Design of an Advanced Pneumatic Deicer for the Composite Rotor Blade

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Operating principles of the pneumatic deicer and rubber's self-shedding characteristics are applied to the rotor blade. The deicer system operation is discussed. Design criteria for the deicer on a composite blade cover chordwise/spanwise coverage considerations, air connection location, and airfoil profile retention. Also discussed is a method for determining the extent of deicing tube coverage and the limit of self-shedding material at the outboard end of the blade. The use of smaller tubes to reduce deicer inflation drag is also discussed.

Introduction

As with fixed-wing aircraft airfoils, icing adds drag and loss of lift to rotor blade airfoils. Because the rotor blade must provide thrust as well as lift, the drag due to icing has greater significance in terms of helicopter operating power requirements. As compared to a propeller, the rotor blade rotates much slower and can collect ice to the blade tip, where 1000-*g* centrifugal forces add an operational concern. Uncontrolled ice shedding results in blade imbalance, which causes severe vibration and operational problems.

Selection criteria for rotor blade ice protection puts primary importance on system weight, with appropriate emphasis on system performance and operating endurance. The last requirement usually rules out fluid-type systems.

Chargeable weight for operating power can become the principal weight factor, especially for electrothermal systems. Since chargeable power (and weight) for a four-blade rotor anti-ice system would be at least 10 times greater, deice systems have been used for electrothermal systems.

The design of the pneumatic deicer addresses concerns about controlled ice shedding, low power, and low weight. Details of comparative lower weight and power values for the pneumatic deicer system have been documented earlier.[1]

The pneumatic deicer uses a mechanical principle to remove accumulated ice and, thus, avoids a hazard of thermal deice systems that can cause melted ice to refreeze beyond the protected zone and form "runback" ice. The comparatively low weight and very low operating power requirements are principal reasons supporting the choice of pneumatic deicers for rotor blade ice protection.

Background

The prohibitively high energy requirements of an anti-ice system have led designers to choose deice systems for rotor blade ice protection. The low weight and low energy requirements are among the factors leading to the choice of pneumatic deicer systems for wing and tail surfaces of most general-aviation fixed-wing aircraft. These same factors led to the adoption of a pneumatic deicer system to helicopter rotor blades.

Presented as Paper 88-0017 at the AIAA 26th Aerospace Sciences Meeting, Reno, NV, Jan. 11–14, 1988; received Aug. 18, 1988; revision received May 1, 1989.

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The initial use of pneumatic deicers on rotor blades raised new design issues, which were addressed by the following tests.

NASA Lewis Icing Research Tunnel (IRT) tests[2] affirmed the choice of a deicer design that effectively removed ice on an airfoil with a small leading-edge radius. The IRT test also showed that, when inflated, the deicer's profile did not increase the aerodynamic drag rise to a value greater than that caused by the ice accumulated on a bare rotor blade. Other tests confirmed the integrity of the deicer bond to the blade and the retractability of the deicing tubes when acted on by high centrifugal forces produced at the outer sections of a rotor blade.

The deicing system demonstrated the ability to consistently and effectively remove rotor blade ice, as verified by icing tests at the Canadian National Research Hover Icing Facility in Ottawa, tests at Duluth behind the U.S. Army Helicopter Icing Spray System, and in natural icing tests.[3]

Preliminary rain erosion testing proved the merit of the polyurethane weathering materials, which led to a design change to improve maintainability further.

Principles of Operation

Rotor blade ice protection is provided by two mechanical deice principles. The primary deicing mechanism is provided by a pneumatic deicer. The second deicing mechanism is provided by the self-shedding action of ice on an elastomeric surface under high centrifugal force loading.

Pneumatic Deicer

The pneumatic deicer is a thin elastomer/fabric blanket containing inflatable tubes that break and remove ice when inflated. The deicer is designed so that the deicing tubes cover the area to be protected.

The deicer is made up of several layers of elastomers and fabrics. The outer surface layer is a weather-resistant elastomer, chosen for good rain erosion resistance as well as slow weathering properties. Directly beneath is a natural rubber layer, whose resilience aids expulsion of air after the deicing tube is inflated. The outer surface and natural rubber layers are bonded to a stretchable fabric layer to form the outer tube wall, which flexes to remove ice (Fig. 1). The opposite wall of the tube is formed by sewing the stretchable fabric to nonstretchable fabric, which is adjacent to another elastomer layer that forms the installation surface for bonding the deicer to an airfoil. Other materials are added to form a pneumatic seal of the ends and edges of the deicing tubes. An autoclave cure is used to fuse these layers into a relatively thin, smooth blanket. The deicer is designed with internal venting, which permits all tubes in a deicer to be inflated and deflated through an air connection normally located within the deicing tube

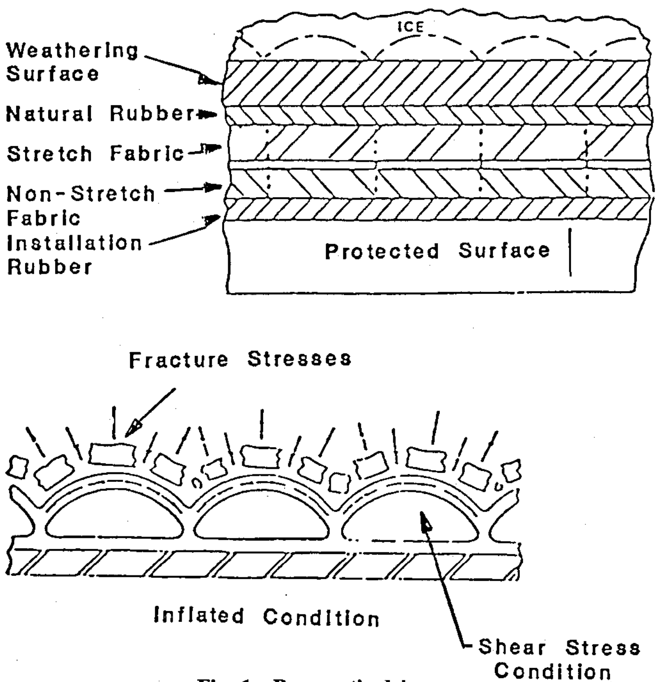

Fig. 1 Pneumatic deicer.

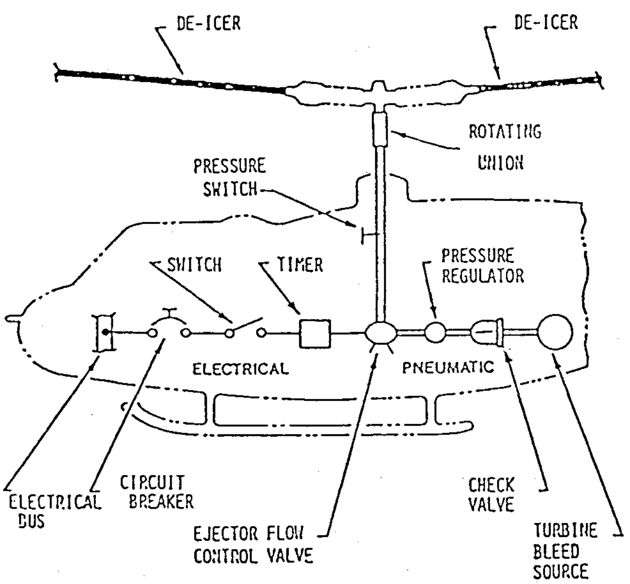

Fig. 2 Rotor blade/pneumatic deicer system.

area and on the installation side of the deicer where it projects through a mating hole in the airfoil outer skin.

Deicing occurs when air is valved through the air connection to inflate and stretch the deicing tubes. As the outer surface distorts, fracture stresses are produced in the ice, causing it to be broken. As the deicing tubes fully inflate, the stretched outer wall surface causes shear stress, which separates the ice from the deicer surface. The broken and sheared particles of ice are then removed by the combined action of the aerodynamic and centrifugal forces produced by the rotating blade.

Elastomeric Self-Shedding

An ice-shedding principle applicable to the rotor blade was evolved from a test procedure used to measure the apparent adhesion of ice to various materials, including elastomers. This test[4] was part of a series of studies aimed at reducing ice adhesion to the pneumatic deicer surface. The test procedure used centrifugal force to determine the level of shear adhesion of a button of ice frozen to the test surface. These tests provided two important design values. The adhesion value of ice to a material was shown to increase as the ambient temperature decreased, and the apparent adhesion of ice to an elastomeric surface decreased when the elastomer thickness increased from a few mils to a test thickness of 0.040 in.

The decrease in ice adhesion to the thicker elastomer was caused by the elastomer's lower modulus of elasticity, which caused it to distort slightly (under the shear force loading), thus creating shear-stress concentrations at the ice/elastomer interface that resulted in lower shear values. At the outer section of a rotor blade, where there are high centrifugal forces, the low ice/elastomer shear-strength phenomena can be used to control the thickness of ice accumulated and ultimately self-shed.

This principle has been verified by icing tests of a U.S. Army UH-1 helicopter that had only an elastomer layer at the outboard 44 in. of the main rotor blades.[3]

System Description

Functional Description

As with all rotor blade deice systems, the pneumatic deicers must be operated in a manner that retains rotor system balance. Since a pneumatic deicer normally would be designed to deice the full length of the protected blade area in a single inflation sequence, the deicers on opposing blades must then be inflated together so that aerodynamic changes in opposing blades will be more balanced. The designer should consider simultaneously inflating the deicers on all rotor blades. This approach simplifies the routing of operating air and can reduce rotor system imbalance tendencies on helicopters having more than two blades.

The system should be designed so that failure of one component does not cause rotor system imbalance. The hazard of a single failure causing an imbalance is reduced by operating deicers in opposing blades through a common air control valve and through air routing through a common line. Then, any failure in a deicer or its air supply line will have the same effect on all deicers.

Positive air pressure is applied to the deicer to cause ice removal. At all other times in flight, negative air pressure (vacuum) is applied to keep the deicing tubes deflated. All air pressures are supplied to the deicer through a single air connection.

Operating Equipment

The deicer system uses pneumatic and electrical equipment. The components described are for a turbine-powered helicopter (Fig. 2). Different equipment is required for a piston-engine-powered helicopter.

Pneumatic Equipment

The deicer system's pneumatic supply is obtained from the compressor section of the helicopter's turbine engine(s). The air is routed through check valve(s) to a pressure regulator, which reduces the air to deicer system operating pressure. The check valve(s) allows the system to be tested on the ground with the helicopter engine inoperative. In addition, the check valves allow for single-engine operation for helicopters having more than one engine.

From the regulator, air is routed to a solenoid-operated valve, which controls application of inflation air or vacuum to the deicer. Vacuum is necessary to resist the negative aerodynamic force that could partially inflate the deicer. Vacuum can be obtained through a separate source or by using a unique ejector flow control valve, which also performs the deicer air inflation function. When the system timer energizes the ejector flow control valve solenoid, the ejector is shut off and system air pressure is directed to inflate the deicer. When the solenoid is de-energized, all air in the deicer is expelled overboard and vacuum is reapplied to the deicing tubes. A rotating union transfers deicer operating air and vacuum from the rotor mast to the rotor hub, where a pneumatic connection is made to each blade deicer.

Electrical Equipment

An electronic system timer controls application of electrical power for a preset time period to the solenoid of the ejector flow control valve.

A normally open, two-pole diaphragm-operated pressure switch is located in the air line between the control valve and the deicers. System air pressure actuates the switch to provide a control panel electrical signal that indicates the deicers are inflated.

Design Criteria

Extent of Protection

The area to be protected is bound by the spanwise length and chordwise extent of icing on the upper and lower airfoil surfaces. The chordwise extent on the upper and lower surfaces can vary according to many parameters.

For initial consideration of a mechanical deicing system, the chordwise extent is governed primarily by determining the impingement limits of the selected icing droplet size for all representative flight conditions.

The inboard end of the spanwise extent is set by practical considerations and by analyzing the effect of accumulated icing on rotor lift, drag, and balance.

The spanwise extent at the rotor blade's outboard end can be affected by aerodynamic heating, which results from high tip velocities. The ice self-shedding effect must also be considered. Self-shed factors include the level of centrifugal force at the tip, the blade tolerance to ice thickness (before self-shedding occurs), and the apparent ice adhesion properties of the surface materials.

Type of Installation

Since accuracy of blade airfoil profile contour is critical to a helicopter's flight performance, it is presumed that the pneumatic deicer installation does not compromise the airfoil's design shape. Therefore, the deicer will fit into or be formed into a recess for an accurate base airfoil profile.

Aerodynamic Drag of Inflated Deicers

During the brief (1-2 s) inflation period of the deicing tubes, the blade aerodynamic profile is changed, which results in a significant increase in blade drag. However, this drag increase is not a problem since the increase in drag caused by deicing tube inflation is no greater than the ice thickness the helicopter can tolerate (before deicing occurs).

Design Application

It is essential that deicer design considerations begin at the preliminary design stage of the rotor blades, when two important design choices are made. The first decision is the method of keeping the deicer within the basic blade airfoil contour. This goal can be achieved by recessing or contouring the blade so that the installed deicer surface matches the desired airfoil contour. As with fixed-wing airfoils, the blade recess can be made with a constant depth to accept a uniformly thick deicer, which has excess peripheral material trimmed away to create a smooth butt joint. Since the deicer has a finite service life, the design allows for replacement of the deicer using established installation procedures.[5]

An alternative method is to autoclave cure the deicer in an airfoil contour mold using a fiber-reinforced prepreg material to form a leading shell assembly. The shell assembly is then bonded to the rotor blade as a replaceable assembly. This method forms a very smooth contour profile with no perceptible discontinuity at the deicer edges.

The second important preliminary design consideration is the routing of operating air to the deicer. Although air from the hub to the blade can be routed using normal flexible line techniques, the air line from the blade hub to the deicers' inflation tubes must be located internal to the blade. For more effective deicing action and rapid deicer deflation, operating

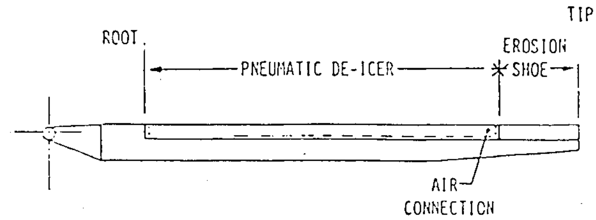

Fig. 3 Deicer/blade layout.

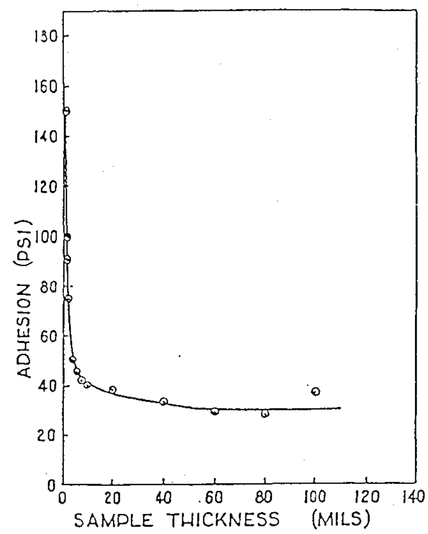

Fig. 4 Effect of rubber thickness on apparent adhesion to ice at −25°C.[4]

air should enter and exit the deicer tubes near the outboard end of the inflatable area (Fig. 3).

The chordwise extent of the deicing tubes can be set by an appropriate icing droplet limit-of-impingement procedure since mechanical deicing does not require additional deicing beyond the impingement limit of the design droplet diameter. A nominal 1-1½-in. extension of noninflatable material is used beyond the inflatable area to allow for edge seal of the deicer tube area and to relieve installation bond stresses at the edges of the tube area. The spanwise extent at the inboard end is set by the practical limits of the blade. The inflation area can extend to within 2 in. of the inboard end, if required, to provide aerodynamic profile control or blade balance in icing.

Although ice protection to the blade tip must be assured, the self-shed principle of an elastomeric surface can allow the deicing tube area to terminate at a shorter blade station. Since the effects of sand and rain weathering are greatest at the tip, using the self-shed principle allows the erosion protection concerns to be addressed without being compromised by deice-tube material requirements. Determining the minimum blade station for the junction of the active (deicing tubes) and passive (self-shed) deicing functions requires analysis that includes blade centrifugal force, the minimum design icing temperature, and the maximum ice thickness accumulation the blade can tolerate. In addition, it is assumed that a minimum elastomeric shed area thickness of 0.04 in. (Fig. 4) is used and that greater elastomeric thicknesses increase the conservatism of the analysis.

Self-shedding occurs when the ice centrifugal force acting on a unit thickness of ice exceeds the apparent ice adhesion level to the elastomeric surface.

The ice shear-stress plots are determined as the product of the centrifugal force resulting from blade rotational speed and blade station radius and the unit mass of the ice thickness that can be tolerated at a given blade station.

The ice adhesion shear value to be overcome by the centrifugal force action is determined by the minimum design icing temperature. Assuming that the ice is at least 0.1 in. thick, Fig.

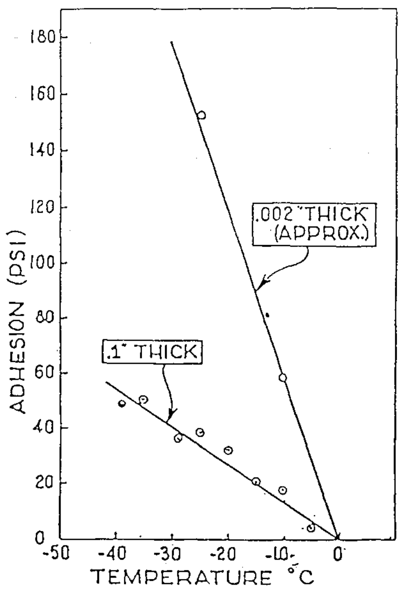

Fig. 5 Variation of apparent adhesion of rubber to ice.[4]

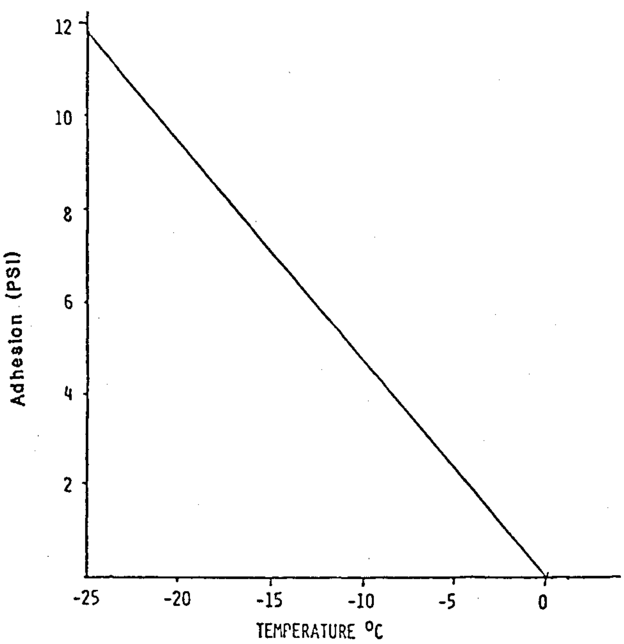

Fig. 6 Apparent adhesion of droplet ice to abraded neoprene.

5 determines the corresponding ice adhesion. The Fig. 5 data are based on the properties of liquid frozen water. An analysis (Ref. 4 vs Ref. 6) of ice adhesion values to a common material shows that the adhesion of liquid frozen ice is substantially higher than droplet-formed ice. A comparison of adhesion values to similar materials yields about a 5.9 ratio of liquid to droplet frozen ice. The adjusted adhesion curve for droplet ice to abraded neoprene is shown in Fig. 6.

There are two considerations in the operation of the deicing tubes: 1) effective ice removal is accomplished, and 2) aerodynamic effect is minimal.

For fixed airfoil use, deicers contain either spanwise tubes, where deicing tubes are parallel to the airfoil leading-edge centerline, or chordwise tubes, where the tubes are normal to the leading-edge centerline or are in freestream planes. The popular spanwise tube deicer effectively removes ice on small leading-edge-radius airfoils such as those on rotor blades. The chordwise tube deicer produces substantially lower aerodynamic drag when inflated and is normally used on airflow-sensitive airfoils.

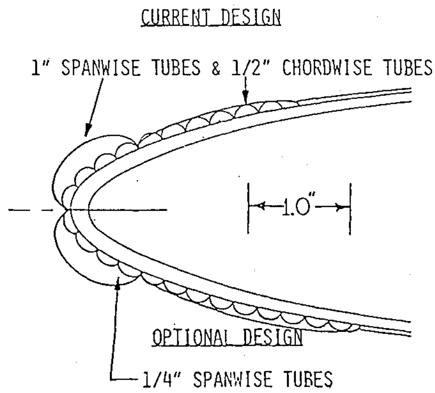

Fig. 7 Inflated pneumatic deicer profiles.

For rotor blades, a combination spanwise/chordwise tube deicer has been successful. The deicer effectively removed ice, and the inflated deicer aerodynamic drag was no more than the drag of the accumulated ice (before removal) that the helicopter could tolerate. The deicer consisted of two spanwise tubes centered on the blade leading edge, with the balance of the protected area filled with smaller chordwise deicing tubes.

For future applications having smaller leading edges and more airflow-critical airfoils than the NACA 0012 used for prior tests, there are two options.

The first option is to use the spanwise/chordwise tube design with a smaller spanwise/chordwise tube than the 1-in. spanwise/½-in. chordwise arrangement used on the 21-in.-chord 0012 airfoil. Using smaller tubes reduces the aerodynamic effect when the tubes are inflated.

A second option is using deicers containing all small spanwise deicing tubes. Recent icing tunnel tests show that ¼-in.-wide deicing tubes consistently remove ice thicknesses on the order of 0.03–0.04 in. The aerodynamic drag of these small tubes when inflated has not been measured. Figure 7 shows a representative scale drawing comparing the inflation profiles of the current spanwise/chordwise tube design with the smaller spanwise tube design. Examination of the comparative profiles suggests that the drag of the inflated small spanwise tubes will be lower.

Conclusion

A pneumatic deicer designed for a composite rotor blade provides a simple, effective method of ice protection. The mechanical deice principle eliminates a concern for "runback" icing and minimizes the required chordwise extent of ice protection. At the outboard end of the blade, deicing tubes are replaced by an elastomer layer whose ice shelf shed properties limit the amount of ice accumulated. The rotor blade deicer design retains the low weight/power features typical for pneumatic deicer systems.

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