

Application of a High-Fidelity Icing Analysis Method to a Model-Scale Rotor in Forward Flight

*Robert Narducci and Stanley Orr
The Boeing Company, Philadelphia, Pennsylvania*

*Richard E. Kreeger
Glenn Research Center, Cleveland, Ohio*

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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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The Boeing Company
Philadelphia, Pennsylvania 19078

Richard E. Kreeger
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

An icing analysis process involving the loose coupling of OVERFLOW-RCAS for rotor performance prediction and with LEWICE3D for thermal analysis and ice accretion is applied to a model-scale rotor for validation. The process offers high-fidelity rotor analysis for the non-iced and iced rotor performance evaluation that accounts for the interaction of nonlinear aerodynamics with blade elastic deformations. Ice accumulation prediction also involves loosely coupled data exchanges between OVERFLOW and LEWICE3D to produce accurate ice shapes. Validation of the process uses data collected in the 1993 icing test involving Sikorsky's Powered Force Model. Non-iced and iced rotor performance predictions are compared to experimental measurements as are predicted ice shapes.

Introduction

Many helicopters in the world today are restricted from flying in any condition that causes the rotors to be susceptible to ice accumulation. The result of ice on rotor blades is a loss in lift that can cause a critical safety hazard within minutes of encountering ice. Ice on the rotor is also accompanied by an increase in required power and an increase in vibration. The high centrifugal force field on the rotor can cause ice to shed once the accumulation becomes large causing dangerous projectiles in the surrounding areas.

A reliable analysis system would be useful in understanding the limitations of helicopters once icing conditions are encountered so that the operating envelope can be safely expanded for flight through light or moderate icing conditions. Until recently the development of ice analysis tools have been focused on the fixed-wing icing problem. Much can be leveraged for the rotorcraft problem; however rotor icing poses additional significant challenges. The rotor blade chord and airfoil thickness are smaller than fixed wing aircraft causing ice growth to be larger relative to the chord. Larger shapes are harder to predict and their impact to aerodynamic performance is more critical. Rotors also experience a diverse and changing aerodynamic environment within a single rotor revolution. In forward flight, one side of the rotor—the

advancing side—experiences higher airspeeds and lower angles of attack than the opposite side. Likewise, near the hub, the relative airspeed is much lower than at the tip where Mach numbers approach one. Many of the fixed-wing ice accretion codes are not calibrated for such diverse operating conditions. These diverse conditions also cause the rotor to accrete both rime and glaze ice for the same atmospheric conditions.

The approach taken to develop an icing analysis system for rotors leverages methods developed for fixed-wing aircraft. Bidwell (Ref. 1) coupled ice accretion analysis with computational fluid dynamics (CFD) to evaluate ice on a high-lift wing configuration. He used LEWICE3D (Ref. 2) to evaluate droplet trajectories, heat transfer, and ice growth while relying on OVERFLOW or CFD++ for aerodynamic analysis. OVERFLOW (Ref. 3) is well suited for aerodynamic assessments of rotorcraft and therefore Bidwell's approach is a natural point of departure for an icing analysis system for rotors.

Accurate rotor performance must account for the complex interactions between aerodynamics and elastic deformations. Additionally, trimmed rotor solutions where thrust targets are met and moments are balanced across the rotor disk are required to accurately model the environment for the icing analysis. Therefore, the pure CFD solutions used in Bidwell's approach are replaced with solutions generated by coupling CFD solvers with rotorcraft comprehensive analysis codes. To address the rapidly changing aerodynamic environment, ice is accumulated with multiple data exchanges between aerodynamic solutions and LEWICE3D. This approach was introduced by Narducci (Ref. 4) to address ice accretion on rotors in hover however rotor trim and elastic coupling were de-emphasized. These elements cannot be ignored for forward flight rotor analysis.

Details of the analysis method are presented in this paper. The process is applied to a model-scale rotor that was studied for ice accumulation and performance degradation in the NASA Glenn Icing Research Tunnel (IRT). A description of the test and conditions for validation follow the explanation of the analysis method. Results of the application to the model-scale problem are presented next with comparisons to test data for non-iced and iced rotor performance and the accumulation of ice. Important conclusions, known limitations, and future work are discussed in the final section of this paper.

Analysis Approach

The high fidelity icing analysis approach developed for rotor systems follows three basic steps:

- Establish rotor trim and non-iced rotor performance and the initial flow field environment using CFD or coupled CFD-rotorcraft comprehensive analysis as appropriate;
- Extract representative two-dimensional airfoil conditions for blade sections at radial and azimuthal locations and predict ice buildup accounting for the diverse operating environment of the rotor;
- Reestablish rotor performance for the iced blades.

The approach is appropriate to address ice accumulation on rotors for flight regimes from hover to high-speed forward flight. The process is shown pictorially in Figure 1.

The first step involves establishing the non-iced (hereafter referred to as “clean”) analysis of the rotor in forward flight. This utilizes a coupled process between CFD and a rotorcraft comprehensive analysis code. Atmospheric conditions of the icing event are modeled with the exception of water drops which are assumed to have little impact to the aerodynamic solution. The rotor performance for clean blades serves as the baseline with which to compare iced rotor performance. The rotor solution also provides details including pressure distributions and flow conditions local to the blades that are useful for the ice accretion analysis.

There are many CFD and rotorcraft comprehensive codes that can be used to produce the rotor solutions needed for the icing analysis. OVERFLOW for CFD and RCAS (Ref. 5) for the rotorcraft comprehensive analysis are commonly used in the rotorcraft community and have been adopted here. OVERFLOW, developed and maintained at NASA, is a Reynolds Averaged Navier Stokes finite volume CFD solver that uses an overset system of grids to produce flow solutions for complex rotorcraft geometry and conditions. Though mass, momentum, and energy are not strictly conserved in the grid overlap region, the overset system of grids is ideal for the rotorcraft problem because it readily allows motion of one component relative to another.

Coupling CFD with a rotorcraft comprehensive code means that the blade response to air loads (pitching, flapping, and lead-lag motions, and aeroelastic bending and twisting) is represented in the solution and that control settings are trimmed to provide a balanced rotor. The coupling process is well-established and has been validated against several rotor data sets including the UH-60A (Refs. 6 to 9). Essentially the process uses a combination of quick-running lifting-line air loads and air loads from CFD solutions to efficiently produce a high-fidelity solution. The method uses lifting-line air loads during trim, while successively using CFD-produced air loads for blade deflections. This loose-coupling method is outlined in Figure 2. At iteration $n=0$, the comprehensive code trims and converges with only lifting-line air loads. Blade motions for

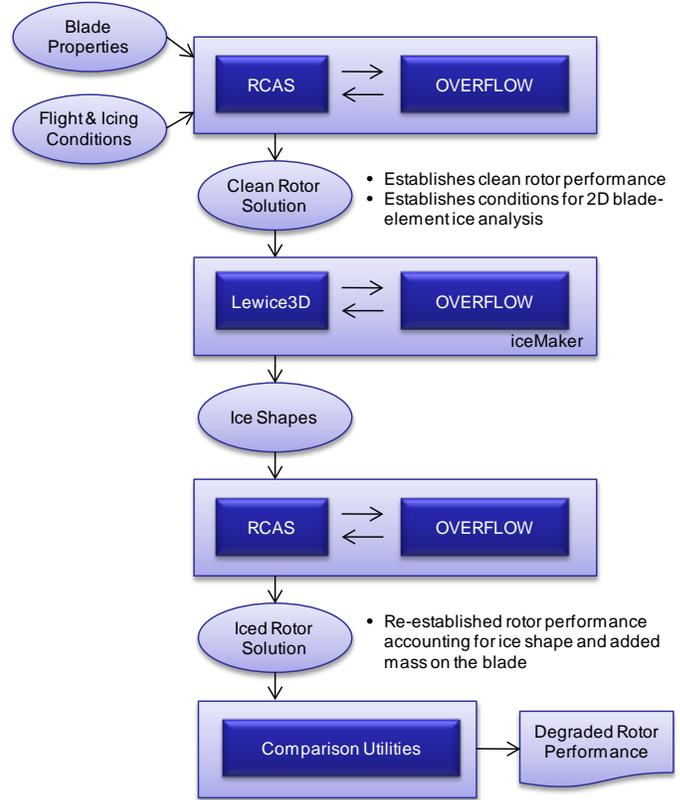


Figure 1.—High-fidelity ice accretion and performance degradation methodology.

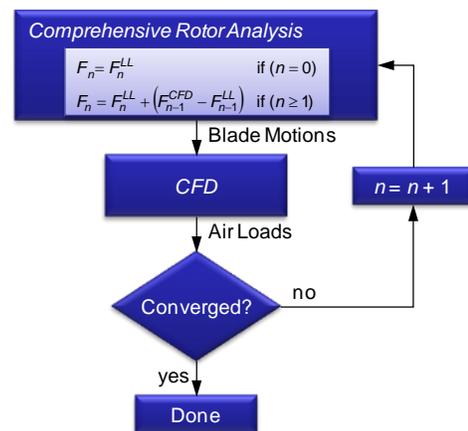


Figure 2.—The CFD rotor comprehensive analysis coupling process.

one rotor period are then passed to the CFD solver. These motions contain gross pitching motions from controls as well as the elastic response. It is not necessary to achieve a perfect periodically-converged solution from CFD at this point; successive iterations between the comprehensive code and the CFD code will move the solution towards convergence. At subsequent iterations, CFD-based air loads are passed back to

the comprehensive code and used with lifting-line air loads from the previous solution. The comprehensive code continues to compute lifting-line air loads during trim while adding the previous iteration CFD and lifting-line “delta” for the total air load to drive the aeromechanical solution towards convergence. These iterations continue until there is no change in trim controls or air loads, at which point the lifting-line air loads from the previous iteration cancel the lifting-line air loads from the current iteration leaving only the CFD as the total air load. This process is fairly efficient and usually requires between two and five rotor revolutions as trim and periodic convergence move together.

The solution is time-dependent, but periodic as the blades respond to local aerodynamic conditions around the azimuth. Like the blade response, ice accretion is also influenced by local aerodynamic conditions that change over the course of a rotor revolution. Ice accumulation is predicted in an engineering approach that divides the blade into radial elements and accounts for the changing environment that each two-dimensional section experiences as it rotates around the azimuth. This two-dimensional strip approach is possible provided representative blade-element conditions can be extracted from the three-dimensional rotor solution. Specific required radial data include local angle-of-attack and relative velocity as a function of azimuthal position.

The required data for the ice accretion analysis is not readily available from the CFD rotor solution as local angle of attack and velocity are somewhat nebulous quantities in this setting. Regardless of how this information is approximated, the two-dimensional blade-fixed flow solution that is used to predict ice should closely represent conditions on the rotor blade. One way to do this is to closely match the pressure distribution that results from a two-dimensional analysis with the instantaneous pressure distribution from the three-dimensional rotor solution. This can be accomplished by following a recipe.

Extracted pressure from the rotor solution is typically presented in coefficient form, using the hover tip speed, V_{tip} :

$$Cp^* = \frac{P - P_\infty}{\frac{1}{2} \rho V_{tip}^2} \quad (1)$$

Assuming mostly two-dimensional flow along the blade and that the flow stagnates on the airfoil section, the pressure coefficient can be renormalized by some reference velocity, V_{ref} , such that Cp_{max} is equal to $1/\sqrt{1 - M_{ref}^2}$. The reference velocity can be determined by solving:

$$Cp_{max} = \left[\frac{P - P_\infty}{\frac{1}{2} \rho V_{tip}^2} \right]_{max} = \frac{1}{\sqrt{1 - M_{ref}^2}} \quad (2)$$

The solution is

$$V_{ref}^2 = \frac{a^2}{2} Cp_{max}^* M_{tip}^2 \left[\sqrt{Cp_{max}^{*2} M_{tip}^4 + 4 - Cp_{max}^* M_{tip}^2} \right] \quad (3)$$

where a is the speed of sound and M_{tip} is the hover tip Mach number.

A representative angle of attack can be determined a number of ways, for example, by utilizing an airfoil database of Mach number, force coefficients, and angle of attack. An alternative is to use an airfoil analysis tool to find the angle of attack that best matches the extracted pressure distribution at the reference velocity determined from (3).

The extracted aerodynamic conditions along with the conditions of the icing environment allow for an ice accretion analysis. The process begins by considering one radial location at a time. At a given radial location ice accumulation is influenced by local angle of attack and velocity which vary along the azimuth as idealized in Figure 3(a). With the assumption that the ice shape is not influenced by the frequency, the pitch and velocity variation can be characterized by a very slow oscillation, for example as illustrated in Figure 3(b). Furthermore if we assume the ice shape can be approximated by only considering the mean angle of attack and the extreme excursions from the mean, the blade motion can be represented as a series of quasi-static events, as shown in Figure 3(c). This approach segments the icing event into discrete time-steps with each time segment characterized by conditions at a different azimuthal location. The prediction of ice accumulation for the simplified characterization follows the methodology represented by the flow diagram in Figure 4. It is a loosely coupled approach involving data exchanges between CFD and LEWICE3D at each time increment.

The analysis begins by gridding the non-iced airfoil for a given radial station. Any grid generator can be used, but the Boeing-developed grid generator, MADCAP (Ref. 10), is an

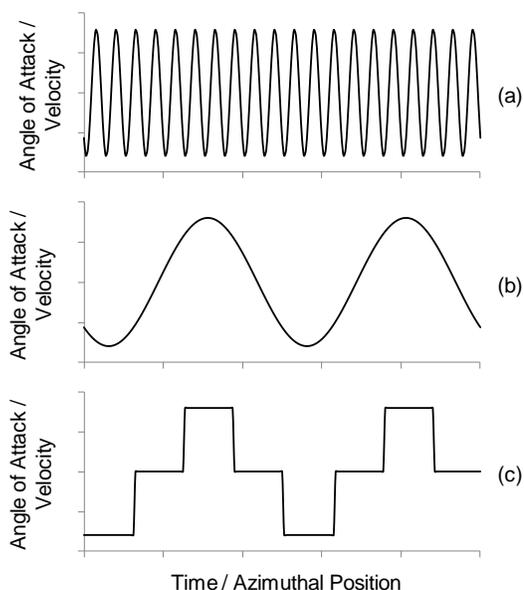


Figure 3.—Characterization of angle of attack and velocity as a function of time or azimuthal position.

attractive choice because it is scriptable for batch running and has many powerful features to smooth the grid. MADCAP can be used, hands free, for many complex ice shapes. This will be useful for subsequent time steps which will have ice shapes. The next step involves generating an aerodynamic solution. LEWICE3D will use the flow solution for its thermodynamic calculation and is open to accept solutions from a wide variety of flow solvers. The requirement is a robust solver that is capable of generating high-quality simulations for complex ice shapes. OVERFLOW is a logical choice since it is used in the three-dimensional rotor solution and is a standard in the rotorcraft community. OVERFLOW can generate time-accurate solutions which is often necessary to determine the aerodynamic impact of the ice shape. However, in the process of predicting ice it is sufficient to produce steady solutions which require less computational resources.

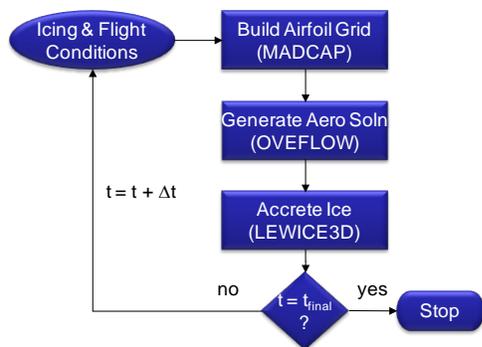


Figure 4.—Rotorcraft ice buildup prediction process.



Figure 5.—Photo of the Sikorsky Powered Force Model in the NASA IRT.

The flow solution is passed to LEWICE3D for the first ice accretion on the clean airfoil. References 11 and 12 explain the analysis process of LEWICE3D. The ice is grown for only a fraction of the total icing event time. The ice shape is extracted from the LEWICE3D output files and fed back into the grid generator for analysis of subsequent time steps. The process continues with updated flow conditions representing a different azimuthal location. For each step, ice is accreted directly on the shape from the previous step. In this way shadowing effects are taken into account. Shadowing is the result of the interaction of the developing ice shape on the local aerodynamics and the deposit of droplets on the airfoil. It is postulated that the majority of the effect can be captured by considering only the minimum and maximum angles of oscillation. The process continues until the entire icing event time has elapsed. Conditions at each selected azimuthal location can be used more than once.

This process is repeated for multiple radial locations along the blade. The final three-dimensional ice shape is a composite of the two-dimensional shapes computed in the strip approach. Once the ice has been established on the blade, the three-dimensional rotor analysis is repeated for the iced rotor. In addition to accounting for ice in the CFD rotor grid, the input files to the comprehensive rotor analysis are also modified to reflect the additional mass and change to the blade center of gravity. It is assumed that the effect on blade stiffness is small. Rotor performance degradation is obtained by comparing the forward flight performance characteristics of the iced rotor to the clean rotor.

One element of ice prediction on rotors is ice shedding. Rotor centrifugal force and aerodynamic loads can cause segments of ice to leave the rotor, increasing vibration levels. The prediction of ice shedding events, though important, is currently not addressed in this process. Furthermore, each blade is assumed to have identical ice growth.

Forward Flight Test Case

NASA and the Sikorsky Aircraft Company conducted an experimental program to investigate ice accumulation and performance degradation for a model-scale rotor. The test was conducted at the NASA Glenn IRT in the spring of 1993. The model was the Powered Force Model (PFM), pictured in Figure 5, and featured a four-bladed rotor with rectangular blade tips. The test conditions included a range of liquid water content, median volume drop diameters, and temperatures. Flight conditions also included a range of tunnel velocity, rotor tip speed, rotor lift, and propulsive force. A large quantity of data was collected including ice shapes, rotor lift degradation, power increase, and ice shedding events. The test is documented in References 13 and 14. The controlled testing environment and detailed documentation make this test ideal for validating the high fidelity icing analysis system.

The rotor for the PFM used SC2110 airfoils from root to tip. The chord was 4.222 in. and the diameter was 6.093 ft

producing a solidity of 0.147. The rotor was modeled in the analysis with a 21.5 percent cutout and hinges for flap and lag at 8.2 percent. The rotor had a linear twist of 11.5°. Though tested with a scaled Blackhawk fuselage, the analysis featured only the rotor and an idealized centerbody.

While the 1993 PFM test featured a wide variety of flow and icing conditions, Condition “17” is ideal for code validation since ice shapes and rotor performance degradation data were recorded. The condition also did not experience any ice shedding events which would be unaccounted in the analysis. Data for Condition 17 was gathered on several runs, particularly 8, 47, 63, and 64. The details of those runs are shown in Table 1. The rotor was flown in dry air to a specific shaft angle, lift and condition of zero flapping. During ice accumulation, runs 8, 47, and 63 operated at zero flapping and constant collective; Run 64 operated at zero flapping and constant lift. Both modes of operation were analyzed.

TABLE 1.—VALIDATION CONDITIONS (CONDITION “17”)

| Run | 8, 47, 63 | 64 |
|-------------------------------|------------|----------|
| Tip speed (ft/s) | 675 | 675 |
| Ts (°C) | -15.1 | -15.0 |
| Density (sl/ft ³) | 0.00254 | 0.002559 |
| LWC (g/m ³) | 0.5 | 0.5 |
| Drop diameter (µm) | 15 | 15 |
| Time (sec) | 93 | 91 |
| Advance ratio | 0.198 | 0.200 |
| Trim variables | Collective | Lift |

Results

The initial calculation with OVERFLOW coupled to RCAS simulated Condition 17 of the 1993 powered force model test in the IRT. The simulation provides the baseline for clean rotor performance. The calculation estimated 18.2 hp and a propulsive force coefficient of 0.089 for the targeted lift condition of $C_L/\sigma = 0.064$. The propulsive force coefficient, shown as the solid triangle in Figure 6, was over-predicted compared to experimental data. However for this condition, being relatively benign, the propulsive force prediction produced exclusively with RCAS using lifting-line aerodynamics agrees very well with the coupled OVERFLOW-RCAS solution. Rotor solutions with lifting-line aerodynamics, being an order of magnitude faster to run, were produced for a sweep of shaft angles and advance ratios. Agreement with experimental measurements is very good at advance ratios of 0.3 and 0.4; unfortunately, the largest discrepancy occurs at the validation condition. It is speculated that at the lower advance ratio, interaction of the blades with the rotor wake is more important and ignoring the tunnel walls, floor and model fuselage could have affected the wake position to an extent greater than expected.

The OVERFLOW-RCAS solution also serves as the basis to extract local conditions acting on the blade. Solving Equation (3) along the blade from root to tip at azimuth positions of 0° (behind the pilot), 90° (advancing side), 180° (directly in front of the pilot), and 270° (retreating side) produced the curves shown in Figure 7. These represent the free stream velocity experienced by blade elements in the airfoil fixed reference frame. The local angle of attack distribution, shown in Figure 8, is determined by using these velocity values and matching the aerodynamic load acting on the blade. The flow field for the 50 percent radial location on the retreating side produced the pressure distribution and velocity field shown in Figure 9. The two-dimensional pressure distribution has slightly more suction on the leading edge but otherwise represents the three-dimensional slice well.

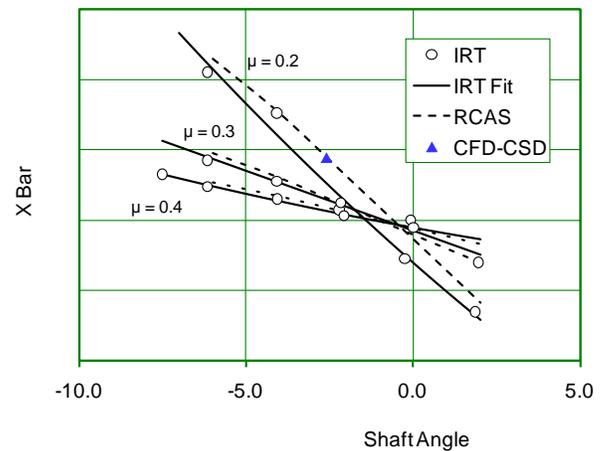


Figure 6.—Propulsive force for $C_L/\sigma = 0.064$ for the clean PFM rotor.

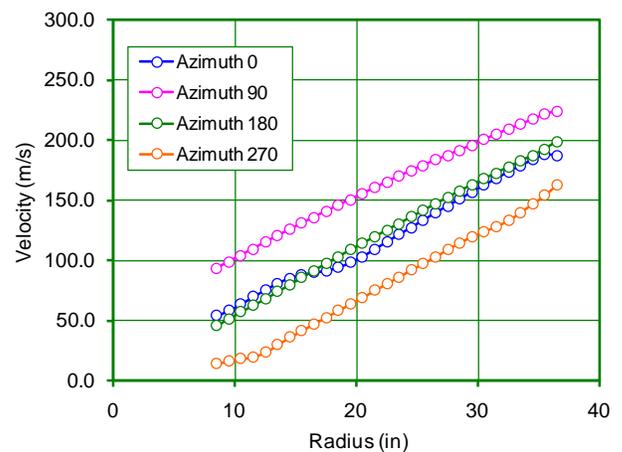


Figure 7.—Distribution of local velocity at azimuthal positions of 0°, 90°, 180°, and 270°.

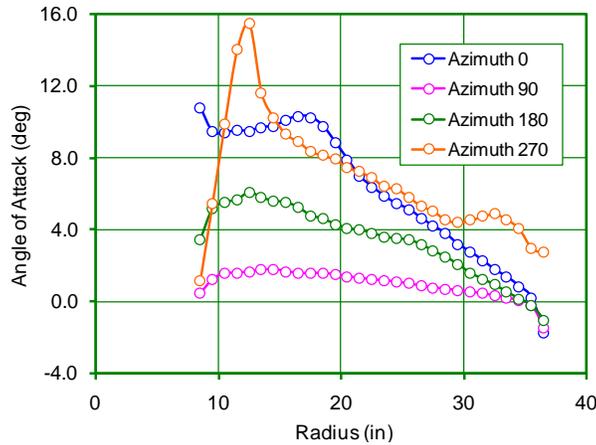


Figure 8.—Distribution of local angle of attack at azimuthal positions of 0°, 90°, 180°, and 270°.

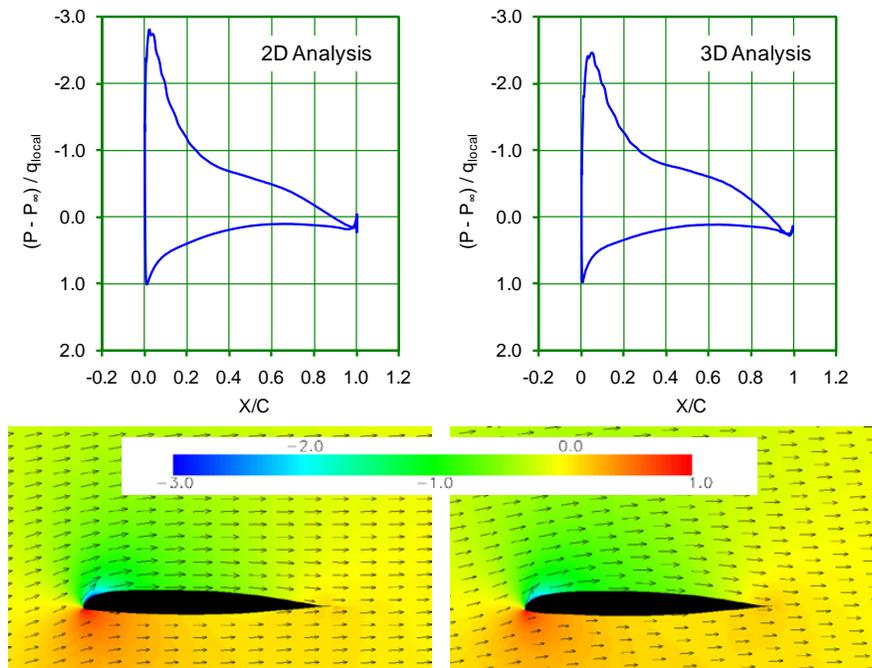


Figure 9.—Comparison of local flow conditions; the left computed from two-dimensional analysis, the right extracted from the three-dimensional solution on the retreating blade at 50 percent r/R.

The ice accretion process uses the results in Figure 7 and Figure 8. For the OVERFLOW-LEWICE3D coupling, OVERFLOW solutions are generated on very fine airfoil grids with 699 chordwise points and 121 points normal to the surface. The grid features clustering near the leading edge to resolve flow features that arise from the ice shape. In addition to clustering normal to the airfoil surface to resolve the boundary layer, cells remain small in the vicinity of the airfoil to resolve separation wakes which tend to be prevalent with ice.

For this approximation of ice growth, the event time is segmented in four steps and considers local conditions at

azimuthal positions of 0°, 90°, 180°, and 270°. The sequence of ice growth for radial location r/R = 90 percent is shown in Figure 10 as an example. Ice is grown on a clean airfoil section when the blade is directly in front of the rotor hub. The next sequence of ice growth is accumulated on top of the previous ice shape using conditions on the retreating side. The next step predicts the further accumulation of ice using conditions directly behind the pilot. The final accumulation uses conditions from the advancing side.

One advantage of this process is that it takes into account the varying conditions on the rotor. However, it can introduce

a bias in the resulting shape depending on which azimuthal location is used to initiate the ice accretion. Using conditions around the rotor several times mitigates the bias; however this may not be possible for short icing events. In this validation case, ice is accreted using conditions at each of the four azimuthal conditions only once. The resulting shapes at 40, 50, 70, and 90 percent agree well with recorded ice tracings from the experiment as shown in Figure 11.

The reasonable correlation of the ice shapes shown in Figure 11 allows the process to be confidently applied in 1-in. increments along the blade. Ram heating typically prevents ice from forming at the tip, however fairly large ice masses exist on the tip at these conditions. The ice shapes are stacked to create a three dimensional geometry of the iced blades. All four blades are considered identical. Ice feathers and the increase in surface roughness are not captured in the CFD model. In addition to the CFD grid, the RCAS model is also updated to account for the additional ice mass on the leading edge. The NASA invented tool, THICK, computes the mass of ice and was used to generate the results shown in Figure 12 and which are reflected in the RCAS model. Updates include mass, CG location, and moments of inertia. The iced rotor performance was quantified in two separate OVERFLOW-RCAS simulations. The first targeted the same lift condition and zero-flapping; the performance quantities of interest include the increase in required power and loss of propulsive force. The second analysis maintained constant collective, but adjusted cyclic control to zero the flapping. In addition to the increase in power and decrease in propulsive force, this scenario also experiences a loss in lift. Not all performance increments were experimentally reported, but where possible the comparisons are made in Table 2 and Table 3. The changes in performance are generally over-predicted but are reasonable. Figure 13 shows the experimental trends in horsepower increase as a function of time. Also shown in the figure with solid symbols are the results of the analysis representing the conclusion of the icing event.

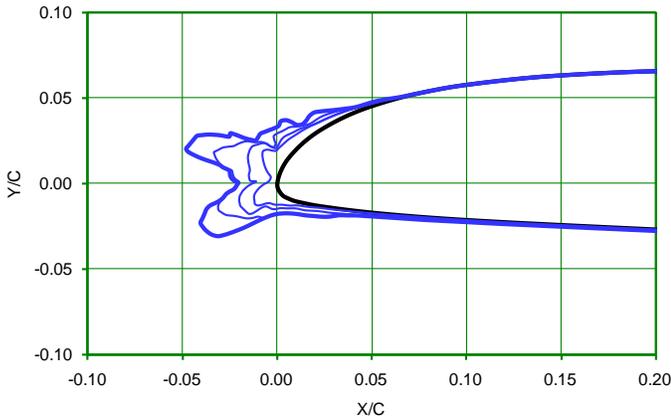


Figure 10.—Sequential build up of ice at the 90 percent radial station using the flow conditions at 180°, 270°, 0°, and 90° azimuthal positions.

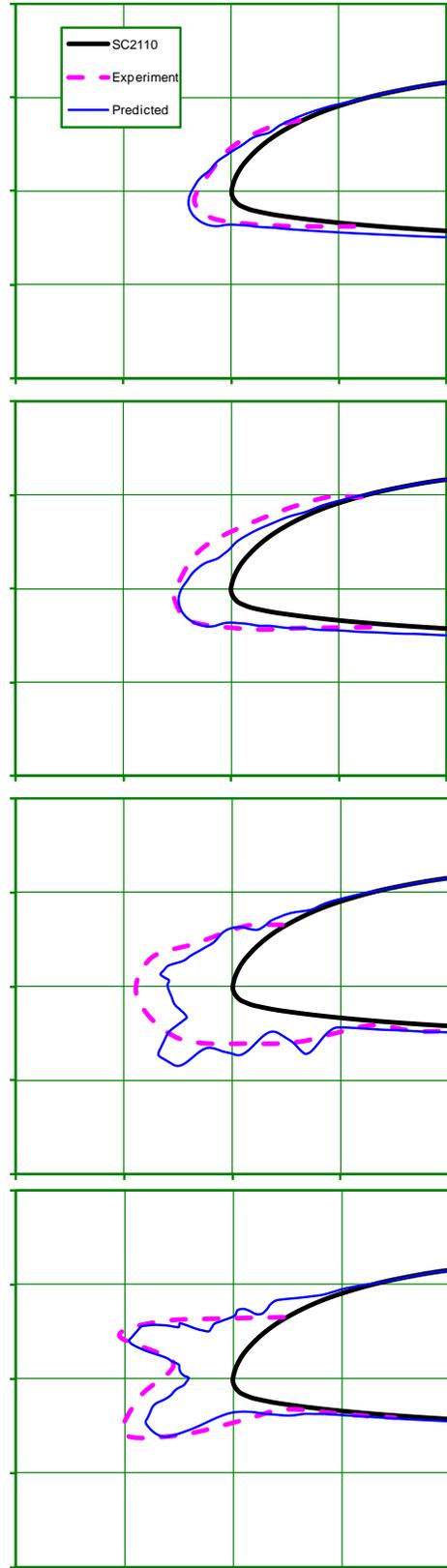


Figure 11.—Correlation of predicted and measured ice shapes.

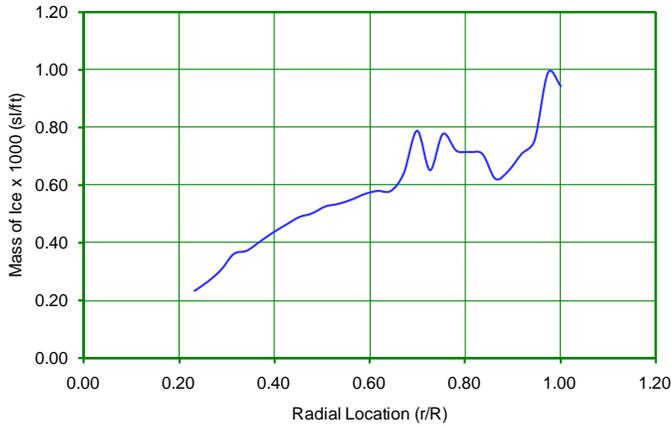


Figure 12.—Mass of ice growth on the leading edge of the PFM for Condition 17.

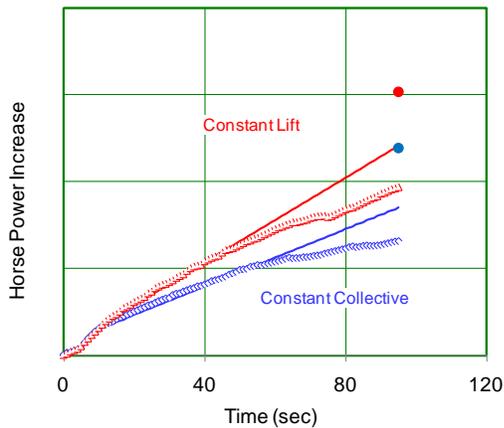


Figure 13.—Horsepower increase.

TABLE 2.—ICED ROTOR PERFORMANCE CHARACTERISTICS WITH CONSTANT LIFT

| | | Experiment | CFD-CSD |
|--------|---------------------|------------|----------|
| Input | Shaft angle | -2.6 | -2.6 |
| | V_{tip} | 675 fps | 675 fps |
| | T_{∞} | -15.1 °C | -15.1 °C |
| | Target C_L/σ | 0.064 | 0.064 |
| | Advance ratio | 0.198 | 0.198 |
| Output | Thrust | N/A | 332.0 lb |
| | Power | N/A | 48.5 hp |
| | Drag | N/A | -6.4 lb |
| | X-bar | N/A | 0.044 |
| | Δ Thrust | N/A | 11.5 lb |
| | Δ Power | ~19.0 hp | 30.3 hp |

TABLE 3.—ICED ROTOR PERFORMANCE CHARACTERISTICS WITH CONSTANT COLLECTIVE

| | | Experiment | CFD-CSD |
|--------|-----------------|------------|----------|
| Input | Shaft angle | -2.6 | -2.6 |
| | V_{tip} | 675 fps | 675 fps |
| | T_{∞} | -15.1 °C | -15.1 °C |
| | Collective | Constant | 6.9° |
| | Advance ratio | 0.198 | 0.198 |
| Output | Thrust | NA | 264.5 lb |
| | Power | NA | 42.0 |
| | Drag | NA | -0.97 lb |
| | X-bar | NA | 0.008 |
| | Δ Thrust | ~ -40 lb | -56.0 lb |
| | Δ Power | ~13.5 hp | 23.9 hp |

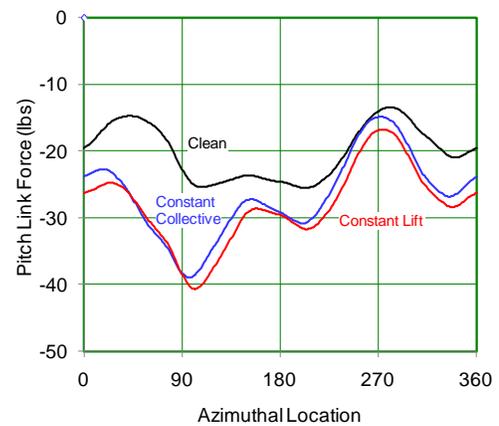


Figure 14.—Effect of blade ice on pitch link loads.

Understanding the sources of the discrepancy requires additional experimental parameters for Condition 17 which unfortunately are not readily available. However, there is hope for predicting iced rotor performance decrements having achieved good correlation with the ice shape prediction. Additional iced rotor testing is planned in 2012 to provide the additional insight needed to improve the performance decrement prediction.

Aeroelastic analysis offers a direct benefit by providing icing analysis with proper trim and blade motions. Coupled CFD-rotorcraft comprehensive analysis also provides internal loads that may allow designers to accommodate icing when sizing parts. The effect on pitch link loads was quite clear in both OVERFLOW-RCAS simulations, where blade ice produced a 47 percent increase in steady and a 97 percent increase in vibratory load (constant lift case). The increase in pitch link loads as a function of blade position is shown in Figure 14.

Summary and Conclusions

- An analysis method to evaluate a rotor in icing conditions was presented and applied to a model-scale rotor in forward flight. The method is a combination of two- and three-dimensional analyses, using three-dimensional methods for rotor performance and degradation and two-dimensional for ice accretion.
- The process to predict rotor forward flight performance utilized loosely coupled CFD analyses with rotor comprehensive analyses to establish trim and rotor blade deformation.
- The clean rotor analysis predicted rotor power to approximately 12 percent of experimentally measured power for 320 lb of thrust and an advance ratio of 0.2.
- Ice shapes were reasonably well-predicted from root to tip using a loosely coupled OVERFLOW-LEWICE3D process for two-dimensional airfoils. Analysis conditions were extracted from the clean three-dimensional rotor flow solution.
- Rotor performance degradation was predicted and measured for two conditions: 1.) fixed collective, shaft angle, and zero-flapping; 2.) fixed lift, shaft angle, and zero-flapping. In both cases the power increment was over-predicted.
- For fixed collective, analysis predicted a 17 percent loss in lift and a 130 percent increase in power; experiment showed a 13 percent decrease in lift and a 65 percent increase in power.
- For fixed lift, analysis predicted a 166 percent increase in power; the experiment measured 92 percent.
- Pitch link loads were predicted to increase significantly—47 percent increase in steady and 97 percent increase in vibratory for fixed lift.
- The analysis process has provisions to include shedding in the future. The experimental test case did not have an ice shed event.

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