Improvements to Expulsive Separation Ice Protection Blankets

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Abstract

A number of improvements to expulsive blanket ice shedding capabilities are described. Detailed mechanisms of expulsive blanket ice shedding are discussed. Recent improvements in expulsive system components size and weight are quantified. Use of expulsive blankets as ice detectors is introduced.

Background

Expulsive separation blankets are applied to an aerodynamic surface that is subject to ice accretion. They protect that surface by mechanically expelling ice periodically. The force to expel the ice is developed magnetically by passing a large pulse of current through the internal conductors of the blanket. The macroscopic ice shedding mechanisms of expulsive blankets have been previously described in our earlier paper (Ref. 1). Expulsive blankets have the ability to cleanly shed all forms of meteorological ice at virtually any thickness. When blankets are fired frequently, they act almost as an anti-icing system.

Introduction:

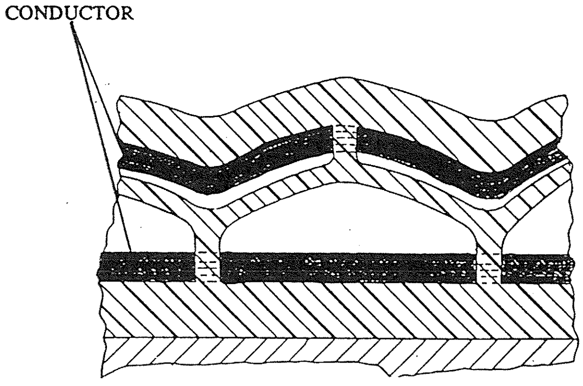
Expulsive Ice shedding has advanced from an exciting laboratory technique in 1988 to become a viable candidate low power deicing system in 1992. Expulsive blanket life has been extended so that in deicing applications it far exceeds pneumatic systems (1,000,000 cycles versus 25,000 for pneumatic). Expulsive blankets have been tested in a variety of icing tunnels, and in natural icing and have been shown to be extremely effective. Expulsive blanket designs are now available that provide redundancy at the blanket level. The data base showing blanket compatibility with various metallic and composite substrates has grown substantially. Their erosion performance has been steadily improved.

While these blanket features have been developed, a comparable development in the required electronic controllers has reduced their size and weight greatly. Two years ago, eight square feet of expulsive blanket required a power supply that weighed nearly forty pounds, was not flight worthy and did not support any reasonable maintenance concept. In 1991, a flight worthy power supply weighs less than ten pounds, can drive twenty square feet of blanket and is self diagnosing.

Areas of Improvement: [1/]

1. Extended Life has been achieved by providing controlled internal conductor deformation. The controlled deformation limits the deflection of the blanket conductor during firing and therefore virtually eliminates conductor metallic fatigue. (Refer to Figure 1). By providing a periodic variation in the spring rate between the top and bottom layer of the blanket, the copper is deformed sinusoidally, by the firing forces. Distributing the deformation in this manner prevents permanent deformation from occurring and causing a local, fatigue inducing, high stress of the copper conductors.

This type of periodic spring gradient geometry also provides a very steep non-linear spring gradient to decelerate the blanket surface after the firing pulse. The geometry of the inter-layer provides initial rotary motion that becomes tension as the top layer moves away from the bottom layer. It has been shown that thin ice is shed not by the acceleration of the blanket surface, but by the deceleration of this surface. When an expulsive blanket is fired, the top layer and the ice on its surface are accelerated normal to the substrate. While ice is relatively strong in compression, it is relatively weak in tension (Ice cube trays all use this



FIRED POSITION

Figure 1 - Internal Conductor Deformation

principle). Thus the sudden stop generated by this type of spring geometry enhances the blanket's ability to shed ice and lower accelerations. Lower accelerations mean lower input energy.

The periodic spring gradient also provides the bonding from top to bottom layers of the blanket. The same internal bonding of the blanket top layer to the bottom layer required to shed ice also provides a blanket natural frequency that is quite high and well damped. This means there are no aerodynamic resonances to produce fatigue damage in the elastomer[2/] of an expulsive blanket. These improvements have lowered the energy required to deice. This reduces the energy which the elastomer must ultimately absorb and therefore improves its fatigue life (Refer to Figure 1.1).

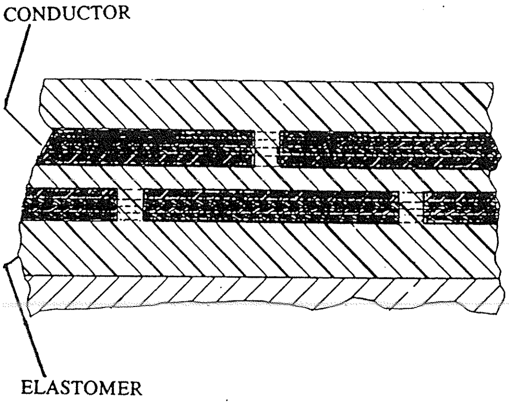


Figure 1.1 - Internal Bonding from Top to Bottom Layer

The forces required to shed ice, while minimized in any practical expulsive system are still quite significant. Thus any connection from top layer to bottom layer offers the potential for high stress and fatigue damage to the copper conductors. When a connection between top layer conductor and bottom layer conductor is required, a hinge design has been developed to minimize and tailor stresses so the conductor life is not compromised by fatigue damage. (Refer to Figure 1.2). By reducing current density, and by increasing conductor spacing as shown, forces are reduced and conductor life is dramatically increased.

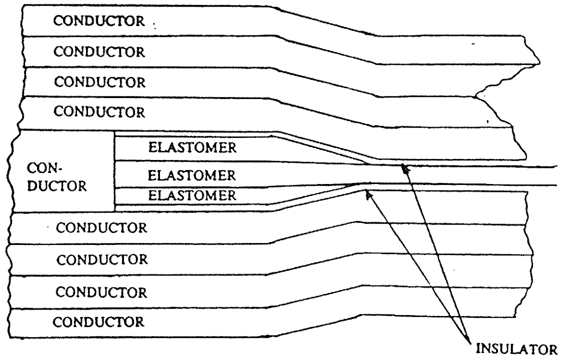


Figure 1.2 - Long Life Hinges

Blanket efficiency has been improved significantly by providing better conversion of electrical energy into mechanical energy. This has been accomplished by applying the basic expulsive blanket force equation and understanding the time response of the blanket materials to the applied force. When conversion efficiency is increased, total energy required to deice is decreased. This lowers stresses in the blanket and therefore reduces fatigue damage. Table 1 gives a comparison of energy required to deice per square inch in 1988, July 1990, March 1991 and September 1991. Recent work on surface coatings to reduce the tensile strength of the ice-to-blanket bond has demonstrated no performance improvements. This result has confirmed the data of most other investigators. Much remains to be done to assure coating durability in sand and rain erosion.

2. Blanket Level Redundancy provides for ice protection after the failure of an electrical segment within a blanket. This user requirement arises whenever an aircraft system impacts safety of flight. In electro-thermal deicing systems redundancy is achieved by protecting alternate blocks of the aerodynamic surface. After the first failure, the

Table 1 - Expulsive Blanket Efficiency

SEPT. '88	1.1 Joules/cm^2
JULY '90	0.65 Joules/cm^2
MARCH '91	0.33 Joules/cm^2
JULY '91	0.17 Joules/cm^2

aerodynamic penalty of a portion of the surfacing collecting ice must be accepted. This type of redundant protection is also available in expulsive systems.

For bleed air, two sources of bleed air are provided and the valves and ducting to connect either source to each protected surface is required. There is no performance penalty after first failure. There is a weight and cost penalty in that the additional equipment is a part of the basic aircraft design.

Expulsive ice protection provides a third type of redundancy. By connecting alternate blanket segments to different electronic controllers and by using the horizontal shear icing shedding mechanism described in our first paper, it has been possible to shed ice in a failed segment using the remaining good segments. Physical separation is achieved and independent failure modes are maintained. This approach, as well as the separation of surfaces, allows expulsive blankets to become part of a primary ice protection system (Refer to Figure 2). Data taken in the Dataproducts icing wind tunnel shows that on a blanket maintaining an average ice thickness during continuous icing of 0.020 inches (0.51mm), when a segment fails, the residual average thickness increases to 0.030 inches (0.76mm). Initial tests have been performed whereby the firing energy level of the remaining good segments is increased. This seems to improve performance so that the residual ice is approximately the same thickness as before the failure. The higher energy levels reduce blanket life an as yet undetermined amount.

Boosting the firing energy from 10% over threshold to 30% over threshold increases the firing energy per unit area by 40%. This increase could on an analytical basis reduce blanket life to 15% of normal. While this is a substantial reduction, it would allow completion of the flight and considerable delay until repairs must be affected.

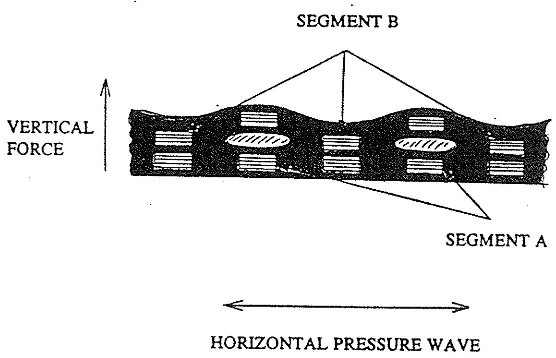


Figure 2 - Blanket Level Redundancy

A redundant controller topology has also been developed to support the blanket level redundancy. In all but the smallest systems this topology exacts almost zero penalty in total system hardware. By providing separate charging circuits, separate switching circuits and separate connecting harness, all of which were required in the same multiplicity, whether or not they are separate, full fail operational performance can be achieved with good design practice (Refer to Figure 2.1).

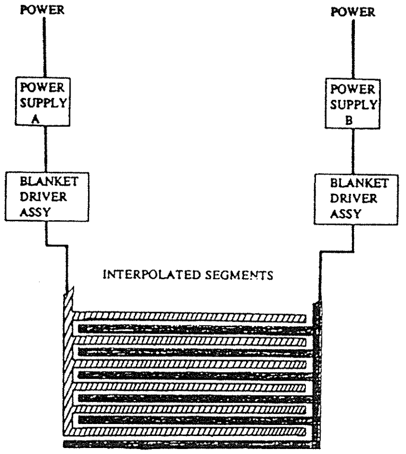


Figure 2.1 - Redundant Controller Topology

In some cases, the control electronics are now small enough and rugged enough that they can be built into the interior of the surface to be protected. Blanket life is sufficient that an ice detector may not be required. Surfaces such as horizontal tails or engine inlet lips can be protected by switching on the expulsive system (less than 10 watts/ft.^{2} = 108 watts/m^2 is required) whenever there is visible precipitation and the temperature is less than 10°C. An expulsive system may be operated during take off since the energy consumption for the entire aircraft is comparable to the landing lights and the aerodynamic distortion during operation is negligible.

3. <u>Blankets/Substrate Compatibility</u> is essential. Compatibility has two aspects. The method of attachment must (normally adhesive is used) be simple to accomplish, be durable and long lived. In this, expulsive blankets which use materials similar to pneumatic blankets and some electro-thermal blankets, have borrowed existing technology liberally. In the case of pneumatic blankets, adhesive shear strength is vital to keep the pneumatic blanket from peeling when it is inflated. For expulsive blankets the forces are almost completely normal to the substrate.

As long as the materials are compatible, almost all adhesives used for pneumatic blankets will bond expulsive blankets. For the future, we expect that adhesives with less shear strength will be used so as to enhance the removability (maintainability) of expulsive blankets without damaging a composite substrate. Analysis and tests have shown expulsive blankets to be compatible with a wide variety of substrates. (See Table 2 for details)

Table 2 - Expulsive Blanket Efficiency on Different Substrates

ALUMINUM NACA 0012	0.19 Joules/cm^2
ALUMINUM EPOXY FILLED NACA 0012	0.17 Joules/cm^2
COMPOSITE PROPELLER	0.19 Joules/cm^2

When a blanket is fired it creates a force on the substrate, just as it applies force to the ice which has accreted on its surface. The force is reacted by the strength of the substrate material, and by its inertial mass. Most substrates are much more massive than the moving blanket mass, and therefore most blanket forces are reacted by the inertial stiffness of the substrate. In tests on a typical airfoil composite structure over 100,000 cycles of blanket firing were applied and no damage to the substrate occurred.

When a blanket is installed on a curved surface, the stresses associated with firing the blanket and with substrate deformation due to aerodynamic loads must be considered in the blanket's design. Compound curves provide the greatest challenge. Convex curvature implies internal conductors must accommodate to a greater radius when fired. Concave curvature implies internal conductors must accommodate to a lesser radius when fired. The potential stretching of hoop stress and buckling of compressive stress has been handled by corrugating the copper inside the blanket (Refer to Figure 3). EEDS[3/] blankets are designed to minimize hoop stress while conforming to the substrate shape.

Each new shape to be protected requires application of the several design techniques developed in the last few years. When a surface routinely flexes (such as a propeller) this type of bending must also be part of blanket design considerations.

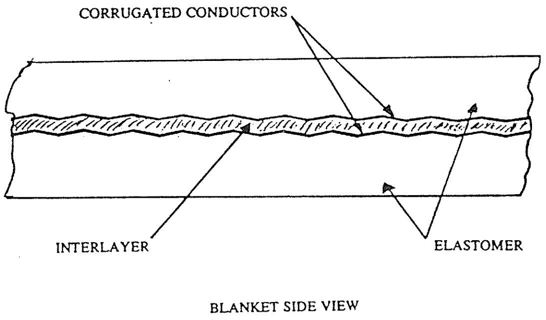


Figure 3 - Corrugated Internal Conductor

Blankets for the leading edge of flat wings are made up of long narrow span wise electrical segments built as a single elastomeric blanket or as multiple butted segments. The segments can be interpolated if blanket level redundancy is required. Whether they are or not, care is generally taken to place adjacent electrical segments on both sides of the leading edge. The effect of this type placement is to minimize the in plane stress when each segment is fired (Refer to Figure 3.1). As the radius of the surface is decreased this type of design becomes essential to efficient blanket ice shedding. For very small radii, copper conductors within the blanket must be moved closer to each other to overcome the adverse geometry.

Other techniques, such as varying copper width within a single blanket, changing copper spacing within a single blanket and providing serpentine copper within a single blanket are proven design tools that have been successfully tested in various design situations.

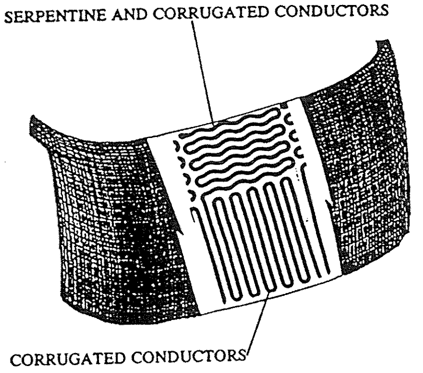


Figure 3.1 - Segments Arranged to Minimize In-Plane Stress Due to Radius

The motion of expulsive blankets is so small (less than 0.020" = 0.51mm) when they are fired, that aerodynamic penalties due to span wise segment distortion is negligible. Additionally, the blanket deformation is present for such a short period of time that aerodynamic disturbances cannot grow to significant size. When a blanket is fired it returns to its rest position in less than 0.0005 second.

When the aerodynamic surface to be protected routinely experiences significant deformation, such as a propeller or helicopter rotor blade, the copper inside the blanket must accommodate this motion. EEDS blankets for this type application are constructed with internal corrugations (Refer to Figure 3.2). The corrugations provide additional copper to allow flexing without significant additional strain on the copper. Corrugations also permit cord wise segments to be built when a complex surface must be protected. In-plane corrugations are formed in both top and bottom layers of copper so that copper spacing is maintained. Test data confirms that blanket efficiency does not suffer significantly when copper is corrugated.

By varying the depth of corrugations and their pitch, a wide variety of motions and compound curves can be accommodated. Tests in DNE's icing tunnel show the penalty for corrugations is less than 5 percent in energy.

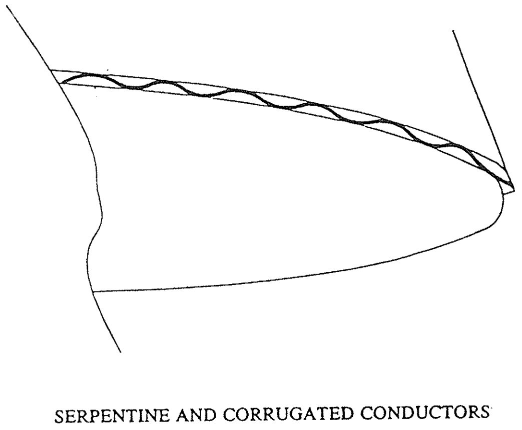


Figure 3.2 - Corrugations in a Blanket with chordwise Segments

Shedding Mechanisms:

At least three distinct mechanisms operate to shed ice when an expulsive blanket is fired. For thick ice, (accretion of more than 0.2" =0.5 cm) blanket normal acceleration creates compressive forces within the ice sufficient to destroy its structure. This results in a layer of fragmented ice 0.1 mm or less between the blanket and the ice layer. Fracture lines generally pervade the entire thickness of the ice. Effectively, without necessarily shattering the entire accretion, the bond between blanket and ice is broken. External forces (aerodynamic, gravity, centrifugal) or a second blanket firing will then remove thick ice. A corollary for this type of shedding is that particle size is not well defined. Data from Reference 2 suggests maximum particle size can approximate the length of the segment fired.

For accretion well under 0.5 cm, inertial forces are insufficient to affect the blanket-ice bond. The force created by the pulse of current through the blanket accelerates the blanket upper layer and the ice bonded to it. Subsequently, the internal springs of the blanket decelerate the blanket and the ice. Ice-to-blanket bonds are relatively weak in tension. Efficient expulsive blankets have been constructed to incorporate non-linear springs; springs whose gradient increases abruptly with upper layer travel normal to the substrate. The effect of rapidly absorbing blanket-ice momentum in the blanket springs is to rapidly decelerate the upper blanket and to sunder the blanket-ice bond in tension.

For blankets operating in this mode, there is a reasonably good correlation between particle size and frequency of blanket firing (See reference 2).

Most practical expulsive deicing systems are designed to operate in the region. The limited data of reference 2 suggests that if a blanket is operated once every 60 to 90 seconds, at 150 knots (274 K/HR.), 0.5 gram/m^3 the particle size will approximate an equivalent 6.4 mm diameter sphere.

The third shedding mechanism, described in our earlier paper (AIAA 89-0774), is "horizontal shear." This pressure wave operates most effectively where there is no internal copper conductor. It is the mechanism that allows blankets to shed ice to their very edge. It allows adjacent, butted segments to shed ice seamlessly when they are properly joined. It allows blanket level redundancy by shedding ice from a failed interpolated segment.

In practice, a combination of these three shedding mechanisms operates whenever a blanket segment is fired. The effect is to virtually clean the blanket surface above each segment when it is fired.

Ice Detection with EEDS Blankets

By use of strain sensor, installed between two adjacent runs of upper layer copper conductors, an EEDS blanket can provide ice detection capability. When a blanket is fired, the elastomer in the space between copper conductors is dynamically distorted by the firing forces. The resulting strain generates a characteristic electrical signature from the strain sensor. When ice is present and bonds intimately to the blanket elastomer, the distortion is greatly reduced, and the resulting electrical signature easily distinguished from the no ice condition. Icing tunnel data suggests preliminary sensitivity of 0.020" +/- 0.005" can be achieved.

Summary and Conclusions

Expulsive blankets have been developed that can be applied to a majority of aircraft surfaces that are subject to adverse icing effects. In the next few years test programs on aircraft should lead to systems that protect fixed wing surfaces, engine inlets, propellers and helicopter rotor blades. As these systems are developed and certified they will support the safety of air travel in icing conditions while removing the major power drain of most present deicing systems.

Notes:

1/ Most of the technical details describing specific blanket characteristics are covered under the claims of U.S. Patents 4,894,569, 4,982,121 and 5,107,154 as well as other patents pending. These patents have been assigned to Dataproducts New England, Inc.

2/ "elastomer" is a term applied any of various polymers with elastic properties resembling those of natural rubber.

3/ "EEDS" is an acronym for Electro-Expulsive Deicing System

References:

1. Goldberg, J. and Lardiere, B., Developments in Expulsive Separation Ice Protection Blankets, AIAA-89-0774, January, 1989.
2. Bond, T.; Shin, J.; et al, Results of USAF/NASA Low Power Ice Protection Systems Test in the NASA Lewis Icing Research Tunnel, July, 1991.
3. Goldberg, J. and Lardiere, B. Improvements to Expulsive Serparation Ice Protection Blankets, AIAA 92-0533, January, 1992.