Measurement of Ice Accretion Using Ultrasonic Pulse-Echo Techniques

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Results of tests to measure ice thickness using ultrasonic pulse-echo techniques are presented. Tests conducted on simulated glaze ice, rime ice, and ice crystals are described. Additional tests on glaze and rime ice samples formed in the NASA Lewis Icing Research Tunnel are also described. The speed of propagation of the ultrasonic wave used for pulse-echo thickness measurements is found to be insensitive to the type of ice structure, and is determined to be 3.8 mm/μs. An accuracy of ±0.5 mm is achieved for ice thickness measurements using this technique.

Nomenclature

a = radius of transducer element
C = speed of propagation of ultrasonic wave
D = thickness
E = Young's modulus
I_i = intensity of incident wave
I_r = intensity of reflected wave
R = reflection coefficient
T = pulse-echo time
Z = acoustic impedance
λ = wavelength
ν = Poisson's ratio
ρ = density

Introduction

AIRCRAFT icing remains one of the most severe aviation weather hazards. A system to measure aircraft ice accretion and accretion rate in real time could directly reduce this hazard. Real-time measurement of ice accretion rate can provide the pilot with a quantitative evaluation of icing severity. Therefore, the effectiveness of changes in flight path to minimize ice accretion can be determined. In addition, by measuring ice accretion on critical components such as wings, engine inlets, propellers, or rotor blades, an ice accretion measurement system can be used to automatically activate and optimally control ice protection systems. Although many schemes have been suggested for measuring aircraft ice accretion,[1-3] there remains a need for the development of a practical system capable of performing real-time, in situ measurement of ice accretion. The purpose of this study is to evaluate the feasibility and potential performance of an ice detection system using pulsed ultrasonic waves to measure ice thickness over a small transducer mounted flush with the aircraft surface. Since the technique of ultrasonic "pulse-echo" thickness measurement produces a real-time ice thickness signal, the ice accretion rate may be determined by electronically differentiating this thickness measurement with respect to time.

Theoretical Background

Ultrasonic Pulse-Echo Thickness Measurement

An ultrasonic transducer containing a piezoelectric element is mounted flush with the aircraft surface on which the ice thickness is to be measured. An ultrasonic pulse is emitted from the transducer and travels upward through the ice in a direction parallel to the emitting axis of the transducer (see Fig. 1). When this pulse reaches the ice/air interface above the transducer, it is reflected from the interface back down into the ice layer. This "echo" from the ice/air interface then returns to the aircraft surface where it is detected by the transducer, which now acts as a receiver. The velocity of the pulse-echo signal through the ice layer is determined solely by the density and elastic constants of the ice, and, hence, by measuring the time elapsed between the emission of the pulse and the return of the echo from the ice/air interface, the ice thickness D may be calculated from the following formula:

$$D = CT/2 \tag{1}$$

where C is the velocity of the pulse-echo signal in ice (speed of sound in ice), and T the time elapsed between the pulse emission and echo return from the ice/air interface.

Speed of Propagation

The "pulse" produced by the ultrasonic transducer is a short-duration compression wave (longitudinal wave). The

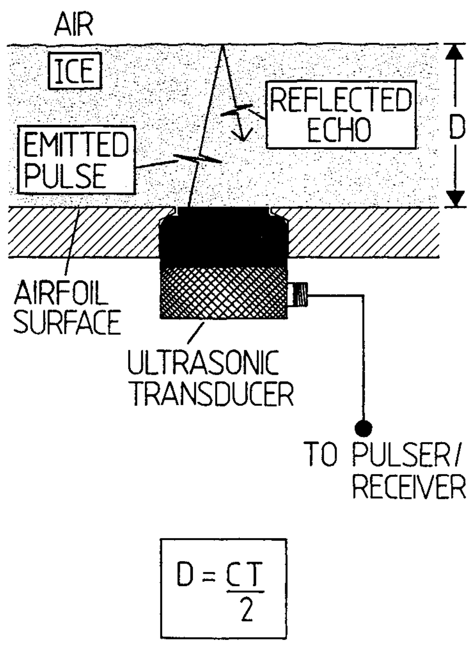

Fig. 1 Ultrasonic pulse-echo thickness measurement.

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velocity C at which such a compression wave propagates through a solid medium is theoretically predicted[4] to be

$$C = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \tag{2}$$

where E is the Young's modulus for the medium, ν the Poisson's ratio, and ρ the density of the medium. Hence, the pulse-echo signal propagates through a solid medium at a constant velocity that depends only on the density and elastic constants of the medium.

Reflection of Ultrasonic Signal from Ice/Air Interface

The ultrasonic pulse is reflected back toward the transducer (as the echo signal) at the ice/air interface (Fig. 1) because of the difference in the acoustic impedances of ice and air. The acoustic impedance, Z, of a medium is defined as the product of the medium's density, ρ, and the speed of sound in the medium, C, given by Eq. (2); hence,

$$Z = \rho c \tag{3}$$

The reflection coefficient, R, for an interface is defined[4] as the ratio of the intensity of the reflected wave, I_r, to that of the incident wave, I_i, and is given by

$$R = \frac{I_r}{I_i} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 \tag{4}$$

where Z_1 and Z_2 are the acoustic impedances of the two media forming the interface. From this equation it can be seen that the intensity of the reflected wave, or echo signal, depends on the acoustic impedance mismatch between the two media. Since both the density and speed of sound in air are considerably lower than those for solids, the acoustic impedance mismatch for a solid/air interface is large, resulting in strong reflection at a solid/air interface. For an ice/air interface the reflection coefficient is calculated to be greater than 0.99, i.e., more than 99% of the incident wave energy is reflected at an ice/air interface.

Coupling

For the vibration of the transducer element to be transmitted into a solid medium, a "coupling" mechanism between the transducer and the solid must be available. Although it is often necessary to use a fluid to provide this coupling mechanism, no such fluid is required for ice thickness measurement since the ice is atomically bonded to the transducer face and, therefore, is constrained to vibrate with the transducer element.

Ultrasonic Field Shape

At the high frequencies (5-20 MHz) used for pulse-echo ice thickness measurement, the wavelength λ in the ice is typically small (<1 mm) compared to the radius a of the radiating transducer element. Under these conditions the ultrasonic wave propagates from the transducer as a collimated beam of the same diameter as the transducer element. This beam, or near-field region, extends for a distance given by the ratio a^2/λ, after which the wave diverges in the far-field region. Typical near-field ranges are approximately 2 in. for a 0.5-in.-diam, 5-MHz transducer and 1 in. for a 0.25-in.-diam, 10-MHz transducer.

Attenuation

Attenuation of the received echo signal can be divided into three components: absorption and scattering within the ice, and reflection at the ice/air interface. Absorption occurs as part of the vibrational energy of the wave is stored as heat by the ice molecules and then lost through irreversible heat transfer within the ice layer. Scattering is caused by any inclusions within the ice (such as air bubbles), since, by definition, these inclusions have a different acoustic impedance to that of the ice and, therefore, present spurious reflective interfaces to the incident ultrasonic wave. The third factor affecting the received strength of the echo signal is the shape of the ice/air interface itself. While almost 100% of the incident wave energy is reflected at the ice/air interface, the shape of the interface determines the direction(s) of reflected wave propagation. Rough ice surfaces will reflect the incident wave diffusely, while ice surfaces that are not parallel to the transducer face will cause the echo signal to propagate at an angle to the emitting axis of the transducer. In both cases the intensity of the echo received by the transducer will be diminished over that received from an identical ice thickness with a flat, parallel ice/air surface.

Experimental Apparatus

Three components comprised the pulse-echo thickness measurement system tested: a transducer, a pulser/receiver unit, and an oscilloscope (Fig. 2). The function and important performance characteristics of each of the components are outlined below. The experimental apparatus constructed to simulate and test the application of this pulse-echo system to ice accretion measurement is then described.

Transducer

The transducer used to produce and receive the ultrasonic pulse-echo signal was a broadband, highly damped contact transducer. This type of transducer allows maximum signal penetration in attenuating and scattering materials such as rime and glaze ice. Excellent thickness resolution is also possible with this type of transducer. A single transducer was used for all of the tests described. The transducer tested had a center frequency of 5 MHz and an element diameter of 0.5 in.

Pulser/Receiver

The pulser/receiver provides the electrical signals necessary for the operation of the transducer in a pulse-echo mode. The pulser section of the pulser/receiver supplies the transducer element with a short, high-voltage pulse of controlled energy.

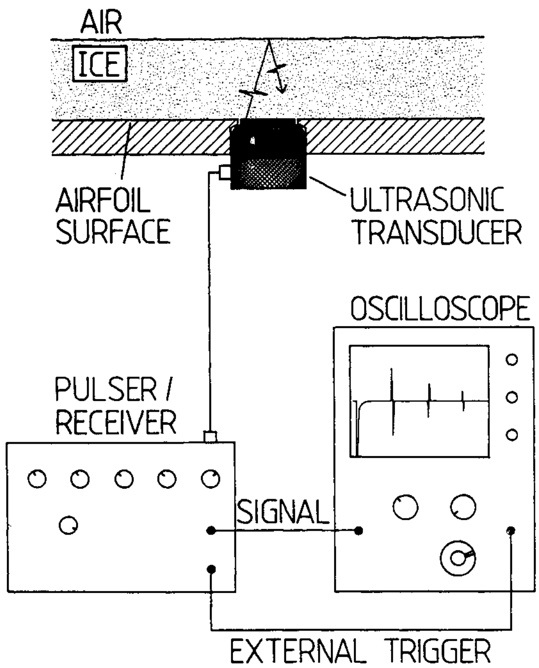

Fig. 2 Ultrasonic pulse-echo system.

This voltage pulse causes the transducer element to vibrate, thus producing the ultrasonic pulse utilized in pulse-echo thickness measurement. The voltage applied to the transducer element is typically on the order of 200 V. The voltage pulse is reapplied to the transducer element several hundred times per second to produce a "continuous" pulse-echo thickness reading. The receiver section amplifies and conditions the small echo voltage produced by the transducer element itself. The typical gain required is approximately 40 dB. In addition, the pulser/receiver provides a synchronizing voltage used to trigger an oscilloscope sweep momentarily before the main voltage pulse is applied to the transducer element. For experimental purposes, an oscilloscope was used to observe the pulse-echo signal characteristics in different ice formations and measure the pulse-echo time. Figure 3 shows a typical pulse-echo trace obtained from a 5.0-mm-thick ice layer.

Experimental Apparatus

To allow ice to be frozen over the transducer face and the pulse-echo system tested, the apparatus shown in Fig. 4 was used. A circular 9-in.-diam aluminum plate served as a test surface on which the ice accretion was to be measured. The transducer was mounted in the center of this plate with the transducer face flush with the plate surface. An 8-in.-diam plexiglas cylinder could be used to contain water poured onto the plate surface when it was desired to freeze liquid water over the face of the transducer (in order to simulate glaze ice). A removable plexiglas lid could be fitted over this cylinder; the purpose of the lid was to provide a reference level from which the ice thickness over the plate surface could be accurately measured by inserting a steel probe graduated in millimeters through one of a grid of small holes drilled into the lid. The aluminum plate was also instrumented with two chromel/alumel thermocouples to monitor the plate/ice temperature.

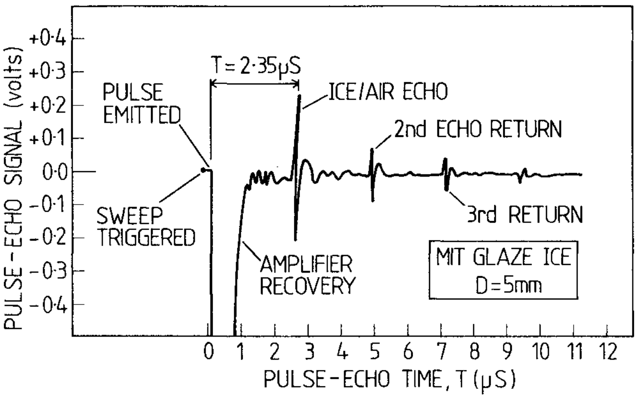

Fig. 3 Typical pulse-echo trace for ice.

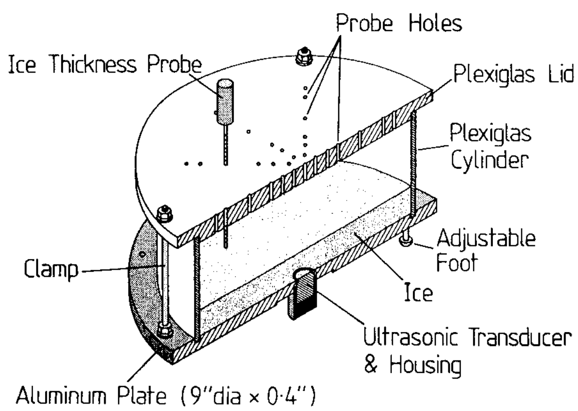

Fig. 4 Experimental apparatus.

Testing

In order to calibrate the configured pulse-echo system, aluminum and plexiglas samples of different thicknesses were measured using the ultrasonic pulse-echo technique. By comparing the measured speed of sound in the material,

$$C = 2D/T \tag{5}$$

with well-established values, the error in the obtainable pulse-echo thickness measurements was determined to be less than 5% for equivalent ice thicknesses from 1 to 30 mm. Testing of the pulse-echo system comprised two consecutive series of trials. The first series consisted of tests performed on ice formed at MIT. Both glaze and rime ice structures were simulated and ice thicknesses from 1.5 to 31 mm were tested. Additional tests were also performed on ice crystal formations. The second series of tests utilized ice samples obtained from the Icing Research Tunnel (IRT) at NASA Lewis Research Center. Glaze and rime ice formations from 4.5- to 15-mm thick were tested in this series of tests.

MIT Glaze Ice Simulation Tests

Glaze ice was simulated by pouring water into the plexiglas cylinder/plate apparatus (Fig. 4) to a depth approximately equal to the desired ice thickness, and then the apparatus was placed in a cold box thermostatically maintained at $-20°C$. Once the water was completely frozen, the pulse-echo time T was recorded from the oscilloscope display. The apparatus was then removed from the cold box so the ice thickness could be measured with the graduated probe as described earlier. The ice thickness was always recorded within 1 min of removal from the cold box and no appreciable rise in ice temperature (as indicated by the plate thermocouples) took place between the recording of the pulse-echo time and the corresponding ice thickness measurement.

MIT Rime Ice Simulation Tests

To simulate rime ice, the aluminum plate containing the ultrasonic transducer was first placed in the cold box. Once the plate had reached its steady-state temperature (typically $-18°C$), water droplets at 0°C were sprayed onto the plate/transducer face using a misting nozzle connected to a small electric pump and ice/water reservoir (Fig. 5). The droplets were sprayed intermittently rather than continuously to prevent the ice temperature from significantly increasing as a result of the heat of fusion released by the freezing water droplets. Droplets were typically observed to freeze within 2 s of impact with the plate surface. Measurement of the pulse-echo time and ice thickness was made in a manner similar to that described for the glaze ice simulation tests.

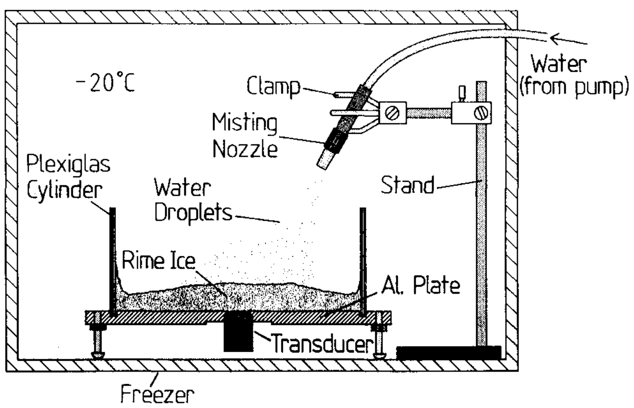

Fig. 5 Rime ice simulation method.

MIT Ice Crystal Tests

To simulate a limiting case for air entrapment within an ice structure and investigate the propagation of an ultrasonic wave through such a structure, ice crystals were compacted over the plate/transducer surface. The structure thus formed contained air gaps on the order of 1-3 mm between individual ice crystals. As in the previous simulations, pulse-echo time and ice thickness were recorded for these ice formations.

NASA Lewis Ice Tests

The second series of tests conducted with the pulse-echo system involved ice samples obtained from airfoil sections installed in the NASA Lewis Icing Research Tunnel. The ice samples were obtained under a variety of documented tunnel/icing cloud conditions and shipped in dry ice to MIT, where the tests with the pulse-echo system were conducted. In order to bond the ice samples to the flat transducer surface, a thin film (<0.1 mm) of water at 0°C was applied to the "airfoil" side of the ice sample. The ice sample was then simply placed over the transducer face (at −18°C), the water film under the ice sample freezing on contact with the cold transducer face thus bonding the ice sample to the transducer in the same orientation as would have occurred if the transducer had been mounted in the airfoil. No appreciable change in either the internal structure of the ice or the "top" ice/air surface of any of the NASA ice samples tested was observed as a result of this procedure. Once the ice sample under test had been successfully bonded to the transducer, the pulse-echo time in the sample was recorded from the oscilloscope display, as in the other ice simulation tests. The aluminum plate was then removed from the cold box and the average ice thickness over the transducer was measured.

Results and Discussion

MIT Glaze Ice, Rime Ice, and Ice Crystal Results

The results from the tests conducted on ice formed at MIT are plotted together in Fig. 6 as ice thickness D vs pulse-echo time T. Regression lines were fitted to the glaze and rime ice results in order to calculate the experimentally measured speed of sound for these ice structures. Therefore, the speed of sound C in Eq. (5) is simply twice the slope of the regression line. The experimentally determined values for the speed of sound in the glaze and rime ice formed at MIT were 3.78 and 3.95 mm/μs, respectively. A regression line was not fitted to the data from the ice crystal tests due to the small number of data points. However, it can be seen from Fig. 6 that the speed of sound in the ice crystal structure does not differ significantly from the values obtained for the glaze and rime ice structures. The typical error bar shown represents the inherent uncertainty for any ice thickness measurement made with the mechanical probe arrangement described earlier.

NASA Lewis Ice Results

In order to compare the results from the tests performed on the NASA Lewis IRT ice with those from the MIT ice structures, each of the NASA Lewis ice samples tested was categorized as either glaze or rime ice. The ice samples were categorized according to the tunnel temperatures at which they were formed and their physical characteristics (e.g., milky, clear, double-ridged surface, etc.). Figure 7 shows a scatter plot of the results obtained from the NASA Lewis ice samples, again with ice thickness plotted against pulse-echo time. Due to the small number of tests performed on each type of ice (glaze or rime), regression lines were not fitted to these results. However, the linear relationship between ice thickness and

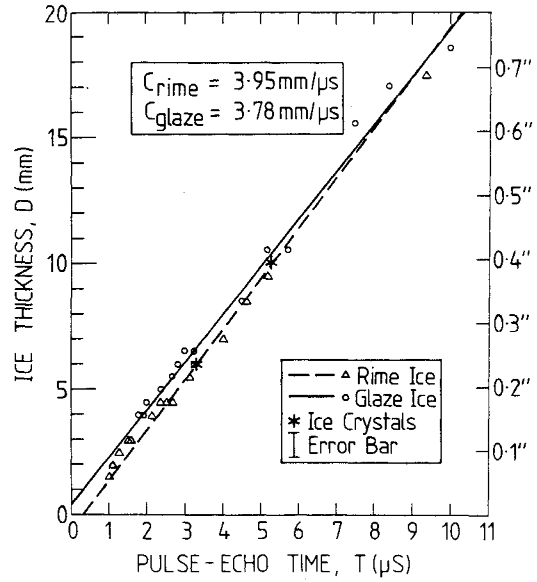

Fig. 6 Ice thickness vs pulse-echo time for MIT glaze and rime ice samples.

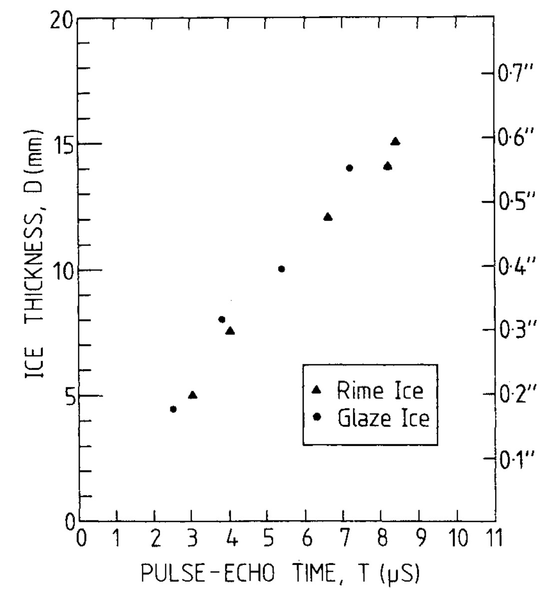

Fig. 7 Ice thickness vs pulse-echo time for NASA Lewis ice samples.

pulse-echo time—indicating a constant speed of sound—readily can be seen. Furthermore, the speed of sound, as indicated by the slope of the data, does not seem to be sensitive to the type of ice present. The greater spread in the data obtained for the NASA Lewis ice can be explained as follows. The NASA Lewis ice samples were all collected from airfoil surfaces in the IRT and all displayed either rough (rime ice) or concave (glaze ice) ice/air surfaces, while the ice surfaces produced during the MIT glaze and rime ice tests were generally flat and uniform. As a result of the surface irregularity of the NASA Lewis ice samples, it was often necessary to record an average ice thickness over the transducer and similarly a corresponding average pulse-echo time, since the echo from the ice/air interface above the transducer was now broadened by the irregular interface. Therefore, the NASA Lewis results have a larger typical error in both measured ice thickness and recorded pulse-echo time than the more "ideal" MIT ice results.

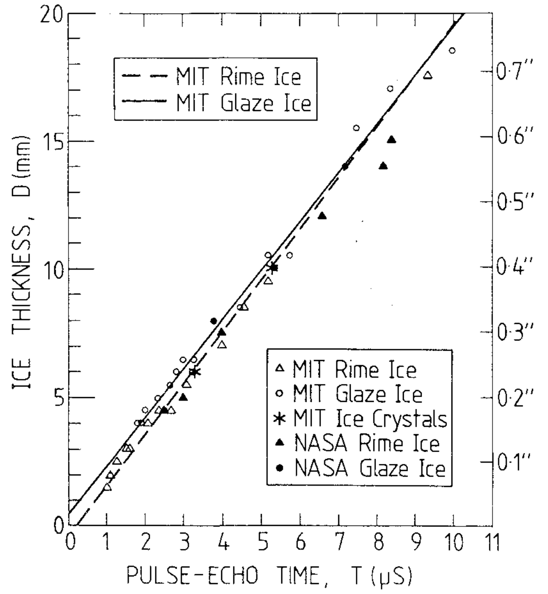

Fig. 8 Ice thickness vs pulse-echo time: MIT glaze and rime ice, NASA glaze and rime ice.

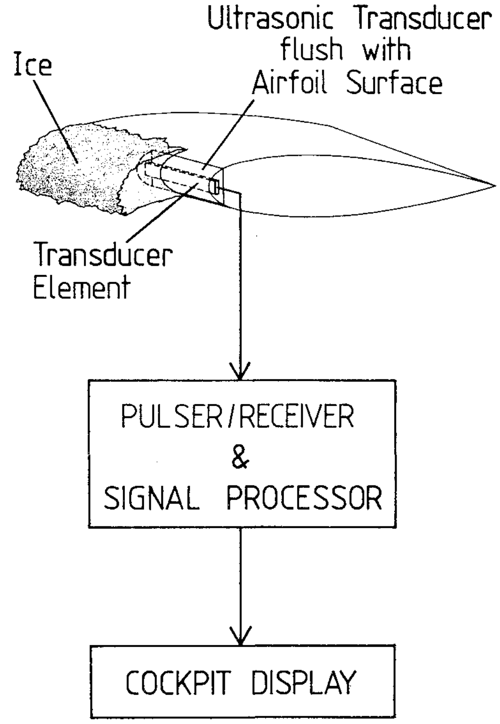

Fig. 9 Pulse-echo ice accretion measurement, system layout.

Although the actual uncertainty for any single NASA Lewis result depended on the particular ice sample geometry, the average uncertainty in these test results is approximately ± 1 mm for ice thickness and ± 0.5 μs for the corresponding pulse-echo time. Comparing the results from the MIT and NASA Lewis ice tests (Fig. 8) it can be seen that the results from the two series of tests correlate extremely well‡—especially considering the wide range of "icing" conditions under which the ice tested was formed. The slight difference between the experimentally determined speeds of sound for the MIT glaze and rime ice is within the expected data spread due to experimental error (primarily in measuring ice thickness with the mechanical probe), and the results from the tests conducted on the NASA Lewis IRT ice samples confirm that the speed of sound is insensitive to the type of ice present. Therefore, the results from both series of tests (MIT and NASA Lewis) may be regressed together to give an average or "effective" speed of sound in ice of 3.8 mm/μs. (This compares with a value of 3.98 mm/μs quoted by Filipczynski et al.[4] for "ice.")

Since the speed of sound in ice must be known to calculate ice thickness from a measured pulse-echo time, the observed insensitivity of this speed of sound to the type of ice present permits pulse-echo time to be uniformly converted to ice thickness using this average speed of sound. One explanation for the similar speeds of sound measured in both rime and glaze ice formations is that, despite their optical differences, these ice structures are acoustically equivalent. Macklin[5] has shown ice density to be relatively constant ($0.8 < \rho < 0.9$ g/cm^3) at higher droplet impact velocities over a wide temperature range. If, in addition, the elastic constants for glaze and rime ice are also approximately equal, then ice structures formed under different icing conditions would yield similar speeds of sound, as observed. However, further study of both the speed of propagation and attenuation of ultrasonic compression waves in different ice structures is still needed to confirm the physical basis for the observed insensitivity of the speed of sound in different ice types.

The practical resolution of ice thickness achievable using the ultrasonic pulse-echo technique depends primarily on the diameter and frequency of the transducer element used. Since, within the near field, the ultrasonic wave propagates as a collimated beam of the same diameter as the transducer element, the resolution is limited by the ice thickness variation across the beam diameter at the ice/air interface. The spread in the data obtained from the tests conducted on ice shape geometries typically encountered on airfoils during flight in icing conditions (NASA Lewis ice tests) suggests an accuracy of better than 1 mm should be achieved for practical ice accretion measurements using pulse-echo techniques. The uncertainty due to ice thickness variation over the transducer can be minimized by the use of smaller diameter transducers; however, higher frequencies must be employed to remain in the near-field region.

‡The bulk correlation coefficient for all of the tests performed is 0.994.

Conclusions

Tests conducted on simulated rime and glaze ice formations and rime and glaze ice samples removed from airfoil sections installed in the Icing Research Tunnel at NASA Lewis Research Center have provided the following information.

1) An ultrasonic pulse, or compression wave, can be propagated through all ice formations likely to be encountered during flight in icing conditions and a return "echo" from the ice/air interface clearly discerned, using relatively inexpensive ultrasonic pulse-echo equipment.

2) An ultrasonic pulse propagates through ice at a velocity that does not significantly depend on the type of ice formation present. This velocity was experimentally determined to be 3.8 mm/μs. Therefore, ice thickness may be calculated from the measured pulse-echo time and this "constant" speed of sound, regardless of the type of ice accreted.

3) Ice thickness variations across the ultrasonic field produced by the radiating transducer result in a corresponding broadening of the echo from the ice/air interface. If the pulse-echo time is measured from the pulse emission to the "center" of the echo return, then an average ice thickness over the transducer is obtained. Likewise, if the pulse-echo time is taken to be the time elapsed between the pulse emission and the start of the echo return from the ice/air interface, then the minimum ice thickness over the transducer is measured.

4) The rough and/or concave ice surfaces characteristic of rime and glaze ice formations scatter the incident ultrasonic pulse and, therefore, reduce the strength of the echo signal received by the transducer. However, the echo signal is not

obscured and the pulse-echo time can be measured in all of the ice shapes typically encountered during flight in icing conditions.

Therefore, ultrasonic pulse-echo thickness measurement is considered to offer a practical solution to the problem of real-time ice accretion measurement for aircraft encountering icing conditions. The operational accuracy achievable with such a system depends primarily on the transducer specifications (frequency and element diameter) and the location of the transducer. An accuracy of ± 0.5 mm for ice thickness measurement is predicted. The configured ultrasonic pulse-echo system would comprise three components: an ultrasonic transducer, a pulser/receiver and signal processing unit, and a cockpit display (Fig. 9). The transducer is nonintrusive and mounted flush with the surface on which ice accretion is to be measured. The transducer units are small and lightweight and, therefore, may be mounted on almost any vulnerable surface, including helicopter rotor blades and engine inlets. The signal processor calculates the ice thickness from the measured pulse-echo time and also differentiates this real-time measurement with respect to time to obtain the ice accretion rate. The cockpit display unit provides the pilot with an automatic "icing encountered" alert and indicates icing severity as well as controlling and/or monitoring the operation of fitted ice protection systems.

Acknowledgment

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References

[1]Perkins, P. J., McCullough, S., and Lewis, R. D., "A Simplified Instrument for Recording and Indicating Frequency and Intensity of Icing Conditions Encountered in Flight," NACA RM-E51E16, 1951.

[2]Magenheim, B. and Rocks, J. K., "Development and Test of a Microwave Ice Accretion Measurement Instrument (MIAMI)," NASA CR-3598, 1982.

[3]Ide, R. F. and Richter, G. P., "Evaluation of Icing Cloud Instrumentation for 1982-83 Icing Season Flight Program," AIAA Paper 84-0020, Jan. 1984.

[4]Filipczynski, L., Pawlowski, Z., and Wehr, J., *Ultrasonic Methods of Testing Materials*, Butterworths, London, 1966.

[5]Macklin, W. C., "Density and Structure of Ice Formed by Accretion," *Quarterly Journal of the Royal Meteorological Society*, Vol. 88, No. 375, Jan. 1962, pp. 30-50.