Full-Scale Testing of a Centrifugally Powered Pneumatic Deicing System for Helicopter Rotor Blades

Matthew Drury
Research Assistant
The Pennsylvania State University
University Park, PA 16802

Joseph Szefi
President
Invercon LLC
State College, PA 16801

Jose Palacios
Professor of Aerospace Engineering
The Pennsylvania State University
University Park, PA 16802

ABSTRACT

A full-scale centrifugally powered pneumatic deicing system for helicopter blades was developed. The designed system makes use of the pressure differential created within a spinning rotor blade to deform a 0.03 in. (0.762 mm) thick metallic leading edge cap, producing the transverse shear stresses necessary to delaminate accreted ice. Two prototype designs were fabricated and parametrically tested. Both designs consist of a stainless steel leading edge cap tied to the blade surface via flexible stainless steel ribs. The leading edge section is sealed to the blade surface such that it can be pressurized, inflating and deflating as a microvalve is cycled between high and low pressure lines that run along the blade span. Both designs were fabricated and installed on a truncated 12 in. (0.3048 m.) span K-MAX blade section. Icing testing of the prototypes was conducted at The Pennsylvania State University Adverse Environment Rotor Test Stand. Input pressures representative of those produced by centrifugal pressures generated along a full-scale 24 ft. (7.3 m.) radius blade rotating at 270 RPM were provided to the prototypes via a pneumatic slip ring. Parametric testing of the two configurations demonstrated the superiority of one of the designs. The selected configuration was reproduced and installed on the outboard 8 ft. section of a full-scale 24 ft. (7.3 m.) K-MAX blade. Full-scale icing testing was conducted at Kaman's whirl tower during the month of February. A portable icing cloud generator capable of providing 40 minutes of continuous icing through 12 NASA Standard icing nozzles was developed to provide representative icing conditions. A second cloud generator providing uncontrolled water droplet sizes was also implemented due to power availability limitations to operate the portable icing cloud generation system. The full-scale system was tested at static air temperatures within the Federal Aviation Regulation (FAR) Part 25/29 icing envelope and was able to delaminate ice thicknesses as small as 0.08 in. (2.03 mm.) at 270 RPM.

Nomenclature

LWC	Liquid Water Content, g/m^3
MVD	Water droplet median volume diameter, µm
P	Air Pressure, Pa
r	Rotor blade radial location, m
R	Rotor blade radius, m
Ω	Rotor speed, rpm
ρ	Air density, kg/m^3

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INTRODUCTION

The mission of the rotary wing aircraft is typically one which requires operation in extreme environments, often at a moment's notice, which can lead the helicopter into icing conditions. When the vehicle enters these conditions, super-cooled water droplets impact and freeze to the leading edge of the blade. The buildup of ice alters the aerodynamic characteristics of the blade and results in unwanted effects such as reduced lift, and increased drag, as well as increased weight and blade vibrations[1]. As the leading edge shape is changed, blade profile drag rises, requiring a greater collective input by the pilot. If the aircraft continues to operate in these conditions with no protection, maximum engine power will be required to maintain level flight[1, 2]. When ice shedding does occur due to centrifugal forces acting on the accreted ice, it will almost never occur simultaneously on opposing blades without the presence of a deicing system. This asymmetric shedding creates large rotor mass imbalances that can subject the airframe to unacceptable levels of vibration[2].

Currently, electro-thermal is the only system certified by the FAA to protect helicopter rotor blades. Often, these systems require such large amounts of power (usually 25 W/in^2) that they exceed the capacity of available electrical system, requiring the addition of a secondary alternator, and therefore increasing the overall weight of the system. Total overall system weights for mid-sized helicopters can range from 100-200 lbs. (45.4 kg. to 90.7 kg.) [3]. The high power output also limits the duration for which the system can be run. Electro-thermal deicing systems melt the blade-ice interface via heating elements bonded to the inner surface of the leading edge. The system is activated once the accreted ice has reached a critical thickness (typically up to 0.25 in., 6.35 mm ice thickness) and relies on centrifugal loads to shed the accreted ice [3]. There is no control over the azimuthal location where ice shedding occurs, and therefore introduces a ballistic concern, since debonded ice could impact the tail of the vehicle, be ingested by the engine, or impact the fuselage in the case of tilt-rotor configurations.

Pneumatic deicing boots have been used successfully since the 1920's to protect fixed-wing aircraft and were migrated to helicopter proof-of-concept testing in the 1980's. The use of pneumatic deicing systems for fixed-wing applications is straightforward, requiring little more than a rubber boot bonded to the leading edge of the lifting surface. This boot inflates to debond accreted ice which is then carried away by airflow over the surface. The application of pneumatic deicing systems to rotorcraft requires complex pneumatic slip-rings to transfer engine bleed air to the rotors. In the un-deployed state these systems create undesirable increases in required power for level flight and excess vibrations in the deployed state. These factors, along with the erosion of the polymer boots, has hindered development of pneumatic deicing systems for rotor blades[4].

A centrifugally powered pneumatic deicing system for helicopter rotor blades has been developed by Palacios et al[5]. This system uses the pressure differential created by a spinning rotor blade and consists of two tubes that run from root to tip. The high pressure channel is open at the root and sealed at the tip while the low pressure line is of the opposite configuration, as seen in Figure 1. The pressure, p, at any point in the channels can be calculated with the relation shown in Equation 1.

$$\frac{dp}{dr} = \rho(r) r \Omega^2 \qquad (1)$$

where ρ is the density of the fluid, r is the radial location along the blade and Ω is the rotor speed. The generated pressures by centrifugal forces acting on the columns of air inside the tubes are then used to deploy a pneumatic boot, resulting in debonding of the accreted ice. In the undeployed state, suction from the negative air pressure line along with the stiffness of the leading edge cap prevents the cap from being pulled away from the blade surface by aerodynamic pressures. The pressures generated in a 24 ft. (7.3 m.) radius Kaman K-MAX blade have been experimentally measured by Szefi et al for a rotor speed of 280 rpm and are displayed in Figure 2[6].

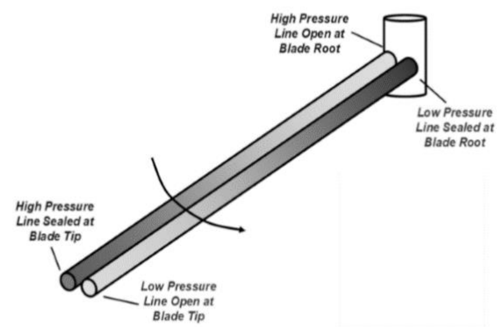

Figure 1. Schematic depicting pressure differential created by a rotating cylinder [5].

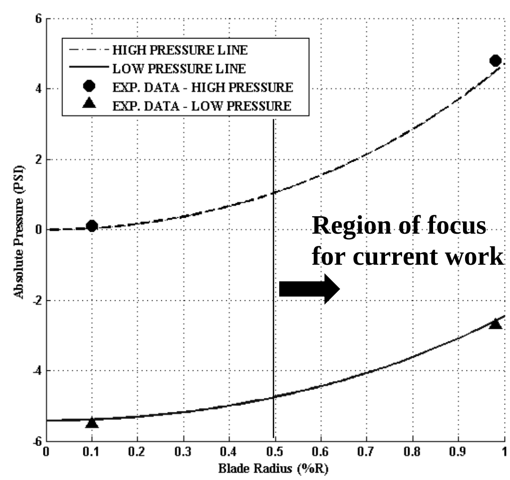

Figure 2. Pressure differential available for centrifugal pumping measured along span of a 24 ft. (7.3 m.) radius rotor blade [6].

The pneumatic deicing system developed by Palacios et al [6] consisted of polyolefin tubing bonded to both an erosion resistant leading edge cap on one side and to the blade on the other as depicted in Figure 3. Pressurization of the tubing introduced the transverse shear stresses necessary to promote delamination in the ice leading edge interface. To achieve the pressures representative of those generated on the full-scale K-MAX blade, a pneumatic slip ring was used in The Pennsylvania State University's Adverse Environment Rotor Test Stand (AERTS) facility, since the truncated span blades are not able to reproduce such pressures. Results from this testing confirmed that this system was capable of delaminating ice of thicknesses ranging from 0.06 in. to 0.1 in. (1.524 mm. to 2.54 mm.). However, it was observed that the polyolefin tubing became stiff at the lower temperatures of the Appendix C icing envelope. This resulted in an increase in the accreted ice thickness necessary for centrifugal forces to assist with shedding, due to the degraded performance of the deicing system.

The research effort presented in this paper describes improvements to the pneumatic deicing system design presented by Palacios et al.[5], as well as a full-scale test to demonstrate the deicing capability of centrifugally powered pneumatic deicing.

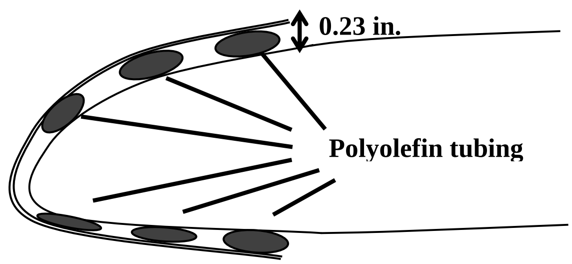

Figure 3. Schematic of pneumatic deicing system developed by Palacios et al [5]. System deformation is exaggerated.

OBJECTIVES

The goal of the presented research is to conduct full-scale rotor ice testing of a centrifugally powered pneumatic deicing system. The effort will focus on protection of the outboard half (0.5r/R to R) of a 24 ft. (7.3 m.) radius K-MAX blade. This region is illustrated in Figure 2. The objectives of this work are: 1) Design a centrifugally powered pneumatic deicing system without the use of inflatable rubberized structures, 2) Evaluation of the selected prototype under rotor icing conditions in the AERTS facility using truncated rotor blades, 3) Integration of the selected system into the outer tip region of a full-scale K-MAX rotor blade, 4) Design and testing of a portable ice cloud generator system to assist with the creation of icing clouds surrounding a full-scale whirl tower, 5) Rotor ice testing evaluation of the full-scale prototype.

PROTOTYPE DESIGNS

Two centrifugally powered pneumatic deicing system prototypes were designed, fabricated, and tested at the AERTS facility. The goal of the first design was to address the issue of diaphragm stiffening at cold temperatures encountered by Palacios et al[5]. This was accomplished by eliminating the polyolefin tubing and using the metallic leading edge as the pressure sealing surface. A single pressurized zone was separated by chord-wise 0.005 in. (0.127 mm.) thick strips of 1095 Carbon Spring Steel bonded to the blade and leading edge cap, located both on the upper and lower surfaces as seen in Figure 4.

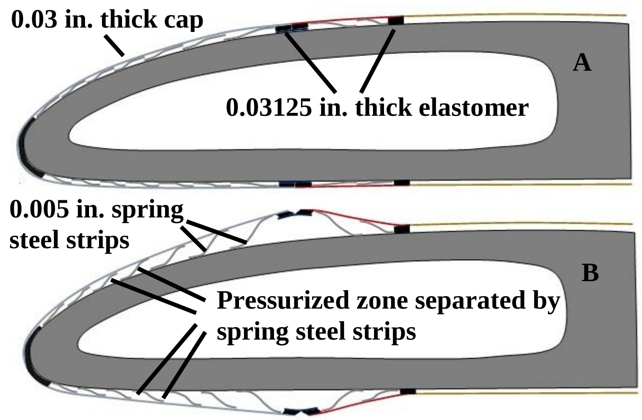

Figure 4. Initial prototype pneumatic deicing design show in deployed (B) and undeployed (A) states. Deflection is exaggerated.

During system actuation, the bonds are subjected to large shear stresses created by centrifugal loads. For this reasons a high shear strength methacrylate adhesive (Loctite H4500) was selected to bond the spring steel to the blade and cap. Adhesion strength testing was conducted on the adhesive to verify manufacturers quoted strengths as well as to confirm the surface preparation of the substrates to be bonded. A standard lap joint shear[7] method was used for this test. The quoted shear strength for this adhesive on steel is 3000 psi (20.7 MPa). Adhesion strength testing revealed a shear strength of 2755 psi (19 MPa), 8% lower than the value quoted.

The leading edge cap material used was comparable to that currently used for rotorcraft blade leading edge caps, 0.030 in. (0.762 mm) thick 304 stainless steel. In an effort to maintain the original aerodynamic shape of the airfoil, the original 0.03 in. (0.762 mm.) thick metallic leading edge cap was removed from a K-MAX blade and the new system was installed in its place.

Helicopters operate in harsh environments and are constantly subject to aggressive flight maneuvers that impart high aerodynamic pressures on blade surfaces. However, for the first prototype, the negative air pressures produced by centrifugal pumping provided the only force to hold the leading edge cap onto the blade surface normal and aggressive flight maneuvers. Therefore, an aggressive maneuver could potentially create aerodynamic pressures large enough to pull the leading edge cap away from the blade surface, altering the helicopter's flight characteristics unknowingly to the pilot. A second prototype design was developed to yield a system that was capable of surviving these extreme flight conditions while still producing the stresses necessary to promote ice delamination. To accomplish this, the leading edge cap was constructed from two 0.015 in. (0.381 mm.) thick 304 stainless steel sheets bonded together. The inner sheet was segmented spanwise along the leading edge and 1 in. (25.4 mm.) aft of the leading edge on the top and bottom surfaces. This was done to introduce localized stresses in critical ice accretion areas while maintaining overall cap thickness and comparable stiffness. A 0.0625 in. (1.586 mm.) thick ethylene propylene diene monomer (EPDM) elastomer was bonded to the inner surface of the cap trailing edge and the blade surface, creating flexible attachment points. An illustration on the second system design is shown in Figure 5.

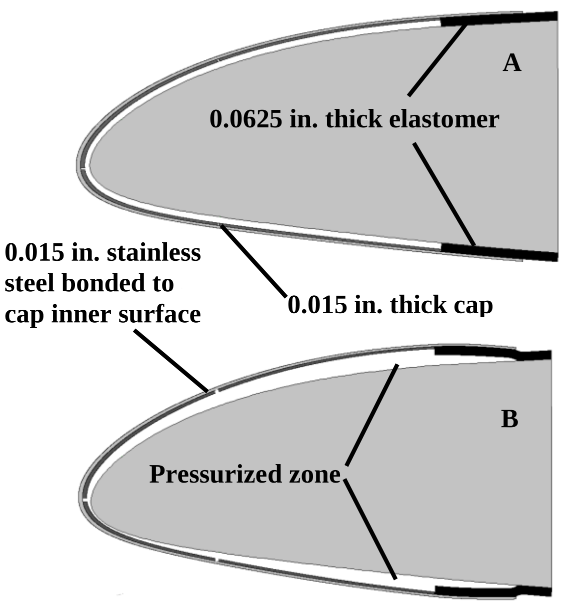

Figure 5. The second design has a flexible attachment point at the aft portion of the cap and is less constrained forward of this point. Deflection is exaggerated in B.

Both systems were controlled by a microvalve located at the root of the blade that oscillate at a low frequency to deflect and retract the leading edge cap during icing conditions.

ROTOR ICING TESTING

Both prototype deicing systems were installed on 12 in. (0.3048 m.) truncated paddle sections of a Kaman K-MAX blade and mounted at the tip of a 36 in. (0.914 m.) radius carrier blade. Each system was tested separately at the AERTS facility. A schematic of the test facility is provided in Figure 6. To evaluate the systems deicing capability, a test matrix was developed which reproduced centrifugally generated pressures experienced along the outboard half (0.5r/R to R) of a 24 ft. (7.3 m.) radius blade operating at 280 RPM. The radial pressures along the same blade were measured by Szefi et al.[6] and are shown in Figure 2. These pressures were used as the basis for testing.

Since the span truncated prototype blades are not capable of producing the necessary pressures, a pneumatic slip ring was used to deliver the desired pressures to the deicing system. Due to blade manufacturing limitations and blade imbalances upon shedding, the rotor speed tested was 450 RPM for the first design, producing a centrifugal acceleration equivalent to that seen at 0.5r/R of the 24 ft. (7.3 m.) blade. The first prototype was tested at a temperature of -14^{o}C, MVD of 20 µm and LWC of 1.9 g/cm^3.

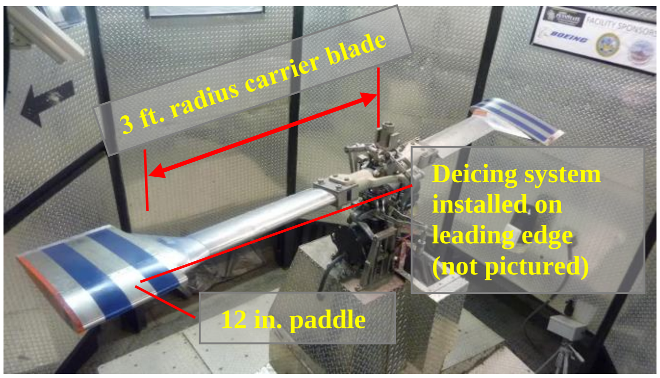

Figure 6. AERTS facility used for prototype ice testing.

For prototype icing tests, blade spool up to the desired RPM (450 for prototype 1 and 385 for prototype 2) was done with the deicing system undeployed. When the desired rotor speed was reached, the icing cloud was turned on for the allotted time. At the end of icing time, the cloud was turned off and the deicing system was then cycled to delaminate accreted ice. Once ice shedding occurred or was decided would not occur in the current condition, the rotor was spooled down and the paddle test area was examined.

In Table 1 a testing summary for the first prototype is given and lists the average ice thicknesses required for shedding at input pressures representative of those produced by centrifugal pumping at various radial locations along a 24 ft. (7.3 m) K-MAX blade. The pressures and suctions applied were determined from Figure 2. As expected, the minimum ice thickness required for shedding increases with decreasing radial location along the blade due to a decrease in available pressure and centrifugal force. A sample photograph of the first prototype before and after system actuation is shown in Figure 7.

The second prototype was again, due to blade imbalances upon ice shedding, unable to operate at an RPM representative of the centrifugal acceleration seen at the tip of a 24 ft. (7.3 m.) radius rotor. Instead, tests were run at 385 RPM. Note that testing at reduces RPM is a conservative approach, since there will be reduced forces assisting with the ice removal process. Icing conditions were identical to that of the first prototype with an LWC of 1.9 g/cm^3, and an MVD of 20 µm. An additional warmer temperature was added to the test matrix to examine the system's performance in different icing regimes.

Table 1. First Prototype Test Summary.

KMAX r/R	Temp. (^{0}C)	Pressure (psig)	Suction (psig)	Ice Thick. (in)
1	-14	4.5	-3	0.25
0.9	-14	4	-3	0.28
0.7	-14	2	-5	0.32
0.5	-14	1	-5	0.39

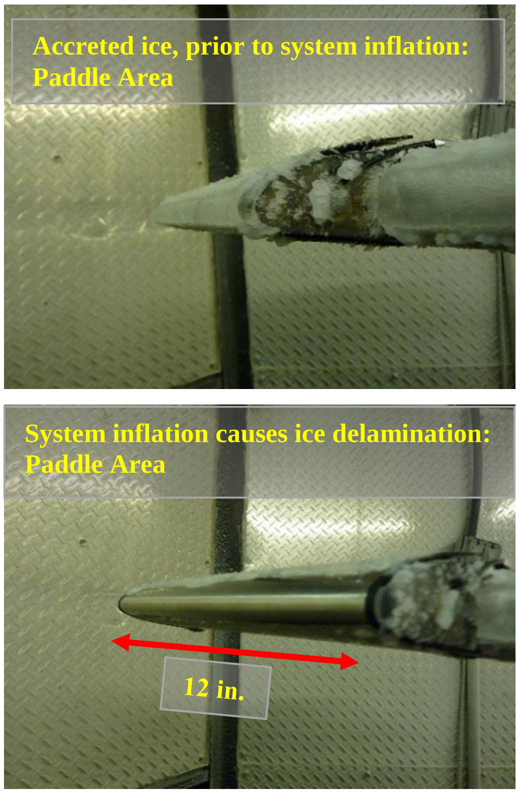

Figure 7. First prototype before and after system deployment.

Results from testing of the second prototype are summarized in Table 2. Glaze ice regimes can be recreated at temperatures warmer than -10°C [8]. In this regime, ice has a lower adhesion strength as demonstrated by Soltis[9]. The failure mode of the pneumatic deicing system relies on transverse shear stresses to fracture accreted ice. Therefore, it was expected that the system would perform better at lower temperatures where ice is less compliant. The predicted behavior is seen in Table 2.

At low temperatures, the second prototype was able to remove ice 0.078 in. (1.98 mm.) thick with centrifugal pressures corresponding to those seen at the tip of a 24 ft. (7.3 m.) radius blade, with centrifugal acceleration representative of only 50% radius. The system was not tested at a KMAX r/R of 0.5 and -14°C. However, the required ice thickness for shedding could be estimated from the linear trend of the preceding data points.

Table 2. Second Prototype Test Summary.

KMAX r/R	Temp. (°C)	Pressure (psig)	Suction (psig)	Ice Thick. (in)
1	-14	4.5	-3	0.078
0.9	-14	4	-3	0.097
0.7	-14	2	-5	0.133
0.5	-14	1	-5	--
1	-5	4.5	-3	0.11
0.9	-5	4	-3	0.15
0.7	-5	2	-5	0.17
0.5	-5	1	-5	0.2

To compare the performance of the two prototype deicing systems, the minimum ice thickness required for delamination was normalized by g's of centrifugal acceleration experienced at 0.9r of the 1.422 m carrier blade. This was done because the first and second prototype were not tested at the same rotor speed. The minimum ice thickness required per g is illustrated in Figure 8. Comparing results from the first and second prototype, the ice thickness required for ice delamination for the second design is 58% lower than that of the first at input pressures equivalent of those generated at tip of a 24 ft. (7.3 m.) rotor blade. A sample photograph of the first prototype before and after system actuation is shown in Figure 9.

The second design proved to debond thinner ice layers at equal input pressures. The second design was chosen to be implemented to a 24 ft. (7.3 m) radius K-MAX blade to perform full-scale testing.

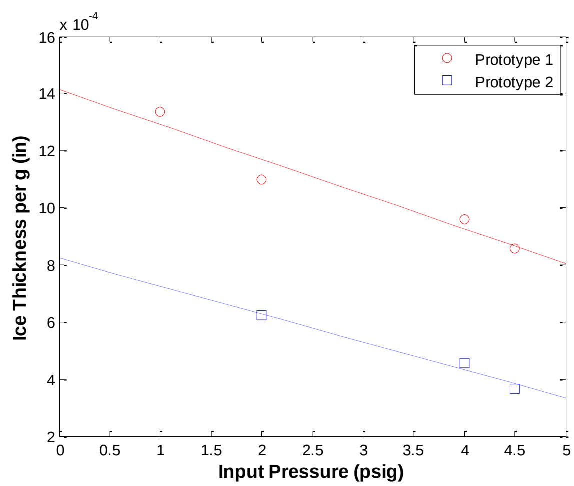

Figure 8. Comparison first and second prototype minimum ice thickness required for delamination at -14°C.

PORTABLE ICING CLOUD GENERATOR

Currently, rotor ice testing of a full-scale blade requires the use of one of two facilities: The Helicopter Icing Spray System (HISS) or McKinley Climactic Laboratory. A third option would be to test the vehicle in natural adverse weather conditions. Mentioned approaches are cost prohibited for prototype development. Penn State has developed a portable icing cloud generator to allow testing of full-scale blades at a reduced cost. The cloud generator consists of twelve NASA Standard icing nozzles arranged on spray bars which are mounted to an 8 ft. (2.44 m.) diameter fan as shown in Figure 10. The system is portable and requires a source to refill its water supply, and power to provide air pressure to the system. A schematic of the system is provided in Figure 12.

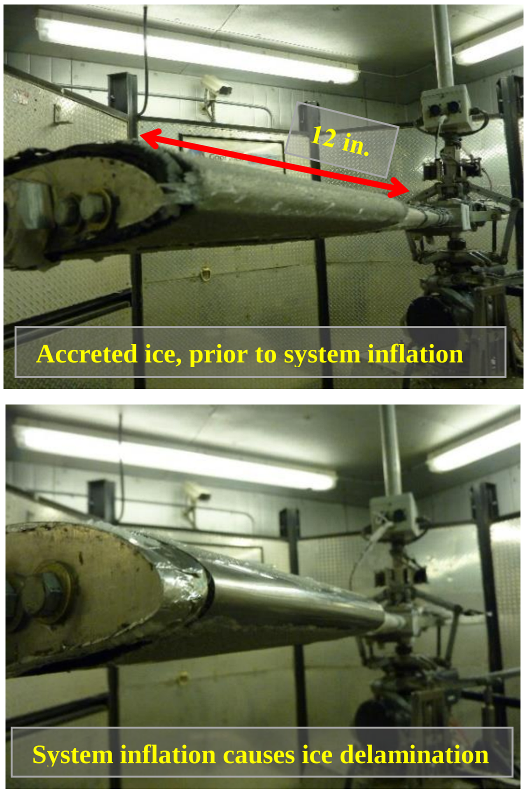

Figure 9. Second prototype before and after system deployment.

The nozzles operate by aerosolizing air and water to produce an icing cloud. Droplet size is controlled by maintaining specific air and water input pressures as per calibration curves of Figure 11 [10]. Selected nozzles instrumented with pressure sensors, along with electronic pressure regulators, are used as inputs to a feedback control loop that maintains the desired MVD. Each nozzle consumes up to 15 CFM of air for an input pressure of 50 psi (344.7 kPa) [11]. A 30 HP air compressor supplies the required air flow rates to the nozzles as well as to pressurize two 40 gallon (151.4 liter) hydro-pneumatic water tanks. These tanks are filled by pumping water through a reverse osmosis filter which purifies the water to 1 ppm.

Electronic air and water shutoff valves allow the icing cloud to be turned on and off remotely and are controlled by a custom Lab View code. Unlike an icing wind tunnel or Penn State's AERTS facility, during operation the entire system is exposed to extreme temperatures. For this reason, all components that come in contact with water are insulated and heated. Also, a bypass valve sends air through the water lines when the water valve is closed to help prevent the lines from freezing.

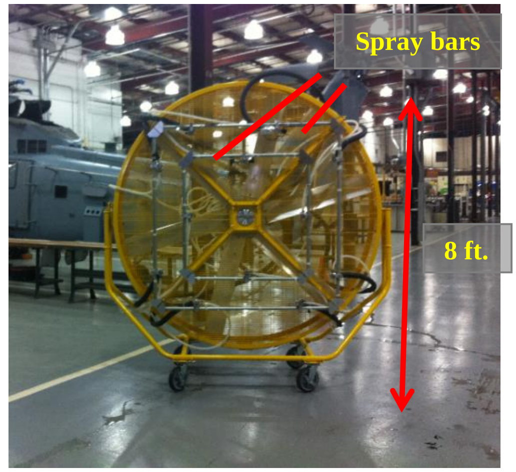

Figure 10. Twelve NASA Standard nozzles are attached to spray bars mounted on an 8 ft. diameter fan.

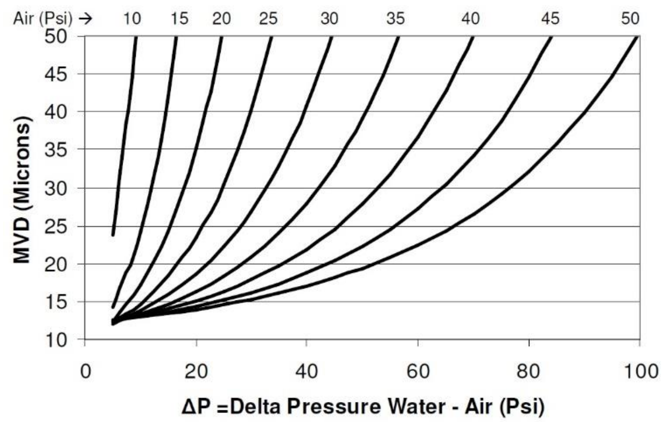

Figure 11. NASA Standard icing nozzle calibration curves [10].

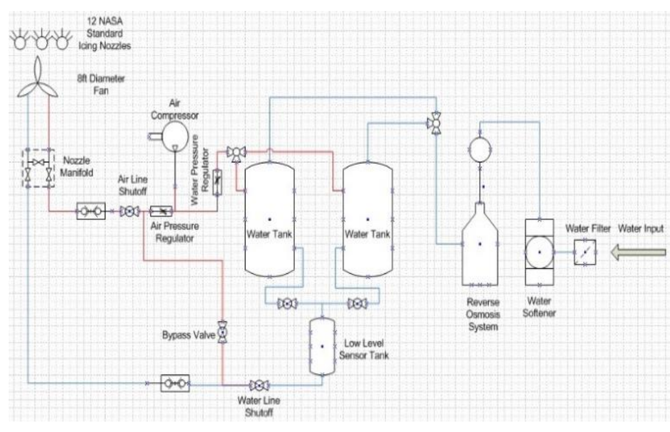

Figure 12. Schematic of portable icing cloud generator.

FULL-SCALE BLADE MODIFICATIONS

A 24 ft. (7.3 m.) radius Kaman K-MAX blade was supplied by Kaman and delivered to Penn State for installation of the deicing system. Lead by Invercon, the blade was fitted with a pneumatic deicing system similar to the second prototype evaluated at Penn State AERTS. The deicing system protected an 8 ft. (2.4 m.) section of the blade measuring from the tip inboard as depicted in Figure 13. Modifications were performed at Penn State and blade balancing was conducted by Kaman at their Bloomfield, CT location.

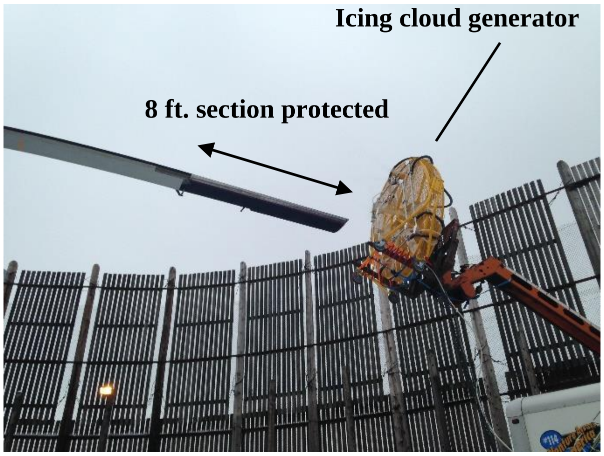

Figure 13. Modified K-MAX blade on Kaman whirl tower.

The leading edge cap was constructed of two 0.0015 in. (0.381 mm.) thick 304 stainless steel sheets bonded together and pressed with a die into the shape of a NACA 23012 airfoil. As with the prototype, the inner cap was segmented spanwise along the leading edge and 1 in. (25.4 mm.) aft on both upper and lower surfaces. The outer 0.01 in. (0.254 mm.) protection layer did not have any discontinuities, providing a smooth aerodynamic surface. Thirteen 6 in. (152.4 mm.) by 4 in. (101.6 mm.) by 0.005 in. (0.127 mm.) thick 1095 spring steel sheets were bonded in an alternating fashion to the top and bottom surface of the blade in the spanwise direction as depicted in Figure 14 and Figure 15. This was done to increase the surface area bonded to the blade while not impeding the cap motion during system actuation. EPDM elastomer was bonded to the blade and inner cap surface to form a flexible seal on all edges. In addition, energy is stored in the spring sheets when elastically deformed to follow the blade contour during installation. This stored energy assists the deicing system in moving the leading edge cap during inflation.

A total bond area of 282 in^2 (1819 cm^2) between the elastomer and spring steel provided a factor of safety of 13, ensuring the deicing system would withstand centrifugal forces during rotation. Strips of 0.015 in. (0.381 mm.) thick 304 stainless steel were bonded on top of the elastomer to reduce the likelihood of tearing as shown in Figure 14.

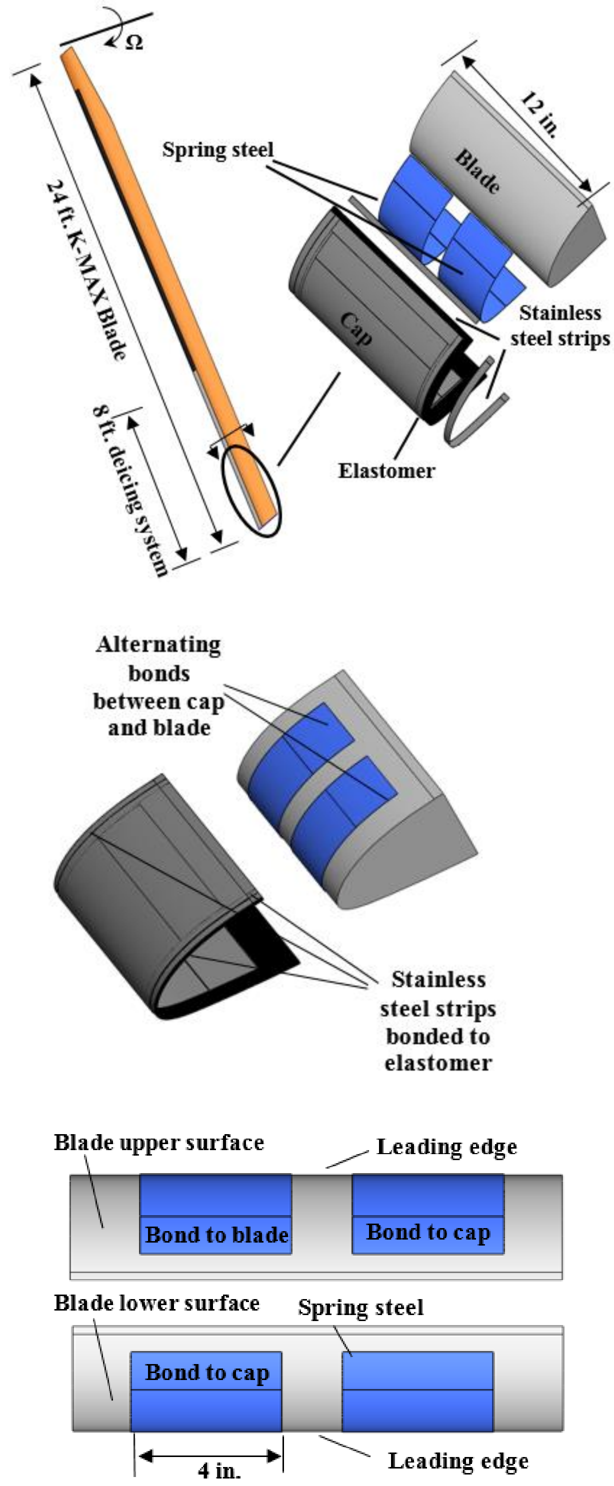

Figure 14. Schematic of deicing system assembly installed on full- scale blade.

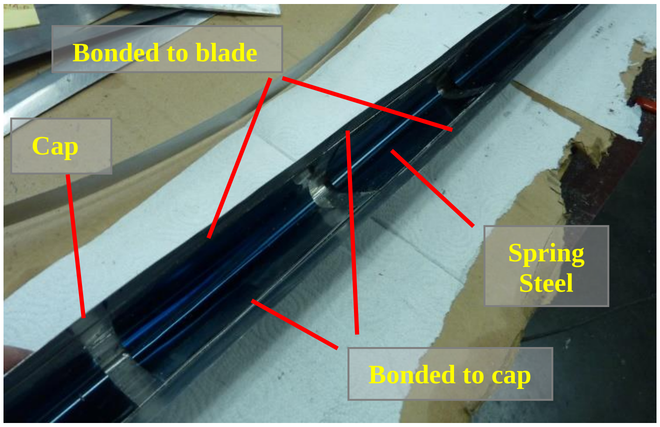

Figure 15. Schematic of alternating spring steel sheets bonded to the inner surface of the leading edge cap.

During bench-top testing, pressure was supplied to the system via a 0.165 in. (4.191 mm.) diameter tube running along the blade leading edge and entered the system at the inboard cap edge. A 0.75 in. (19.05 mm.) diameter low pressure line was installed in the center of the blade and ran from root to tip. This line provides low pressure during rotation. A 24V microvalve located at the blade root was cycled at 0.07 Hz to open and close the 0.165 in. diameter line to atmospheric pressure. When open to atmosphere, centrifugal loads pressurize the air inside the line thus inflating the deicing system. 10 mW of power and a 5V signal to the valve was supplied through a slip-ring and controlled by a data acquisition computer. A Hall sensor was installed near the inboard edge of the system as a method of monitoring the motion of the cap.

The final full-scale pneumatic deicing system provides significant weight and power savings compared to electrothermal deicing systems, which typically require 25 W/in^2 for effective ice protection[3]. The only electrical power draw of the pneumatic system is 10 mW to power a microvalve. Also, a power loss is introduced to the main rotor while compressing the air used to inflate the system, however this loss is negligible (~1 W).

The high power requirements of electrothermal systems often require the addition of additional alternators resulting in a final system weight of 100-200 lbs. (45.4 kg. to 90.7 kg.). Since the pneumatic system consists of only the modification to the leading edge cap and lightweight hoses, and does not require heavy non-rotating electrical components, its weight is comparable to that of the existing protective leading edge cap.

FULL-SCALE ICING TESTING

Testing of the centrifugally powered pneumatic deicing system was conducted at Kaman's whirl stand located in Bloomfield, CT. during the month of February (February 9 – 13 2015). The portable icing cloud generator was also tested during this time, however due to power limitations, sufficient compressed air was not available thus reducing the number of nozzles that could be operated from twelve to four. For this reason the ability of the cloud generator to operate in a cold environment and produce a realistic icing cloud with measurable ice accretion was demonstrated separately before testing the deicing system. In addition to using the portable spray system during initial testing, two water pressure lines producing 2400 psi (16.55 MPa) each and equipped with a 45^0 angle non-air assisted aerosolizing spray nozzle at their tips were used to increase the liquid water concentration in the cloud, speeding-up the ice accretion process. The benefit of direct water pressure nozzles is that the large air flow rates needed for the NASA nozzles in the portable icing system is not required. For the purpose of this test, providing uncontrolled water droplet mixtures of super-large droplets (estimated to range between 40 µm to 400 µm) provides a conservative worst-case ice accretion scenario, since larger droplets at high liquid water concentrations will be generated. The larger particles size and water content will increase the ice accretion impingement limits. Large droplets were visually observed at the exit of the nozzle, and a reduction on droplet size was qualitatively observed at approximately 20 ft. (6.09 m.) from the water output. The water pressure lines were mounted on the ground providing sufficient distance for the reduction in size of the water droplets created. The cloud dissipation provided a more realistic (but unmeasured) droplet size to enter the rotor plane. The cloud LWC was calculated to be 0.6 g/cm^3 with an assumed MVD range of 40-200µm at the rotor plane. A photograph of the final setup is shown in Figure 16. Tests were conducted at static air temperatures ranging from -5°C to -15°C, thus spanning a large portion of the Appendix C icing envelope [12].

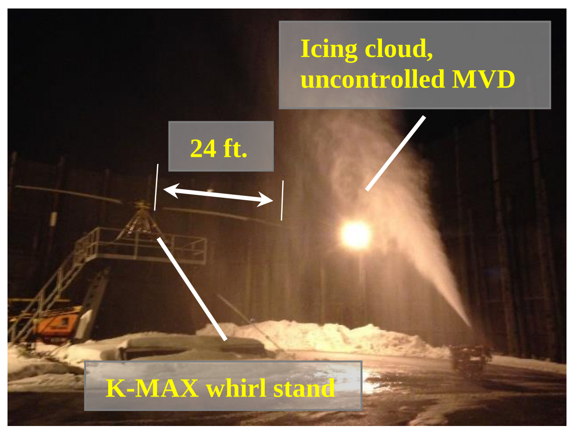

Figure 16. Final icing cloud set up for deicing system testing.

Two different test methodologies for ice protection were explored with the pneumatic deicing system: continuous ice protection and single deicing occurrence. For the continuous ice protection method, ice was allowed to accrete for a set amount of time with the deicing system turned off. At set time intervals the deicing system was turned on and cycled three times at 0.07 Hz and subsequently turned off. This process was repeated throughout the entire test multiple times in an attempt to exercise the ability of the system to operate as it is envisioned during flight (intermittent operation post ice accretion for controlled time intervals). The single deicing method tests consisted of accreting ice for a set time length with the deicing system turned off followed by a 30 second period of cycling the system once the pre-determined icing time had elapsed. After the deicing system was turned off, the rotor was also spun down. A schematic of the test process for single-shot deicing is provided in Figure 17.

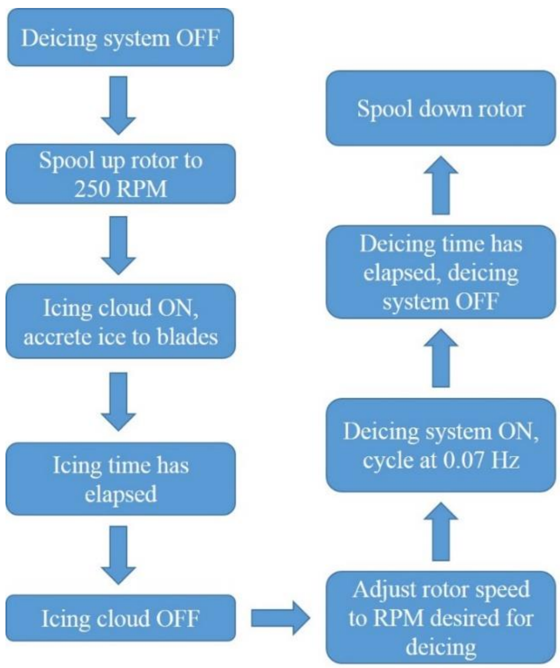

Figure 17. Method for single-shot deicing testing.

For both deicing methods, system deployment was monitored using real-time time data provided by a Hall sensor. A sample of this output is displayed in Figure 18. In the Hall sensor output, system inflation and deflation corresponds to motion of the of airfoil surface. An increase in voltage represents system inflation, while deflation causes a decrease in voltage. Selected icing times were determined by measuring accreted ice thicknesses in early tests. Rotor speed for ice accretion was 250 RPM and was increased to 270 RPM for deicing system deployment in the single shot deicing tests. Rotor speed was held constant at 270 RPM for the continuous ice protection tests. Several tests were also conducted at a deicing rotor speed of 230 RPM to observe the deicing systems ability to operate at lower input pressures and centrifugal forces acting on the ice. Both test methods were successful to remove accreted ice and proved the ability to protect full-scale rotor blades with semi-passive centrifugally powered pneumatic deicing systems. Selected successful deicing test results are presented in Table 3. Detached ice thicknesses measured as small as 0.08 in. (2.032 mm.), and were successfully shed during the single shot deicing tests for a rotor speed of 270 RPM and at temperatures as low as -15°C. Ice thicknesses for a rotor speed of 230 RPM were measured to be as small as 0.1 in. (2.54 mm.). It is worth noting that the minimum thickness required for electro thermal deicing systems is 0.3 in (7.62 mm) [3]. A sample photograph of the protected result of semi-continuous ice protection are shown in Figure 19.

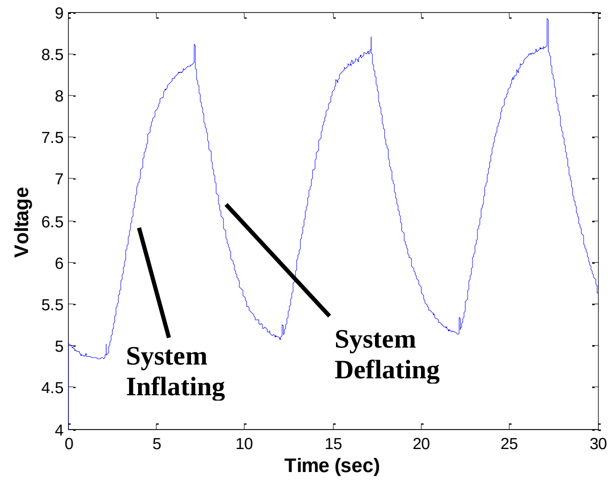

Figure 18. Hall sensor output voltage from a standard deicing test.

Table 3. Sample single-shot deicing test results.

Temp. (°C)	Ice RPM	De-ice RPM	Ice Thick. (in)
-10	250	230	0.1
-12	250	230	0.15
-14	250	270	0.08

The large droplets produced by the non-air assisted nozzles created ice shapes much more severe than what would be encountered in flight. Impingement limits were noted to be further aft than those of standard icing conditions, creating a more difficult ice protection scenario for the deicing system. An example of the severe ice shapes encountered during testing is given in Figure 20. These severe ice shapes were successfully removed by the proposed pneumatic deicing system.

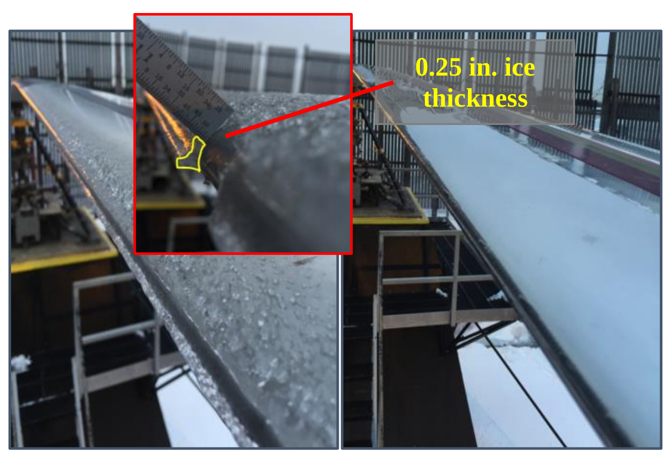

Figure 19. Comparison of protected (right) and unprotected (left) blades after a single-shot deicing test.

During icing tests, it was noticed that a small section of the protected blade consistently left residual ice after the deicing system had been inflated as seen in

Figure 21. It was determined that this portion of the cap was unable to deform completely and thus unable to create the stresses necessary for ice delamination. The restriction of cap movement in this area was attributed to unwanted adhesive bonding during system manufacturing.

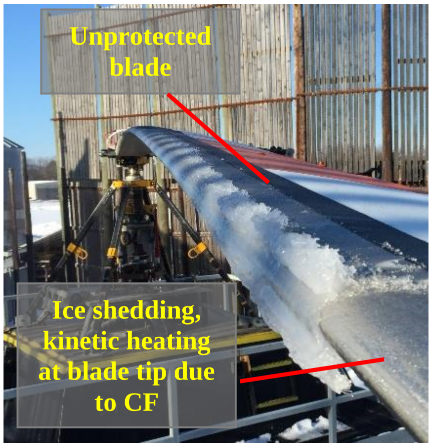

Figure 20. Large water droplets during ice testing created ice shapes more severe than typically encountered.

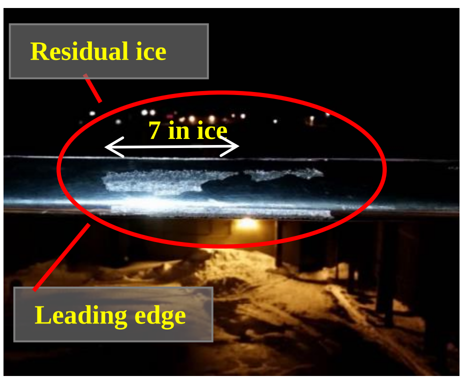

Figure 21. A small portion of the leading edge cap consistently left accreted ice behind after inflation. This was attributed to unwanted adhesive bonding during manufacturing.

CONCLUSIONS

Two prototype centrifugally powered pneumatic deicing systems were developed, fabricated and tested. The system is formed by a stainless steel leading edge sealed to the blade. The metal is deformed by pressures generated by centrifugal forces acting on a column of air inside the blade. Input pressures to the system during truncated span rotor blade prototype testing were provided via a pneumatic slip ring. Results from prototype ice testing showed that a configuration concentrating stresses within the ice accretion impingement limits delaminated ice shapes 69% thinner than deicing configurations that had maximum stresses on a further aft location. A system introducing maximum stresses within the ice impingement limits and consisting of a single pressurized zone was installed on the outboard 8 ft. (2.4 m.) section of a 24 ft. (7.3 m.) radius K-MAX blade. Removal of the existing stainless steel K-MAX leading edge cap allowed the deicing system to be installed in its place (0.03 in thick, 0.762 mm), thus maintaining the original aerodynamic shape of the blade. Full-scale qualitative icing tests were conducted at Kaman's whirl stand. Unlike prototype testing using truncated blades, input pressures to the system were produced by centrifugal forces. The deicing system was successfully tested at static air temperatures within the FAR Part 25/29 Standard Icing Envelope and was able to delaminate ice thicknesses as small as 0.08 in. (7.62 mm.) Specific conclusions that can be drawn from the conducted research are:

1) The current centrifugally powered pneumatic deicing system is capable of delaminating ice thicknesses as small as 0.08 in. (2.032 mm.) at temperatures of -15°C along a blade section spanning 0.6r to the tip of a 24 ft. (7.3 m.) blade. This ice thickness is 73% less than ice thickness required by electro thermal deicing systems (0.3 in., 7.62 mm.).

2) The developed pneumatic deicing system presents significant power and weight savings compared to electrothermal deicing systems. A microvalve requiring 10mW and a small power loss due to air compression (~1W) are the only power sources required for the pneumatic deicing system. The pneumatic system directly replaces existent leading edge caps and introduces minimal weight related to plastic pressure lines spanning the length of the rotor. The system does not require heavy non-rotating electrical components, and its weight is negligibly more than that of the existing protective leading edge cap.

3) A portable icing cloud generator was designed, fabricated and tested. The system was able to provide controllable water droplet size. The system requires a 30 HP air compressor to power all twelve nozzles needed to provide representative in-flight liquid water concentrations.

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Author contact: Matthew Drury, mdd5127@psu.edu.
Jose Palacios, jlp324@psu.edu.
Joseph Szefi, joe.szefi@invercon.net.

REFERENCES

[1]Withington, T., "Bad Vibrations," Aerosafetyworld Magazine, Helicopter Safety, Flight Safety Foundation Feb 2010, pp. 26 – 28.

[2]Gent, R.W., Dart, N.P., and Candsdale, J.T., "Aircraft Icing," Philosophical Transactions of the Royal Society of London Series A, Vol. 358, 2000, pp. 2873 – 2911.

[3]Coffman, H.J., "Helicopter Rotor Icing Protection Methods," Journal of the American Helicopter Society, Vol. 32, No. 2, April 1987, pp. 34 – 39.

[4]Martin, C. A, and Putt, J. C., "Advanced Pneumatic Impulse Ice Protection System (PIIP) for Aircraft," Journal of Aircraft, Vol. 29, No 4, 1992, pp. 714 – 716.

[5]Palacios, J., Wolfe, D., Bailey, M., Szefi. J, "Ice Testing of a Centrifugally Powered Pneumatic Deicing System for Helicopter Rotor Blades," 70th American Helicopter Society Annual Forum and Technology Display, Montreal, Quebec, May 20-22, 2014.

[6]Szefi, J. T., Cormier, B., and Ionno, L., "Full-scale Experimental Validation of Dynamic, Centrifugally Powered, Pneumatic Actuators for Active Rotor Blade Surfaces," 70th American Helicopter Society Annual Forum and Technology Display, Montreal, Quebec, May 20-22, 2014. (D1876-08)

[7]ASTM Standard D1002-10, 2010, "Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded to Metal Specimens by Tension Loading (Metal to Metal)", ASTM International, West Conshohocken, PA. 2008. DOI: 10.1520/D1002.10.

[8]Han, Y. *Theoretical and Experimental Study of Scaling Methods for Rotor Blade Ice Accretion Testing*. University Park, PA: The Pennsylvania State University Department of Aerospace Engineering, August 2011. MS Thesis.

[9]Soltis, J. *Design and Testing of an Erosion Resistant Ultrasonic De-Icing System for Rotorcraft Blades.* University Park, PA: The Pennsylvania State University Department of Aerospace Engineering, August 2013. MS Thesis.

[10]Ide, R., Oldenburg, J., "Icing Cloud Calibration of the NASA Glenn Icing Research Tunnel," AIAA-2001-0234, March 2001.

[11]Palacios, J., Brouwers, E., W., Han, Y., and Smith, E., C., "Adverse Environment Rotor Test Stand Calibration Procedures and Ice Shape Correlation," 66th American Helicopter Society Annual Forum and Technology Display, Phoenix, AZ., May 11-13, 2010.

[12]Federal Aviation Regulation Part 25 "Airworthiness Standards: Transport Category Airplanes" and Part 29 "Airworthiness Standards: Transport Category Rotorcraft", FAA, Washington DC.