

DRONE ROTOR PERFORMANCE UNDER ICING CONDITIONS

Avani Gupta, Linde Inc., Tonawanda, NY, USA

Aishwerya Gahlot, Georgia Institute of Technology, Atlanta, GA, USA

Lakshmi N. Sankar, Georgia Institute of Technology, Atlanta, GA, USA

Low- and high-fidelity physics-based models for assessing the aerodynamic performance of drone and eVTOL rotors under icing conditions are examined. The low fidelity model in this work makes use of a lifting line model of the rotor with a prescribed inflow coupled to an ice accretion solver for modeling ice growth, and an interactive boundary layer model for the generation of airfoil drag polars. The higher fidelity model employed in this study uses a 3-D unsteady Navier-Stokes analysis with a tightly coupled water droplet transport model for modeling the collection of liquid droplets over the rotor. The rotor shape is periodically updated to account for the ice formation. Low fidelity calculations for an 81% scaled-down version of the Bell APT70 drone rotor tested at Université du Québec à Montréal provide reasonable estimates of the loss in thrust and rise in power during the initial stages of ice growth. Higher fidelity models are found to be better suited for multirotor configurations with nonlinear wake interactions, while eliminating the needs for airfoil drag polars, tip loss models, and empirical compressibility corrections.

1. INTRODUCTION

Over the past five decades there has been considerable interest in the use of drones and other unmanned autonomous systems in civilian and military applications such as package and medical supply delivery, aerial surveillance, and search and rescue operations. These systems are usually designed for hot, out of ground conditions, and the rotor system and the power plant are carefully sized to minimize the gross weight and cost of the system, while maximizing the range, endurance, and operating altitude. The number of UAS available for these operations, and staffed air taxi operations are rapidly growing. A market analysis indicates that the Air Taxi market alone has a potential demand of ~55,000 daily trips (or ~ 80,000 daily passengers)

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which would require 4,000+ aircraft and the annual market value is projected to be ~\$2.5 billion (Ref. 1). With the increase in the number of systems in operation, the risk of accidents would also proportionately rise, especially under adverse weather conditions. Published data indicates that that nearly 25% of UAS operations by the military were impacted by adverse weather effects, particularly icing (Ref. 2).

While much work has been done to model the effects of icing on conventional helicopter performance, relatively less work has been done on assessing how freezing rain and icing would affect the performance of small rotors (Ref. 3-10). Over the past two decades, present researchers have developed physics-based modeling tools for the assessment of aerodynamic performance of small rotors under dry, rain, and icing conditions (Ref. 11-15). Satisfactory agreement with test data for ice growth and performance loss has been demonstrated for a two-bladed teetering tail rotor tested at NASA Glenn Research Center (Ref. 11). Work has also been done on the modeling of icing on the helicopter/UAV fuselage airframes (Ref. 13).

2. OPERATING ENVIRONMENT OF DRONES AND eVTOL SYSTEMS

Prior to modeling the effects of icing on drone and eVTOL operations, it is important to understand the environment in which these systems would operate.

The atmosphere, and the cloud structure, is classified by altitude as shown in Table 1.

Table 1: Classification of Cloud Structure by Altitude

Altitude	Type of cloud	Characteristics
Above 20,000'	cirrus, cirrostratus, and cirrocumulus	Very cold temperature, ice crystals
Between 6500' and 20,000'	altostratus and altocumulus	combination of ice crystals, supercooled liquid drplets
Below 6500'	stratus and cumulus	liquid water droplets or supercooled droplets

Source: <https://www.weather.gov/media/lmk/soo/cloudchart.pdf>

Helicopters and drones typically operate below 6500 feet (2000 m). Therefore, liquid water droplets and fog are the primary concern from a wet weather perspective. The reader is referred to web site <https://www.epfl.ch/labs/lapi/wp-content/uploads/2020/03/Clouds.pdf> for a visual representation of the various types of clouds.

Table 2 below shows the liquid water content (LWC) in grams per cubic meter, typically present in the environment.

Cloud Type	LWC (g/m ³)
cirrus	0.03
fog	0.05
stratus	.25-.30
cumulus	.25-.30
stratocumulus	0.45
cumulonimbus	1.0-3.0

https://en.wikipedia.org/wiki/Liquid_water_content

Measured data for liquid water content at geographical locations including Indonesia, Thailand, and Israel indicate that the liquid water content in cloudy and foggy weather is typically below 0.5 grams per cubic meter (Ref. 16).

From this information, it may be concluded that only the liquid water content below 0.30 g/m³ is of importance from an icing perspective.

Another factor that affects the performance of drones and helicopters is the smaller size of rotor. To illustrate this point, consider a NACA 0012 airfoil operating at an angle of attack of 3 degrees at -15 degrees C, at a nominal forward speed of 134 m/s, typical of the rotor tip speed of small-scale drone and eVTOL systems. The liquid water content is chosen to be 0.25 g/m³ with a mean droplet diameter of 120 microns. Two chord lengths - 0.353 m (typical of helicopters) and 0.12 m (typical of

drones) are considered. The resulting ice shapes computed using the NASA Glenn Ice Accretion modeling tool LEWICE (Ref. 17), are significantly different, as seen in Figure 1a. This is attributable to the higher heat transfer rate, in watts per square meter per degree Kelvin, seen in Figure 1b in the vicinity of the leading edge for the smaller chord airfoil at the same freestream conditions. The sharp rise in the heat transfer rate, seen for both airfoils, is attributable to flow transition, caused by the roughness of the accreted ice.

The lower Reynolds number of the drone rotor would further affect the lift and drag characteristics, both. In other words, all things being equal, a small-scale drone will be more susceptible to ice formation and experience a greater performance loss than a geometrically scaled larger rotor used on helicopters.

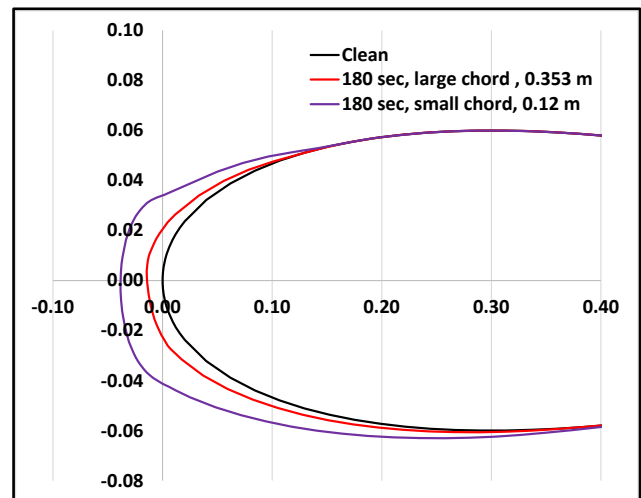


Figure 1a. Effect of Airfoil Chord Length on the Resulting Ice Shape

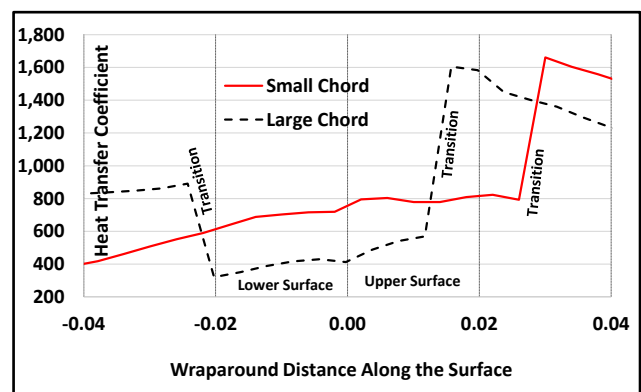


Figure 1b. Effect of Airfoil Chord Length on the Heat Transfer Rate in the Leading Edge Region

3. NUMERICAL FORMULATION

Physics-based models for drone rotor icing phenomena are inherently costly, given the large number of parameters (rotor collective pitch, RPM, liquid water content, droplet diameter distribution, and ambient temperature) that must be systematically varied. In industries, for conventional single rotor helicopter and drone rotors, it is customary to use lower order lifting line-based aerodynamics models of the rotor, coupled with a suitable inflow model, and an external ice accretion model. This approach is adequate for obtaining a rapid preliminary estimate of the loss in thrust and rise in power.

3.1. Low Fidelity Models

In the present study, the classical blade element-momentum theory approach (BEM) has been used with airfoil lift and drag as a function of the angle of attack characteristics generated using CFD tool ANSYS. At subfreezing temperatures, some of the water droplets would freeze upon impact, creating a rough airfoil surface. In this work, the roughness effects associated with ice accretion have been crudely modeled by tripping the boundary layer at 10% of the chord on both the upper and lower surfaces.

Ice accretion on solid surfaces is a slow process, with a time scale of the order of minutes. The aerodynamic properties, on the other hand, adapt quickly within a few chord lengths of travel. Given the disparity in the time scales, it is not necessary to tightly couple the flow solve to the ice accretion solver. Therefore, it was sufficient to update the airfoil shape to account for the resulting ice accumulation once every 60 seconds. In the present study, NASA Glenn 2-D ice accretion solver LEWICE (Version 3.2) has been used (Ref. 17).

In summary, the steps involved in the traditional low fidelity formulation are as follows.

- i. Initialize the flow field parameters (liquid water content, ambient temperature, water droplet diameter distribution, rotor geometry and RPM, collective pitch or target thrust)
- ii. Initialize time $t=0$.
- iii. Generate airfoil lift and drag characteristics as a function of angle of attack, sectional Mach number, at a nominal Reynolds number (at 75% R in this study) using 2-D computational fluid dynamics analyses.
- iv. Perform a blade element model analysis of the rotor with a suitable inflow model,
- v. Extract partial angle of attack distribution along the rotor as a function of radial location.
- vi. Grow the ice layer for a specified time increment Δt (1 minute in the present illustration) using LEWICE.
- vii. Compute the iced airfoil shapes at selected radial locations.
- viii. Update time level t to the new value $t + \Delta t$.
- ix. Repeat steps (iii) through (viii) till the desired shape is reached.

3.2. High Fidelity Models

In the present study, a hybrid Navier-Stokes/free wake analysis called GT-Hybrid is used. This analysis employs a Lagrangean free wake methodology for capturing the wake structure as shown in Figure 2. Both the inner wake and the tip vortex are modelled. The detailed flow field needs to be resolved only within a small computational domain with a structured grid surrounding a reference blade. Within the body-fitted structured grid, the discretized Navier-Stokes solutions are solved using a time-accurate flux-limited MUSCL scheme that is third order accurate in space and first order accurate in time. A variety of algebraic, one-equation, and two-equation models are available within the solver. In this work, the Spalart-Allmaras Detached Eddy Simulation (SA-DES) model has been used. An empirical transition model that limits or turns off the production of turbulent kinetic energy has been used to capture free transition.

Blade elastic deformations due to bending and elastic twist may be supplied to the flow solver as a function of radial location. In the present exploratory studies, the blades are assumed to be rigid.

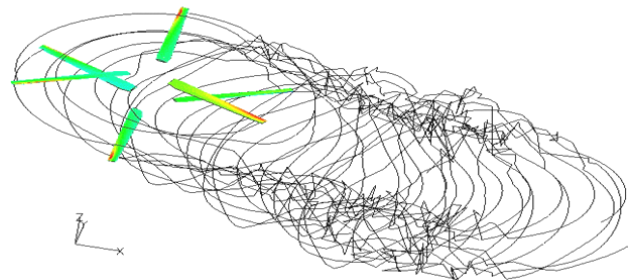


Figure 2. Overview of the GT-Hybrid Methodology for Coaxial Rotors

Because Navier-Stokes simulations are done only in a small flow domain, and usually only for a single blade, the CPU time per revolution is low compared to wake capturing methods, of the order of 2 to 4 hours on a multi-core desktop PC system. Furthermore, no modifications to the flow solver for specific rotor configurations (e.g. single rotor vs. coaxial rotor vs. Tandem rotor) is necessary.

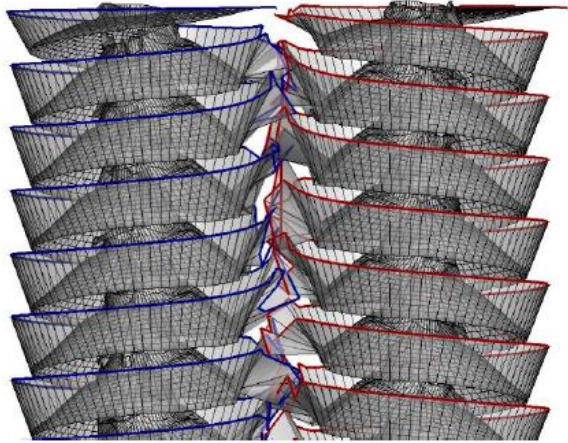


Figure 3. Overview of the GT-Hybrid Methodology for Tandem Rotors with Nonlinear Wake Interactions

To model the effects of rain, this solver has recently been modified to include the rain effects. The transport of water droplets is modelled as transport of discrete non-reacting species using a Eulerian approach. The droplets have considerable inertia, and would, in general, travel at a velocity that differs both in magnitude and direction compared to air molecules. A Stokes drag force would be exerted by the air molecules on the water droplets, and a reaction force would be exerted by the droplets. Ref. 17 gives further details of the fully coupled (air + water droplet) flow solver methodology.

From the droplet velocity field in the vicinity of the solid surface, the mass flow rate of water droplets entering the surface layer is computed within the coupled Navier-Stokes-droplet transport solver. This information, along with the surface pressure distribution and the surface skin friction data is passed onto LEWICE, or an in-house ice accretion solver GT-ICE for modeling ice growth. Standard ASCII human readable data format is used, compatible with LEWICE input data format and PLOT3D formatted data, as applicable. The iced surface geometry is periodically updated, and the process repeated till the desired time level is reached.

4. RESULTS AND DISCUSSION

Preliminary results for the low- and high-fidelity models have been obtained to assess the effects of icing on drone rotor performance. As stated earlier, the low fidelity model is well suited for single rotor configurations with no significant nonlinear wake interactions, while the high-fidelity approach is well suited for multi-rotor eVTOL configurations with strong, nonlinear wake interactions.

4.1. Sample results for the Low Fidelity Approach

The low fidelity model described above has been used to examine the effects of icing on the performance of the 81% scaled-down version of the Bell APT70 drone rotor and compare with published test data in Ref. 5. This is a four-blade rotor with a diameter of 0.66 m, made of NACA 4412 airfoil sections. Ref. 5 provides curve fits for the radial variation of blade chord and twist.

Dry rotor calculations were done at a representative RPM of 3880. A script based on combined blade element-momentum theory has been used in this study. For the dry rotor, the computed thrust force was 115 N (25.74 lb) and the power consumed was 1.91 KW (2.54 HP). In propeller notation, this corresponds to a thrust coefficient of 0.118 and a torque coefficient of 0.0073. These values compare favorably with the dry rotor thrust and torque values reported in Ref. 5 for the dry rotor, prior to the triggering of water spray to cause icing.

Following the dry rotor analysis, the effects of icing were examined. Ref. 6 includes data for a variety of operating conditions – RPM, liquid water content (LWC), ambient temperatures, and surface coating. In this work, results are presented for an ambient temperature of -12° Celsius, for 2.3 grams per cubic meter of LWC at 3,880 RPM. Ice accretion takes place over 180 seconds. The ice shapes were computed using LEWICE, while the sectional lift and drag characteristics of the iced geometry were computed using the commercial CFD analysis ANSYS Fluent®. Figure 4 shows the computed ice shapes from LEWICE at selected time levels for a representative condition (7° angle of attack). Figure 5 shows representative velocity fields over the iced airfoils at several instances in time. The region shaded in blue corresponds to low velocity separated flow.

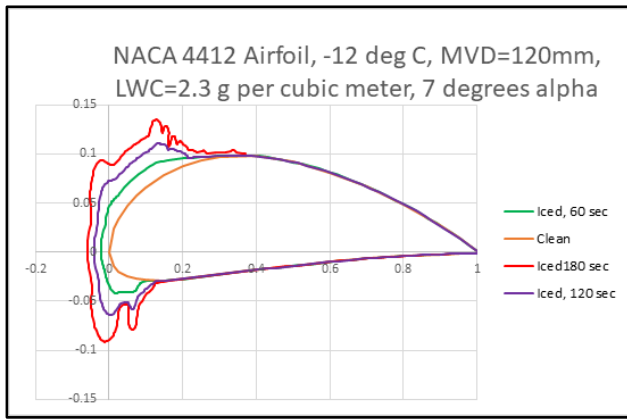


Figure 4. Representative Ice Shapes, 2.3 g per cubic meter LWC, -12 degrees C.

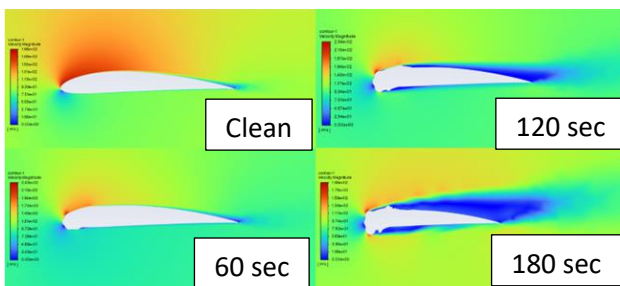


Figure 5. Velocity Contour Plots for Representative Ice Shapes indicating Flow Separation

Table 3 presents representative computed values of the computed aerodynamic loads for the clean and iced airfoil sections. It is seen that there is a substantial degradation in lift production with significant rise in sectional drag, after just 3 minutes of operations.

Table 3. Assessment of the Degradation of the Sectional Load Characteristics after 3 minutes of Ice Accretion at 75% Radius, 2.3 g per cubic meter LWC, -12 degrees C.

Alpha, degrees	C_l , Clean	C_d , Clean	C_l , Iced	C_d , Iced
6	0.9784	0.0230	0.5422	0.0834
7	1.0638	0.0251	0.5362	0.0936
8	1.1448	0.0276	0.5958	0.0975
9	1.2206	0.0307	0.6497	0.1176
10	1.2864	0.0345	0.7609	0.1275

Second order polynomial curve fits of the clean and iced airfoil load characteristics computed from the CFD software ANSYS Fluent were used in the combined blade element-momentum theory analysis. The analysis indicates that the thrust level

for the iced rotor drops to 70 N, from 114 N for the clean rotor, a loss of 40 N. This represents a 35% thrust loss, while test data indicates a 40% loss. The required power rises from 2.22 KW for the dry rotor to 3.24 KW for the iced rotor. This is an increase of nearly 1.02 KW (45% of the power for the dry rotor). The measured data indicates a power rise of 50%.

An estimate of the loss in thrust and rise in power may also be done from blade element theory with uniform This rotor has a nominal solidity σ of 0.08. Thus, a rise in the nominal drag coefficient from 0.02 to approximately 0.10 (as shown in Table 3 above), would lead to a rise in power coefficient ΔC_P (in helicopter notation) of 0.001. This translates into a substantial rise in power consumption of 1 KW for the same thrust setting.

Blade element theory also states that the thrust coefficient C_T (in helicopter notation) is of the order of $\sigma C_l / 6$ where C_l is the nominal lift coefficient. Table 3 indicates that the sectional lift coefficient at 75% radius drops by nearly 50% over this range due to extensive flow separation, reducing the thrust production by ~50%. In the case of drones powered by electric motors, thrust production is controlled by varying the rotor RPM rather than the blade pitch. A 20% to 25% increase in RPM would be needed to recover the loss in thrust. Since the rotor is already operating at a high tip speed of 134 m/sec, higher tip speeds would lead to a further increase in profile power, and power consumption. Furthermore, higher tip speed would also mean an increase in the collection of water over the rotor surface, and somewhat thicker ice shapes. The required thrust likely cannot be achieved, given the drastic reduction in lift coefficient, and the significant rise in drag and power consumption. In other words, the time of operation of this drone under the specified icing conditions (-12° C, 2.3 g LWC) is less than 2 minutes.

4.2. Sample Results for the High-Fidelity Approach

The high-fidelity approach outlined earlier has been extensively validated for clean and iced rotors in the past. A modified version of the classical Messinger model was used. Hover and forward flight simulations of iced rotors have been done. For teetering rotors, the blade motion is accurately modeled through a rigid body rotation of the body fitted grid appropriately about the flapping hinge at

each instance in time and considering the resulting grid velocity. Figure 6, reproduced from Ref. 11, shows the computed ice shapes for a two bladed teetering rotor in forward flight, tested at NASA Glenn Research Center. Good agreement has been observed.

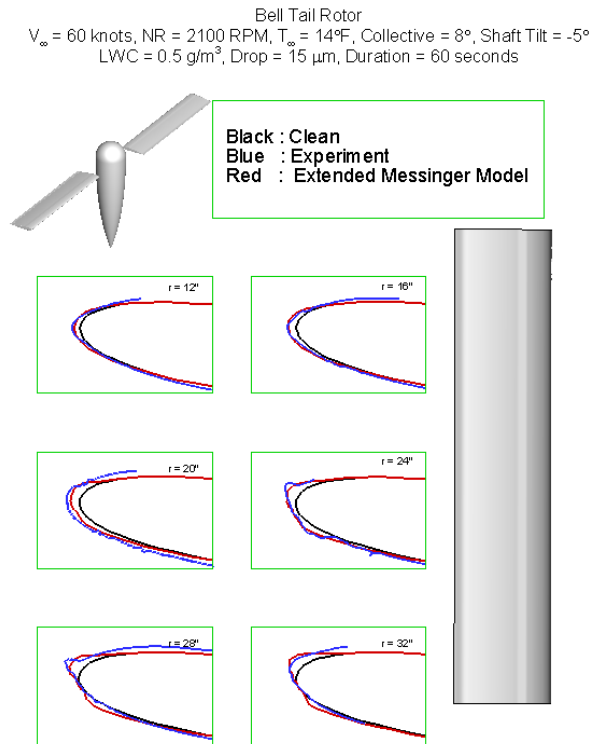


Figure 6. Computed and Measured Ice Shapes for a bell Two-Bladed teetering Tail Rotor tested at 60 Knots at NASA Glenn Research Center (Reproduced from Ref. 11)

The analysis indicated that the required power, after 180 seconds of ice accretion, increases by 35% while thrust is decreased by 16% compared to clean rotor. The computed and measured thrust values were in reasonable agreement. The predicted power for the clean rotor was also well captured. Predicted power for the iced rotor, however, was lower than the experiment due to the lack of a surface roughness model, and the attendant rise in profile power, in the high-fidelity approach.

The flow solver used in Reference 11 has recently been extended to multirotor configurations, allowing full nonlinear wake interactions, as discussed in Ref. 18-21. Additionally, the droplet transport model has been fully integrated into the Navier-Stokes analysis, allowing for full two-way interactions between the water droplets and air flow, as discussed in Ref. 18. The collection efficiency of the water droplets on the

surface (a non-dimensional representation of the amount of water entering the thin water layer above the rotor surface prior to freezing), the surface skin friction data, and the surface pressures are saved in a format that may be directly used with LEWICE, and the in-house ice accretion model GT-ICE. As a result of these enhancements, multirotor drone configurations may now be modeled under rain and icing conditions.

Sample calculations are presented here for a tandem rotor tested by Sweet (Ref. 23) shown in Figure 8. Both the rotors have an identical radius of 2.32 m (7.62 feet), with a rectangular planform, and an identical solidity of 0.0968 each. Overlapping and non-overlapping cases, with no vertical offset, have been experimentally studied. These configurations have been modeled in detail for dry rotors in Ref. 19. The effect of rain on the rotor has subsequently been studied in Ref. 18.

At a nominal thrust coefficient of 0.004, at a tip speed of $\sim 130 \text{ m/s}$, this tandem rotor system would generate a thrust force of ~ 2800 Newton ($\sim 629 \text{ lb}$), representative of a large-scale system capable of carrying a payload of ~ 930 Newton ($\sim 210 \text{ lb}$, 30% payload fraction), requiring $\sim 15 \text{ KW}$ in hover ($\sim 20 \text{ HP}$). For this reason, this configuration has been chosen in this study.

The very high values of LWC considered in Ref. 11 were purposely chosen to establish the icephobic characteristics of various blade coatings, as also seen in Table 2 earlier. For this reason, in the present study, the LWC was set to 0.25 g per cubic meter.

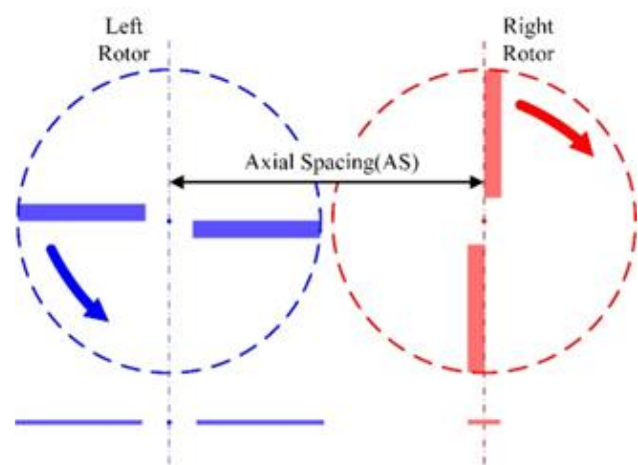


Figure 7. Tandem Rotor Configuration tested by Sweet (Ref. 23)

Warm weather conditions, with ambient temperatures well above the freezing temperature, are considered first. Figure 8, reproduced from Ref. 17, shows the computed and measured power for the dry rotor, as well as wet rotor for two LWC values.

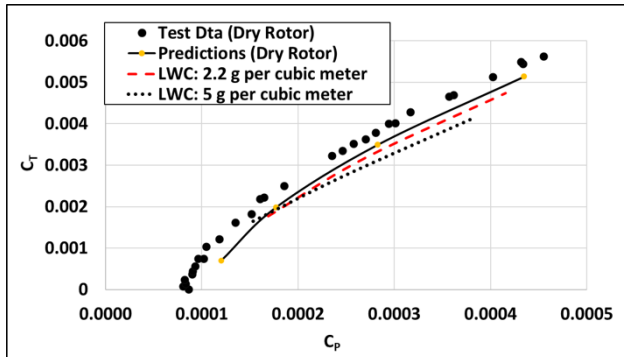


Figure 8. Tandem Rotor Performance in Hover under Dry and Wet Conditions, warm temperatures (Ref. 17)

The above simulations with Spalart-Allmaras model with an empirically prescribed transition model (Ref. 17) tend to predict higher profile power. As a result, the predicted total power is higher than measured data. Additional work is needed to improve the performance of the analysis to properly account for transition effects, and surface roughness effects attributable to ice formation. It is also seen that the power coefficient increases for a given thrust setting, as the liquid water content is increased.

In addition to integrated hub forces and moments, the high-fidelity flow field analysis provides a wealth of information on the sectional loads, surface pressure and skin friction data, radial variation of sectional load, and collection efficiency. This information may be used in LEWICE, or in the in-house ice accretion model GT-ICE (Ref. 11) to compute the ice shape at user specified time levels.

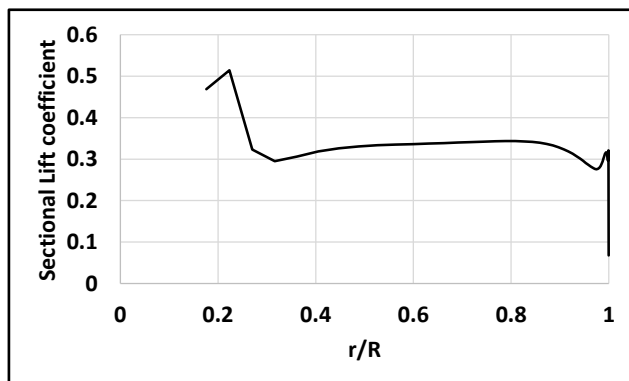


Figure 9. Radial variation of Sectional Lift Coefficient at 8 Degree Collective Pitch for the Front Rotor

Figure 9 shows the radial variation of sectional lift coefficient at 8-degree collective pitch for the front rotor. The sharp rise in lift near the root is attributable to the upwash caused by the root vortex, and a smaller rise in lift coefficient near the tip is attributable to the upwash caused by the contracting tip vortex. Much of the rotor operates at a near constant nominal lift coefficient of 0.33, which corresponds to an effective angle of attack of 3 degrees for NACA 0012. This effective angle of attack, along with ambient conditions, has been used to compute the iced airfoil shapes within LEWICE, utilizing the panel method and the interactive boundary layer method within LEWICE.

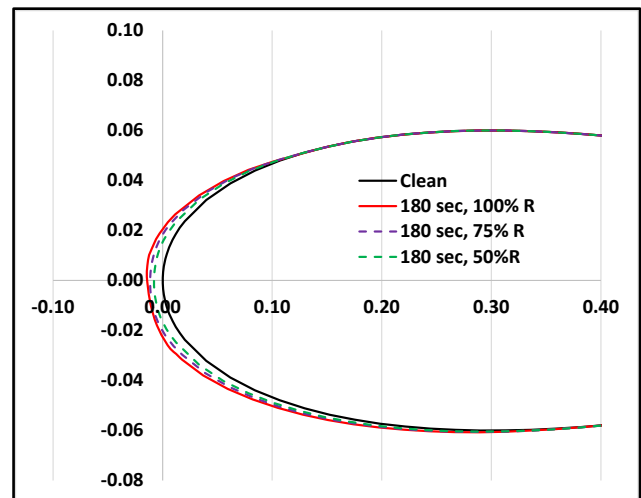


Figure 10a. Rime Ice Shapes at Selected Radial Locations for the Tandem Rotor, -15 degrees Celsius, LWC of 0.25 grams per cubic meter.

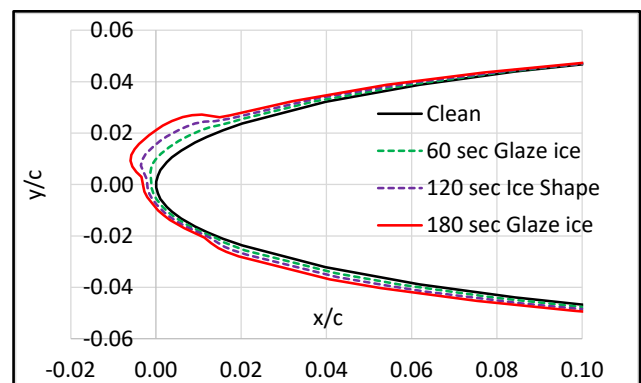


Figure 10b. Computed Glaze Ice Shapes for the Tandem Rotor at 75% Radius at Selected Time Levels

Figure 10a shows the computed iced geometry after 180 seconds of ice accretion, at an ambient temperature of -15 degrees, LWC of 0.25 grams per cubic meter, at several radial locations. Near the

rotor tip, the amount of water collected in the water layer is higher due to the higher tip speed, leading to a somewhat thicker ice shape compared to inboard stations. The iced shape had a slight nose-down droop, due to the asymmetric growth of ice on the upper and lower surface.

Figure 10b shows the growth of the glaze ice shape (at a warmer temperature of 268 degrees K) at 75% radius. In the glaze ice case, some of the water deposited on the rotor runs back over the rotor surface prior to freezing, compared to the rime ice case (258 deg K) where the freezing occurs in the immediate vicinity of the leading edge.

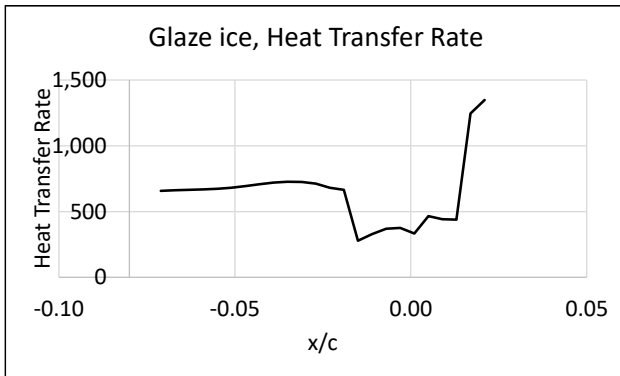


Figure 11. Surface Heat Transfer Rate at 75%R for the Tandem Rotor indicating Transition Locations

The roughness of the iced surface causes transition to occur prematurely for both the glaze and rime ice configurations. Figure 11 shows the surface heat transfer rate, as predicted by LEWICE, for the glaze ice case. It is seen that transition (as indicated by an abrupt rise in the heat transfer coefficient) occurs within the first 3% of the chord. For the baseline rotor, on the other hand, transition occurs downstream of 25% chord on the upper surface, and much of the lower surface experiences laminar flow.

The iced rotor configuration after 180 seconds was reanalyzed using GT-Hybrid, at the same 8-degree collective pitch as the dry rotor, assuming fully turbulent flow. Figure 12 shows the radial variation of $C_n(M)^2$ where M is the section Mach number. It is seen that the ice shape produces a small increment in thrust production, only in the tip region. The integrated rotor thrust coefficient of the dry rotor C_T at this collective pitch was 0.00514, compared to the rotor with the rime ice shape (C_T equal to 0.00536) and the glaze ice shape (C_T equal to 0.00510). This small increase in thrust for the rime ice rotor is likely caused by the asymmetric growth of ice shape,

causing a slightly drooped leading edge. Additional work is needed to verify this hypothesis.

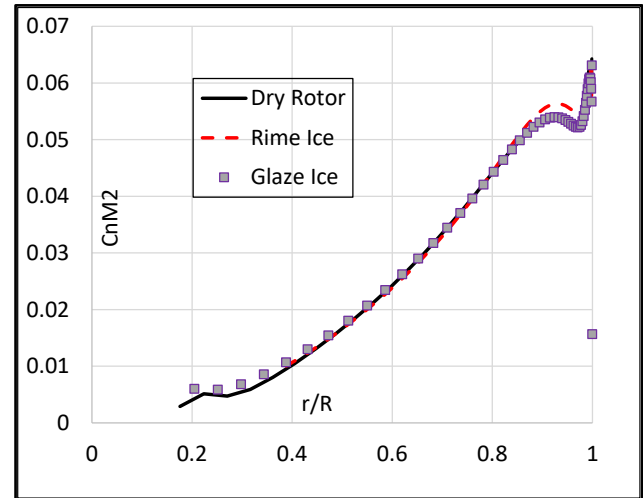


Figure 12. Radial variation of Thrust Production for the Clean and Iced Rotors for Rime Ice Shapes Shown in Fig 10.

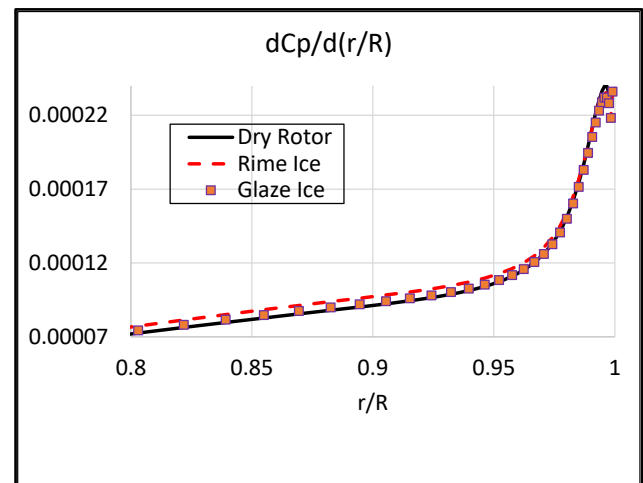


Figure 13. Radial variation of Power Consumption for the Clean and Iced Rotors for Rime Ice Shapes Shown in Fig 10.

Figure 13 shows the radial variation of power consumption for the clean and rime-iced rotor configurations. It is seen that the power consumption is uniformly high over the entire radius. This increment is primarily due to the rise in profile drag for the rime ice shapes, caused by the early transition of the flow to turbulent flow at the leading edge. The integrated power coefficient for the dry rotor is 0.000435 at this pitch setting, while the rime iced rotor has a power coefficient of 0.000490. The glazed ice shape had a power coefficient of 0.000480. This represents a 10% to 12% increase in required power for the iced rotor after 3 minutes of ice growth.

5. CONCLUDING REMARKS

Two approaches, one based on the classical blade element momentum theory with precomputed drag polars, and a fully 3-D Navier-Stokes/free wake analysis have been used to model propellers and drone rotor configurations. The low-cost BEM approach provides first order estimates of the loss in thrust and rise in power consumption and is considered a useful approach for quickly evaluating the ability of rotors to operate under a wide range of icing conditions. Application of the BEM approach to multi-rotor configurations with interacting/interfering wake structures would be difficult since the inflow models do not capture the changes to the inflow due to the interactions. The computationally more expensive Navier-Stokes simulations, on the other hand, are well suited for single rotor as well as multirotor configurations.

For tandem rotor drones operating well below stall conditions in cumulus clouds at low altitudes, the iced rotor simulations for a LWC of 0.25 g/m³ indicate a 10% to 15% increase in power after 3 minutes of icing with negligible impact on thrust. This increase in power consumption is well within the reserve power margin for drones powered by a piston engine or electric motors. As a result, the vehicle would be able to safely descend to lower altitudes below the cumulus clouds.

The calculations for the Quebec rotor using the low fidelity approach, and the calculations for the tandem rotor with the higher fidelity approach, both indicate the critical role transition to turbulent flow due to iced surface roughness plays on the rotor power. During the first few minutes of icing, and for low values of liquid water content encountered at low altitudes, transition due to surface roughness is the primary consideration in evaluating the operability and availability of a drone or an UAS system. Transition location also affects the rate of ice accretion. Additional work is needed to understand the effects of surface roughness on the ice accretion and on profile power, both.

Author contact:

Avani Gupta avani.gupta@linde.com

Aishwerya Gahlot aishwerya@gatech.edu

Lakshmi N. Sankar lsankar@ae.gatech.edu

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