Centrifugally Powered Pneumatic Deicing for Helicopter Rotor Blades

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POC: Eric Kreeger, Icing Branch/RTI, NASA Glenn
Agenda

• Background and Motivation
• Objectives
• Prototype Design/Fabrication
• Aerodynamic Testing
• Rotor Ice Testing Results
• Erosion Testing
• Conclusions
Helicopter icing is introduced by both its mission requirements and operation environments:

- Urgent transportation
- Search and rescue
- Low altitude
- Low temperature
- High humidity, icing cloud possible

**Motivation**

- **Ultimate goal of helicopter icing research:** All weather aircraft
- **Need for fundamental research to:**
  - Improve and validate ice accretion tools
  - Develop and evaluate ice protection systems and protective surfaces
  - Develop facilities and testing procedures
Motivation – Electrothermal Deicing

- Only system qualified by the FAA and the DoD
- Heavy system (4 Blades 12,000 lbs Model: >160 lbs.)
- Does not allow for continuous application due to high power consumption (4 Blades, 12,000 lbs Vehicle: >20 KW, ~25 W/in²)
- Allows ice accretion up to 0.3 in (10% Torque Increase)
- Melted ice may flow aft and refreeze further
- Difficult to integrate with polymer erosion-resistant materials

A low-power, non-thermal IPS is desired to have an impact on all-weather capabilities:

- Compatibility with smaller vehicles
- Compatibility with polymer leading edges

ARMY HISS Icing Certification Testing

Ice Protection System (S-92™)
• Pneumatic de-icing boots → used on fixed-wing aircraft for decades
• In the 80’s, NASA and Goodrich attempted to develop rotorcraft de-icing boots
• Boots were successful in de-icing rotor blades, several problems were identified:
  1) Complicated pneumatic slip-ring transferred engine bleed air out to rotating frame
  2) Erosion of polymer boots
  3) Altered airfoil shape led to rotor performance degradation
• These problems were technology development barriers

The Innovation:
- Avoid pneumatic slip rings:
  CENTRIFUGAL PUMPING
- Avoid pneumatic diaphragm exposure:
  Ti-Al-N Erosion resistant coating
- Avoid rotor performance degradation:
  CONTROLLED DEFLECTION ZONES
Goal: Surface De-Icing Treatment can be Retrofitted to Existing Blades

- No Pneumatic Slip Ring
- Insignificant Electrical Power Use
- Insignificant Added Blade Weight

\[ \frac{dp}{dr} = \rho(r)r\Omega^2 \]

\( p = \text{Pressure}, \rho = \text{Density}, r = \text{Radius,} \quad \Omega = \text{Rotor Speed} \)

Channel to Low Dynamic Pressure

Channel Sealed at Tip

3-Way Microvalve Off under Non-icing Conditions, Diaphragm Connected to Low Pressure

Under Non-Icing Conditions, Erosion Cap is “Vacuumed” onto Airfoil using Low Tip Pressure

During Icing Conditions, Microvalve Oscillated at Low Frequency to Cycle Diaphragm through Inflation and Deflation
Proof-of-concept: Pneumatic Deicing

- Initial designs considered allowed for local deformation of individual 0.02” thick Ti strips
- Goal: minimal impact on existing blade design (surface treatment)
- Power Consumption: < 1 W of power with no insignificant additional blade weight

Design 1

Ti Cap: 0.02”

Pneumatic Diagrams
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Objectives

1) To conduct rotor icing experimental testing of a centrifugally powered pneumatic de-icing prototype for helicopter rotor blades

2) To confirm the system effectiveness:
   • Low-power consumption
   • Robustness under centrifugal loads (CF)
   • Reduced aerodynamic penalty
   • Erosion resistance
Pneumatic De-Icing Design: Prototype I

- **Blade Tip**
  - Thin, hollow channel at end of erosion cap spanning to blade root to access low dynamic pressure

**Diaphragm**
- Power off condition. Volume under diaphragm connected to low dynamic pressure
- Erosion segments conform to desired airfoil shape
- Leading edge maintains rigidity

**Segments Separated Slightly**
- Microvalve activated at root
- Volume under diaphragm allowed to inflate slightly under CF
- Segments pulled apart slightly, cracking ice
- Vectran bonded to airfoil at cap edges and periodically around entire leading edge
Entire leading edge expands slightly, thus delaminating ice

Shearing elastomer connections between segments

Electrical Discharge Machined Wire Cutting of leading edge segments
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Aerodynamic Testing Prototype I

Model with deployable leading edge fabricated for wind tunnel testing

Detail of Segmented Leading Edge
Aerodynamic Testing Prototype I

Unacceptable aerodynamic performance degradation
Must mitigate aerodynamic performance degradation concerns
In operation, low internal blade pressure will pull the system ( <= 0.2”) onto the leading edge
- Conforming airfoil shape
- No major rotor aerodynamic performance degradation

Goal: Design System Thin Enough to Replace Current Erosion Caps with Little or No Blade Redesign

Exaggerated Displacement

Erosion Cap Slightly Deformed by Pneumatic Diaphragms

Diaphragms inflated using Centrifugally Generated Pressure Differential
Deflection Modes: concentrate ice interface transverse shear stresses at desired chord locations

Titanium Nitrade Based Erosion Resistant Coating (PSU ARL – Dr. Wolfe)

Localized Stresses Introduced into Ice-Cap Bond

Exaggerated Displacement
Cohesive zone method FEM

Aerodynamic Testing Prototype II

Wind Tunnel Testing Leading Edge Deployment
Aerodynamic Testing Prototype II: Results

Cl vs Angle of Attack

Deployment of pneumatic deicing degrades the lift performance of the airfoil. The performance penalty does not exceed the degradation related to ice accretion.

Deicing system 0.05” thick

Ice thickness
Main ice shape
Ice feathers

Ice limit
Surface roughness

0.2 in
Aerodynamic Testing Prototype II: Results

Cd vs Angle of Attack

Deployment of pneumatic deicing degrades the drag performance of the airfoil.

The performance penalty does not exceed the degradation related to ice accretion.
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**Testing Facility**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>LWC [g/m³]</td>
<td>0.1 ~ 5 (increments of 0.2)</td>
</tr>
<tr>
<td>MVD [µm]</td>
<td>10 ~ 50</td>
</tr>
<tr>
<td>Temperature [° C]</td>
<td>-20 ~ 0</td>
</tr>
<tr>
<td>Rotor Speed [RPM]</td>
<td>200 ~ 1200</td>
</tr>
<tr>
<td>Blade Diameter</td>
<td>3 [m] / 10 [ft]</td>
</tr>
<tr>
<td>Blade chord</td>
<td>12.4 ~ 81.3 [cm] / 4.9 ~ 32[in]</td>
</tr>
</tbody>
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Icing Nozzles control LWC and MVD

- Signal and Power Transmission: 48 signal / 24 power channel slip ring
- Measurement Instrument: Shaft torque sensor / 6-axis load cell
- Facility proven to create representative icing conditions (and ice shapes)
Hub from QH-50 DASH Unmanned Helicopter

10.5 inch chord NACA 0012 blade

Collective & Cyclic Pitch Actuators

Bell Housing w/ 6-axis Load Cell Built-in

Inside: 120 Hp Motor w/ Torque Sensor Built-in
AERTS Facility Video

Rotor Icing Testing Conducted at PSU AERTS

Representative Icing Conditions and Centrifugal Loads
Sample Result

Pneumatic Deicing without Centrifugal Loading
Sample Result

- Ice shedding was achieved at 250 RPM (20% CF) and 540 RPM (90% CF)
- Ice thickness as small as 0.06” were shed at temp. above -15 deg. C
- Air pressure used +/- 3.7 psi (representative rotor blade generation)
- Electrical power consumption: 2.9 Watts
Continuous Icing Cloud Test Results

Successful deicing for all icing conditions

Average Ice Thickness Required: 0.1”
Min.: 0.06”

Average Ice Thickness Required: 0.2”
Min.: 0.096

Diaphragm material stiffens beyond pressure capabilities at Temp. < -15°
Intermittent Icing Cloud Test Results

Successful deicing for all icing conditions

LWC (g/m$^3$)

MVD (µm)

-10°C

-0°C

-20°C
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Proof-of-concept: Erosion Resistance Coating

PSU – ARL:

Orders of magnitude increase in erosion resistance by Ti-AL-N
Erosion Testing Ti-AL-N Coating: SEM
Surface Morphology 500 g. Exposure

Uncoated Ti

Ti-AL-N: 100µin Thick

Ti-AL-N: 200µin Thick

30 degrees, 156m/s, 50 µm alumina, 0.5 wear diameter, 9” stand-off distance, 100g/min
Conclusions

- Smooth leading edge configurations are critical to avoid aerodynamic performance degradation of the blade.
- Aerodynamic performance degradation due to system deployment was less than the effects of the ice accretion.
- The proposed pneumatic deicing configuration is able to delaminate ice accretion (Appendix C icing envelope) with input pressures as low as +/- 3.7 psi.
- Ice thickness as small as 0.06 in. were successfully removed for temperatures above -15 deg. C.
- The maximum ice thickness needed to promote ice delamination at colder temperatures could reach up to 0.2 in. (comparable to ice accretion allowed by electrothermal deicing).
- The larger ice thickness requirements are attributed to the stiffening of the prototype diaphragm used.
- The system performed at 90% and 20% representative CF loads.
- Ti-AL-N shows orders of magnitude improvement on sand erosion resistance compared to Ti → allows for a reduction in thickness of the Ti substrate.
Goal: Full-scale proof-of-concept testing

– Design system with temperature rated diaphragms
– Access a whirl tower in cold climates
– Full-scale rotor blades to be modified to accommodate pneumatic de-icing
– Design portable cloud generators
– Design an optimized de-icing system (FEM)
– Perform full-scale rotor blade pneumatic deicing
– Rock and small ballistic Impact testing
• Abstract submitted to the American Helicopter Society 70th Forum.
• Briefing given to Bell on April 2013
• Briefing given to Sikorsky on June 2013
• Briefing given to Boeing on July 2013
• Rotor Icing and Protection Demonstration given to Boeing on September 2013
• Rotor Icing and Protection Demonstration to be given to NASA and GE on Nov 2013 – Dec 2013 (POSTPONED)
Questions?
Ice Shape Correlation: Facility Validation

[Palacios et al. AHS Journal, 022006-2012]