A BLACK HAWK in icing conditions. The computed torque rise compares favorably to the measured torque rise. Additional experimental data on blade ice shapes and sectional loads is needed to fully evaluate the methodology.

Introduction

Modeling rotorcraft icing phenomena requires integration of several disciplines and analyses including grid generators capable of modeling arbitrary ice shapes; flow solvers that can model unsteady flow over 2D and 3D configurations with supplied ice shapes; comprehensive analyses that can compute the elastic behavior of the blades and re-trim the rotor for a specified thrust, hub moments, and tip path plane angle; and ice accretion modeling analyses. Each of these modules should be independently validated, and the coupled analysis compared against test data. Work is also needed on improving the fundamental assumptions and approximations inherent in these models. These include improved methods for ice accretion analysis by modeling collection efficiency in 3D unsteady flows, improved heat transfer models for compressible flow with heated and cold surfaces, and improved models for transition.

Numerical Approach

Ice accretion on helicopter rotors is a process that depends on many physical variables – blade geometry, number of blades, operating conditions (thrust setting, hub moments, advance ratio, rotor RPM), ambient temperature, air pressure, liquid water content, and the time period over which accretion occurs. In the present study, these conditions were specified at the start of the simulation. The specific values and conditions chosen are discussed later in the paper.

The present approach is a multi-disciplinary methodology that involves aerodynamics, structural dynamics, rotor trim, ice accretion, and shedding. The overall methodology/process is shown in Figure 1. The individual pieces that form this collection of tools are discussed below.

LEWICE3D:

LEWICE3D is a grid-based ice accretion software analysis tool developed at the NASA Glenn Research Center that can interface with a variety of 3D computational solvers for computing ice shapes on three-dimensional external surfaces. The streamlines and ice particle trajectories are computed using the provided flow solution. The ice accretion analysis is done over the blade surface that is divided into 2D sections-of-interest. A 2D heat transfer module is used to calculate the ice growth along the streamline. LEWICE3D, developed for fixed-wing aircraft, and previous versions of LEWICE have been validated for a wide range of airfoils and icing conditions.[1,2]

Chimera Grid Tools (CGT)

Chimera Grid Tools is a package of numerous grid tools for use with the Graphical User Interface OVERGRID or with scripts developed at NASA Ames Research Center.[3] Various elements of the CGT toolset are used to automate the regeneration of the computational grid due to the changing blade surface.

Computational Fluid Dynamics (CFD)

Several different Navier-Stokes flow solvers have been used in this framework including OVERFLOW, TURNS, and GT-Hybrid. GT-Hybrid is used for these forward flight calculations.

GT-Hybrid is a three-dimensional unsteady viscous compressible flow solver that uses a free wake solver to model the effects of the rotor wake. The flow is modeled from first-principles using the Navier-Stokes methodology. The three-dimensional unsteady Navier-Stokes equations are solved in the transformed body-fitted coordinate system using a time-accurate, finite volume

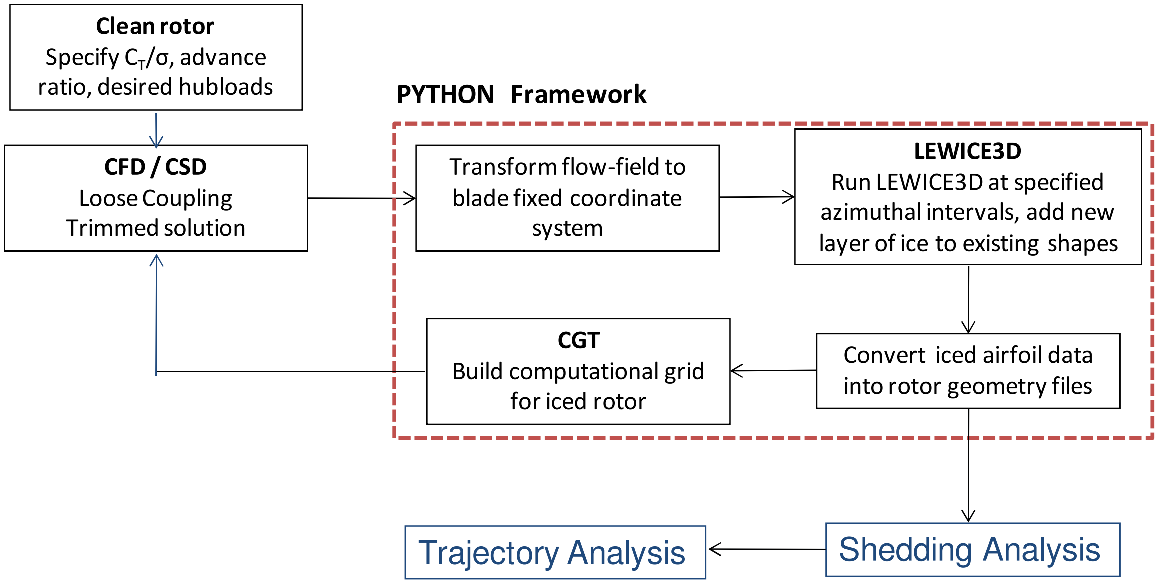

Figure 1. Overview of the Ice Accretion, Shedding and Trajectory Analysis

scheme. A third-order spatially accurate Roe scheme is used for computing the inviscid fluxes and second order central differencing scheme for viscous terms. The Navier-Stokes equations are integrated in time by means of an approximate LU-implicit time marching scheme. SA-DES turbulence model is used to compute the eddy viscosity. The flow is assumed to be turbulent everywhere, and hence no transition model is currently used.

A single blade is resolved in the Navier-Stokes domain. The influence of the other blades and of the trailing vorticity in the far field wake is accounted for by modeling them as a collection of piece-wise linear bound and trailing vortex elements. The near wake is captured inherently in the Navier-Stokes analysis. The use of such a hybrid Navier-Stokes/vortex modeling method allows for an accurate and economical modeling of viscous features near the blades, and an accurate "non-diffusive" modeling of the trailing wake in the far field.[4,5]

Because of the modular nature of the present coupling methodologies, either of these solvers (OVERFLOW or GT-Hybrid) may be used based on user's experience and preference. The CFD solver communicates with the icing analysis using standard PLOT3D format flow field and grid information. It communicates with the structural analysis using standard Fluid-Structure-Interaction files.

Computational Structural Dynamics (CSD):

In the present framework, any industry standard comprehensive analysis may be used that exchanges with the CFD solver the grid motion, grid deformation, and airloads in a predefined format. In the present study, DYMORE[6] is used. This is a finite element-based solver that is used for structural dynamics analysis. The solver can handle multi-body dynamics, and may be used for the analysis of complex geometrical configurations with arbitrary topologies. For example, each component in a rotor system including the blade, hinges, hub and pitch link may be modeled as separate elements, with their connectivity modeled as constraint equations. The rotor blades are modeled as elastic beams with a geometrically-exact composite beam finite element formulation. DYMORE is also considered a rotorcraft comprehensive solver because it provides an internal aerodynamic model and autopilot trimmer which may be used to do a trimmed aeroelastic rotorcraft analysis. The aerodynamic model is a lifting line-based analysis with table lookup of aerodynamic coefficients. A dynamic inflow model is used to compute the downwash.

CFD-CSD Loose Coupling Methodology:

Rotorcraft aeromechanical studies involve coupling the rotor aerodynamics with the structural dynamics of the system. The airloads computed by the CFD solver is used to drive a forced response simulation with the CSD solver. The computed structural deflections are used in the CFD analysis, leading to a change in the airloads. The two solvers are thus inherently coupled. The CFD-CSD coupling may be performed primarily in two ways – loose and tight. In tight coupling, the data is exchanged every time step of the simulation. In loose coupling, the data is exchanged between the two solvers at periodic intervals, typically once per revolution. Since loose coupling is driven by the inherent periodicity in the solution, it is used for analysis of rotors in steady flight conditions.

The coupling methodology framework is shown in Figure 1. Within the CFD/CSD process, the first step involves running the CSD code to compute airloads using its internal lifting line-based aerodynamic model. These airloads are applied on the rotor structural model to compute the elastic deformations. The CSD solver also trims the rotor to match the measured hub loads by adjusting the blade pitch controls. The periodic blade deformations obtained from this run are transferred to the CFD solver using a fluid structure interface. The CFD solver deforms the blade mesh and computes the periodic airloads, which are subsequently transferred back to the structural dynamics system. The loose coupling iterations are executed with the CFD and CSD solvers exchanging information once after every revolution until convergence is observed in hub loads obtained from the CFD solver and pitch controls obtained from the CSD solver.

Shedding and Trajectory Analyses:

Due to the large centrifugal force, large sections of the ice buildup may shed from the blade. Details of the shedding analysis are presented in Reference.[7] Once a piece has shed, it is of interest to compute its trajectory. Shed ice particles can impact the tail of the aircraft and cause damage. This additional analysis is being developed.

Results and Discussion

In the simulations presented here a multiple-step ice shape update process was used, meaning that LEWICE3D was invoked multiple times. Typically two icing updates were done. The calculations start with a CFD/CSD coupled analysis of the clean rotor to compute the airloads and the flow field. The flow field information at azimuth positions of 0°, 90°, 180°, and at 270° was supplied to LEWICE3D. At each of these azimuths LEWICE3D was run for a simulation time of one quarter of the total icing period for the current update.

For example, for the 76.2 case, the total ice accretion time was divided into two 150 second intervals. The ice build-up occurs at each of these four azimuth locations over a 37.5 second period. CFL3D uses the flow field at that location supplied by the CFD solver, transformed from an inertial frame to a blade fixed frame.

The LEWICE3D calculations were performed over the rotor one radial station at a time, marching from the blade root to the blade tip. After LEWICE3D has updated the ice shape, the grid was automatically regenerated using CGT. The CFD/CSD coupling analysis was repeated after each icing update period, to ensure that the iced rotor was retrimmed to meet target hub loads.

It should noted that the number of updates (equal to 2) and the azimuth locations where the ice shapes are computed (90, 180, 270, 360 deg for a total of four) were all arbitrarily chosen in this study. Further studies are needed to understand the sensitivity of the computed ice shapes to the number of updates and the number of azimuth locations where the ice shapes are computed.

Calculations have been completed for the three flight conditions, for which experimental data is available.[8] The present methodology was able to model these conditions in a robust manner without user intervention to adjust the flow parameters or ice shapes.

In these simulations, the drop diameter was 30 μm. For the 76-2 case, a 5.1% main rotor torque rise was predicted after 2.5 minutes, and the main rotor torque rise reached 5.7% after 5 minutes of accretion (see Table 1). This compares qualitatively well with the observed total aircraft torque rise of 6%. For the 76-3 case, the warmer ambient temperature led to smaller amounts of ice build-up. The predicted main rotor torque rise was 3.6% after 5 minutes, and was 4.4% after 10 minutes. For the 76-15 case, the combination of low ambient temperatures and increased liquid water content led to considerable build-up of ice. The computed main rotor torque rise was 13.4% after 2 minutes, and was 20.1% after 4 minutes.

While the torque rise is of the most interest from a performance point of view, the present analysis yields a wealth of information - instantaneous flow field over the rotor; surface pressure, skin friction, and heat transfer data; ice shapes; radial and azimuthal variation of sectional lift, drag, and pitching moments; structural loads and elastic deformations at the blade sections; vibratory loads at the hub; and pitch link load. These quanities may be anlayzed, and compared with test data, where available, to improve the modeling capability. A small subset of this data is discussed below.

Figure 2 shows the variation of the torque rise with azimuth, after ½ of the ice accretion time and at the end of the accretion time. The majority of the torque rise occus during the first half of the icing time. It is also seen that for the cases 76-2 and 76-3, most of the torque rise took place over the advancing side of the rotor disk. An examination of the sectional forces indicated that this is caused by the higher dynamic pressures (and associated total pressure) on the adancing side acting on the leading edge blunted by the ice build-up. In the 76-15 case, the ice build-up was large enough so that drag rise and sectional torque rise was significant over the entire rotor disk.

Figure 3 shows the ice shapes at a representative radial location (70% R) for the three cases at the end of the total accretion period. Cases 76-2 and 76-3 have a comparable ice build-up and torque rise. Case 76-15 leads to sizeable build-up due to the increased liquid water content.

The flow fieed has been examined to get additional insight into the ice accretion process and the associated torque rise. Figure 4 shows the Mach number contours for the 76-15 case at 75% R at 90 degree azimuth at the end of the ice accretion period. A large locally supersonic region is evident on the upper surface. More importantly, from a torque rise perspective, the blunted nose region gives rise to a large frontal area exposed to the highest local stagnation pressures. Additional flow seperation is also present behind the end of the ice shape on the upper and lower surface.

Table 1. Flight Conditions

Case/ Flight Number	Gross Weight kg	Advance Ratio	Static temp, deg C	LWC (g/ m^3)	Accretion Time, sec	Total Torque Rise Observed %	Main Rotor Torque Rise Predicted %
76-2	7080	0.208	-11	0.25	300	6	5.7
76-3	7120	0.208	-5.5	0.25	600	2	4.4
76-15	6890	0.208	-12	0.5	240	20	20.1

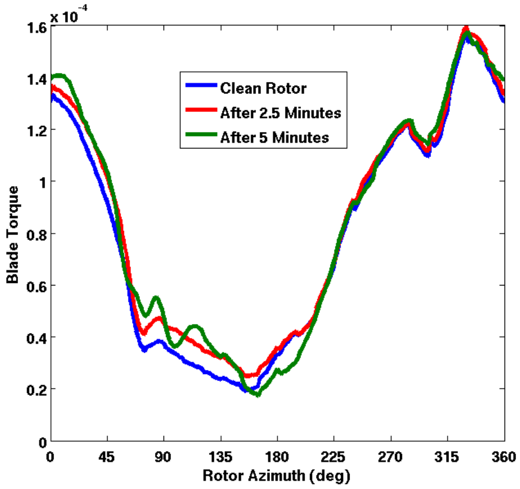

Figure 2a. Variation of Blade Torque with Azimuth (case 76-2)

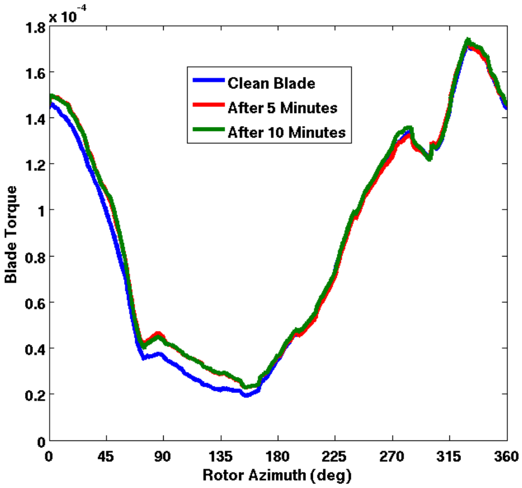

Figure 2b. Variation of Blade Toruqe with Azimuth (case 76-3)

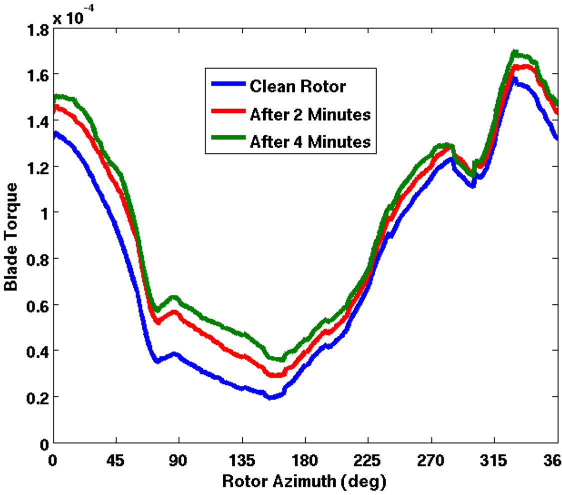

Figure 2c. Variation of Blade Toruqe with Azimuth (case 76-15)

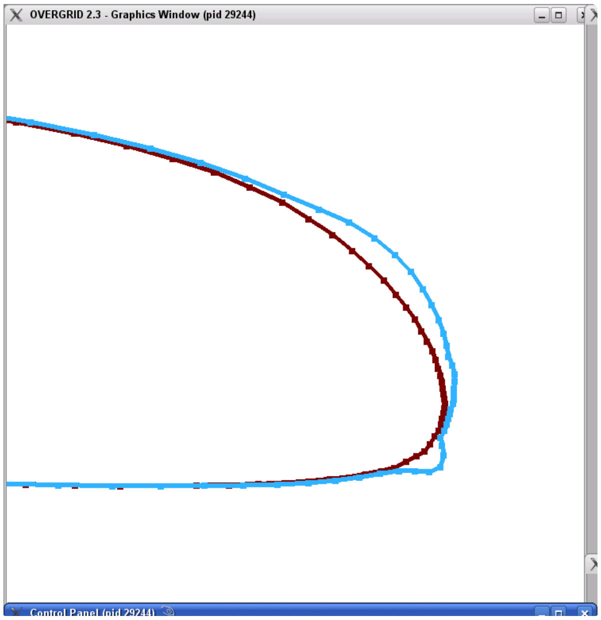

Figure 3a. Ice Shape at 70% radius at the end of Accretion period (Case 76-2)

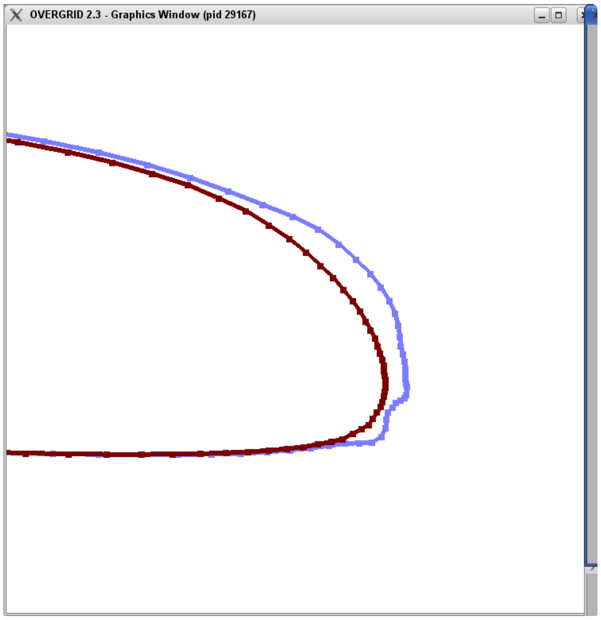

Figure 3b. Ice Shape at 70% radius at the end of Accretion period (Case 76-3)

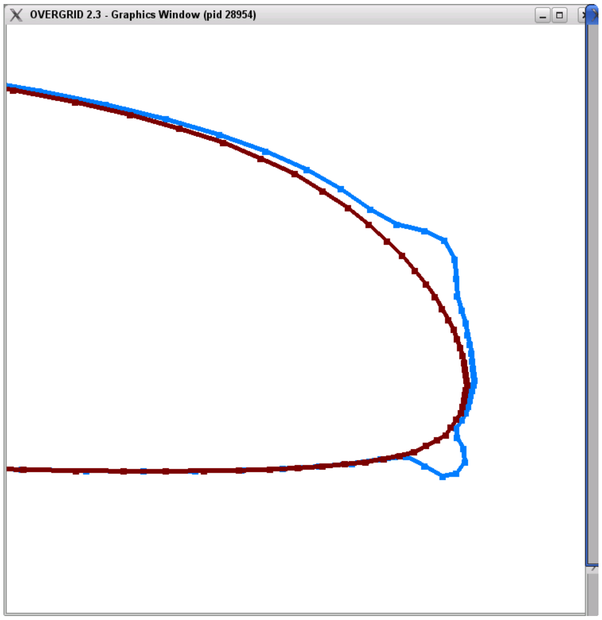

Figure 3c. Ice Shape at 70% radius at the end of Accretion period (Case 76-15)

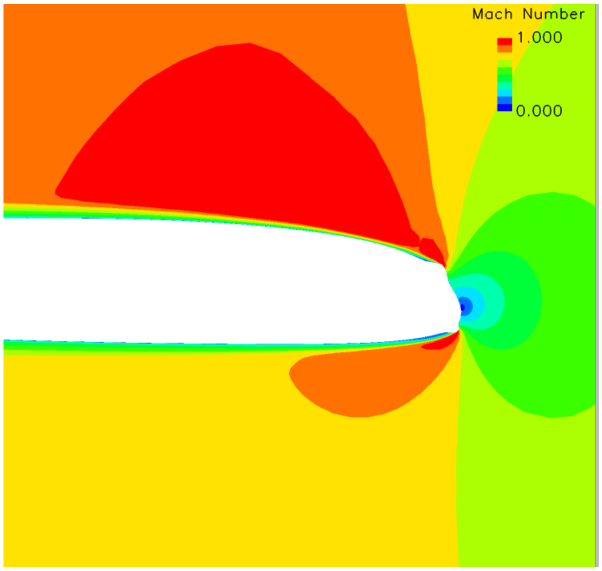

Figure 4. Mach Number Contours (Case 76-15, 75% Radius, 90 degrees azimuth, 240 sec of total accretion

Concluding Remarks

An integrated tool set, made of Computational Fluid Dynamics, Computational Structural Dynamics, grid generation, and ice accretion modeling software, has been coupled to work together with a Python-based script. The collected tool set is capable of modeling ice accretion process and the overall effects on rotor performance. The modeling of the underlying physical phenomena require considerable advancements in areas of transition and surface heat transfer prediction, replacement of quasi-steady ice build-up with fully unsteady models, and improved unsteady models for collection efficiency. The present approach provides a framework in which improved models may be inserted without modifying the overall logic or data flow. Encouraging preliminary results have been obtained for three forward cases of practical interest.

Acknowledgments

This work was supported under the NASA NRA Co-operative Agreement: NNX08AU71A.

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