Microwave Ice Accretion Measurement Instrument (MIAMI)

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This paper describes a highly sensitive, accurate, rugged, and reliable microprocessor controlled device using low-level microwave energy for nonintrusive real-time measurement and recording of ice growth history, including ice thickness and accretion rate. New experimental data are presented, obtained with the instrument, which demonstrate its ability to measure ice growth on a two-dimensional airfoil mounted in the NASA Lewis Research Center Icing Research Tunnel. The microwave ice accretion measurement instrument (MIAMI) is suitable for aircraft icing protection. It may be mounted flush, nonintrusively, on any part of an aircraft skin, including rotor blades and engine inlets.

Nomenclature

d	= thickness of surface waveguide
d_{oo}	= thickness of surface waveguide used in transducer which is resonant at f_{00}
d_{med}	= droplet size
df	= change in resonant frequency
df_a	= asymptote of change in resonant frequency
di	= change in frequency index
di_a	= asymptote of change in resonant frequency
dI/dt	= accretion rate
e	= base of natural logorithm
f	= frequency
f_{oo}	= quiescent resonant frequency
fm	= parameter of VTO
g	= parameter of VTO
i	= frequency index
i_{oo}	= quiescent frequency index
I	= ice thickness
k, k'	= constant used in empirical calibration curve
LWC	= liquid water content
m	= parameter of VTO
p	= normalization factor
r	= dynamic range of MIAMI
T	= temperature
TE	= transverse electric
w	= width of MIAMI transducer
V_{oo}	= quiescent VTO voltage
VEL	= airspeed
λ_o	= free space wavelength
λ_g	= guide wavelength of surface waveguide
λ_{goo}	= guide wavelength of quiescent resonant frequency

I. Introduction

THE purpose of this program was to perform an engineering study to confirm that it is technically and economically feasible to develop a microwave instrument system (MIAMI) for research purposes that can simultaneously perform the following functions on a two-dimensional airfoil: a) detect the presence of ice, b) measure the ice thickness, and c) measure the ice accretion rate.

Icing instrumentation is an area of research so fundamental that it is probably the single most important area. There cannot be an "icing science" without the ability to measure the icing accurately. In the 1940s and 1950s, relatively clumsy and slow measurement techniques were used with questionable accuracy. Advances in instrumentation have been so dramatic since that time that it is now possible to achieve highly accurate measurements of icing with real-time data displays. The microwave ice accretion measurement instrument (MIAMI) described here is one such device that can be used as a research, as well as an operational, instrument.

II. Results of Experimental Program

A. Description of the MIAMI

The MIAMI developed in this program is a device that is responsive to the thickness of ice layers accreting on its surface. An illustration of the MIAMI mounted on an airfoil is shown in Fig. 1. Its output, illustrating the growth of ice on an airfoil mounted in the icing research tunnel (IRT), recorded in real time, is shown in Fig. 2. The MIAMI consists of two major elements: a transducer for mounting under the surface being monitored and a microprocessor connected to the transducer by a long multiconductor cable. The microprocessor sends signals to the transducer and, based upon the response received from the transducer, computes the ice thickness and accretion rate and digitally displays these values on the front panel. The displays are instantaneous. The MIAMI can be programmed to log and printout a permanent record of ice thickness and accretion rate as a function of time. A sample printout appears as Fig. 3. It can also be programmed to store ice thickness and accretion rate in computer memory for later statistical analysis for use in icing or cloud studies.

Additional important features of the MIAMI are that it is nonintrusive; it *does not* use probes protruding into the airstream, but is mounted flush, below the surface being monitored. The MIAMI is constructed from components that can be packaged in miniature integrated circuits having almost negligible mass so that it can be mounted almost anywhere on the skin of the aircraft, including rotor blades and engine inlets.

The transducer, mounted just below the surface being monitored, is a resonant microwave device, the resonant frequency of which is very sensitive to the thickness of ice accreting on its surface. As the ice layer grows, the resonant frequency is reduced as illustrated in Figs. 4a and 4b.

The microprocessor is programmed to continually monitor the change in resonant frequency indicated by df in Fig. 4 and convert this change into a dc voltage which varies in time in a manner proportional to the ice thickness as illustrated in the real-time recording (Fig. 2).

B. Performance of the MIAMI

The MIAMI was tested in the icing research tunnel during two weeks in June and one week in August 1981. Thirty-one tests were run in June and 29 in August.

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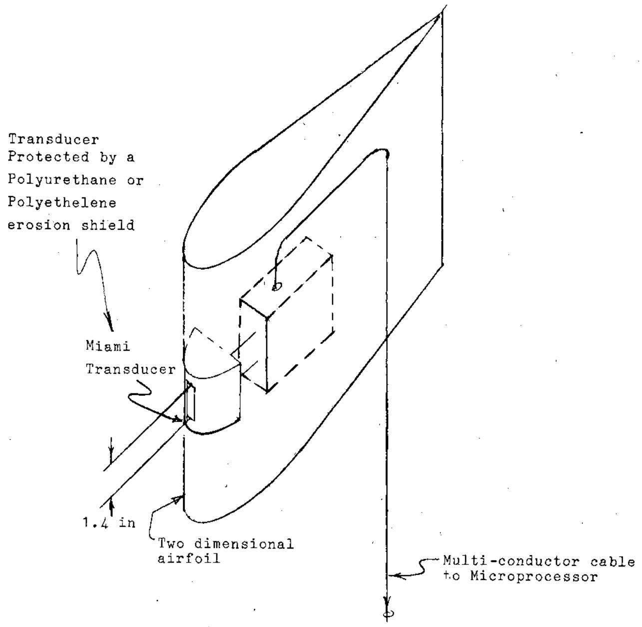


Fig. 1 MIAMI mounted on a two-dimensional airfoil.

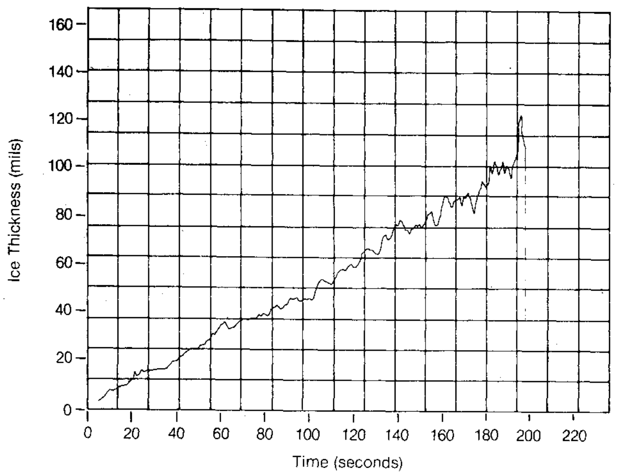


Fig. 2 Typical pen recording of MIAMI output illustrating ice growth in real time.

.....8/25/81 RUN NUMBER: 10
TUNNEL PARAMS: VEL=100 TEMP(F)=30 DROPLET SIZE=15 WATER CONTENT=1.8
COMMENTS:
TRANSIT COEFFICIENT: .93

TIME	D-INDEX	TRANSIT ICE	MIAMI ICE
77.64	512.00	18.60	24.17
117.24	736.00	37.20	43.72
154.00	865.00	55.80	57.05
187.64	1016.00	74.40	75.27
216.20	0.00	0.00	0.00
0.00			

Fig. 3 Sample printout provided by the MIAMI illustrating permanent record of ice growth history.

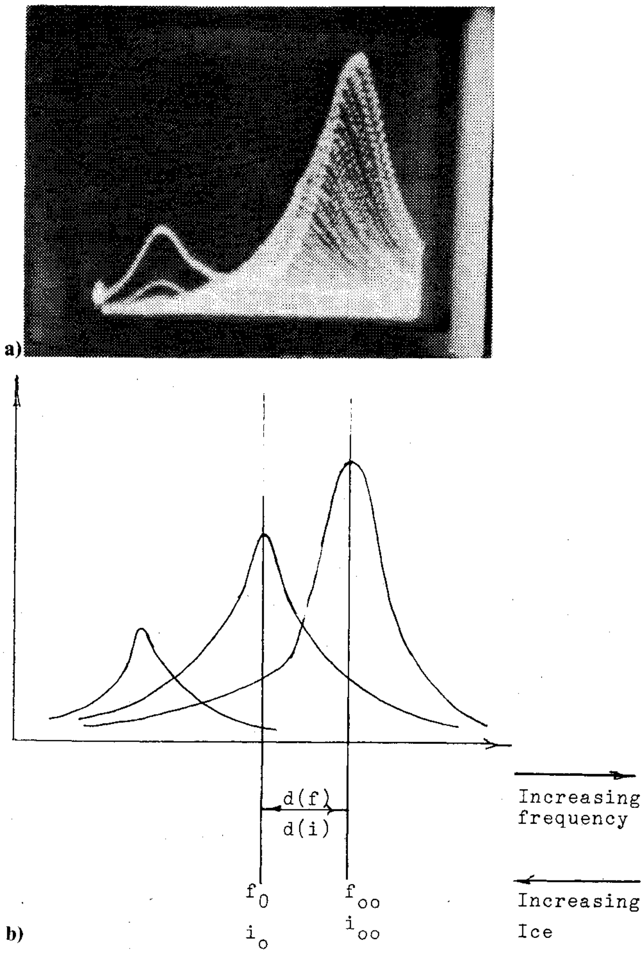


Fig. 4 Variation of MIAMI resonance as ice accretes on its surface: a) storage oscilloscope trace in real time; b) definition of parameters displayed by storage oscilloscope trace.

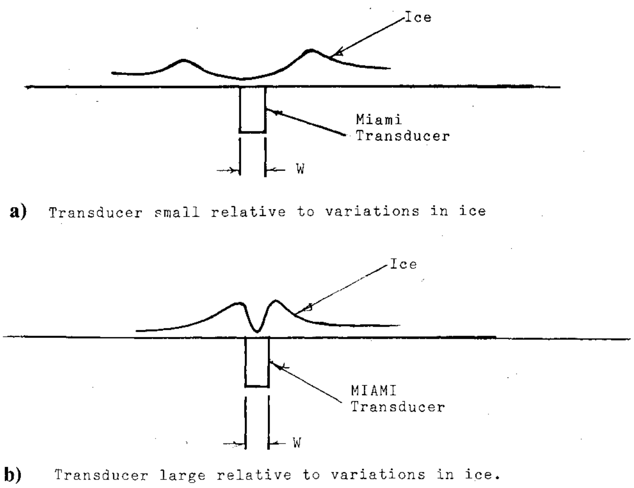


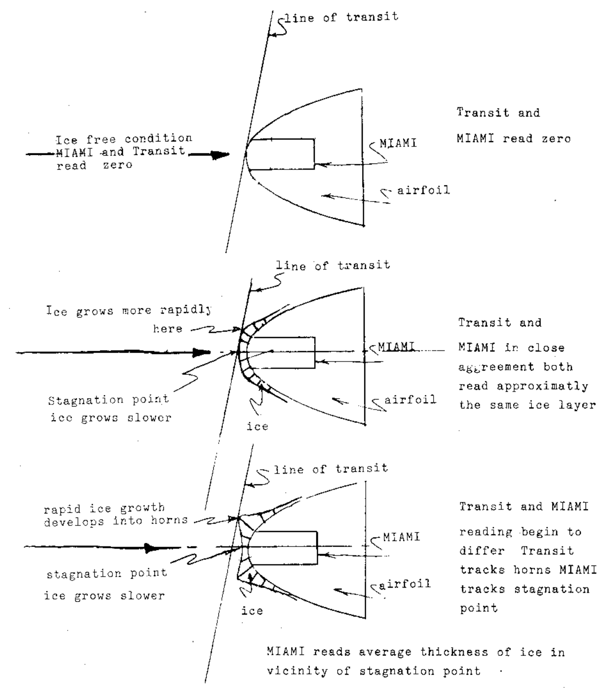
Fig. 5 Size of MIAMI transducer relative to gross variations of ice thickness.

The purpose of the tests was to determine the ability of the MIAMI to measure the thickness of ice accreting on its surface under conditions simulating those of natural icing.

The transducer logic assumes that the ice is growing in uniform layers above it. This approximation is true if the transducer width *w* is small relative to major variations in the ice as illustrated in Fig. 5a. When the ice is nonuniform, as illustrated in Fig. 5b, the reading produced by the MIAMI represents an average value of the ice thickness in the vicinity of the transducer.

For many everyday aircraft applications, the condition that the transducer is small relative to the gross variations in the ice layer is satisfied and the MIAMI readings of average thickness will closely represent the thickness of the ice layer. For research applications where the ice layers are intentionally permitted to grow into odd shapes, care must be taken that the particular MIAMI chosen for the measurement is sufficiently smaller than the gross ice variations in its vicinity so that the readings are truly representative of the thickness of the ice accreting above it.

Impact ice under a wide variety of tunnel conditions was permitted to accrete on the MIAMI, which was mounted at the stagnation point of a two-dimensional airfoil, as shown in



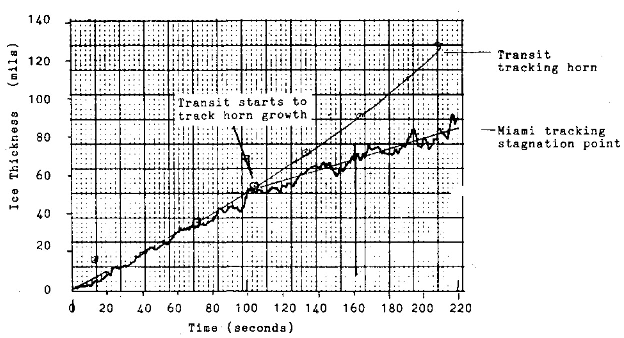


Fig. 6 Pen recording of MIAMI output illustrating horn growth.

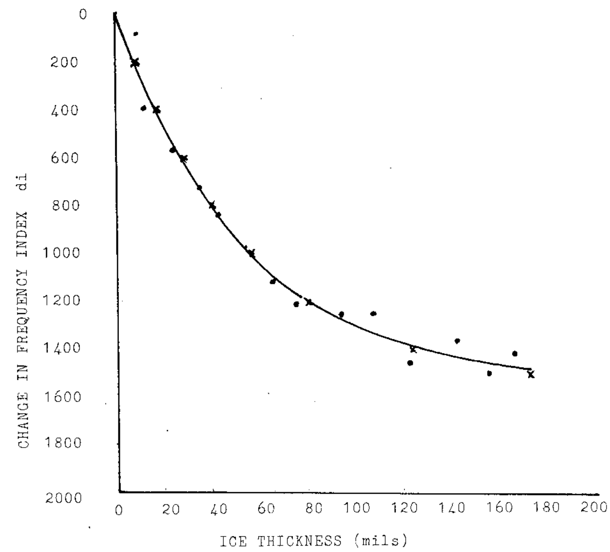


Fig. 7 Experimental curve illustrating shift in frequency index vs ice thickness.

Fig. 1, and the thickness of the ice measured by the MIAMI and another independent means. The independent means used to measure ice thickness at the stagnation point was a calibrated transit located in the control room viewing the ice layers accreting on the MIAMI surface. The accuracy of this technique, however, is limited to relatively thin layers of ice not more than about 125 mils.

Ice growth on an airfoil is nonuniform, being less at the stagnation point than at the neighboring locations so that as the ice grows a time is reached when the transit can no longer see the ice at the stagnation point, it being obscured by the more rapid growth on either side of it. When this happens, the transit begins to track the more rapidly growing ice, or horns, on either side of the stagnation point. This phenomenon is illustrated in Fig. 6, which is one of 18 plots demonstrating this phenomenon. A more ideal way to test the MIAMI in thick ice would be to mount the MIAMI on a rotating cylinder since ice will accrete uniformly in a predictable manner on this surface.

Examination of data taken in the icing research tunnel overwhelmingly supports this thesis, and the calibration of the MIAMI is thus based solely on data gathered during early growth stages, when the ice is less than about 125 mils (⅛ in.) and transit measurement and MIAMI measurements are in close agreement.

1. Calibration of the MIAMI

Equation (1) represents the theoretically derived relationship between ice thickness and shift in resonant frequency:

$$I = \frac{1}{k} \ln\left(1 - \frac{df}{df_a}\right) \tag{1}$$

where df is the shift in resonant frequency with ice; df_a is the asymptote of shift in resonant frequency with ice; and k is a constant.

$$I = \frac{1}{k'} \ln\left(1 - \frac{di}{di_a}\right) \tag{2}$$

where di is the shift in frequency index with ice; di_a is the asymptote of shift in resonant frequency with ice; and k' is a constant.

It has been found more practical to use Eq. (2), however, where i, the frequency index or count generated by the computer, is used in place of frequency since for every frequency index there is a corresponding value of frequency f so that a measurement of di is equivalent to a measurement of df; but di, being continually generated by the computer, as the ice grows, is readily available from computer memory. Curves of measured di vs measured ice thickness (Fig. 7) are readily obtained from the computer printout (Fig. 3) and serve as a means for calibrating the MIAMI. The calibration process is one of determining values of k' and di_a that causes Eq. (2) to fit the measured data. Since these terms were established from measurements on ice layers up to 125 mils, Eq. (2) is rigorously applicable only to ice layers less than 125 mils; however, since Eq. (2) has been verified theoretically, it can be expected to give useful information up to the maximum, or dynamic, range of the MIAMI transducer. Rigorously speaking, future tests on thicker ice layers would be required to verify that the equation is applicable to thick layers.

C. Measured Dynamic Range of the MIAMI Model 6

In 15 runs made with model 6 the tunnel parameters were set to produce rapid and thick icing so that the ice thickness soon exceeded the range of the MIAMI transducer. The maximum range of the transducer was taken to be the maximum reliable reading provided by the MIAMI that was not obscured by noise. Using this criteria, the average dynamic range recorded was 210 mils.

Model 6 operates in the 6-GHz frequency band. Theory indicates that if the operating frequency is lowered the dynamic range will increase (e.g., if the frequency is divided by two the dynamic range will double). Thus larger MIAMIs will have larger dynamic ranges. Dynamic ranges to 1 in. are not unreasonable.

III. Miami Design Theory

A. Theoretical Basis for the MIAMI

The fact that the resonant frequency of a resonant surface waveguide is altered or tuned by the growth of ice on it is the theoretical basis for the MIAMI. Oscillograms illustrating and verifying this phenomena are shown in Fig. 4 for MIAMI model 6.

If the shift in resonance caused by the ice of known thickness is measured, an empirical relation between ice thickness and frequency shift can be established which, from then on, can be used to measure the ice thickness from a measurement of the frequency shift. A typical curve of ice thickness vs frequency shift is shown in Fig. 7 for MIAMI model 6.

The MIAMI transducer thus consists of a resonant surface waveguide on which the ice is permitted to accrete and an instrumentation which continually monitors its resonant frequency and converts the measured change in frequency to ice thickness by means of the empirical equation illustrated in Fig. 7 and described by Eq. (2). The surface waveguide is composed of a layer of stable dielectric material such as polyethylene which has approximately the same dielectric constant as ice and is placed just under the surface on which ice is to be measured, as illustrated in Fig. 8.

In the ice-free condition, the surface waveguide is made resonant by making its length equal to an integral number of half wavelengths. As layers of ice begin to form on the dielectric surface of the waveguide, they have the effect of thickening the waveguide and altering its resonant frequency.

IV. The MIAMI System Theory

A block diagram of the MIAMI system is shown in Fig. 9. The microprocessor is programmed to generate a repetitive countdown from the number 2047 to zero. The count is converted in the digital to analog converter (DAC) to an analog voltage. This voltage appears as a negative going sawtooth the amplitude of which is directly proportional to the count. This voltage is transmitted to the MIAMI transducer via a long multiconductor cable where it is amplified and used to sweep the voltage tuned oscillator (VTO) through its frequency range. Each count or number generated by the microprocessor corresponds to a different frequency output of the VTO. The count, a number generated by the microprocessor, is also called the frequency index. The microwave signal generated by the VTO is then passed through the resonant surface waveguide whose resonant frequency is a function of the ice thickness and then detected by the crystal detector. The voltage out of the crystal detector is then amplified and transmitted to the analog to digital converter via the long multiconductor cable where it is converted into a digital number. A peak sensing algorithm in the microprocessor then determines the frequency index (count) that produced a peak output of the resonant surface waveguide. This is called the resonant frequency index.

In the ice-free condition, the resonant frequency is called the quiescent value of resonant frequency, f_{oo}. The resonant frequency index that generated the quiescent resonant frequency is called the quiescent index i_{oo}. When ice forms on the transducer, tuning the surface waveguide, the resonant frequency index decreases in value and the difference between the quiescent resonant frequency index i_{oo} and the resonant frequency index i_o is a function of ice thickness.

The functional relationship between ice thickness and frequency index is established experimentally and stored in the microprocessor. The microprocessor then continually monitors the change in frequency index and, using the stored function, calculates the ice thickness. The microprocessor then computes the accretion rate of the ice by calculating the first time derivative of ice thickness. These values are then available for subsequent display.

A. Theoretically Derived Relation Between Ice Thickness and Frequency Index

The relationship between frequency index and ice thickness may be obtained functionally from Fig. 9 provided the transfer constants of the surface waveguide as a function of ice, the VTO, the VTO driver, and DAC are known. All of these transfer characteristics can be measured.

From Eq. (1), the ice thickness is a function of the shift in resonant frequency:

$$I=\frac{1}{k}\ln\left(1-\frac{df}{df_a}\right) \tag{3}$$

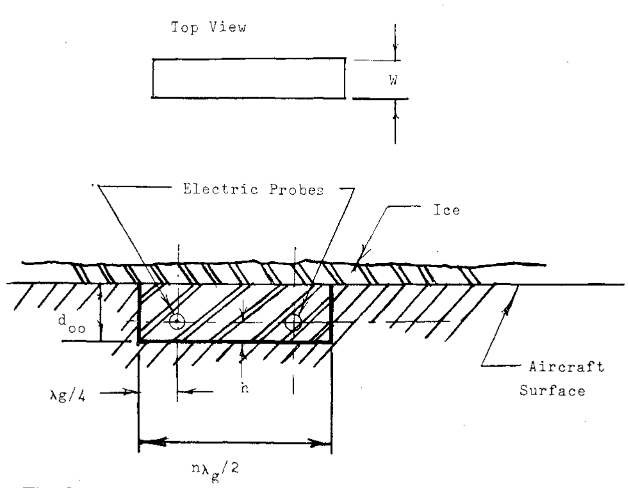


Fig. 8 Diagram illustrating construction of MIAMI transducer.

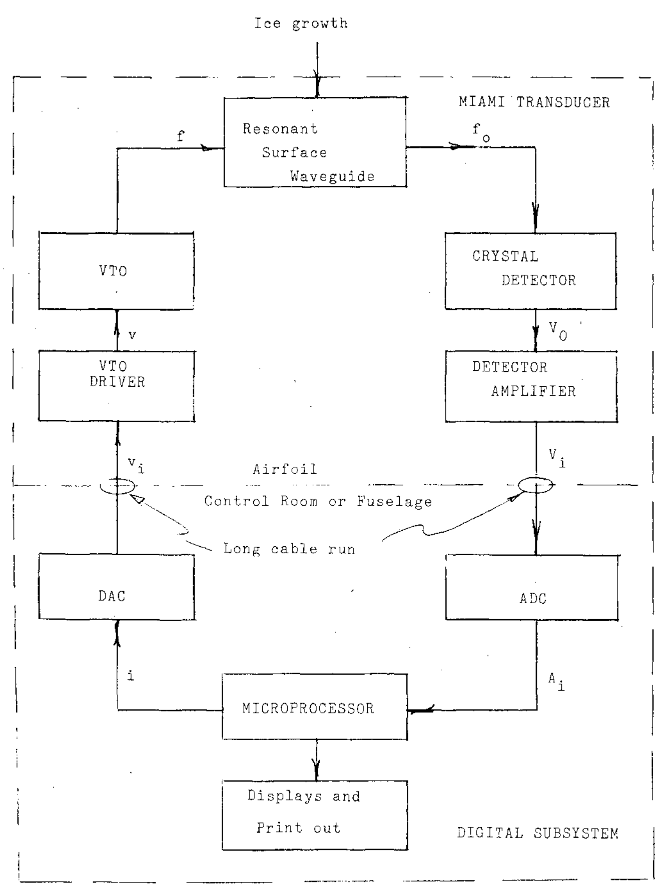


Fig. 9 MIAMI system block diagram.

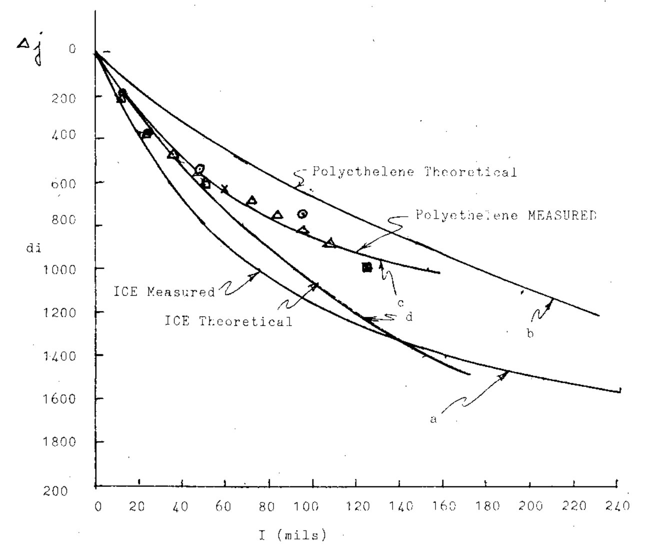


Fig. 10 Comparison of theoretical and experimental data obtained with mathematical model of MIAMI system.

The VTO tuning curve is represented by

$$f=f_a-f_m e^{gv} \tag{4}$$

and the transfer characteristics of the DAC and VTO driver are

$$v=mi+b \tag{5}$$

and

$$dv=m di \tag{6}$$

from which it can be shown that df is related to di by

$$df=f_m e^{gv_{oo}}(e^{-gm di}-1) \tag{7}$$

Thus, the ice as a function of di, can be obtained from Eqs. (3) and (7) as

$$I=\frac{1}{k}\ell n\left[1-\frac{f_m e^{gv_{oo}}(e^{-gm di}-1)}{df_a}\right] \tag{8}$$

Parameters in Eqs. (3-8) are defined in Table 1.

Figure 10 was prepared to illustrate the agreement between the theoretically derived Eq. (8) and measurements. Four plots of Eq. (8) are shown for ice measured, ice theoretical, polyethylene measured, and polyethylene theoretical.

Parameters of the MIAMI, once established and set, do not change with measurement, only the ice parameters do. These were established from experiments on ice and polyethylene and theoretical considerations for ice and polyethylene.

B. Variation of Dynamic Range with MIAMI Dimensions

The dynamic range of the MIAMI system is limited primarily by the design of the MIAMI transducer. The tuning curve as measured during tests performed in June 1981, is illustrated in Fig. 7. The practical dynamic range achieved during these tests is indicated at about 210 mils. How this dynamic range varies with p is illustrated in Table 2.

Physically, the dynamic range is limited by the following considerations. The low end of the tuning range becomes useful only when the operating frequency is far enough above cutoff for the coupling efficiency to be sufficiently high to couple useful energy into the surface waveguide. The high end

Table 1 Parameters in Eqs. (3-8) (f_{oo} = 6.29 GHz; f_m = 1.30; g = −0.0735; m = 0.0058; V_{oo} = 11.68)

	Frequency asymptote, df_a	Constant, k
Polyethylene, theoretical	0.8	−2.5
Polyethylene, measured	0.354	−11.45
Ice, theoretical	1.4268	−2.5
Ice, measured	0.573	−9.51

Table 2 Variation in dynamic range, r, with normalization factor, p, established from MIAMI model 6

Normalization factor, p	Dynamic range if rp = 2 cm r, cm	(in.)	Quiescent resonant frequency f_{oo} GHz	Thickness of surface waveguide d_{oo}, in.	(cm)
0.5	4	(1.57)	0.787	6.29	(16)
1	2	(0.787)	1.573	3.149	(8)
2	1	(0.393)	3.145	1.574	(4)
4	0.5	(0.196)	6.29	0.787	(2) Measured

of the tuning curve becomes useless when the asymptote is approached and a small change in ice thickness produces only an unmeasurable change in resonant frequency.

This table shows that the dynamic range of the MIAMI may be adjusted upwards or downwards to accommodate the particular ice measurement at hand.

Conclusion

A microwave ice accretion measurement instrument (MIAMI) incorporating a microprocessor has been developed that can 1) detect the presence of ice and sound an alarm; 2) measure and digitally display ice thickness; 3) measure and digitally display ice accretion rate; 4) plot ice thickness, accretion rate, and other parameters on a pen recorder; 5) log and printout a permanent record of ice thickness and ice accretion rate vs time; and 6) store data for delayed time statistical analysis and printout.

The instrument is nonintrusive; that is, it does not use probes, but is mounted under the surface being monitored and does not interfere with its aerodynamic properties.

One or more transducers may be mounted anywhere on an airfoil or other aircraft surface—all can be monitored by a single microprocessor.

Electrothermal deicing of the MIAMI to remove existing ice is feasible. Ice removal is not necessary, however, until the ice thickness exceeds the dynamic range of the instrument.

The MIAMI transducer is constructed from solid state components, all of which have very little mass and are therefore capable of miniaturization and ruggedization.

The development described herein represents research that was performed over a period of one year at IRI. The fundamental principle exploited is that layers of ice accreting on the surface of a resonant surface waveguide will alter its resonant frequency; and the thickness of the ice layer is related to degree of shift of the resonance. To take advantage of this phenomenon the research proceeded in two areas: 1) the microwave transducer and 2) the microprocessor for monitoring its resonant frequency and real-time display of ice thickness and accretion rate.

Acknowledgment

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