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MICROWAVE SENSOR FOR ICE DETECTION

BY

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ABSTRACT

A microwave technique has been developed for detecting ice build-up on the wing surfaces of commercial airliners and highway bridges. A microstrip patch antenna serves as the sensor, with changes in the resonant frequency and impedance being dependent upon the overlying layers of ice, water and glycol mixtures. The antenna sensor is conformably mounted on the wing. The depth and dielectric constants of the layers are measured by comparing the complex resonant admittance with a calibrated standard. An initial breadboard unit has been built and tested. Additional development is now underway.

Another commercial application is in the robotics field of remote sensing of coal seam thickness.

1.0 INTRODUCTION

Ice build-up on the orbiter low temperature fuel tanks, airfoil surfaces and highway structures can create hazardous transportation conditions. Ice build-up on the orbiter's low temperature fuel tanks is a safety concern in NASA'S Space Shuttle Program. After filling insulated fuel tanks on the booster rocket, the count down time period can continue until ice build-up reaches 1/16 inch. During the insertion phase of flight, the ice layer could fragment and damage heat shield tile and windows of the shuttle. Presently, ice depth measurements are made manually by scratching away the ice layer and determining its thickness. Because of the large physical size of the fuel tanks, the number of measurements is limited.

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computerized system, in which the information about the thickness of the chromium film is processed along with other information such as plating current or velocity of the liquid solution, to control and optimize the plating process. Further improvements of the system, from the point of view of process control and of increased accuracy is planned but not developed at this time.

SUMMARY AND CONCLUSIONS

Ultrasonics and computer technology have been integrated to obtain the means for "seeing" during plating. The thickness of a chromium film can be measured in real time with resolution and accuracy much better than that of the mechanical measurements which can be performed only after the plating process is finished. The advantages of this are many. Among those the possibility of intervention for remedial action in the case of problems. A detailed description of the system was given, starting from the theory of the measurement to the experimental details. The system is now being incorporated into process control so to stop plating as soon as the desired thickness is reached, or to monitor any unpredictable or irregular behavior of the process.

TABLE I. Results from Error Analysis

Parameter	Standard Deviation	Error [μm]
Thickness of Standards [μm]	0.25	1.27
Velocity Ratio ($\gamma = v_C/v_S$)	0.03	6.42
Temperature Dependance β [°C^{-1}]	10^{-5}	2.00
Time delay Meas. on Standards	.0001	6.22
Time Delay Meas. on Sample	.0001	1.39
Temperature Meas. [°C]	1	0.75
	TOTAL [μm]	9.41

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Commercial airline disasters in Washington, DC, Denver, Colorado, New Foundland, New York and Europe have been caused by wing icing prior to the take-off role. Adherence of ice to the wing can reduce lift by as much as thirty-four percent and on some aircraft ice may dislodge and damage the jet engine. Formation of ice on airfoil surfaces caused 127 fatal commercial aircraft accidents and claimed 496 lives between 1977 and March 1992. All of these tragedies could have been prevented had there been a reliable device to determine whether deicing was needed. The Federal Aviation Administration (FAA) has projected that unless safety improvements are made, there could be eight additional air carrier icing accidents within the next ten years claiming 134 lives. In addition, the cost to improve safety operations during winter time could cost approximately $181 million.

Type I anti-icing fluid is spread on the aircraft prior to take-off. In one airport alone, 700,000 gallons of highly toxic ethylene glycol are used during the winter season. The airport waste water treatment load is equivalent to a city of 500,000 people. Icing on highways is another national concern. Nearly 4 million miles of U.S. roadways and 500,000 bridges are subject to icing conditions at some time during the year. Almost one third of all U.S. traffic accidents occur on wet, ice or snow/slush covered roadway surfaces. The microwave ice detection sensor project will improve transportation safety by developing thin conformally mounted sensor technology. The sensor and associated microcomputer controlled electronics can determine the electrical parameters of the contaminant layer overlying the sensor. Fusion of data from surface temperature and piezo electric sensors enable complete characterization of the physical and electrical parameters of the contaminant layers.

Prior to the development of the microwave ice detection sensor, many technologies have been investigated and proven unreliable in measuring ice build-up under adverse weather conditions. One of the technical problems relates to the discrimination of ice, snow and water conditions on critical surfaces. Measurement of overlying layer depth is another problem. Protruding sensors may unreliably determine ice conditions on airfoil surfaces. Some sensor thermodynamic properties can also alter the ice forming characteristic near the monitoring point.

Theoretical and experimental studies of a resonant circular microstrip patch antenna sensor have shown that its measurable electrical properties are highly sensitive to the contaminant layer properties. The resonant frequency and terminal impedance of the patch antenna depend upon the layer depth, resistivity and dielectric constant of the overlying layer. Laboratory tests have shown that the sensor and associated electronics can discriminate between water, ice, snow/slush and antifreeze layers. Measurements can determine the thickness of the layer, as well as the ethylene-glycol mixture. This paper will describe the microstrip patch antenna sensor as well as the theoretical and laboratory measurement results.

2.0 THEORETICAL BASIS OF ANTENNA SENSOR

The microstrip patch antenna which is used for ice layer measurements has its theoretical basis in a sensor suggested by Chang and Wait for measurement of uncut coal layer thickness. The Chang and Wait sensor consists of a resonant loop antenna positioned over a thin coal layer as illustrated in Figure 1.

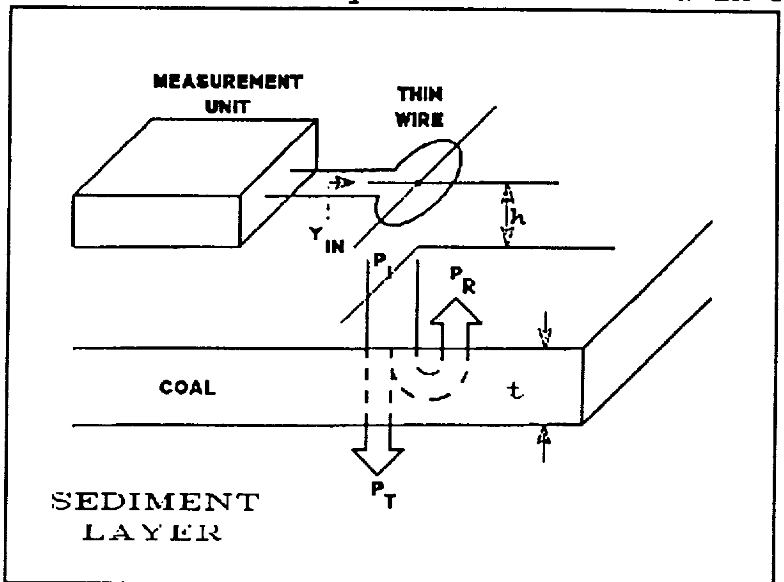

Figure 1 Uncut coal sensor.

The sensor measures the uncut coal layer thickness by measurement of the scattering of EM wave energy from the uncut and hidden surface. An antenna launches an incident EM wave (incident power [P_I]) that enters the uncut surface and travels a distance (t) to the sediment layer. A small part of the incident wave energy propagates (transmitted power [P_T])into the sediment layer. The scattered wave (reflected power [P_R]) depends upon the thickness and the EM wave propagation constants of the uncut coal layer. Scattered wave energy returns to the antenna where it alters the admittance of the antenna.

Chang and Wait (1977) describe the theory of a resonant loop antenna operating over a coal layer covering the front of a thicker sediment layer. The conductivity (σ) and permittivity (ϵ) of the sediment layer is greater than that of coal. The coal and sediment layers form a two-layer half space with the coal layer of finite thickness and the second layer of infinite thickness. Chang (1973) developed formulations of the self admittance by applying a voltage of amplitude V_0 across the terminals of the loop antenna illustrated in Figure 1. The perfectly conducting wire radius is assumed to be very small as compared with both the radius of the loop and the height (h) above the layered half space. The admittance of the loop at the feed point is given by:

$$y = I/V_0 = G + iB \tag{1}$$

$$= I_0 + 2 \sum_{m=1}^{\infty} I_M \text{ Siemens} \tag{2}$$

where V_0 is the applied test voltage,

I is the current,

$$I_{M-1} = i\ 120\pi^2 \quad (a_m^p + a_m^s) \tag{3}$$

a_m^p is the primary contribution of an isolated loop in the absence of the half space,

and, a_m^s is the contribution due to the half space.

The conductance (G) corresponds to the power radiated from the loop. The susceptance (B) of the loop is proportional to the amount of reactive energy stored in the vicinity of the antenna. King (1969) has developed a mathematical expression for a_m^p. For the case of a resonant loop, $|a_1^p|^{-1}$ is the largest term and current on the loop is basically cosinusoidal. The radiated power is greater at the resonant frequency than at a lower frequency. A resonant loop is expected to be more sensitive to thickness than a non-resonant loop.

To account for the influence of the layered half space, a_m^s needs to be included into the expression for current. Chang and Wait (1977) have used transcendental equations to evaluate the behavior of a_m^p and a_m^s for different heights of the coal layer and operating frequencies near resonance. As the uncut layer thickness increases, the conductance G exhibits a damped sinusoidal characteristic.

3.0 PRELIMINARY LABORATORY TESTS WITH PATCH SENSOR

Theoretical and experimental investigation of the resonant microstrip antenna sensor found that the percentage change in resonant frequency and conductance due to overlying ice and water layer depth could be measured with a practical instrument. The thin microstrip antenna sensor is illustrated in Figure 2.

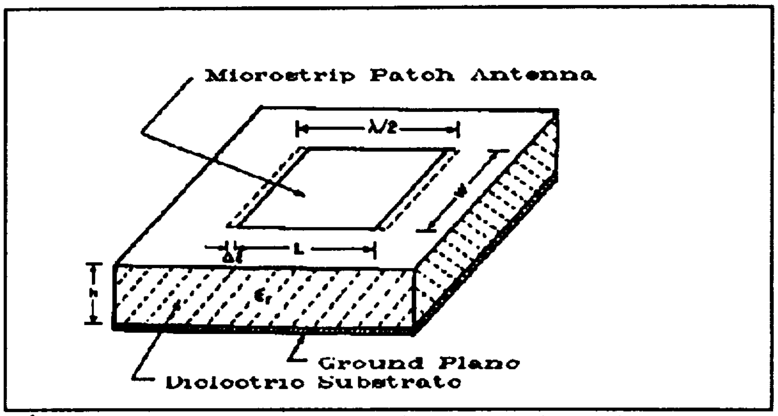

Figure 2 Resonant antenna structure for measuring ice thickness layers.

Computer codes were developed and used to determine the resonant frequency change of a microstrip antenna due to ice buildup. The theoretical results are illustrated in Figure 3.

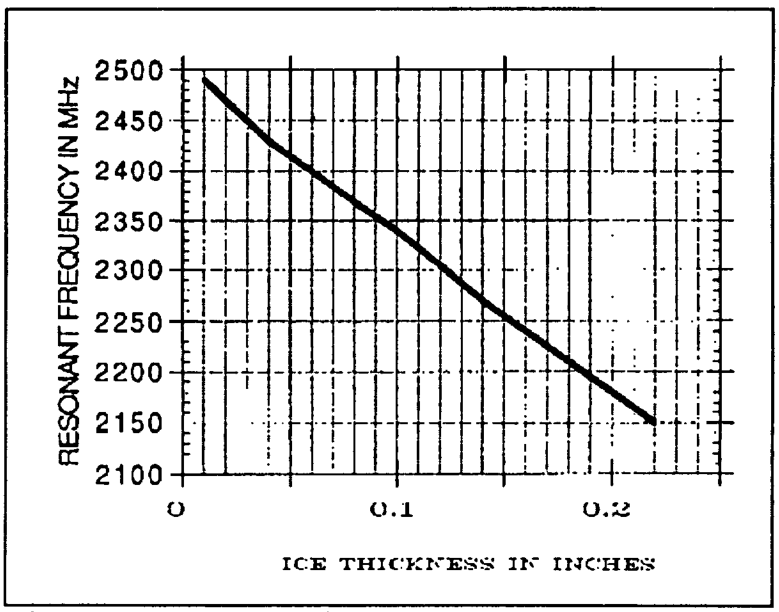

Figure 3 Theoretical resonant frequency versus ice thickness.

The resonant frequency changed by 140 MHz (5.6 percent) for a 0.1 inch change in ice layer depth. A 0.25 inch layer of ice caused the resonant frequency of the antenna to decrease by 14 percent. To investigate the ice and ice-water layering behavior in detail, a series of experimental tests were conducted in a temperature controlled chamber. In these tests, 0.1 inch depth increments of water were added to a tray in which the microstrip antenna sensor formed the bottom of the tray. The resonant frequency and conductance were independently measured after each incremental change in water depth. The measurements were repeated after one hour when 0.1 inch water layer turned to ice. The test data is illustrated in Table A.

TABLE A

CIRCULAR MICROSTRIP ANTENNA
RESONANT FREQUENCY AND RESONANT CONDUCTOR
VERSUS ICE AND 0.1 WATER-ICE DEPTH

ICE DEPTH	ICE		0.1 INCH WATER AND ICE	
INCH	f_0(MHz)	G(mS)	f_0(MHz)	G(mS)
0.0	821.21	13.4	797.09	21.5
0.1	812.98	15.4	784.14	28
0.2	815.28	17.0	786.21	30.7
0.3	812.07	17.7	782.0	39.4
0.4	805.02	22.3	772.78	55.4

The measured data is illustrated in Figure 4.

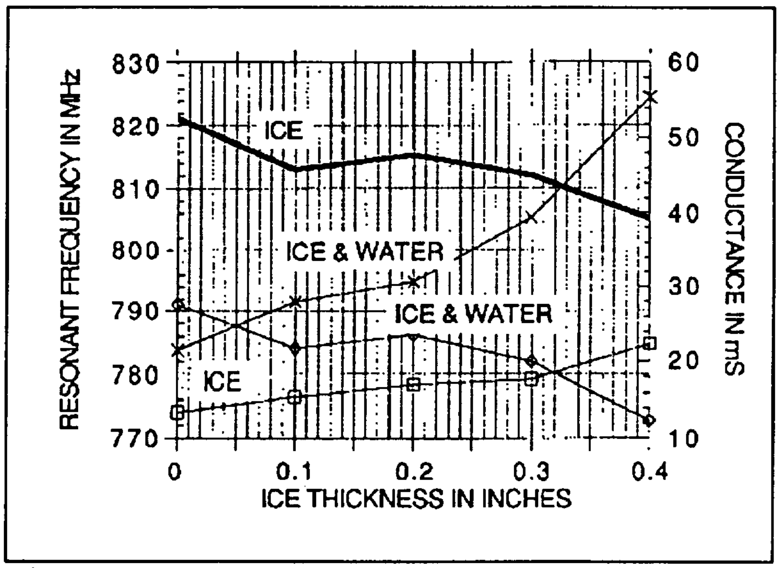

Figure 4 Measured resonant frequency and conductance vs ice thickness at 10° F.

The dark solid and square symbol curves indicate the change in resonant frequency and resonant conductance versus ice layer depth. The diamond and cross symbol curves represent the change in resonant frequency and conductance when 0.1 inch depth of water covers the antenna. The dark solid and diamond resonant frequency curves show that the frequency is significantly changed when a water layer is present.

The application of the sensor array on air transport is illustrated in Figure 5.

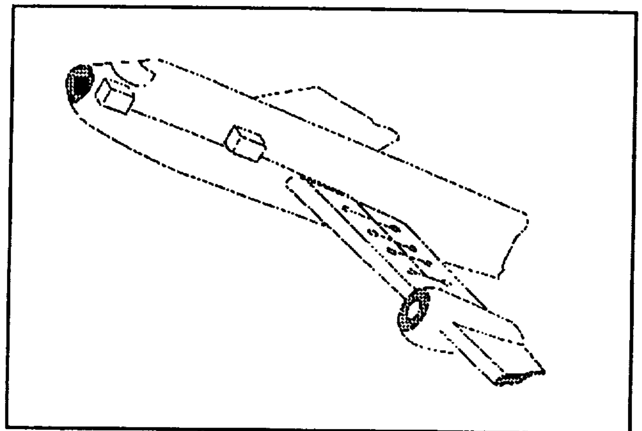

Figure 5: Perspective view of sensor array on airfoil surface

The critical surface of the wing extends outward from the fuselage to approximately 30 percent of the wing. It extends a distance of approximately 20 percent of the wing width. The thin conformal antenna array is multiplexed through a flat transmission line to the microcomputer controlled electronics in the fusalage of the aircraft. The electronics generates the flight deck display illustrating wing icing conditions. Since sensor measurements are continuous, the display can indicate time to freezing of the overlying layer.

<u>SUMMARY</u>

Theoretical and experimental research work has found that the contaminant layer properties can be measured with the sensor. The thin conformal sensor can be applied to the critical areas of the wing without altering its aerodynamic properties. Fusion of wing surface temperature measurements data with sensor data will enable estimation of time to freeze. Fusion of piezoelectric data will enable cross check of ethylene-glycol water mixer and freezing point. Adherence of the layer to the wing surface can also be detected with this type of sensor. The sensor fusion goal is to maximize reliability of ice detection for transportation safety.

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A VERSATILE NONDESTRUCTIVE EVALUATION IMAGING WORKSTATION

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ABSTRACT

Ultrasonic C-scan and eddy current imaging systems are of the pointwise type evaluation systems that rely on a mechanical scanner to physically maneuver a probe relative to the specimen point by point in order to acquire data and generate images. Since the ultrasonic C-scan and eddy current imaging systems are based on the same mechanical scanning mechanism, the two systems can be combined using the same PC platform with a common mechanical manipulation subsystem and integrated data acquisition software. Based on this concept, we have developed an IBM PC-based combined ultrasonic C-scan and eddy current imaging system. The system is modularized and provides capacity for future hardware and software expansions. Advantages associated with the combined system are: (1) eliminated duplication of the computer and mechanical hardware, (2) unified data acquisition, processing and storage software, (3) reduced setup time for repetitious ultrasonic and eddy current scans, and (4) improved system efficiency. This concept can be adopted to many engineering systems by integrating related PC-based instruments into one multipurpose workstation such as dispensing, machining, packaging, sorting, and other industrial applications.

INTRODUCTION

To maintain global technological competitiveness, manufacturers must use a concurrent engineering approach that includes performance, manufacturing, process monitoring, inspection, service and maintenance to design their products. Nondestructive evaluation (NDE), which is an essential test and measurement technology for the advanced concurrent engineering approach[1], offers many advantages over traditional quality assurance measures. Recent advances in computer and electronic technology have increased the processing speed and capabilities of personal computers (PCs), and enabled the development of application specific plug-in expansion boards. A wide range of stand-alone devices also have been converted to this type of circuit boards such as analog to digital (A/D) converters, digital multimeters (DMMs), interface buses, etc. The PCs thus can become various engineering workstations by using these plug-in boards, through interface buses for stand-alone digital instruments or through an A/D card for analog instruments.

Ultrasonic C-scan[2-4] and eddy current imaging techniques[5-7] are the two most widely utilized NDE imaging techniques that are routinely used for qualification, monitoring, and control of manufacturing processes. The ultrasonic C-scan and eddy current imaging systems are of pointwise type systems[8] that have to rely on a mechanical scanner to physically maneuver a sensing probe relative to the specimen point by point in order to acquire data and generate images. Since these two imaging systems are based on the same scanning mechanism, the two systems can be combined using the same PC platform with a common mechanical manipulation subsystem and integrated data acquisition software.

In this paper, we describe the hardware/software requirements and the development of an IBM PC-based combined ultrasonic C-scan and eddy current (UT/EC) imaging workstation. This UT/EC pointwise imaging system includes a common mechanical control, data acquisition and image processing software. Measuring instruments are incorporated into the PC-platform by using an analog ultrasonic pulser/receiver and a digital eddy current impedance analyzer, a plug-in eddy current instrument, a digital multimeter, and an IEEE-488 interface card. Advantages associated with this integrated test and measurement system are: (1) eliminated duplication of the computer and mechanical hardware, (2) unified data acquisition, processing and storage software, (3) reduced setup time for repetitious ultrasonic and eddy current scans, (4) improved system efficiency, and (5) porvided capacity for future hardware and software expansions.

HARDWARE REQUIREMENTS

The hardware of a typical automated NDE system has three major components: a system controller, a mechanical scanner, and appropriate instruments with associated sensors. A PC or a microprocessor based