Electro-Impulse Deicing of the NASA Lewis Altitude Wind Tunnel Turning Vanes

Richard Ross*
Ross Aviation Associates, Wichita, Kansas

This paper presents a brief review of the basic principles and the development history of electro-impulse deicing and its application to the deicing of the turning vanes in NASA Lewis Research Center's Altitude Wind Tunnel (AWT). The results of laboratory and Icing Wind Tunnel tests of the AWT turning vane model are given. Some potential problem areas related to this application are discussed.

I. Introduction

FROM 1984 to 1986, NASA Lewis Research Center funded a project to verify the applicability of electro-impulse deicing (EIDI) for use in deicing the turning vanes of the Altitude Wind Tunnel (AWT). Turning vane deicing was required because NASA planned to refurbish the AWT as an $M = 0.9$ icing research tunnel.[1,2] During the last seven years, the EIDI system has been tested and refined and has been shown to be a low-energy, highly reliable deicing system for a wide range of conditions for aircraft wings and other surfaces. It is therefore likely that it would also work well for the AWT turning vanes

Ice accumulation on aircraft surfaces in flight is a well-recognized hazard. Although ice normally accrues only a few centimeters thick on the forward 2% of a wing, this is sufficient to cause flow separation, increase drag, and destroy lift. Similarly, ice accumulation on the turning vanes of the AWT, where the whole of the pressure surface is apt to be ice covered, could cause reduced turning efficiency and increased drag, thereby causing a dramatic increase in power required to remain "on condition." Perhaps blocking of the flow through the vanes could occur to the extent that transonic flow and shock waves would be present.

Although several methods of deicing (or anti-icing) the turning vanes are available, all have some undesirable aspects in regard to energy requirements, reliability, maintenance required, or space requirements. A method of deicing suggested as early as 1937[3] offered an alternative that had not been adequately developed until recent basic research work was performed.[4-8] A status of EIDI systems design is presented in Ref. 9. The electromagnetic impulse phenomenon holds the promise of ice removal with low energy, minimal maintenance, great reliability, and with costs competitive with other methods.

II. The Basic Principle

The physical form of the EIDI method is shown in Fig. 1. Flat-wound coils made of copper ribbon wire are placed just inside the leading edge of a wing's skin with a small gap separating skin and coil. Either one or two coils are placed at a given spanwise station, depending on the size of the leading edge. Two methods of supporting coils are shown; support by the front spar or from a beam attached to ribs is generally used, but mounting to the skin itself is sometimes used.

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*Director. Associate Fellow AIAA.

The coils are connected by low-resistance, low-inductance cables to a high-voltage capacitor bank, and energy is discharged through the coil by a remote signal to a silicon-controlled rectifier (thyristor). Discharge of the capacitor through the coils creates a rapidly forming and collapsing electromagnetic field, that induces eddy currents in the metal skin. The fields resulting from current flow in the coil and skin create a repulsive force of several hundred pounds magnitude but a duration of only a fraction of a millisecond. A small-amplitude, high-acceleration movement of the skin acts to shatter, debond, and expel the ice. Two or three such "hits" are performed sequentially, separated by the time required to recharge the capacitors, then ice is permitted to accumulate until it again approaches an undesirable thickness.

Figure 1 also shows "doublers," unalloyed aluminum or copper disks, slightly larger than the coils, bonded to the skin opposite the coil. These are used when the skin thickness is less than the minimum required to provide adequate conductance for the eddy currents. Composite, nonmetallic, and other nonconducting materials (such as stainless steel), when used for leading edges, require a similar special treatment.

In Fig. 2, the basic circuit is illustrated. An electroimpulse is initiated by supplying a trigger pulse to the thyristor, allowing the capacitor to discharge through the coil. Since a thyristor has diode properties, the current follows the first positive loop of the RLC response, after which the thyristor reopens the circuit. This leaves the capacitor reverse-charged. Such reverse charging reduces capacitor life substantially. For that reason, a clamping diode is placed across the capacitor. A typical

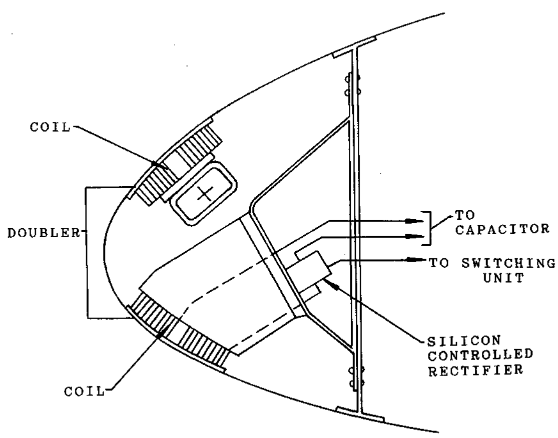

Fig. 1 Typical impulse coil installations in the leading edge of a wing.

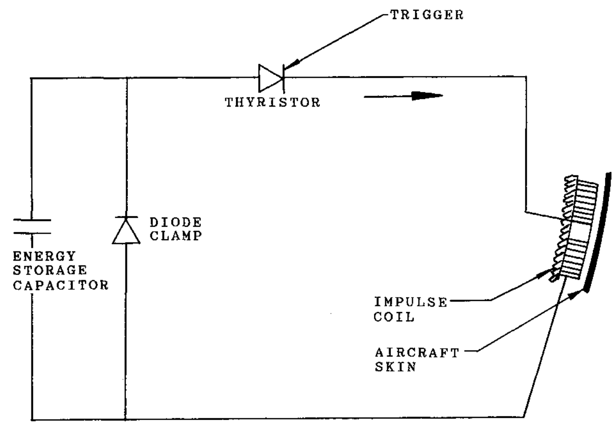

Fig. 2 Basic circuit.

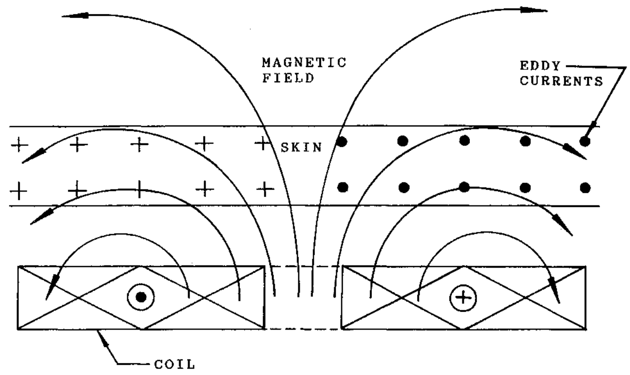

Fig. 4 Illustration of the coil's magnetic field pattern and of the resulting eddy currents.

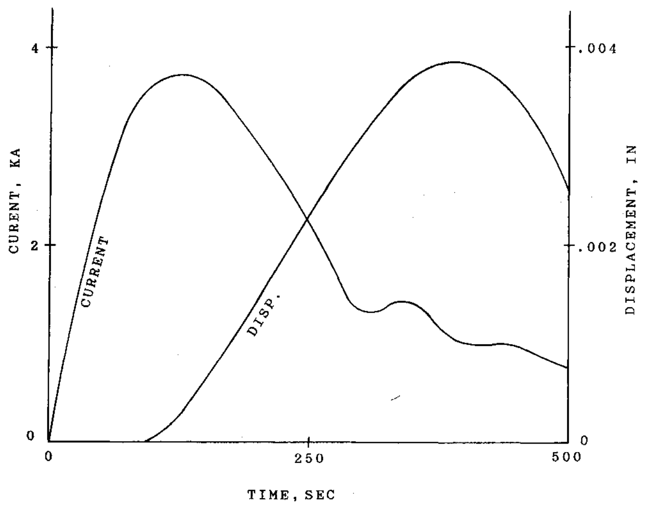

Fig. 3 Typical coil current and skin displacement.

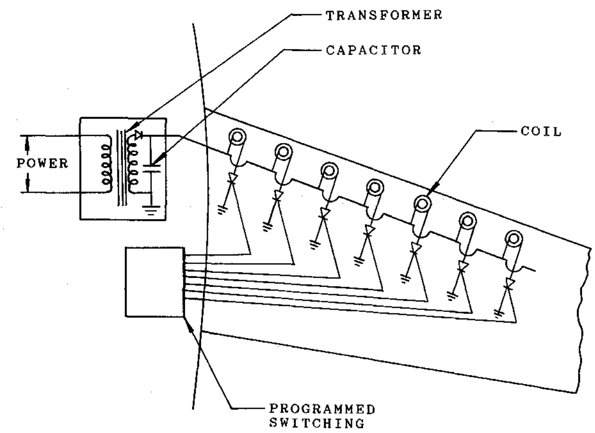

Fig. 5 Typical electro-impulse system in a wing leading edge.

current waveform and resulting skin displacement are shown in Fig. 3.

Figure 4 is a flat geometry illustration of the coil's magnetic field and induced eddy currents in the electrically conducting skin. The magnetic field due to the eddy currents is not shown, but it has a significant influence (by self-induction) on the magnitude, time history, and radial distribution on the eddy currents. In addition, the electromagnetic "skin effect" phenomenon affects the eddy current distribution across the aluminum skin thickness.

Current densities are greatest on the coil side. A reverse coupling effect is also present. Time-changing eddy currents induce a voltage in the impulse coil, modifying its current. From a circuit aspect, the consequence is a modification of the effective inductance and resistance of the coil. The effective inductance decreases, and the effective resistance increases, due to the proximity of the metal sheet.

When the aircraft skin moves in response to the electro-impulse force, the coil-to-skin gap changes, modifying the magnitude of the proximity influence. In addition, the skin's movement relative to the coil's magnetic field further modifies (by motional induction) the electromotive forces that drive the eddy currents. These influences due to skin motion are, however, relatively small because of the time delay involved in the motion, and should be negligible when the skin is ice loaded. The assertion is, in effect, that the coil current and the strength of the force impulse may be calculated without the need to analyze the complex structural response.

Figure 5 shows a wing with coils placed spanwise, separated by about 0.4 m. These are all supplied by a single power unit. Energy requirements are small, being comparable to those typical of landing lights for the same size aircraft. Deicing has been accomplished in the icing wind tunnel and in flight for typical general aviation wings under a wide range of velocities, angles of attack, icing rates, and temperatures.

III. Model Design and Fabrication

Because of the desire to simulate as nearly as possible the full-scale conditions of the AWT, it was decided to construct a short-span, full-scale chord model of the AWT turning vanes. The cross section was that of the "complex vane design"[10] that produces a nearly "flat" Mach number distribution over the initial length of the vane.

Front and rear spar locations and lengthwise rib locations were selected on the basis of past applications of EIDI. A fully cantilevered leading edge was selected because the clear span, uninterrupted by supported members, would produce the best effectiveness of the EIDI as well as optimum placement of the deicing coils. A maximum bay width of 18 in. with three instrumented bays was selected. To provide flow continuity across the entire instrumented section, a noninstrumented bay of 15 in. span was placed at either end of the instrumented sections (Fig. 6). Also shown in Fig. 6 are the coil locations. The coils were mounted on the front spar in the case of the leading edge and to braces mounted between the ribs for the aft two bays of each section. In order to complete the flow simulation, two exact duplicate vanes were constructed to be placed on either side of the one instrumented vane, thus providing a three-vane set of 7 ft length. (Fig. 7). All internal structure was of aluminum. The instrumented vane was constructed of 0.062 in., 301 stainless steel for the pressure and suction surface skins and the leading edge was of 0.040 in., 301 stainless steel. All of the skins for the dummy vanes were 2024 aluminum.

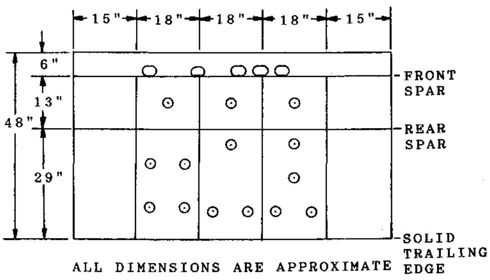

Fig. 6 Electroimpulse system in the vane model.

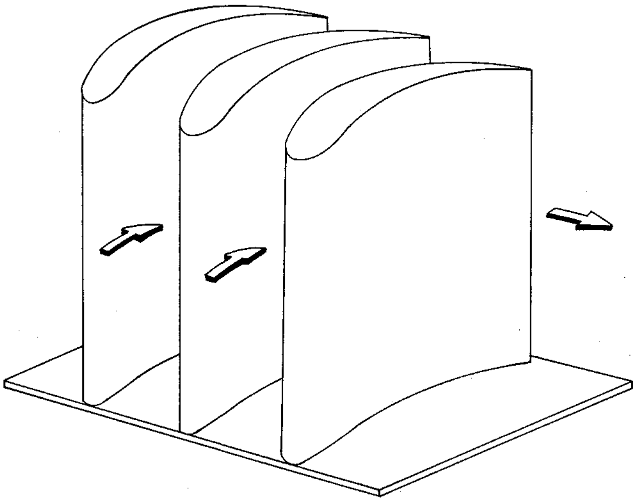

Fig. 7 Turning vane for model tests.

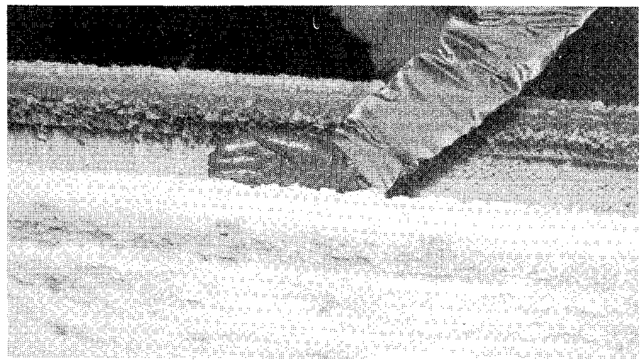

Fig. 8 Ice accumulation on the leading edge.

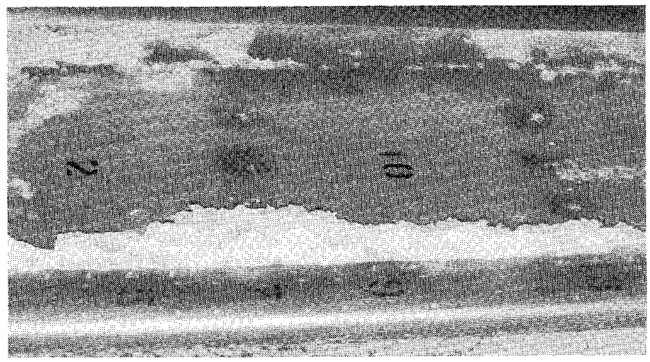

Fig. 9 Ice accumulation on the pressure surface.

The suction surface skin of the instrumented vane was attached with round-head screws for easy removal. The pressure surface was attached with flush-head countersunk rivets. At all skin fasteners in the instrumented bays, the internal bearing surface was reduced to promote a rocking action of the skin across the fasteners, thus improving the clearing action of the EIDI coils. The coils in the leading edge were of a race-track design. All others were circular. All were wound from 0.055-in. thick, 0.15-in. wide ribbon copper wire. The coils ranged in size from 2.5-4.0 in. diam and had 20-35 turns of wire. Each coil had its own supply wire to the power box so that any combination of coils could be fired simultaneously. The gap between the coil faces and the 0.062-in. copper doublers was 0.01 in. The doublers were rectangular and approximately 50% larger in size than the diameter of the coils. These doublers were riveted at their corners as well as being bonded to the pressure and leading-edge skins.

The material called out for the skins and leading edge was 304 stainless steel. Because of the difficulty in forming this material, 301 annealed stainless steel was substituted.

IV. Model Installation

Because of the size of the model, it was physically impossible to install it in the test section of the Icing Research Tunnel (IRT). In addition, the large amount of air that would be deflected 90 deg from the vane inlet direction made it unrealistic to locate the model in the relatively confined size of the test section without the prospects of flow interference within the vanes. It was thus decided to install the model in the IRT diffuser as close to the first-corner turning vanes as possible. The model was located midway between the side walls on an elevated stand to place it in the center of the icing air stream. It was spaced approximately 1½ chords ahead of the IRT turning vanes. Velocity distribution measurements showed that the model was located in a uniform flow stream and that the model location ahead of the IRT turning vanes was sufficient to preclude any interference with the model flowfield.

V. Icing Tunnel Tests

In September 1985, the model was installed in the NASA Lewis Research Center Icing Research Tunnel, and tests were run. Data were gathered by remote television recordings during icing and ice removal, as well as hand-held television, moving-picture camera, and still photographs during the ice removal process. Ice type and thickness were estimated prior to ice removal for each test. Observations were taken for test section air speeds from 100 to 200 mph. This was equivalent to a maximum speed of about 35 mph at the model. Air temperatures ranged from 15 to 27°F (−9 to −3°C). Liquid Water Content (LWC) ranged from 0.8 to 3.0 g/m^3 and water droplet size from 15 to 30 μ. Most tests were run with accumulation times of 15 min; however, a few were run for 30 min. The maximum icing time was 1 h for a very light icing condition. Deicing was accomplished by using 600 and 800 μF capacitance and voltages from 800 to 1200. Most of the coils were connected in pairs; however, some tests were run with singles and other combinations in an attempt to determine the optimum location and power required to optimally deice each of the two major bays as well as the leading-edge section.

Good cleaning was demonstrated on all areas of the center vane with fairly low energy expenditures. Ice removal occasionally required two or three hits.

VI. Results

For most of the test points the vane leading edge accumulated ¼-1 in. of ice for 15 min runs, and 1-2 in. for the longer (30 min) runs (Fig. 8). One run lasted 1½ h, and the ice accumulation at the leading edge was 3.25-3.5 in. thick. The ice accumulation aft of the forward spar on the pressure surface ranged from a light frost to ⅝-in. thick (Fig. 9). Most of these accumulations could be cleared with one or two hits

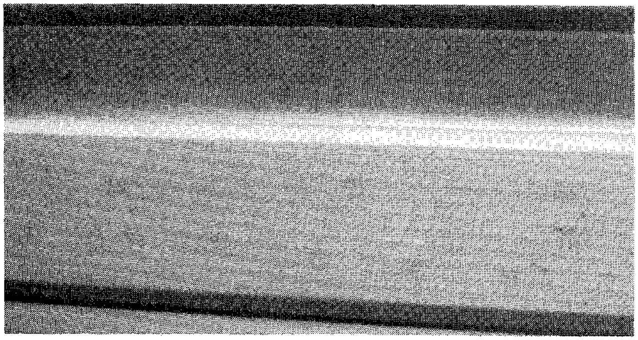

Fig. 10 Surface clearing after EIDI action

from the coils. Occasionally, three hits were required for clearing (Fig. 10).

Depending on the test airspeed and icing conditions (LWC, droplet size, temperature) the ice was either grainy (popcorn ice), had built-up spikes from the surface, or was clear ice of nearly uniform thickness. Generally, the leading edge accumulated the heaviest amount; very little ever accumulated on the pressure surface. On some occasions there was a slight accumulation on the suction surface, but only back to about the forward spar. Generally, there was a light residue remaining, scattered over the surfaces after the deicing. This was not an amount to cause any problems and generally cleared off at the time of the next deicing.

Past test examination of the model revealed no major structural damage. However, many of the doublers were debonded at their edges and were curling due to the electromagnetic forces. Some of the rivet heads for the doubler rivets had been deformed. There was evidence that the soft stainless steel that was used for the skins was becoming deformed at the coil locations. The leading-edge skin, at the forward spar, was deformed and the rivets' heads were beginning to pull through the skin material. These types of problems were expected. It is speculated that if the skins had been constructed of 304 stainless steel, these problems would not have occurred.

VII. Conclusions

Demonstration of the feasibility of applying EIDI to the deicing of the turning vanes in NASA Lewis Research Center's Altitude Wind Tunnel (AWT) was accomplished. This successful demonstration covered a wide range of icing conditions. The only apparent problems were some skin fatigue and debonding of the copper doublers.

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