LOW ENERGY ICE PROTECTION FOR HELICOPTERS

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Abstract

This paper introduces four unique, low energy, mechanical de-ice systems whose performance meets the requirements for rotor blades and inlets. The four systems are: 1) Small Tube Pneumatic De-Icer (STP), 2) Pneumatic Impulse Ice Protection (PIIP),) Electro-Expulsive De-Icing System (EEDS), and 4) Eddy Current System (EC). These systems are designed to remove ice in small particles that would damage engine components or cause fuselage damage resulting from ice particles launched from a rotor blade. The systems are also capable of shedding very thin layers of ice critical to the retention of airfoil shapes on rotor blades, wings and stabilizers. The first two systems, STP and PIIP, are pneumatically powered while the second two, EEDS and EC, are operated electrically. All four systems can use discharged, stored energy de-icing pulses that result in a low power drain from the helicopters' power resources. These systems can all be designed intrinsically into the airfoil to eliminate aerodynamic effects or can be onded onto existing airfoils in retrofit applications.

Background

Over the years many goals have been established for desired improvements for an ideal ice protection system. These goals include 1) low power consumption, 2) improved sand and rain erosion resistance and 3) aerodynamically stable airfoils.

Current helicopter ice protection systems for engine inlets and rotorblades utilize thermal systems.

Anti-ice protection is typically used on engine inlets; although some inlets may use de-icing when a particle separator and bypass are present. Inlets typically use engine bleed air although some electrothermal systems are used. Rotor blades typically use an electrothermal de-ice system due to the prohibitively high amount of energy needed to anti-ice.

As turbine engines become more efficient, less bleed air is available for anti-ice protection. High power for rotor blade electrothermal de-ice systems could require generator upgrades or even an additional generator (weight increases). Given these circumstances, it seems apparent that low energy systems are needed for helicopter use.

Small Tube Pneumatics (STP)

The pneumatic de-icer is an outgrowth of BFGoodrich's research in the 1920's to develop a coating that repelled the formation of inflight ice on wings of airplanes. The first of a continuing series of de-icer patent applications was made in 1930.

Although the specific design, materials and mode of operation has substantially changed in today's de-icer, the basic principle is still used. The pneumtic de-icer removes accumulated ice mechanically through air pressure inflation of flat de-icing tubes.

The Small Tube Pneumatic (STP) de-icing system was essentially formed to provide a means of thinner ice removal and smaller ice particles than the standard pneumatic de-icer. The pneumatic de-icer has already proven its value through its low power requirements and system simplicity.

STP Overview

The STP de-icer is a thin elastomer/fabric blanket containing 6.4 mm wide inflatable tubes that break and remove ice when inflated. The de-icer is designed so that the de-icing tubes cover the area to be protected.

The de-icer is made up of several layers of elastomers and fabrics. The outer surface layer is 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 de-icing tube is inflated. The outer surface and natural rubber layers are bonded to a stretchable fabric layer to form the outer tube wall, that when inflated flexes to remove ice (Figure 1).

The opposite wall of the tube is formed sewing the stretchable fabric to no- stretchable fabric, which is adjacent to another elastomer layer that forms the installation surface for bonding the de-icer to an airfoil. Other materials are added to form a pneumatic seal of the ends and edges of the de-icing tubes. An autoclave cure is used to fuse these layers into a relatively thin, smooth blanket. The de-icer is designed with internal venting, which permits all tubes in a de-icer to be inflated and deflated through an air connection normally located within the de-icing tube area and on the installation side of the de-icer where it projects through a mating hole in the airfoil outer skin.

De-icing occurs when the tubes are infla using 862 KPa air pressure. This is mu higher than the standard pneumatic de-icer which typically uses 124-172 KPa. The smaller size tubes, higher pressure and shorter inflation time are what give STP the capability to remove thinner ice. The small tube consistently removes ice at 2.5 mm inches thick versus 6.4 to 12.7 mm thick for a standard pneumatic de-icer. Figure 2 compares the STP de-icer tubes to that of the conventional size pneumatic de-icer tubes.

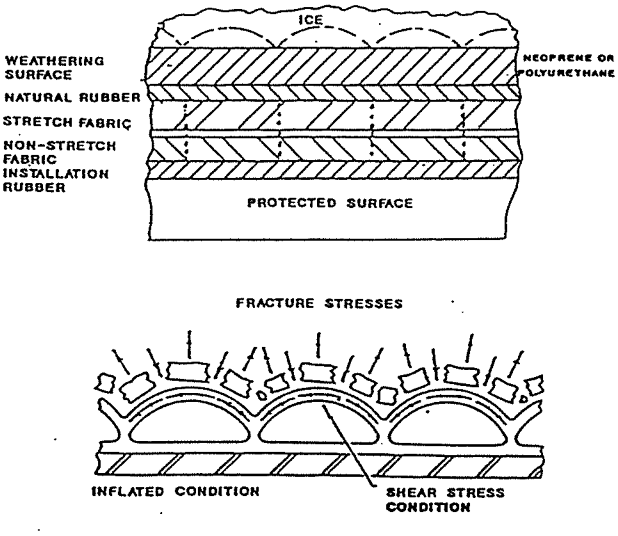


Figure 1

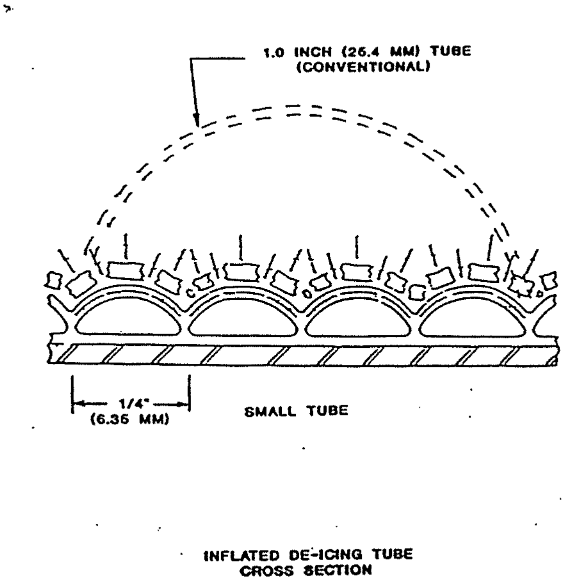


Figure 2

For a rotor blade, de-icer design considerations should start at the preliminary design stages to assure the de-icer is kept within the basic blade airfoil contour. Recessing the blade for de-icer installation is a way to retain the basic airfoil shape.

An alternative method is to autoclave cure the de-icer in an airfoil contour mold using a fiber-reinforced prepreg material to form a leading edge shell assembly. The shell assembly is then bonded to the rotor blade as a replaceable assembly.

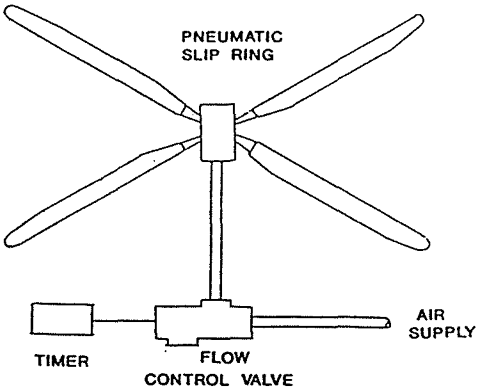
Both de-icer installation methods are currently used by BFG customers for fixed wing aircraft.

STP System Description

As with all rotor blade de-ice systems, the pneumatic de-icers must be operated in a manner that retains rotor system balance. Since a pneumatic de-icer normally would be designed to de-ice the full length of the protected blade area in a single inflation sequence, the de-icers on opposing blades must then be inflated simultaneously so that aerodynamic changes in opposing blades will be balanced. The designer should consider simultaneously inflating the de-icers 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. Figure 3, shown on the right, is a system schematic for a rotor blade application.

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

If an existing air source is not available on the aircraft, a separate electrical motor driven or air driven air pump could be used for de-icer inflation.



ROTOR BLADE SYSTEM

Figure 3

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

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

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

STP History

Initial STP de-icer icing tests were run in October 1987 in Lockheed's Burbank icing tunnel. The test panel removed .76 to 25.4 mm thicknesses of ice. Test conditions consisted of speeds of 46 to 82 m/s, cloud liquid water contents of 1.0 to 1.7 grams per cubic meter, and temperatures down to -20° C.

In 1988, the STP de-icer was tested in the NASA-Lewis Icing Research Tunnel (IRT). The test airfoil was large, representing a commercial transport horizontal stabilizer, and slightly tapered with a 1.8 meter mean chord. For cycle operation at every 15 seconds, the de-icer consistently shed .76 to 1.0 mm of ice at high liquid water clouds and temperatures near the freezing level.

Tests begun in 1989 are continuing in the BFGoodrich Icing Wind Tunnel (IWT). Principal effort has been directed at airfoils representative of main rotor blades and thin .25 mm airfoils similar to the shape of turbine engine inlet vanes. The testing has included de-icing and other critical properties.

As part of a USAF/NASA "low power" de-icing system evalution an STP de-icer was evaluated in the NASA Lewis IRT. The test model was an NACA 0012, 533 mm chord airfoil that represented a helicopter main rotor blade. The test de-icer was 1.9 mm thick and the unit weight of the de-icer was slightly less than 2.4 kg/m^2.

For the test condition, the residual ice remaining was generally 2.5 mm thick or less for icing durations up to 20 minutes.

Currently, an STP de-icer system is being designed for a two-blade, 1.5 meter rotor blade that will be tested for ice shedding properties in the NASA IRT, early in 1992.

Pneumatic Impulse Ice Protection (PIIP)

BFGoodrich has been developing a new advanced type of impulse ice removal system since 1984. This system is quite different from other current dynamic ice removal systems because it uses a pneumatic rather than an electrical impulse to effectively remove thin layers of ice. The principal objectives of this development were to 1) reduce the thickness of accreted ice needed for effective removal, 2) reduce ice shed particle size, and 3) enhance the weatherability of surface erosion material.

PIIP Overview

The PIIP system relies not only on distortion of the surface to debond the accreted ice, but also on rapid movement of that surface to "launch" the ice. The displacements, typically .38 to .76 mm are obtained in as little as 50 microseconds. The surface itself can be either thin titanium alloy or a thermal plastic material like "PEEK" (Poly Ether Ether Ketone) overlying a flexibilized thermoset plastic matrix and spanwise tubes.

These spanwise tubes, also referred to as impulse tubes, channel the burst of air down the span of the leading edge and overboard to ambient through vent ports in the back of the leading edge, at the tube ends. The tubes are located adjacent to one another with sufficient number to cover the ice accreting zone of the leading edge. See Figure 4 on next page.

The rapid pressurization of the impulse tubes "snaps" the surface outward, introducing chordwise tension and resulting shear stresses developed at the ice/surface interface; however, it has been found that simply debonding the ice is not always sufficient to ensure its removal. The experience of numerous icing tunnel tests has shown that for a low deflection system it is necessary to "launch" accreted ice from the surface in addition to debonding. This is achieved by imparting a sufficient amount of momentum to the ice by rapid outward movement of the surface, followed by a sufficiently large deceleration of the surface to allow the inertia of the ice to overcome any residual adhesive forces.

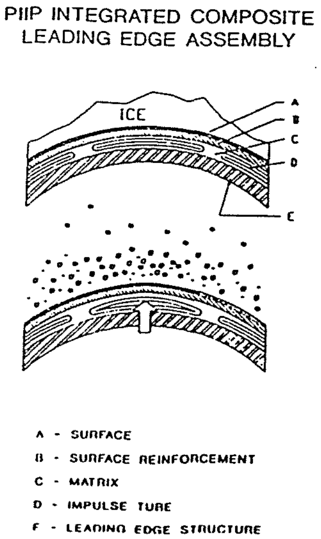


Figure 4

PIIP System Description

A system schematic for a rotor blade application is shown in Figure 5. The system impulse delivered to the de-icer comes from high pressure air 2.8 - 10.3 MPa generated from a small stand-a-lone compressor or tapped from an existing high pressure system on the aircraft. The air is supplied via small diameter tubing or hose to one or more impulse valves, located in the vicinity of the protected surface.

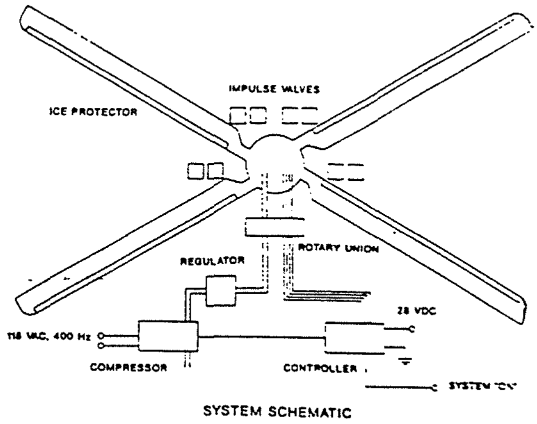


Figure 5

The airfoil geometry determines the number of tubes to be used. On airfoils with large leading edge radii a single tube centered on the stagnation line has proven effective. Airfoils with small leading edge radii (rotor blades), however, may require two tubes, one on each side of the stagnation line. An interstitial or non-bonded region may aid surface distortion. Additional tubes may be required to remove accreted ice on aft airfoil sections.

For fixed wing applications one valve is required for approximately every 3 meters of ice protector. The valves would typically be installed behind the leading edge, either fore or aft of the front spar. A rotor blade application would require two valves per blade, one for the upper surface tube and one for the lower surface tube(s). The valves would be located at the root end of the blade. These valves contain a small internal accumulator chamber of predetermined volume, typically less than .025 cubic meter. Upon actuation of the valve by 28 VDC signal from the controller, the pressurized air in this chamber is discharged rapidly into a port in the back of the leading edge which accesses the spanwise de-icer tube.

The surface, matrix and spanwise-running tubes comprise the active, ice-removing portion of the leading edge. This article may either be bonded to a metal leading edge skin, in a manner similar to conventional pneumatic de-icers, or backed with reinforced-epoxy composite structure. The latter construction may be cured in a female tool built to the airfoil design contour, resulting in a lightweight, non-intrusive composite leading edge structure that incorporates the de-icer. This stand-alone composite leading edge may then be attached to the airfoil afterbody. Figure 6 shown below illustrates such a composite leading edge. The active portion of the de-icer could also be bonded directly into a composite blade.

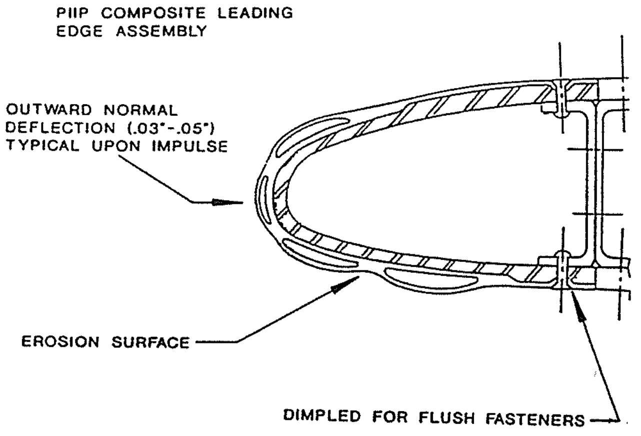


Figure 6

The system is typically operated on a fixed time cycle basis, in which the valves are sequentially and symmetrically actuated by the controller at repeated time intervals while the system is "ON". Initiation the system may be by cockpit command or y input to the controller from a remote ice detector.

For most applications, a dedicated onboard compressor or air intensifier is required to provide source air for the system. The compressor may be either electric or hydraulic motor-driven; the hydraulic option being the lower weight approach.

PIIP History

The first icing tunnel tests with PIIP were conducted in 1985 in the diffuser section of the NASA Lewis IRT in Cleveland, Ohio. These tests were with a rubber matrix, PEEK-surfaced de-icer bonded to an aluminum leading edge. Ice removal performance the order of 2.5 mm was obtaine indicating sufficient promise to warrant further development of the system.

The first natural flight tests of the system were conducted in March, 1986 on a Cessna Model 208 Caravan, a single engine tubroprop. Testing was conducted over the northern plains of the midwest, but due to the lateness of the icing season only three test flights were made. For these tests as well as the NASA IRT tests, an early version of the system was configured. PEEK-surfaced, rubber matrix de-icers were installed on the right inboard wing (approximately 3.8 m long) and on the right strut (approximately 2.4 m long) in place of the standard pneumatic de-icers. A small 28 VDC motor-driven compressor a impulse valve were installed in the cab with hoses routed from the valve to the de-icers for channeling the impulse. The ice protectors were configured with a single leading edge tube located over the leading edge centerline, and were bonded to the aircraft's leading edge skin in a manner similar to conventional pneumatic de-icers. Thickness of the ice removed was typically 6.4 mm or greater, with some thin ice removal noted in the vicinity of the impulse entry ports. The testing underscored the need to tailor tube size and location to the specific airfoil geometry.

It was desired to make the PIIP system a viable system for commercial aircraft, as a low power alternative to bleed air. The PEEK surface, while suitable for many applications did not possess the rain erosion resistance required for commercial aircraft, and was therefore replaced with titanium in 1986.

A number of tests were conducted in Lockheed's icing tunnel in Burbank, California in late 1986 and 1987. Articles for these tests were titanium-surfaced, but still contained a rubber matrix and were bonded over metal leading edge skins. These tests revealed difficulty with the system in removing "wet" ice, or the ice/water mixture that results when the freezing fraction of the incoming water is less than unity. This condition occurs when the temperature and/or liquid water content is sufficiently high that not all of the incoming water freezes on impact; a 2-phase mixture at about 0°C exists on the surface. Generally good shedding performance was observed, however, for ice thicker than 3.2 mm.

Late in 1988, activity was culminated by a series of tests in the NASA-Lewis IRT. The version of PIIP tested was a much changed construction. Instead of the elastomeric materials used previously, composites were used throughout. The test article had a 1.8 meter span, a mean chord of 1.4 meter and a mean thickness of 140 mm. Although of basic composite construction, the skin remained a high modulus metal. These tests demonstrated that the Composite PIIP was able to remove ice as thin as 1.0 mm under most conditions. At the slush ice conditions, formed above -4°C, ice as thin as 2.3 mm was removed most of the time. PIIP has the ability to remove a threshold thickness of ice 2.5 mm thick under all conditions. It also demonstrated the feasibility of an all-composite construction ice protection system.

Ice removal performance continued to be improved in 1989, as the availability of BFG's own recently constructed icing tunnel served to speed development. Tests were conducted again in 1989 in the NASA IRT with basically the same part as was used in 1988, but using a PEEK skin instead of titanium. The results were similar or a little better.

Since these series of tests, development of the system has focused on tailoring the surface dynamics in order to be able to effectively remove the difficult thin and wet ice. Other airfoil sections have been tested, ones with smaller leading edge radii. In addition, a greater number of parts using PEEK skins have been tested.

The most recent series of tests occurred, again in the NASA IRT, in June 1990. PIIP was included as part of the NASA/USAF sponsored "low power icing technology" series. The PIIP de-icer tested consisted of a PEEK surface bonded into a NACA 0012 airfoil. The system worked extremely well in all conditions and demonstrated that PIIP is very capable of thin ice removal as well as small de-ice particle size.

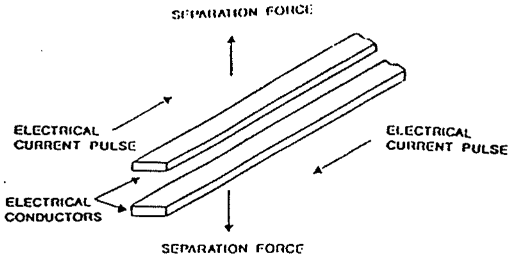
Electro-Mechanical De-Icing System (EMS)

BFGoodrich initiated its activity for the development of electro-mechanical de-icing systems in the mid 1980's. There are two separate types of electro-mechanical systems, the Electro-Expulsive De-Icing System (EEDS) and the Eddy Current System (ECS). These systems, which use electrical discharges to remove ice, have been developed to remove very thin layers of ice and small ice particle sizes, using a much smaller amount of electrical energy than required for the more typical electro-thermal systems.

EMS Overview

The Electro-Expulsive De-Icing System (EEDS) uses an electrical capacitor discharge pulse that is transformed to a mechanical deicing force capable of effectively removing thin layers of ice. BFG has evolved designs that improve EEDS performance and reduce weight of these systems.

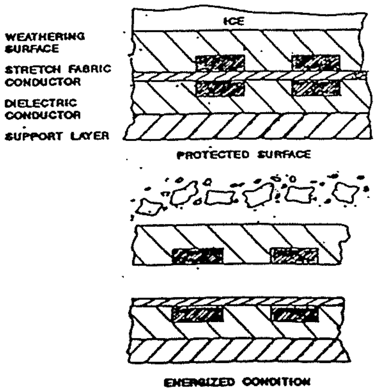
The basic operating principle for EEDS is that a strong mechanical impulse is created when a large electrical current is pulsed in two closely spaced parallel electrical conductors. See Figure 7. When the electrical current flow moves in opposite directions, an electro-magnetic (repulsion) force is created that quickly separates the two conductors.



EEDS PRINCIPLE OF OPERATION

Figure 7

De-icing action occurs when a pulsed conductor is contained in the substrate of an ice covered surface. See Figure 8. As applied to an airfoil surface to be protected, the EEDS de-icer consists of a material layer containing a set of electrical conductors and an outer surface containing a second set of parallel conductors which is bonded to the airfoil. The action of high electrical current impulse, or discharge through the conductors, causes the outer surface conductors to deflect rapidly and forcefully. This expulsive reaction breaks and expels the surface ice into small pieces.



EEDS ICE REMOVAL

Figure 8

The ECS de-icer also operates from a strong mechanical impulse created by a large electrical impulse. The difference between ECS and EEDS is that the ECS de-icer uses flat planar coil conductors which induce an eddy current into a metal target or surface. See Figure 9 on next page. The opposing eddy current creates a repulsive force which is used to break the ice bond. The ECS de-icer construction, except f conductor layout is the same as for t EEDS and the system hardware is identical.

The de-icing force produced by the de-icer is directly related to the electrical amperage in the conductor sets. To produce the necessary de-icing action at the ice covered surface, a high amperage, on the order of 3000 amperes, is required. Since the amperage flow of a circuit is directly related to the applied voltage and inversely related to the electrical resistance of the circuit (Ohm's Law), an optimum combination of high voltage and low circuit resistance is desired. To limit voltage to the 1500-2000 volt discharge range, much work has been directed at achieving low circuit resistance.

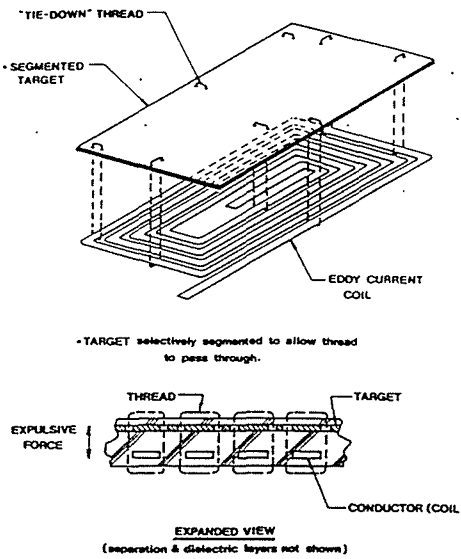


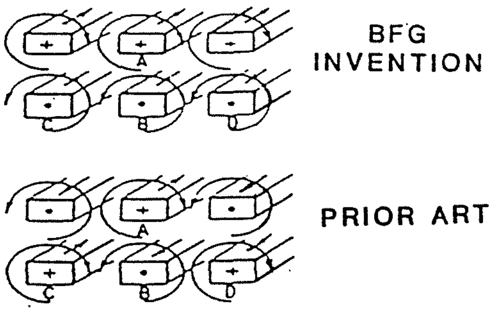
Figure 9

BFGoodrich efforts to increase the de-icer circuit or zone area for EEDS have resulted in a significant increase in the ratio of surface force to applied amperage, which effectively increases the de-ice segment area.

The improved force/amperage ratio results mainly from the following two design features. Both improvements are patented by BFGoodrich. [i]

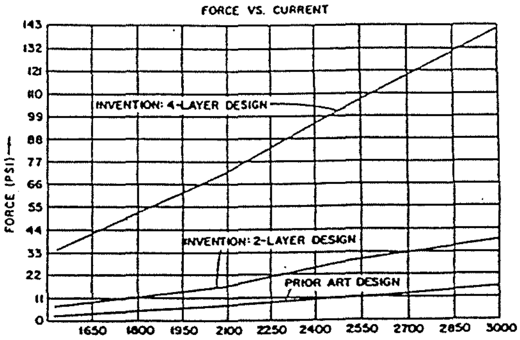
BFGoodrich's first design improvement to EEDS is shown in the upper illustration of Figure 10. The circuits are designed so that the direction of current flow is the same in all conductors of each circuit layer. This can be visualized as a "flattened coil."

For closely spaced layers of conductors, this arrangement allows for more positive separating force reaction than a prior art design. The performance improvement of this design is shown in Figure 11 as the two-layer design which produces over twice the force of a prior art design.



EEDS DEICER - CURRENT FLOW

Figure 10



DEICER-OUTPUT FORCE COMPARISON

Figure 11

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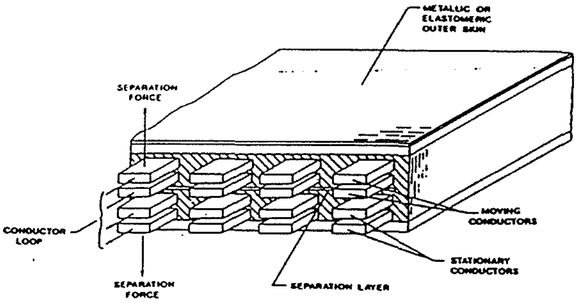
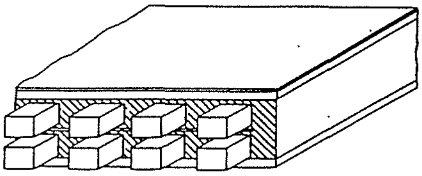
[i] BFGoodrich patents are identified as "Electro-Repulsive Separation System" (ESS).

The second design improvement to EEDS provides an eight-fold improvement of the prior art at 3,000 amperes current. This improvement results from increasing the circuit layers from two to four as shown in Figure 12. Although the four layer doubles the element weight and resistance, the resulting force/amperes ratio improvement is quadrupled, thereby demonstrating that the design be considered for the rotor blade application.



FOUR LAYER DESIGN



TWO LAYER DESIGN

Figure 12

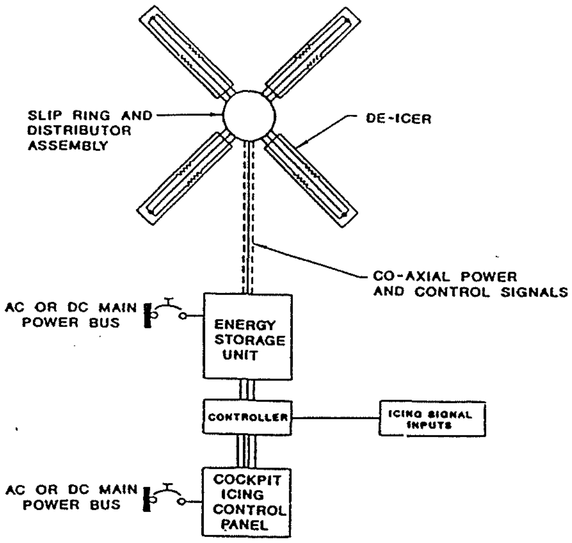
EMS System Description

The electro-mechanical source power for the high electrical current discharge comes from a capacitor bank, which receives its charge from a low voltage power converter, and uses the aircraft's standard power supply. An Energy Storage Unit (ESU) contains the power converter and capacitors.

The separate controller permits control of more than one ESU, while use of distributors permit local sequencing of the high current pulse near the de-icer.

Although there are two (2) choices of de-icers, other system components for the EEDS and ECS are identical and include: slip ring, controller, ESU distributors, and wiring, as indicated in the system schematic.

Figure 13 shows the system schematic for the electro-mechanical application to be used on rotor blades.



ROTOR BLADE SYSTEM

Figure 13

For the rotary interface, a slip ring is used. The slip ring contains a coaxial power channel for the high current pulse and signal channels for control and position signals for the distributor.

The controller interfaces with the control panel, ESU, and if used, an ice detector. The controller contains all system logic, interprets all pilot control inputs, and ice protection or ice sensing signals to operate the system. It also directs and monitors the ESU and the application of igh current pulses throughout the slip ing and distributor.

The ESU consists of a charging converter, capacitor storage bank and distributor interface circuitry. The charging section transforms aircraft voltage to the voltage needed to charge the capacitor bank. The distributor interface circuitry controls and verifies distributor output position and sequences the distributor as needed. The distributor is a multi-output switching unit that directs the high current pulse to the desired de-icer zone. It is operated by the ESU under control of the controller.

The coaxial wiring harness uses a single or multi-conductor feed surrounded by a shield carrying the return current. The high current pulse is thus completely shielded o minimize emissions.

EMS History

In 1986, BFGoodrich began development work on electro-mechanical systems and conducted its first bench test of EEDS. In the following year, a planar coil ECS de-icer as well as an improved version of EEDS de-icer was successfully tested. Parametric studies soon began for the two systems. These initial studies encompassed de-icer designs and the influence of element conductor variations on the overall performance of the de-icer. Another objective was to establish the optimum electrical discharge pulse waveform.

In June 1987, NASA contacted BFG to develop EDS for a flight test on the F/A-18 engine inlet. Prior to installation of the system, an EMI/EMC test was successfully completed per MIL-STD-461. In October of 1987, the F/A-18 de-icer construction was tested in the Lockheed Icing Tunnel located in Burbank, California. The de-icer construction included both EEDS improvements.

The culmination of this development resulted in actual flight testing on the F/A-18 conducted during July of 1988 at The Naval Air Test Center in Patuxent River, Maryland. The de-icing blanket consisted of six de-ice zones integrated into one rubber matrix boot which provide complete coverage of one inlet approximately 1300 sq. cm. The control system was mounted in a test pod external to the aircraft with the photographic instrumentation. The de-icing boot was able to remove both rime and glaze ice from the inlet while flying behind a U.S. Airforce NKC-135 tanker spray rig (Ref. 1).

Also in 1988, natural icing tests were conducted on a smaller de-icer boot using NAS'S DHC-6 Icing Research Aircraft. These tests were conducted in the great lakes region near Cleveland, Ohio.

The following year BFG was issued a U.S. Patent for the "flattened coil" electro-repulsive de-icing element. This design allowed for increased performance while decreasing the input current levels (less power). Additionally, this design is now the baseline for evaluation the U.S. Airforce B-1B engine inlet.

In June 1990, BFG participated in the USAF/NASA "Low Power Icing Technology" series. The basic outcome from this test was that the BFG electro-mechanical de-icing system was capable of shedding small ice particles. The de-icer itself was configured for a NACA 0012 21 inch chord airfoil. This particular de-icer was an eddy current system which had a titanium outer skin for improved erosion life.

Most recently, BFG has completed a six month feasibility study for an electro-repulsive de-icing system. This feasibility study has lead to an actual B-1B engine inlet component test. The test was performed at the NASA Lewis Icing Research tunnel where ice particle shed size was characterized for different de-icer power levels. This de-icer has proven to be compatible with the B-1B aircraft as well as its environment requirements.

Summary

The STP, PIIP and two electro-mechanical systems all offer low energy ice protection when compared to thermal systems. All of the systems have been extensively tunnel tested, and the EED and PIIP systems have been successfully flight tested on fixed airfoils. Although the STP de-icer has not been flight tested, it is based on the conventional de-icer system which has been flown on fixed wing aircraft for over 60 years and successfully flight tested in icing on the UH-1 helicopter rotor blade system in a joint program with NASA and the U.S. Army (Ref. 2).

Currently, each system is being developed for specific applications as they are identified. Although the systems are currently aimed at fixed airfoil applications, their success and low power capabilities warrant consideration for rotor blade application.

References

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