

NASA CASE NO. LAR 15061-1

PRINT FIG. 1

NOTICE

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THICKNESS MEASUREMENT DEVICE FOR ICE/WATER MIXTURE

AWARDS ABSTRACT

A device and method are provided for determining the thickness of an ice and water mixture accumulated on the outer surface of an object. First and second total impedance sensors are operated at first and second frequencies over which the dielectric constants for water and ice are substantially the same. Corresponding first and second AC total impedance measuring circuits are coupled to the first and second sensors to produce output voltages based on the total impedance changes sensed by the sensors. A processor is coupled to the first and second measuring circuits to generate a voltage ratio using the measured output voltages. The voltage ratio is indicative of the thickness of the ice and water mixture.

The novelty of the present invention is the use of two frequencies and dual geometry impedance sensors in order to be sensitive to the formation of ice. Thus, critical situations created by the presence of solid ice can be averted. The device is simple and is easily incorporated into current technology thereby making its realization cost-effective.

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THICKNESS MEASUREMENT DEVICE FOR ICE/WATER MIXTURE

Origin of the Invention

5 The invention described herein was made by an employee of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

10 Background of the Invention1. Field of the Invention

15 This invention relates to ice detection. More specifically, the invention is a thickness measurement device for determining the thickness of ice and water mixtures on a surface.

2. Description of the Related Art

20 A dual-geometry, capacitance-type ice thickness measuring gauge was disclosed by this Applicant in U.S. Patent No. 4,766,369. The gauge disclosed therein uses two capacitance sensors having different electrode configurations and spacing to measure the thickness of surface ice independently of the temperature and impurities in the ice. The device
25 works well if the ice is homogeneously solid where no water or other liquid is mixed in or is on top of the ice. However, ice formation often occurs with some liquid present. In certain applications, e.g., aircraft icing conditions, runway or roadway icing conditions, etc., it is critical to know that ice is forming before it becomes homogeneously solid.

Unfortunately, when using the dual-geometry gauge in the presence of liquids, the apparent dielectric constant and conductivity can vary considerably from areas near the capacitance sensors to the outer surface of the ice or ice/water mixture. The variations can cause large errors in the readings by the dual-geometry gauge readings.

Summary of the Invention

Accordingly, it is an object of the present invention to provide a thickness measurement device and method that determines the thickness of an ice and water mixture on a surface during the process of ice formation.

Another object of the present invention is to provide a thickness measurement device and method that determines the thickness of layers of liquid and ice on a surface.

Other objects and advantages of the present invention will become more obvious hereinafter in the specification and drawings.

In accordance with the present invention, a device and method are provided for determining the thickness of an ice and water mixture accumulated on the outer surface of an object. A first total impedance sensor senses total impedance changes due to very small accumulations of the ice and water mixture. A first AC total impedance measuring circuit is coupled to the first sensor and produces output voltages based on the total impedance changes sensed by the sensor. Output voltages are measured when the first AC total impedance measuring circuit is operated at a first frequency and a second frequency. The frequencies are selected such that the dielectric constant and resistivity of the ice and water mixture are substantially constant. A second total impedance sensor senses total impedance changes due to the ice and water mixture.

A second AC total impedance measuring circuit is coupled to the second sensor and produces output voltages based on the total impedance changes sensed by the second sensor. Once again, the output voltages are measured when the second AC total impedance measuring circuit is
5 operated at the first and second frequencies. A processor is coupled to the first and second measuring circuits and generates a processed voltage ratio using the measured output voltages. The processed voltage ratio is indicative of the thickness of the ice and water mixture.

10 Brief Description of the Drawings

FIG. 1 is a schematic diagram of the thickness measurement device of the present invention showing the relative locations of the various sensors near the surface of interest;

15 FIG. 2 is a schematic diagram of a first total impedance sensor used in the thickness measuring device;

FIG. 3 is a schematic diagram of a second total impedance sensor used in the thickness measuring device;

20 FIG. 4 is a schematic representation of the sensor's impedance components and the impedance measuring circuit;

FIG. 5 is a graphical representation of the dielectric constant variation of ice and water as a function of frequency and temperature; and

25 FIG. 6 is a graphical representation of the resistivity variation of ice and water as a function of frequency and temperature.

Detailed Description of the Invention

Referring now to the drawings and more particularly to FIG. 1, the

thickness measuring device of the present invention is shown and referenced generally by numeral 11. Device 11 includes first total impedance sensor 16, second total impedance sensor 18, and temperature sensor 20. The term "total impedance" generally refers to the combination of resistive, capacitive and inductive impedance. However, in terms of the present invention, inductive impedance is zero or negligible because no coils or coil geometries are present in the components or the electrical representations thereof. Accordingly, the term "total impedance" as used herein refers to only the combination of resistive and capacitive impedance measured by each of sensors 16 and 18.

Device 11 is mounted near outer surface 12 of any surface of interest such as a runway, a roadway, an aircraft surface, etc. By way of example, outer surface 12 is part of an aircraft 10. This outer surface 12 may be on the wing, the engine intake, or any other surface of aircraft 10 where the formation of ice is detrimental. A small section of outer surface 12 is removed and replaced with embedding material 14, which preferably is either plastic or an epoxy-type material.

Sensors 16, 18 and 20 are embedded in embedding material 14. The surfaces of sensors 16, 18 and 20 can be exposed to material 22 residing on outer surface 12. For purpose of the following description, material 22 is an ice and water mixture accumulated on outer surface 12 except where otherwise noted. To avoid corrosion problems, sensors 16, 18 and 20 are covered with a thin layer of embedding material 14 typically on the order of approximately 0.001 inches thick. Positioning of sensors 16, 18 and 20 relative to outer surface 12 is such that each sensor must be close enough to sense the presence of ice and water mixture 22 on outer surface 12. Embedding material 14 is contoured and smoothed so that it is flush with outer surface 12 to minimize any

disruption in the contour of outer surface 12.

First total impedance sensor 16, second total impedance sensor 18 and temperature sensor 20 are connected respectively to first AC total impedance measuring circuit 24, second AC total impedance measuring
5 circuit 26, and temperature measuring circuit 28. The outputs of first and second total impedance measuring circuits 24 and 26 and temperature measuring circuit 28 are connected to processor 42. The outputs of processor 42 is typically passed to an output device such as display 44.

10 Temperature sensor 20 may be any one of several standard temperature sensors, such as a resistance film sensor, a thermocouple or an integrated circuit temperature sensor. Temperature measuring circuit 28 receives the output of temperature sensor 20 and determines the temperature at outer surface 12 and thereby the temperature of ice and
15 water mixture 22 (or any other material accumulation) on outer surface 12. Such circuits are well known in the art for each type of temperature sensor. The determined temperature is shown on display 44 and serves as an indicator or warning that conditions may be suitable for ice formation.

20 In general, total impedance sensors 16 and 18 are of different configurations such that their response to the presence of an ice and water mixture is different. For example, it is assumed herein that total impedance sensor 16 is constructed using small conductors separated by a small gap so that there is a very large change in response for small
25 thicknesses of water and ice mixtures. However, total impedance sensor 18 is constructed using larger conductors separated by a larger gap (relative to sensor 16 and the expected thickness of ice and water mixture 22) so that there is a nearly linear response to changes in thickness of the ice and water mixture.

By way of an illustrative example, first total impedance sensor 16 is shown in FIG. 2. Opposite sides of first total impedance sensor 16 are formed from parallel leads 30 and 32. Each of the two leads has connected respectively thereto a series of interleaved electrodes 34 and 5 36. Electrodes 34 and 36 are connected to leads 30 and 32. Electrodes 34 and 36 do not touch each other and hence the presence of material in the vicinity of electrodes 34 and 36 causes a change in total impedance between electrodes 34 and 36. While the dimensions of first total impedance sensor 16 may vary, a typical distance between the outside 10 edges of leads 30 and 32 is approximately 3/4 of an inch. Likewise, the length of leads 30 and 32 which contain the connections to electrodes 34 and 36 is about 3/4 of an inch. Typically, electrodes 34 and 36 are approximately 0.014 inches wide and have gaps of approximately 0.012 of an inch between them.

15 For pairing with sensor 16 of the configuration/size shown in FIG. 2, an illustrative example of second total impedance sensor 18 is shown in FIG. 3 and consists of two leads 38 and 40 which are parallel to each other. While the dimensions of second total impedance sensor 18 may vary, a typical distance between the outside edges of leads 38 and 40 is 20 approximately two inches. Parallel leads 38 and 40 each are formed from a single electrode which covers almost one-third of the distance between the outer edges of leads 38 and 40. This distance is typically approximately 0.67 of an inch. The length of each electrode is approximately two inches. Both first total impedance sensor 16 and 25 second total impedance sensor 18 can be made from thin conductors with a thickness of approximately 0.001 of an inch. The thickness will be greater if bulk conductors, e.g., conductive rubber, are used.

Referring once again to FIG. 1 first total impedance sensor 16 is connected to first AC total impedance measuring circuit 24 and second

total impedance sensor 18 is connected to second AC total impedance measuring circuit 26. Each of circuits 24 and 26 is the same except for selection of sensitivity setting components to match corresponding signal levels. Each of circuits 24 and 26 is capable of operation at a variety of
5 frequencies.

FIG. 4 is a schematic representation of the sensor/measuring circuit combination representative of either the sensor 16/measuring circuit 24 combination or the sensor 18/measuring circuit 26 combination. An adjustable source 50 produces a sine wave output at a
10 selected frequency f . Source 50 is connected to a resistor R_0 which is in series with the corresponding sensor, i.e., sensor 16 or sensor 18. The sensor is represented by a parallel arrangement of an external resistance R_E (due to external conductivity), a parasitic capacitance C_0 (due to the sensor internal capacitance), and an external capacitance C_E (due to the
15 change in external dielectric constant). Each of circuits 24 and 26 produces an output voltage indicative of a combination of resistive and capacitive changes produced by the proximity of any material on outer surface 12 for the particular operating frequency f .

Source 50 supplies a known AC sine wave voltage with RMS value
20 V_0 to the series hookup of resistor R_0 and corresponding sensor. The RMS voltage measured between the resistor R_0 and the sensor at node 52 is defined as V . The level of voltage V is determined by the total impedance of the sensor. The total impedance equation is

$$\frac{V}{V_0} = \frac{X_T}{X_T + R_0} \quad (1)$$

where, for the parallel components representing the sensor, X_T is

$$X_T = \frac{X_{CT} R_E}{X_{CT} + R_E} \quad (2)$$

where X_{CT} is

$$X_{CT} = \frac{1}{2\pi f (C_E + C_0)} \quad (3)$$

When the sensor does not have external ice or water on it, only the parasitic capacitor C_0 causes a signal. This value can be measured
5 and later used in the data reduction. If the "dry" sensor reading at node 52 is defined V' , the parasitic capacitance C_0 is

$$C_0 = \frac{V_0 - V'}{2\pi f R_0 V'} \quad (4)$$

The present invention utilizes the fact that dielectric constants and conductivity for ice and water can vary with change in imposed frequency over some frequencies, but are nearly constant for others.
10 FIG. 5 shows how the dielectric constant varies with frequency for ice and water for the temperature range from near freezing to well below freezing. More specifically, curve 60 represents -20°C , curve 62 represents -10°C and curve 64 represents -1°C . Water can respond to changes in electric fields very rapidly due to the mobility of the
15 molecules. In contrast, ice responds relatively slowly to the variations in the electric field due to the constraints of the lattice structure of the ice. Since ice and water have strong molecular dipole moments, the dielectric constant ϵ for both water and ice is about 80 at "low" frequencies up to approximately 400 Hz. The water dielectric constant stays constant, as
20 represented by dashed line 66, to at least 100 MHz, but the ice dielectric constant starts falling off at frequencies above approximately 400 Hz. The roll off frequency is dependent on temperature, but for temperature in the range of interest (0° to at least -20°), the dielectric constant

decreases at frequencies above 400 Hz, and flattens to a new value of dielectric constant (of about 3.1) at frequencies above about 20,000 Hz. Lower temperatures can roll off below 400 Hz, and the frequency at which data is taken may be lowered if extremely low temperatures are expected. The dielectric constant of 3.1 is typical of solids with no dipole moment.

The resistivity of ice and water also changes with frequency and temperature as shown in FIG. 6. Curve 70 represents -20°C , curve 72 represents -10°C , curve 74 represents -1°C , and dashed line 76 represents liquid water. The absolute level of resistivity depends strongly on impurity levels in the water and ice, so the curves shown are relative levels. The high mobility of the liquid water permits a high ion mobility resulting in low resistivity that is also frequency independent. At sufficiently low frequencies, even solid ice allows significant ion migration but as the frequency is increased, the lower mobility due to the lattice structure raises resistivity considerably. For 0° to -20° , the resistivity of ice starts to increase at frequencies beyond about 400 HZ and levels off to a higher value above frequencies about 20,000 Hz. The location of the start of roll up is also somewhat temperature dependent.

In order to measure the presence of a non-homogenous layer of ice and water and determine the thickness of the layer, the following approach is taken. Measurements can be made for sensors 16 and 18 at two different frequencies f_1 and f_2 where the dielectric constant and resistivity are not changing with frequency. The subscripts 1 and 2 refer to the lower and higher frequency value of any two frequencies for the remainder of the description. Measurements could be taken at, for example, frequencies selected from the range of approximately 20-400 Hz or from the range of frequencies above approximately 20,000 Hz. The lower range of frequencies, i.e., 20-400 Hz, are preferred for two

reasons. First, since the dielectric constant for ice and water is the same at lower frequencies, the presence of water in the ice does not degrade the accuracy of the thickness measurement even for non-homogenous layers. Second, higher frequencies have significant energy dissipation effects which further complicate the data reduction.

The external resistance R_E can be determined as follows for a dielectric constant ϵ that is constant over frequencies f_1 and f_2 . For simplicity of equation development, a frequency ratio f_1/f_2 of 1/2 is used. (However, at the expense of a more complex equation development, the present invention could be practiced with the frequency ratio f_1/f_2 being greater or less than 1/2. Note that for values of this ratio that are near 1, the required precision of the apparatus increases substantially.) The external resistance R_E is

$$R_E = \frac{VR_0X_{CT}}{[X_{CT}(V_0 - V) - R_0V]} \quad (5)$$

Equations (1) and (2) are combined and solved for R_E at the two frequencies f_1 and f_2 . The two equations for R_E can be equated to each other since R_E is the same for both frequencies. It can be shown that

$$X_{CTS1} = \frac{R_0}{\left(\frac{V_0 - V_{S2}}{V_{S2}}\right) - \left(\frac{V_0 - V_{S1}}{V_{S1}}\right)} \quad (6)$$

where X_{CTS1} is the total capacitive impedance for sensor 16 at frequency f_1 , V_{S1} is the RMS measured voltage at node 52 for sensor 16 at frequency f_1 , and V_{S2} is the RMS voltage measured at node 52 for sensor 16 at frequency f_2 .

Similarly, it can be shown that

$$X_{CTL1} = \frac{R_0}{\left(\frac{V_0 - V_{L2}}{V_{L2}} \right) - \left(\frac{V_0 - V_{L1}}{V_{L1}} \right)} \quad (7)$$

where X_{CTL1} is the total capacitive impedance for sensor 18 at frequency f_1 , V_{L1} is the RMS measured voltage at node 52 for sensor 18 at frequency f_1 , and V_{L2} is the RMS voltage measured at node 52 for sensor 18 at frequency f_2 .

- 5 The ratio of external capacitance's for a dual geometry system was disclosed by this Applicant in U.S. Patent No. 4,766,369. This ratio is adequate to characterize the relative thickness of the external material as long as the dielectric constant is the same for both sensors. This is thus valid for the present invention also. The use of two frequencies
- 10 according to the present invention allows the values of resistivity and dielectric constant to be separated out, and thus allows the capacitance for each sensor to be determined even for non-homogenous mixtures of ice and water. The parasitic capacitance's in X_{CTS1} and X_{CTL1} can be subtracted out and the result ratioed. The final relationship is a ratio of
- 15 the external capacitance of sensor 18 or C_{EL} to the external capacitance of sensor 16 or C_{ES} .

$$\frac{C_{EL}}{C_{ES}} = \frac{\left(\frac{V_0 - V_{L2}}{V_{L2}} \right) - \left(\frac{V_0 - V_{L1}}{V_{L1}} \right) - \left(\frac{V_0 - V'_{L1}}{V'_{L1}} \right)}{\left(\frac{V_0 - V_{S2}}{V_{S2}} \right) - \left(\frac{V_0 - V_{S1}}{V_{S1}} \right) - \left(\frac{V_0 - V'_{S1}}{V'_{S1}} \right)} \quad (8)$$

- where V'_{L1} is the RMS voltage measured at node 52 for sensor 18 when sensor 18 is dry and the frequency of operation is f_1 , and V'_{S1} is the RMS voltage measured at node 52 for sensor 16 when sensor 16 is dry
- 20 and the frequency of operation is f_1 .

The ratio in equation (8) can be used as a parameter to calibrate against thickness variation for known thicknesses. The calibration can then be used to determine the thickness of unknown layers. The variation of thickness with the ratio is nearly linear for a limited range, but begins to roll off toward a maximum value beyond thicknesses of the ice and water layer that are large compared to the spacing of the conductors in sensor 18. More specifically, when the thickness of the ice and water layer is less than 1/2 the electrode spacing of sensor 18, the variation in thickness causes an approximately linear change in the measured total impedance. When the thickness of the ice and water layer exceeds 1/2 the spacing, the response becomes non-linear. Sensitivity decreases substantially once the thickness of the ice and water layer is greater than twice the electrode spacing of sensor 18. Accordingly, electrode spacing for sensor 18 is selected to be at least twice the thickness of any expected ice and water layer.

Referring again to FIG. 1, a preferred operating scenario will be described. Since circuits 24 and 26 are sensitive to the presence of water as well as a mixture of ice and water, temperature measuring circuit 28 can control, via processor 42, when circuits 24 and 26 change operating frequencies. For example, when temperature measuring circuit 28 measures a temperature for which ice formation is not possible, circuits 24 and 26 are inactive. Once temperature measuring circuit 28 measures a temperature in the range of concern for ice formation, processor 42 could control circuits 24 and 26 to toggle between the first (e.g., 200 Hz) and second (e.g., 400 Hz) operating frequencies. As described above, device 11 then produces a measurement based on supply and measured voltages for both sensors at both frequencies. The resultant thickness of the ice and water mixture can be displayed on display 44. Note that processor 42 could also be used to control heaters

or other deicing equipment (not shown) in response to the detection of ice build-up.

The advantages of the present invention are numerous. By being sensitive to the mere formation of ice, the present invention can be an
5 early-warning system. Thus, critical situations created by the presence of solid ice can be averted. The device is simple and is easily incorporated into current technology thereby making its realization cost-effective.

Although the invention has been described relative to a specific
10 embodiment thereof, there are numerous variations and modifications that will be readily apparent to those skilled in the art in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced other than as specifically described.

15 What is claimed as new and desired to be secured by Letters Patent of the United States is:

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THICKNESS MEASUREMENT DEVICE FOR ICE/WATER MIXTURE

Abstract

5 A device and method are provided for determining the thickness of an ice and water mixture accumulated on the outer surface of an object. First and second total impedance sensors are operated at first and second frequencies. Corresponding first and second AC total impedance measuring circuits are coupled to the first and second sensors to produce
10 output voltages based on the total impedance changes sensed by the sensors. A processor is coupled to the first and second measuring circuits to generate a voltage ratio using the measured output voltages. The voltage ratio is indicative of the thickness of the ice and water mixture.

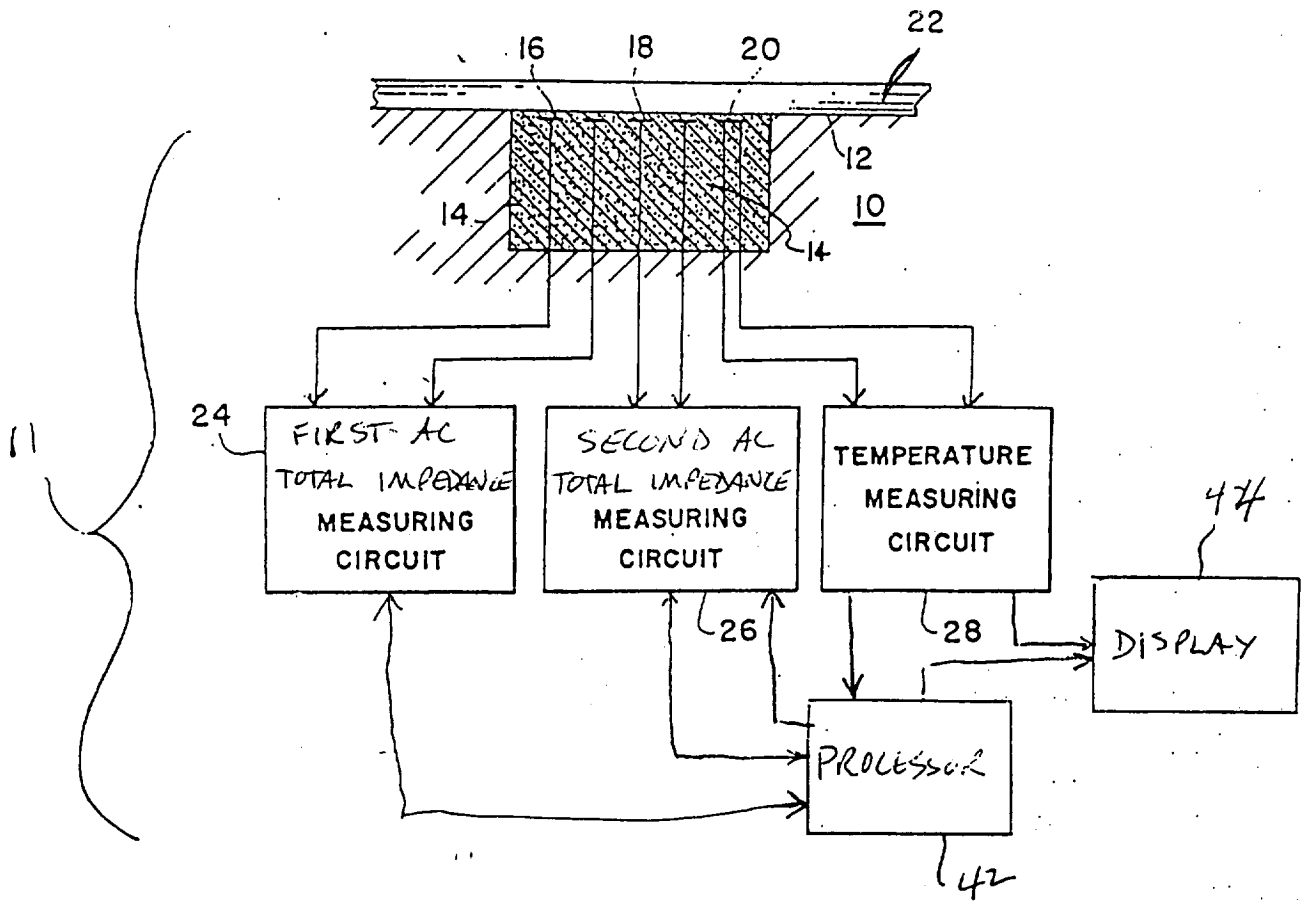


FIG. 1

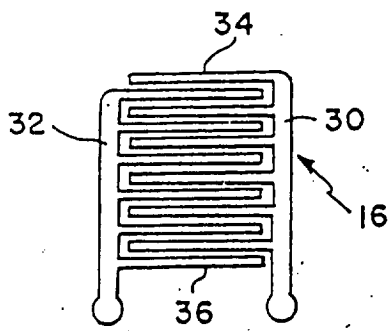


FIG. 2

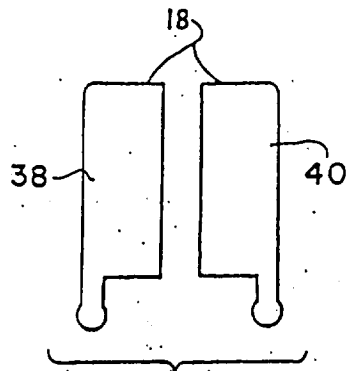


FIG. 3

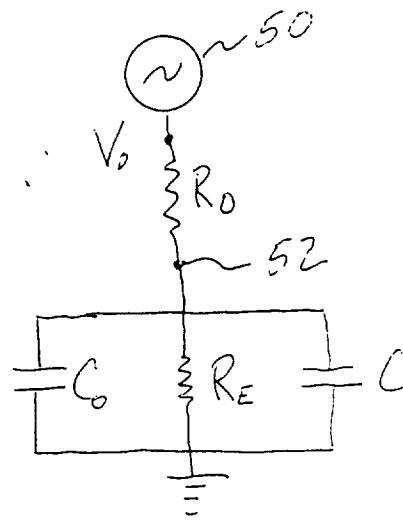


FIG. 4

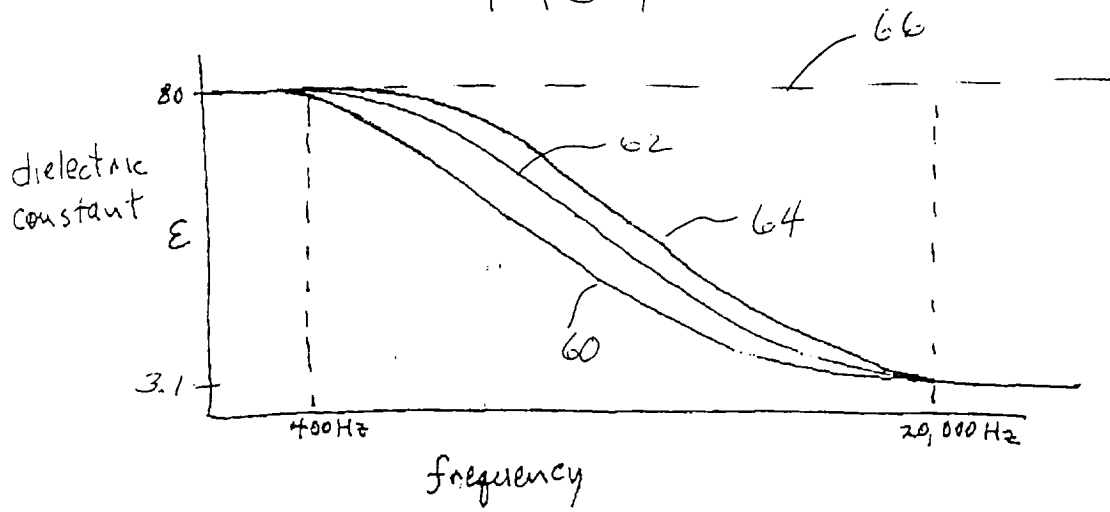


FIG. 5

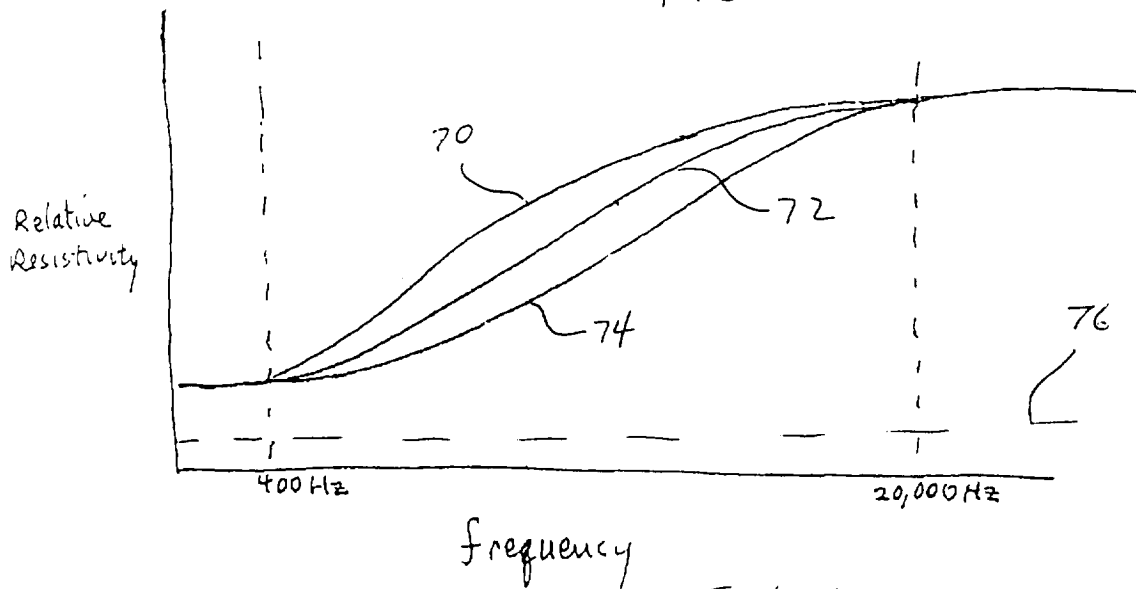


FIG. 6