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In situ ice and structure thickness monitoring using integrated and flexible ultrasonic transducers

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Abstract
Two types of ultrasonic sensors are presented for *in situ* capability development of ice detection and structure thickness measurement. These piezoelectric film based sensors have been fabricated by a sol–gel spray technique for aircraft environments and for temperatures ranging from −80 to 100 °C. In one sensor type, piezoelectric films of thickness greater than 40 μm are deposited directly onto the interior of a 1.3 mm thick aluminum (Al) alloy control surface (stabilizer) of an aircraft wing structure as integrated ultrasonic transducers (UTs). In the other sensor type, piezoelectric films are coated onto a 50 μm thick polyimide membrane as flexible UTs. These were subsequently glued onto similar locations at the same control surfaces. *In situ* monitoring of stabilizer outer skin thickness was performed. Ice build-up ranging from a fraction of 1 mm to less than 1.5 mm was also detected on a 3 mm thick Al plate. Measurements using these ultrasonic sensors agreed well with those obtained by a micrometer. Tradeoffs of these two approaches are presented.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

For the airline industry, the cost of keeping timely scheduled flights drastically increases with unpredicted weather conditions that cause icing on flight control surfaces. In addition to causing delays and reducing profits, ice build-up affects the flight performance and potentially reduces aircraft stability, through the distortion of the air flow over the flight control surfaces. Ice accumulations on leading edges or upper surfaces of wing structures are known to reduce the lift by as much as 30% and increase the drag by 40% for a thickness or roughness similar to a piece of sandpaper [1–3]. To reduce unnecessary deicing actions and increase airplane availability, development of *in situ* ice thickness monitoring capability is strongly desired. Several techniques such as optics [4, 5], microwave [6, 7], microelectromechanical devices [8], and ultrasonics [9, 10] have been reported to monitor ice thickness build-up.

Stress corrosion cracking, corrosion pitting, and exfoliation corrosion are commonly found in aircraft structures [11–13]. There is also a critical need to perform *in situ* quantitative thickness measurement to determine the degree of corrosion and provide correlation to components' residual fatigue life. Most corrosion inspections are qualitative in nature and are carried out in a laboratory environment, requiring access to the aircraft or its component, thus decreasing aircraft availability and increasing maintenance costs. Generally, conventional ultrasonic techniques used to measure corrosion require access to both sides of the component under investigation and require couplant for increased signal to noise ratio (SNR).

In this investigation, two types of ultrasonic sensors are developed for *in situ* monitoring of ice thickness build-up as well as airframe thickness measurement simulating corrosion (thickness reduction) detection. These piezoelectric film based sensors have been fabricated by a sol–gel spray technique. In

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one sensor type, piezoelectric films of thickness greater than 40 μm are deposited directly onto the interior of a 1.3 mm thick aluminum (Al) alloy control surface (stabilizer) of an aircraft wing structure as integrated ultrasonic transducers (IUTs). In the other sensor type, piezoelectric films are coated onto a 50 μm thick polyimide membrane as flexible ultrasonic transducers (UTs). These flexible UTs will subsequently be glued onto similar locations at the same control surfaces. *In situ* monitoring of stabilizer outer skin thickness and ice thickness development from fractions of 1 mm to less than 1.5 mm will be demonstrated. The ultrasonic measurements to be carried out will use longitudinal acoustic waves, and the techniques reported in [9, 10] employed plate acoustic waves (PAWs). The approach in this study can indicate but limit the detection and the size estimation of the ice thickness only in the area underneath the sensor or sensor array surface. The PAW technique in [9, 10] using the variation of the propagation characteristics of the PAWs propagated along a long path length (e.g. meters) due to the effect of ice conditions can inform the averaged ice conditions along the path of the PAWs.

2. Ultrasonic sensor

The sol–gel based sensor fabrication process consists of six main steps [14–16]: (1) preparing high dielectric constant lead-zirconate-titanate (PZT) solution, (2) ball milling of piezoelectric PZT powders to submicron size, (3) sensor spraying using slurries from steps (1) and (2) to produce the thin film, (4) heat treating to produce a solid composite (PZT/PZT) thin film, (5) corona poling to obtain piezoelectricity, and (6) electrode painting or spraying for electrical connections. Steps (3) and (4) are used multiple times to produce optimal film thickness for specified ultrasonic operating frequencies. Silver paste was used to fabricate top electrodes. Such an electrode fabrication approach enables us to achieve the desired sensor array configurations easily and economically. In this study longitudinal ultrasonic wave transducers are used.

Figure 1 illustrates the IUTs that are directly deposited onto the interior of a control surface made of Al alloy. The thickness of the PZT/PZT composite film was 65 μm. The top circular electrodes with diameters of 7.5 mm, define the IUTs active area. It is noted that since the PZT/PZT composite film has a large area, several IUTs with diameters of 7.5 mm may be made within the same film area. The advantages of such IUTs are that they can be directly deposited or coated onto curved surfaces. The maximum fabrication temperature of these transducers can be lower than 175 °C [15]; however, the lower the fabrication temperature the lower is the ultrasonic signal strength. These IUTs can be employed in operational temperatures, ranging from −80 °C to 100 °C, commonly experienced in aircraft environments. The IUTs with a total thickness of less than 100 μm developed here are miniature in size and light weight, and without the need of ultrasonic couplant. Their ultrasonic performance at room temperature is close to the commercial available broadband UT. Three hundred and seventy five thermal cycles of such IUTs have been carried out. Each thermal cycle consisted of 10–15 min heating from room temperature to 150 °C, 30 min remaining at 150 °C, and 15–30 min cooling from 150 °C to room temperature. The high temperature performance, broad bandwidth and high signal strength are superior to those of the piezoelectric disks or polyvinylidene fluoride (PVDF) transducer [17] bonded to the airframe.

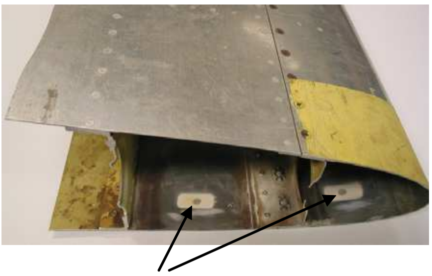

Figure 1. Two IUTs coated directly onto the interior of an Al alloy stabilizer.

The other type of sensor developed for the structure thickness measurement and ice build-up monitoring is the flexible UT. These UTs were reported using PVDF [17], polymer composites [18, 19], and metal foils [20]. Since polyimide film of 50 μm thickness is very flexible and can sustain operational and fabrication temperatures of 350 °C, it is used as the substrate for the flexible UT. Firstly, electroless nickel plating was carried out to produce a ∼1 μm thick nickel film as the bottom electrode for the longitudinal wave UTs. Then PZT/PZT composite films of several tens of microns were coated onto the nickel electrode. After corona poling, the top electrodes were made by silver paste. The schematic diagram and an actual flexible UT used for this study are shown in figures 2(a) and (b), respectively. The thickness of the PZT/PZT composite film for the flexible UT shown in figure 2(b) was 42 μm. The top electrode had a diameter of 5 mm. Such a simple fabrication process is a good alternative to those reported in [17–20]. These flexible UTs have been examined after one hundred times bending test with a curvature of 13 mm diameter. There is no observable damage either in visual appearance or ultrasonic performance.

For the developed PZT/PZT composite film the measured relative dielectric constant was about 320. The d_{33} measured by an optical interferometer was near 30 (10^{-12} m V^{-1}) and the thickness mode electromechanical coupling constant measured was about 0.2 [16]. The scanning electron microscopic images of the film indicate grain size less than 1 μm and 20% porosity. It is believed that the film porosity contributes to the low values of the dielectric constant, d_{33} and the low thickness mode electromechanical coupling constant. The longitudinal wave performance including strength and frequency bandwidth of the developed IUTs is close to those of the commercially available broad bandwidth UTs [16]. In general, the signal strength of the flexible UT using a polyimide film substrate is about 10 dB weaker than the IUT due to the lower fabrication temperature associated with the polyimide film substrate.

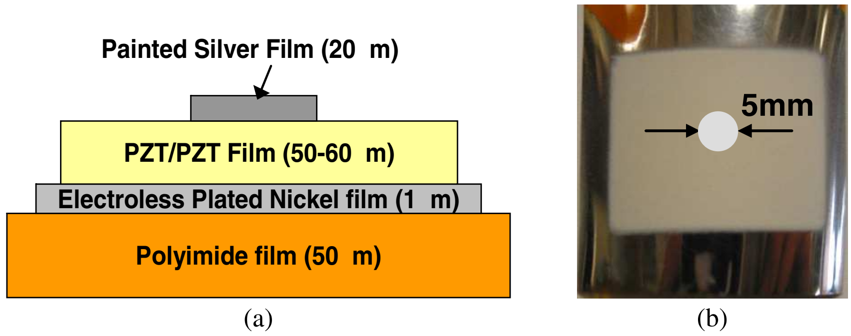

Figure 2. (a) Schematic and (b) an actual flexible UT using 50 μm thick polyimide film as the substrate.

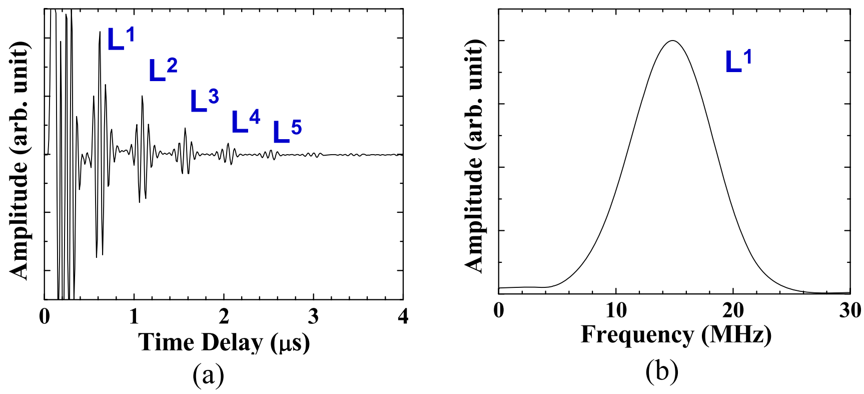

Figure 3. Ultrasonic performance of the IUT in figure 1 in (a) time and (b) frequency domains for thickness measurement of a 1.32 mm thick Al airplane frame shown in figure 1.

3. Airframe thickness measurement

In all experiments the pulser/receiver used was Panametrics model 5072. The output electrical pulse applied to the IUT and flexible UT was one cycle negative pulse with an amplitude of 125 V. This produced a broadband excitation. Figures 3(a) and (b) present the ultrasonic signals, in pulse-echo mode, from one of the IUTs shown in figure 1 in time and frequency domains, respectively. L^n is the nth round-trip echo through the thickness of the Al control surface skin. This thickness measured by a micrometer at the IUT location was found to be 1.32 mm. Due to the IUTs high center frequency of 15.3 MHz and 6 dB bandwidth of 11.0 MHz, the round-trip ultrasonic echoes are well separated. The measured longitudinal velocity, V_L, in the Al control surface skin was found to be 6480 m s^{-1}. If the Al thickness, h_{Al}, is reduced due to corrosion, then the time delay, Δt_{Al}, between the echo L^1 and L^2 will decrease. Then h_{Al} including the corrosion information can be calculated using $h_{Al} = V_L \times \Delta t_{Al}/2$.

In certain situations, accessibility to desired locations of aircraft components is limited for the fabrication of the IUTs, thus an alternative approach using flexible UT may be used. The fabrication of flexible UTs can be made off-line in a laboratory environment. Thereafter, they can be attached to desired sensor locations using adhesives that can sustain operational temperatures. Such adhesives can further be used as ultrasonic couplant. Figures 4(a) and (b) show ultrasonic signals, in pulse-echo mode, using the flexible UT of figure 2 in time and frequency domains, respectively. The control surface thickness of 1.32 mm was obtained by a micrometer at the flexible UT location. The center frequency and the 6dB bandwidth of the flexible UT are 17.5 MHz and 7.2 MHz, respectively. The SNRs of the signals shown in figure 4(a) obtained by flexible UT are slightly less than those obtained by the IUT shown in figure 3(a). The cause of the SNR reduction may be due to the glue used as the ultrasonic couplant between the flexible UT and Al plate. It is noted that there is no couplant between the IUT and Al plate.

Equation (1) (equation (19) in [21]) is used here for the estimation of the measurement accuracy for time delay and the thickness of the Al airframe using ultrasound, where f_0 is the center frequency, T the time window length for the selection of e.g. L^1 and L^2 echoes for the cross correlation, B the fractional bandwidth of the signal (the ratio of the signal bandwidth over f_0), ρ the correlation coefficient used in cross correlation, SNR_1 and SNR_2 the SNR of the first echo (e.g. L^1 in figure 3(a)) and second echo (e.g. L^2 in figure 3(a)), respectively, and σ $(\Delta t - \Delta t')$ the standard deviation of the measured time delay (Δt the true time delay; $\Delta t'$ the estimated time delay). Using equation (1) the calculated σ $(\Delta t - \Delta t')$ is 1.17 ns and 2.49 ns for the IUT and flexible UT, respectively. Since a sampling rate of 100 MHz is used in the experiment, the time measurement error which may be additionally introduced is estimated to be 10 ns. The total uncertainty in time delay measurement is then 11.2 ns and 12.5 ns, respectively for the IUT and flexible UT. Because V_L, the measured longitudinal

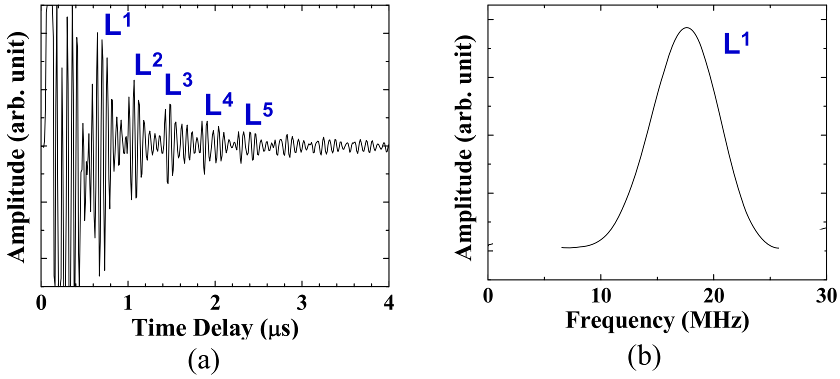

Figure 4. Ultrasonic performance of the flexible UT shown in figure 2 in (a) time and (b) frequency domains for thickness measurement of a 1.32 mm thick Al airplane frame shown in figure 1.

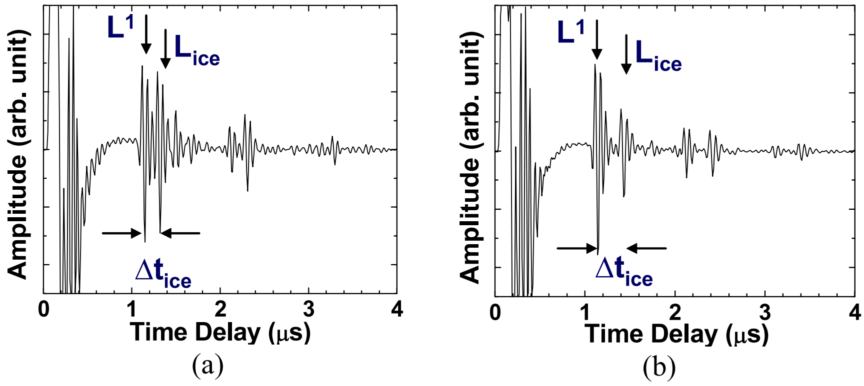

Figure 5. Ultrasonic signals obtained by the IUT, similar to the one shown in figure 1, deposited on top of a 3 mm thick Al plate for (a) 0.32 mm and (b) 0.57 mm ice thickness measured by a micrometer.

velocity in the Al airframe, is 6480 m s^{-1}, the best possible thickness measurement accuracy achievable using the above parameters given in table 1 would be 36 μm and 41 μm for the IUT and flexible UT, respectively.

$$\sigma\left(\Delta t-\Delta t'\right) \geqslant \sqrt{\frac{3}{2f_0^3\pi^2T(B^3+12B)}\left(\frac{1}{\rho^2}\left(1+\frac{1}{\mathrm{SNR}_1^2}\right)\left(1+\frac{1}{\mathrm{SNR}_2^2}\right)-1\right)}. \quad (1)$$

Table 1. Parameters for equation (1) and digitization resolution.

Parameters	IUT	Flexible UT
f_0 (MHz)	15.3	17.5
T (μs)	0.3	0.3
B	11/15.3	7.2/17.5
ρ	0.96	0.87
SNR_1 (dB)	40	23.1
SNR_2 (dB)	33.7	16.9
$\sigma(\Delta t - \Delta t')$ (ns)	1.17	2.49
Digitization resolution (100 MHz) (ns)	10	10
Total time delay uncertainty (ns)	11.2	12.5
V_L (m s^{-1})	6480	6480
Thickness measurement accuracy (μm)	36	41

4. Ice thickness measurement

As mentioned in section 1 the accumulations on the leading edge or upper surface of the wing with a thickness or roughness like a piece of sandpaper can reduce the lift by 30% and increase the drag by 40% or more. One report showed [22] that the ice thickness of less than 1.5 mm could already cause such a dramatic effect. Therefore this investigation focuses on the measurement of ice thickness less than 1.5 mm using the above mentioned IUTs and flexible UTs. It is noted that it is easier to measure thicker ice than thinner ice. For ice measurements, an Al plate of 3 mm thickness was used as a substrate. Such a choice came from the experimental investigation results showing that the reverberating ultrasonic echoes within an Al airframe of 1.3 mm thick will overlap with the echoes associated with ice thickness less than 1.5 mm. Significant digital signal processing techniques may be applied in order to obtain accurate ice thickness measurement. It may be simpler to place the sensors at locations where the Al airframe thickness is greater than or equal to 3 mm.

Figures 5(a) and (b) show ultrasonic signals obtained by the IUT, similar to these of figure 1, on a 3 mm thick Al plate having ice thickness of 0.32 mm and 0.57 mm, respectively,

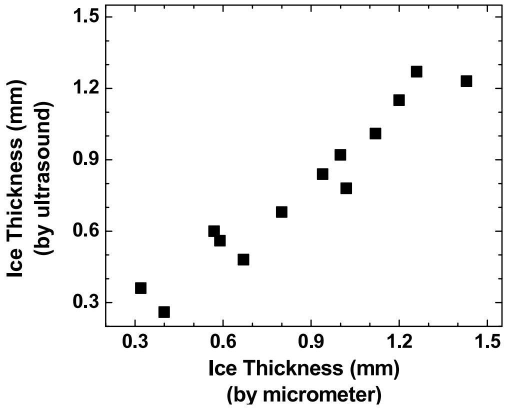

Figure 6. Correlation between ice thickness measurements measured by a micrometer and those by ultrasound using an IUT.

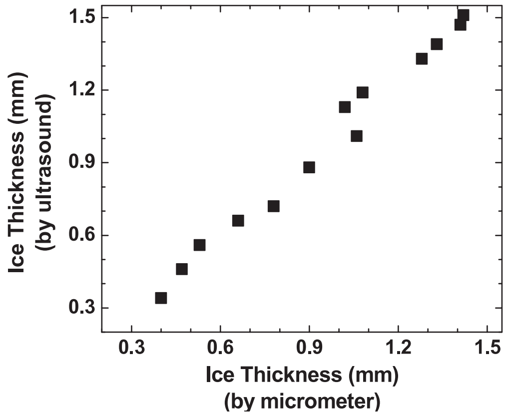

Figure 8. Correlation between ice thickness measurements measured by a micrometer and those by ultrasound using a flexible UT.

measured by a micrometer. The echoes, L_{ice}, reflected from the open air side of the ice are clearly identified in the figure. The longitudinal velocity, v_{ice}, in the ice used was 3980 m s^{-1} [23]; subsequently, the ice thicknesses, h_{ice}, were calculated to be 0.36 mm and 0.60 mm, respectively. It is noted that the velocity of ice is a function of temperature and also depends on its structure [22] which is unknown in this study, therefore minor errors would exist. For ice making, firstly a rubber ring of an inner diameter of 38.1 mm was located at the center of the exterior surface of the IUT sensing region. The proper amount of water was pour into the ring the bottom edge of which was sealed to prevent water leakage. The water was then frozen using a stainless steel container sitting on top of the 3 mm thick Al plate filled by liquid nitrogen and located near the periphery of the rubber ring. Figure 6 demonstrates that the measured ice thicknesses using ultrasound agreed well with those measured by a micrometer. The calculated square of the correlation coefficient (R-squared) value was 0.93.

The ultrasonic signals obtained by the flexible UT attached to the 3 mm thick Al plate for ice thicknesses of 0.40 mm and 0.66 mm measured by a micrometer are shown in figures 7(a) and (b), respectively. The SNRs of the signals obtained by the flexible UT are less than those obtained by the IUT. The cause of the SNR reduction may be due to the glue used as the ultrasonic couplant between the flexible UT and Al plate. It is noted that there is no couplant between the IUT and Al plate. The measured ice thicknesses using ultrasound also agreed well with those measured by a micrometer, as presented in figure 8. The calculated R-squared value was 0.98.

Comparing the time signals shown in figures 5(a) and 7(a), one can find that the SNR for the flexible UT is worse than that of the IUT due to the presence of ultrasonic couplant. However, the R-squared value for the flexible UT is 0.98 which is higher than 0.93 for IUT. The reason for this discrepancy has been investigated. It is found that because the thickness measurements using a micrometer were carried out manually and the temperature of the micrometer was difficult to keep low and constant during measurement, the thickness measurement accuracy is not high. Such manual thickness measurement error caused the above mentioned discrepancy.

5. Conclusions

Two types of ultrasonic sensors fabricated by a sol–gel spray technique have been presented for *in situ* structural thickness and ice build-up monitoring. These were designed

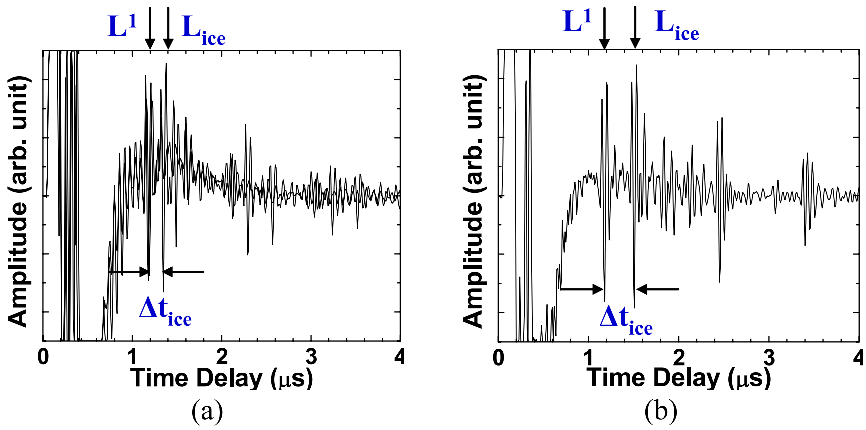

Figure 7. Ultrasonic signals obtained by the flexible UT, shown in figure 2, for (a) 0.40 mm and (b) 0.66 mm thick ice on top of a 3 mm thick Al plate.

and fabricated to operate within aircraft environmental temperatures of −80 to 100 °C. In one sensor type, piezoelectric films of thickness greater than 40 μm were deposited directly onto the interior of a nearly 1.3 mm thick stabilizer outer skin of an aircraft wing structure as IUT. Such an IUT does not require ultrasonic couplant. In many aerospace situations accessibility to desired sensor locations is limited, flexible UTs were developed to address this limitation. These flexible UTs consisted of piezoelectric films of several tens of microns thick coated onto a 50 μm thick polyimide membrane with a 1 μm thick nickel bottom electrode made by the electroless plating technique. These flexible UTs were subsequently glued onto similar locations in the interior of the stabilizer.

In situ monitoring of stabilizer outer skin thickness were carried out by both IUTs and flexible UTs. Using equation (1) (equation (19) in [21]) and a digitizer of 100 MHz, the best possible thickness measurement accuracy achievable under constant temperature is 41 μm. The ice thicknesses on top of a 3 mm Al plate ranging from fractions of a mm to less than 1.5 mm were performed by both sensor types and the measured ice thicknesses using ultrasound agreed well with those measured by a micrometer. The calculated square of correlation coefficient (R-squared) values were better than 0.93. Since arrays of IUTs or flexible UTs can be easily fabricated by the developed sol–gel spray technique, not only accurate ice thickness measurements can be performed during in-flight situations but also conditions of ice at many critical locations may be monitored simultaneously.

Acknowledgment

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