Enhancement of Ultrasonic De-icing via Transient Excitation

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ABSTRACT

Previous ultrasonic de-icing research on rotorcraft has shown that a multi-frequency tone burst actuation scheme has increased the coverage of the deicing system. The physical mechanisms responsible for this increase in de-icing performance are modeled using finite elements and tested using both freezer ice on a titanium plate and impact ice under rotation in the AERTS facility on a NACA 0015 airfoil structure. Burst actuation techniques are shown to have up to 400% increase in de-icing potential when compared to long tone actuation methods.

1 NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>N</td>
<td>Mode number</td>
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<tr>
<td>t</td>
<td>Time</td>
</tr>
<tr>
<td>(\omega_n)</td>
<td>Circular resonant frequency</td>
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<tr>
<td>(\omega)</td>
<td>Circular driving frequency</td>
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<td>b</td>
<td>Damping Coefficient</td>
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<td>A</td>
<td>Surface Area</td>
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<td>I</td>
<td>Area Normalized Shear Impulse</td>
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<td>(\sigma)</td>
<td>Cauchy Stress</td>
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2 INTRODUCTION

When rotorcraft enter an icing environment, super-cooled water droplets impinge on the leading edge of the rotor blades [1]. The water droplets freeze on impact with the rotor. Rotor ice accretion degrades the vehicle performance and handling qualities [2]. The noise and vibration levels of the vehicle are also adversely affected.

To prevent dangerous ice formation to helicopter rotor blades, ultrasonic de-icing has been explored in the past [3, 4]. The use of ultrasonic excitation has shown the ability to promote ice shedding of impact ice during prior wind tunnel and rotor testing efforts [4]. Finite Element Models (FEM) have been used to predict the ultrasonic transverse shear stresses at the ice interface responsible for ice shedding. These
tools have been utilized to guide the design of robust bondline configurations between the PZT actuators and leading edge stainless steel host structures. The power consumption of the de-icing system has been quantified to average 0.63 W/cm² for varying icing conditions within FAR Part 25/29 Appendix: C Icing Envelope. This power consumption is an order of magnitude lower to that of electrothermal de-icing systems currently used for helicopter rotor blades [4]. The de-icing system has demonstrated the ability to promote shedding of ice layers ranging from 1.4 to 7.1 mm in thickness for the mentioned, varying conditions. During the mentioned research efforts, ultrasonic de-icing controllers [4] able to distinguish and record the driving condition that promote ice shedding (optimum driving impedance minimum, actuation frequency, power, and temperature rises in the structure due to mechanical and electrical losses). The driver can also excite the ultrasonic actuator at range of frequencies. It was hypothesized that to promote ice shedding, regions of ice with zero transverse shear stress must be avoided. The bridging of delaminated and adhered regions prevented the shedding of ice. To avoid mentioned ice bridging (lack of ice shedding), multi-ultrasonic frequency control was implemented. It was originally thought, that the modal response of the structure could be varied by shifting the excitation frequency, redistributing the regions of high and low ice transverse shear stresses, therefore increasing the percentage area deiced. It was then hypothesized that in that transient stresses related to the on-off switching introduced when changing excitation frequencies also increased the ice interface transverse shear stresses. The exact cause of introducing ice delamination related to frequency switching was not previously investigated in detailed, but it was observed that the suggested multi-frequency excitation scheme ensured full coverage of the ice interface, and consequent ice shedding.

In this paper, the physical mechanism promoting full coverage ice shedding is investigated by focusing on the ice interface stresses created during the initial transient response of an ultrasonic de-icing system.

3 OBJECTIVES

The goal of this research is to advance the ultrasonic de-icing technology by understanding the physical phenomena involved in promoting ice delamination. The ice interface stresses created by initial transient excitation of ultrasonic de-icing systems is investigated, and model results are correlated to experimental results. The ultrasonic system is evaluated using rotational impact icing experiments that provide representative centrifugal forces and icing conditions. To achieve these goals, the objectives of the present work are to: 1) Use finite elements to model ice interface stresses due to both steady state and transient excitation, 2) Compare time domain FEM predictions with experimental results, 3) Validate that transient driving conditions to promote full ice debonding from a host structure, 4) Conduct bench-top testing of the different driving conditions to confirm predictions.

4 MODELING OF ULTRASONIC TRANSIENT RESPONSE

A commercially available finite element package, ABAQUS/STANDARD® [5], was used to predict the steady-state dynamic and
The transient response of the piezoelectric actuators coupled to a metallic host structure representative of a rotorcraft leading edge erosion cap. The objective of the finite element models is to predict the transverse shear stresses generated at the ice interface due to the application of a voltage potential across the ultrasonic de-icing piezoelectric actuator. The transverse shear stresses at the ice interface can be used to predict ice delamination and overall percentage area of accreted ice successfully debonded.

To demonstrate the higher amplitude of off-resonance initial transient response with respect to steady-state resonance response, an axisymmetric FEM was created. An axisymmetric geometry was chosen for its relative computational efficiency. The modeled system is an axisymmetric titanium grade 2 plate, 13 in. diameter, with a 1.5 in. diameter PZT-4 disk bonded at its center by a representative adhesive layer [3]. The plate is 0.035 in. thick, the PZT is 0.1 in. thick, and the adhesive was 0.015 in thick. The plate is modeled with an annulus of ice with inner radius of 3.5 in., an outer radius of 4.5 in., and 0.08 in. thick tied to the opposite side of the plate as the PZT actuator (Figure 1).

![Figure 1. Schematic cross section of modeled axisymmetric system](image)

Figure 1. Schematic cross section of modeled axisymmetric system

To demonstrate the validity of the transient FEM, comparisons were drawn to experimental measurements made on a titanium grade 5 plate with similar geometry to the model, with no ice on either. Electromechanical impedance was the quantity chosen to legitimize the models and are compared in Figure 2. The frequencies of the impedance minima differ by 3.25% while there is a 51.6% difference between the two impedance values at their respective minimums. Much of the discrepancy can be attributed to variations in piezoelectric properties of up to ±20% from the values quoted by the manufacturer that were used in the model.

![Figure 2. Transient FEM prediction correlates very closely to the experimental measurement](image)

Figure 2. Transient FEM prediction correlates very closely to the experimental measurement

It can be observed in Figure 3, that the ice interface transverse shear stress (stress responsible for ice delamination) is larger for an off-resonance excitation during the initial transient state, than that of the steady-state response. The higher amplitude reached during the transient response would point towards a maximum ice delamination...
as soon as the actuator is turned on. As the actuator reaches steady-state, any ice that would have been debonded has already done so. The interfacial shear stress shown in Figure 3 is that of the same node on the ice interface for both driving conditions. Figure 4 depicts that the ratio of maximum out of plane velocity to the velocity amplitude in steady state (the VR value) is 1.0 at the frequencies of electromechanical impedance minimum (system resonances). The implicit transient solution assumes an input power of 100 W to the system. It must be noted that due to cracking and delamination of portions of the accreted ice and temperature increases of the actuator, the resonant frequency is expected to change during the de-icing process. Due to these shifts in system resonance, driving a system at an ultrasonic tone continuously at resonance is not possible, and relying on the high stresses generated during transient excitation is desired.

Figure 3. Ultrasonic transient response of a system driven at resonance and off-resonance

Figure 4. Ratio of maximum out of plane velocity to steady state velocity at various frequencies compared to impedance.

Portions of the accreted ice debond as the system is actuated at ultrasonic frequencies. The interfacial shear stress is proportional to the voltage potential applied to the
piezoelectric actuator. FEM tools were used to determine the area normalized shear impulse for a given input power (Figure 5). The area normalized shear impulse, \( I \), is shown in Eq. 2 is related to the area under the rectified interfacial shear stress curve. It can be shown that the area normalized shear impulse is linearly related to the square root of applied power. What is most important, actuation in bursts (multiple transient occurrences) provides a larger response than continuous steady-state excitation, preforming up to 30% better.

\[
I = \frac{\int |\sigma_{r2}| \, dt \, dA}{A}
\]

5 EXPERIMENTAL VALIDATION: FREEZER ICE TESTING

To validate the observations proceeding from FEM modeling of an axisymmetric ultrasonic de-icing configuration, bench top tests with freezer ice were conducted. A 13 in. diameter titanium grade 5 plate with a 1.5 in. piezoelectric actuator tested with a ring of freezer ice. The plate was supported on its edges by foam to simulate free-free BCs. The freezer ice ring was segmented into 24 ice patches as shown in Figure 6. The reason to segment the ice is to allow for individual ice patch delamination for a given driving configuration. The number of debonded ice patches for a given driving condition can be use to quantify the de-icing performance of the excitation configuration. Ideally, the ice interface transverse shear stress would be quantified, but sensors able to record these values at ultrasonic frequencies are not available.

Several driving conditions were experimentally tested. The 1.5 in. diameter piezoelectric actuator was driven with multi-frequency bursts (0.55 kHz band, 20
bursts, 0.3s/burst) surrounding the resonance frequency of the system (68 kHz). A second driving condition was single frequency bursts at the resonance frequency (0 kHz band, 20 bursts, 0.3s/burst at 68 kHz). These two conditions provided de-icing capabilities of initial transient configurations.

To compare to non-initial transient configurations, a single frequency tone (0 kHz Band, 1 burst, 6s/burst) was driven at resonance. In addition, a frequency sweeping single tone configuration was also tested (0.55 kHz Band, 1 burst, 6s/burst). The results comparing the four actuation methods are shown in Figure 7. As predicted by FEM, the burst, or initial transient configurations, provided a larger percentage area de-iced than continuous steady-state tones. Transient response showed to be more important than frequency sweeping, since single tone burst outperformed tone frequency sweeping by as much as 70% increase in area de-iced. The frequency of electromechanical impedance (resonance frequency) measured prior to de-icing increased by an average of 1.25 kHz compared to measurements after de-icing. Tests were constrained to less than 225W max net power to preserve the test specimen. These measurements follow similar trends as the area normalized shear impulse calculations and lend credance to their predictive abilities.

![Figure 7. Bench-top testing of axisymmetric de-icing configuration excited at 4 different driving conditions. The trendlines of burst (or initial transient) configurations provide larger de-icing capabilities than constant excitation.](image)

### 6 ROTOR IMPACT ICE TESTING

**Testing Facility**

To evaluate the ice protection performance of a rotor blade ultrasonic de-icing system with initial transient excitation, test were conducted under rotational impact icing conditions at the Adverse Environment Rotor Test Stand (AERTS) Facility [6]. The facility is formed by a 3.05 m diameter hover stand located inside a temperature controlled chamber (0 to -20°C). A 125 HP motor is able to spin full chord blades at representative centrifugal forces. Icing nozzles control the water droplet particle size and liquid water concentration in the
facility, promoting ice accretion to the rotor blades. A photograph of the facility can be seen in Figure 8.

Figure 8. Photographs of AERTS Facility with Ultrasonic De-icing Rotor Blades Installed and Detail of Icing Cloud at Start-up.

**Ultrasonic Specimen**

The same specimen used by Overmeyer et al. [3] was used to evaluate the benefits of transient excitation during rotor ice accretion. A schematic of the 1.52 m radius rotor blade used and detailed photographs of the integrated ultrasonic de-icing system can be seen in Figure 9, together with photographs of the ultrasonically protected erosion cap [3]. As it can be observed in the same figure, the ultrasonic de-icing system was segmented into four independently controllable zones. Each zone was formed by two PZT-4 actuators (38.1 mm diameter, 1.27 mm thick), for a total of eight PZT-4 actuators. Zones four and two are joined in parallel as well as zones three and one. The protected structure is a NACA 0015 airfoil with a chord of 16 in.

Figure 9. a) Photograph of ultrasonic de-icing instrumented test specimen as mounted on rotor blade. b) Schematic of rotor blade carrying test specimen at rotor tip (30.48 cm span, 40.64 cm chord). c) Detailed photograph of stainless-steel erosion cap test specimen [3]
Rotor Ice Testing

Ice was accreted in the AERTS for 8 minutes at -8°C, with a LWC of 0.4 and a MVD of 25um. These icing conditions yielded an ice thickness of 10.8 mm. Ice accreted to the rotor blade was cut into 12 segments using a hot plate, such that the same procedure used during bench-top testing could be used to measure percentage of ice delaminated. In Figure 10, a sample of accreted ice to the rotor blade paddle, the segmented accreted ice, and partial ice delamination (25%) due to ultrasonic excitation is shown. The percentage ice delamination area technique was used to quantify the effectiveness of different driving conditions while varying input power to the actuators. The results are summarized in Figure 11.

![Figure 10](image.png)

**Figure 10.** Photograph of accreted ice, segmented accreted ice prior ultrasonic excitation, and sample of partial de-icing due to low power ultrasonic excitation. Percentage de-iced area can be calculated depending on number of segmented ice patches removed.

![Figure 11](image.png)

**Figure 11.** Experimental percentage de-iced area vs. power for three (3) excitation configurations. Initial transient excitation (bursts) considerably increase the performance of ultrasonic de-icing as compared to steady-state frequency sweeping.

It is clear from the rotor ice test results that initial transient excitation considerably increases the percentage of de-iced area. This excitation method is able to fully de-ice the structure with as low as 150 W. Frequency sweeping without transient burst is not able to fully protect the structure from ice formation, as only 8% of the ice is removed with a net power of 200 W.

7 CONCLUSIONS

Bench top testing and rotor ice testing of representative metallic leading edge structures under the effects of ultrasonic excitation were conducted. The effects of transient interfacial transverse shear stresses at the ice interface were modeled and
experiments were conducted. Modeling and experimental results demonstrated that transient ice interface stresses related to the initial burst that occurs during the initiation of the actuator excitation are responsible for the bulk of the de-icing capability of ultrasonic de-icing. Due to the dynamic nature of ice accretion and shedding, exciting the system continually at resonance is not probable. Off-resonance conditions are usually triggered, and at these conditions, the transient ice interface stresses considerably exceed the steady-state stresses generated.

Based on the results obtained during this investigation, the following conclusions are made:

1) Experimental results showed that simply varying the frequency or driving continuously at resonance provide inferior de-icing capabilities when compared to multiple transient burst to an ultrasonic de-icing configuration.

2) The enhanced de-icing ability observed when employing multi-frequency bursts is due to the transient nature of the actuation method and not the changes in frequency.

3) The amount of ice debonded on bench top tests with freezer ice from burst actuation techniques was up to five times higher than simply changing frequency, for similar powers.

4) In rotor tests the accreted ice could be completely cleared by burst actuation techniques for 20% less power than frequency sweeping took to clear 8% of the blade.

ACKNOWLEDGMENTS

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