

CONTINUOUS MEASUREMENT OF AIRCRAFT WING ICING

Stephen S. C. Yao
Software Manager
Axiomatics Corporation
3G Gill St.
Woburn, MA 01801

ABSTRACT

Ice formation on the wings of aircraft is a problem that has plagued air travel since its inception. Several recent incidents have been attributed to ice formation on the lifting surfaces of wings. This paper describes a SBIR Phase I research effort on the use of small flat dielectric sensors in detecting a layer of ice above the sensor. These sensors are very small, lightweight, and inexpensive. The electronics package that controls the sensor is also small, and could be made even smaller using commonly available miniaturization technologies. Thus, several sensors could be placed on a surface such that a representative ice thickness profile could be measured. The benefits offered by developing this technology go beyond the safety improvements realized by monitoring ice formation on the wings of an aircraft. Continuous monitoring of anti-icing fluid concentrations on the ground would warn the pilot of impending fluid failure as well as allowing the stations to use less de-icing solution per aircraft. This in turn would increase the safety of takeoffs and reduce the overall discharge of de-icing solution into the environment, thus reducing the biohazard of the de-icing procedure.

INTRODUCTION

Several technologies currently exist for detecting ice formation on wings. The older, more established ones use mechanical vibration as the basis for their measurement. These instruments have been proven to be quite bulky, and very difficult to mount on a wing. Newer technologies based on measuring the capacitance of materials above a sensor have shown great promise in measuring ice thickness. All of these technologies measure in-flight icing very well. However, none of them can make accurate measurements in the various ground icing situations.

Axiomatics has applied Shunting Dielectric Sensor (SDS) technology to detecting and analyzing layers of ice on an aircraft surface. This technology measures the complex admittance of materials above the sensor. The admittance is essentially the vector sum of the capacitance and the conductance of the sensor. Using this added information, Axiomatics has been able to simultaneously measure the layer thickness and concentration of solutions.

The coatings on aircraft wings in ground icing conditions could be pure ice, an anti-icing fluid with a variable concentration of water, or an anti-icing fluid/water solution in which ice is starting to form. Since the Axiomatics sensor can measure capacitance, measurements of pure ice layers can be made as well as any of the other capacitive sensors. The advantage of the SDS system is in its ability to make concentration measurements. The concentration of water in anti-icing fluids is thought to be an indication of its ability to function effectively. As the amount of water reaches a certain level ice will begin forming in the solution. The SDS system can be used to monitor the amount of water contained in the solution.

Axiomatics successfully completed a Phase I SBIR contract with the NASA Lewis Research Center in June 1993. The results of this project demonstrated the feasibility of using the SDS sensor in measuring layers of ice, water, de-icing fluid, and mixtures of the three. A \$500,000 Phase II effort has been proposed to begin in the first quarter of 1994. This effort will last for two years, by the end of which Axiomatics will have developed a system ready for flight testing and qualification. Axiomatics is currently seeking partners to participate in this final phase of development.

THE SENSOR SYSTEM

The sensor was designed using Axiomatics' proprietary SDS technology. This technology uses a three terminal flat sensor that provides a distinct advantage over more conventional two terminal sensors. In a two terminal configuration the dielectric measurement relies on the change in energy absorption into the material in question. For many substances the frequency of excitation would have to be in the GHz range before changes in dielectric properties would manifest themselves in absorption changes large enough to be measured.

The SDS introduces a third electrode as shown in Fig. 1. This electrode shunts away some of the electric field from the sensing electrode. This has the effect of increasing the time constant of the sensor and thus lowering the resonant frequency. Using this shunting effect measurement the SDS can provide accurate measurements in the MHz range, thus avoiding the noise problems and high cost of GHz range systems.

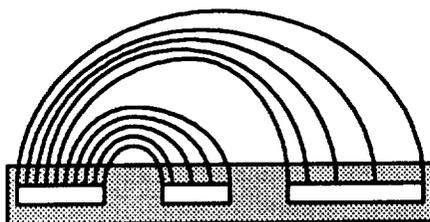


Figure 1: Shunting Dielectric Sensor Electric Field

The field penetration into the material being tested depends on the width and spacing of the electrodes, as well as the dielectric properties of that material. This implies that the amount of shunting will also vary with the same parameters. These facts lead us to an added functionality for the SDS technology, namely, that it is possible, given that the dielectric properties of the material being tested are known, to determine how thick a layer of that material there is above the sensor. The SDS can simultaneously measure both the composition of a material and the thickness.

The sensor is constructed by etching the sensor pattern on a piece of thin film flexible circuit board material. The surface of the sensor is then coated with a tough barrier film to insulate the circuit elements from the environment. This creates a sensor that can be mounted on the exterior of an aircraft with almost no penalty in aerodynamics.

The measurements were made with Axiomatics' Spectrum dielectric measurement instrument. The Spectrum system takes dielectric measurements (capacitance and dielectric loss) of the sensor at ten different frequencies. These frequencies are: 500 Hz, 1 kHz, 5 kHz, 10 kHz, 50 kHz, 100 kHz, 500 kHz, 1 MHz, 5 MHz, and 8 MHz. This dielectric data is then relayed to a computer where it is stored in a disk file.

Temperature measurement of the SDS and sample were obtained using a surface-mounted K-type thermocouple, located just under the sensor. The Spectrum system is currently not able to measure temperatures below 0°C, so a Fluke thermocouple meter was used to make those measurements. Side by side tests of the thermocouple meter and the Spectrum system indicated that they read temperature within 0.5°C of each other for temperatures above 0°C. This is within normal thermocouple accuracy specifications.

ICE/WATER THICKNESS

Testing & Results

Testing was done on layers of ice/water ranging from 0.5 mm to 4 mm. These layers were deposited above the sensor. Measurements were made at temperatures varying from -20°C to 20°C. From the testing we found that there was a dramatic change in capacitance between a layer of ice over the sensor and a layer of water. Figure 2 graphs the capacitance measured by the sensor versus the temperature. The measurement frequency for this graph is 1 MHz. At temperatures below 0°C the

capacitance of the ice layer varies from about 0.45pF to about 0.55pF. There is also a slight linear variation in the capacitance as the temperature varies. At temperatures above 0°C the capacitance of the water layer varies from about 4pF to about 5.5pF. Here there is a somewhat larger variation in capacitance with temperature. At 0°C, as expected, there is a vertical line connecting the ice measurements with the water measurements. Obviously, the variation in capacitance is due to the changing amounts of water and ice in the layer above the sensor.

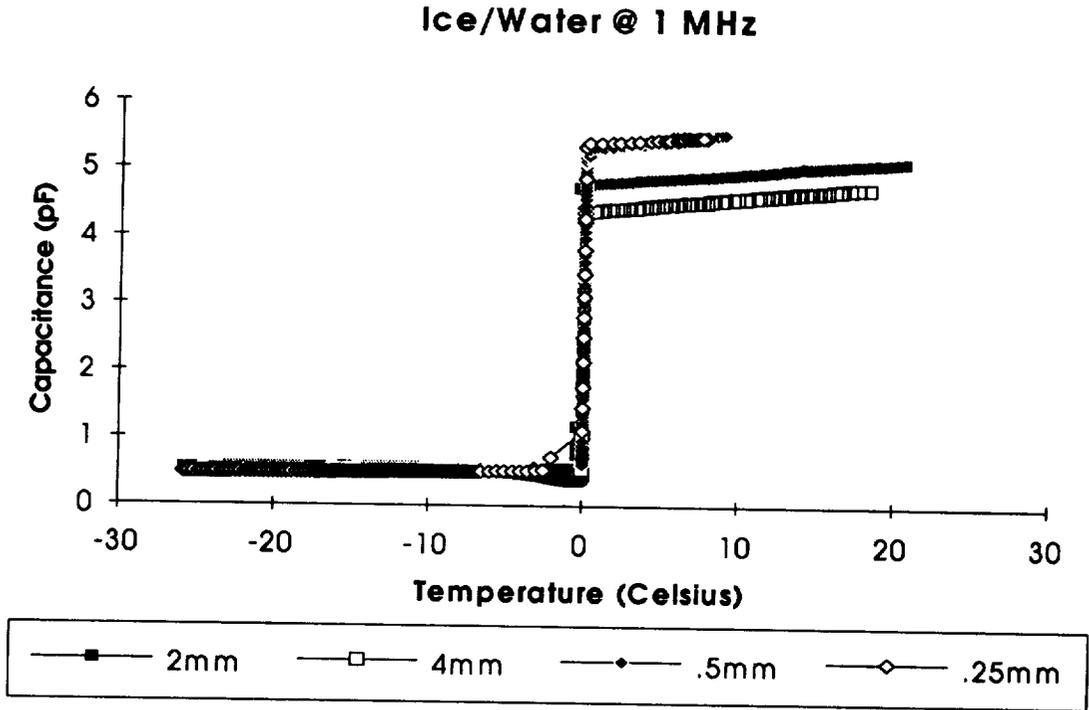


Figure 2

Figure 3 shows the capacitance versus the loss of the ice portion of the testing, i.e., the data taken when there is only ice above the sensor. This graph is essentially the same as a graph in the complex admittance plane (z-plane) with the loss being the real component and the capacitance being the imaginary component divided by 2π times the measurement frequency, in this case 1 MHz. Along with the ice data is data taken with an empty sensor. The capacitance varies almost linearly with the loss as the temperature changes. Also, the slope of this variation seems to be constant for all thicknesses of the ice layer. This is a very interesting result because it implies that it is not necessary to measure the temperature of the ice in order to measure its thickness. In fact, it might even be possible to measure the temperature using only the dielectric information. This may be useful, as it is sometimes difficult to make an accurate measurement of the bulk temperature of the material with a surface mounted thermocouple.

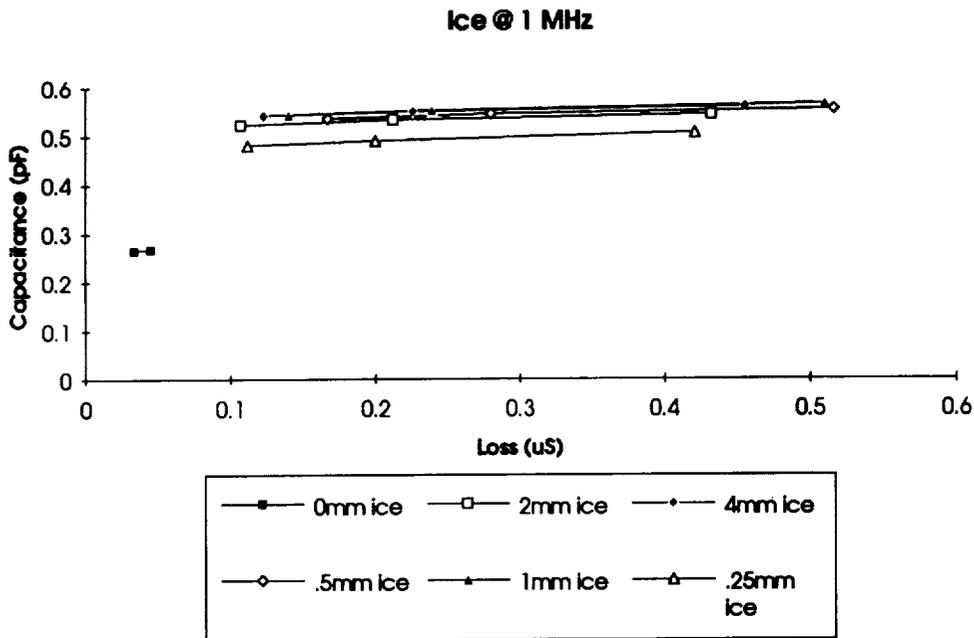


Figure 3

From the data illustrated in the above graph it can be theorized that, as the thickness of the ice layer increases, the capacitance also increases. The thicknesses listed on the graphs are only approximate. It was not possible to make precise measurements with the equipment available for the testing. Even so, the graph shows a definite trend of increasing capacitance until the 0.5mm thickness is reached. At that point all of the thicker layers seem to exhibit the same dielectric response, to within acceptable experimental error. This would imply that the electric field generated by the sensor penetrates 0.5mm into ice.

Ice Thickness Prediction Algorithm

The results of the testing seem to show that all of the data with ice only exhibited a capacitance of 1 pF or lower at 1 MHz. All of the data with water or de-icing fluid exhibited a capacitance of 3 pF or higher. The first step in the algorithm, then, is to check the capacitance at 1 MHz. If the capacitance is below 1 pF but above the C_0 of the sensor, i.e., the capacitance of the sensor in air, then it would be inferred that there is a layer of ice on the sensor.

The second step in the algorithm is to normalize the temperature effects on the ice measurements. This is done by looking at the loss and capacitance in the z-plane. From the results it can be shown that the dielectric values vary linearly with temperature in the z-plane. Not only this, but all of the slopes for the various thicknesses are equal to 0.065. To normalize temperature it only requires that we extend a line through the measured point in the z-plane with the slope equal to 0.065 and determine the capacitance intercept. This will give a temperature normalized capacitance that can then be related directly to ice thickness.

The equation for temperature normalizing the capacitance at 1 MHz is

$$\text{Normalized Capacitance} = \text{Capacitance} - [0.065(\text{Loss})]$$

The relationship of thickness to normalized capacitance at 1 MHz is shown in Figure 9. The prediction equations is

$$\text{Thickness} = 1.54902 \times 10^{-8} e^{33.8207(\text{Capacitance})}$$

To verify these equations, a test similar to the data collection tests was run. The data was taken at one or two temperatures for each layer thickness. The prediction algorithm yields results that predict the thickness of the ice layer within about 0.1mm. Even this small error would probably be considerably

reduced if more data were taken and a better fitting equation were developed. The errors are due more to insufficient modeling points than to inaccuracies in the measurements.

It should be noted that errors exist in the actual thickness. It is very difficult to measure this thickness because of several factors. The surface of the layer is not smooth. Also, for the 0.1mm layer it is not certain whether the entire sensor surface was covered or not. There might be air bubbles trapped in the layer. For the purposes of this feasibility test, however, the accuracy of the measurement was deemed sufficient.

DE-ICING FLUID THICKNESS

Testing & Results

Testing was done on layers of de-icing fluid ranging from 1 mm to 4 mm. These layers were deposited above the sensor. Measurements were made at temperatures varying from -20°C to 20°C . The capacitance data at 1 MHz of varying thicknesses of de-icing fluid shows that the capacitance of layers of de-icing fluid 1mm deep or greater is about 4pF and higher. This would mean that it is quite easy to differentiate between ice over the sensor and thicknesses of de-icing fluid of 1mm or more. In fact, it is reasonable to assume that it would be difficult to create a layer of de-icing fluid over the sensor that would mimic the response of ice.

Figure 4 shows a z-plane graph of data taken at 100 kHz. There seems to be a regular behavior as the temperature changes. The behavior follows the theoretical SDS spiral shape as the temperature changes. This indicates that the dielectric properties of the de-icing fluid change with temperature, which allows us to normalize the dielectric readings according to the temperature. Thus, it should be possible to develop an equation to predict the thickness of a layer of de-icing fluid from the dielectric measurements.

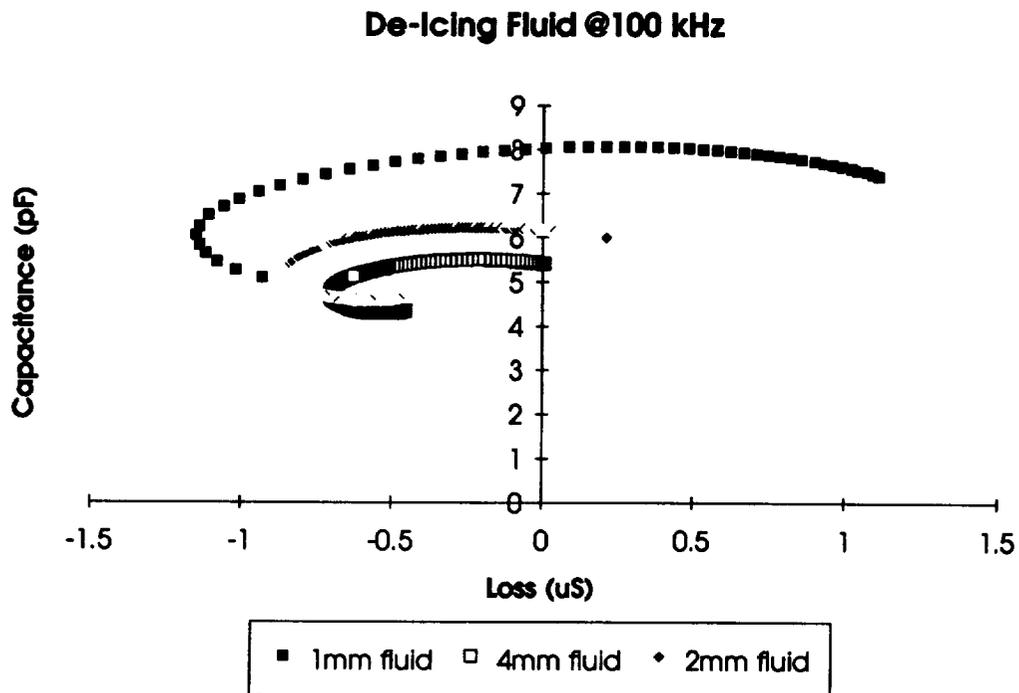


Figure 4

DE-ICING FLUID CONCENTRATION

Testing & Results

Tests were run to determine the response of the sensor to variations in the concentration of de-icing fluid. Solutions were prepared of distilled water in Type II de-icing fluid ranging in concentrations from 0% to 75% water. A thickness of 2 mm of each of these solutions was placed over the sensor. Measurements were made at a temperature of -10°C . Figure 5 shows a graph in the z-plane of the results of this testing. The graph suggests that this sensor system can be used to measure the concentration of the de-icing fluid.

SDS Response to Water in Type II De-Icing Fluid

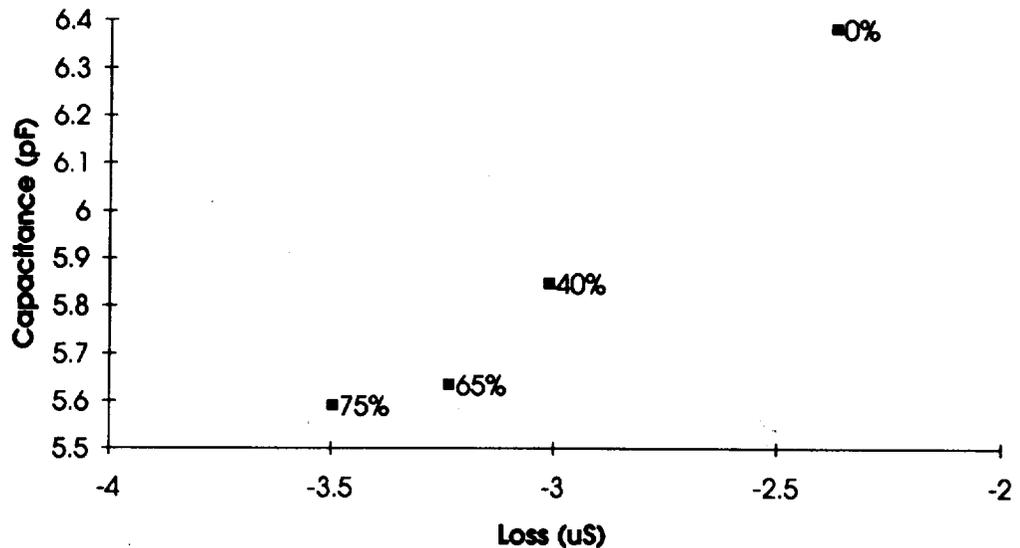


Figure 5

CONCLUSIONS

Axiomatics has achieved the goal of establishing the feasibility of measuring various thicknesses of ice and differentiating ice from water and de-icing fluid under conditions which simulate those of aircraft icing. This conclusion is reached on the basis of the results of the testing done on water, ice, and de-icing fluid. Ice had a very different dielectric response from water and from de-icing fluid, so it was very easy to determine whether a layer was composed of ice or not. The feasibility of measuring the thickness of layers of water or de-icing fluid was also demonstrated.

The accuracy to which the thickness of a layer of ice can be determined, and the maximum measurable thickness of that layer, depend on the geometry of the sensor. In this project the sensor used could measure ice thicknesses up to 0.5mm to within about 0.1mm. The data indicates that improvements could be made if a better method of measuring the thickness of the layer were available. If thicker layers or thinner layers are to be measured then the geometry of the sensor will be changed. It may also be possible to achieve the same results by changing the construction materials.

In addition, the feasibility of measuring the concentration of de-icing fluid has also been shown. It is believed that the effectiveness of de-icing fluid is linked to the amount of water in solution. Having a continuous measurement of de-icing fluid concentration could provide early warning of its impending failure.