Application Note

Measuring Thickness of Dielectric Materials using MTI Instruments Accumeasure Capacitance Sensors

Introduction

Although the MTI Instruments Accumeasure™ capacitance based instrumentation is designed primarily to make noncontact measurements of position, displacement, vibration, or runout, it can also be used to make noncontact thickness measurements of dielectric1 materials. If the thickness is known or can be independently measured, the Accumeasure System can also be used to measure the dielectric constant of insulating materials.

Operation

The Accumeasure System uses a constant current signal source at either 16kHz (Accumeasure 500 & 1500) or 100kHz (Accumeasure 5000) carrier frequency. The transducer (probe) is a passive element, in that it contains no active electronic circuitry. All of the active circuitry is contained within the Accumeasure electronic amplifier and supplied to the probe through low noise coaxial cable. The Accumeasure constant current amplifier circuitry supplies the control voltage required to keep the sensing current at a constant level over the rated displacement sensing range of the probe and amplifier combination. A high precision buffer amplifier is used to electrically drive the coaxial cable shield and the coaxial capacitance probe structure at the same amplitude and phase as the sensing signal. This effectively cancels all stray capacitances and permits the amplifier to respond only to the capacitance between the face of the sensor probe and the target surface. This results in the Accumeasure amplifier having a linear response to either gap changes, or dielectric material thickness changes.

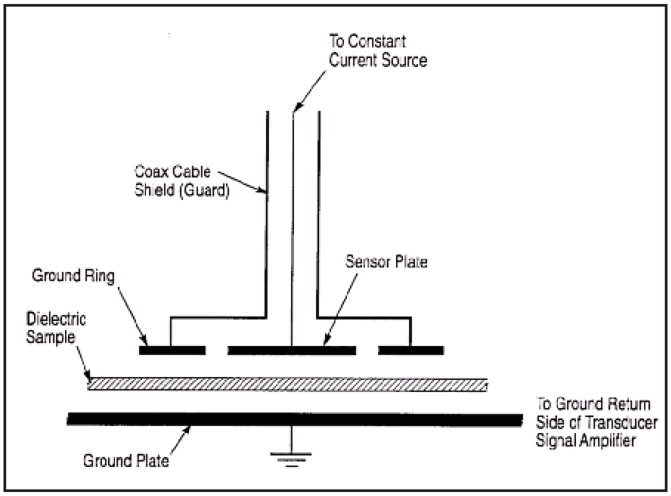

Figure 1

The Accumeasure equipment operates as a classic parallel plate capacitor system with the face of the probe being one of the plates, and the target or surface being measured as the other plate. As shown in Figure 1, a ground return path must be provided from the target back to the low side of the Accumeasure amplifier in order to complete the current path. In many practical situations or applications, the target is already at ground potential and the ground return path is automatically provided through the power line grounding and the grounded power cords, but it is usually best to attach a grounding wire directly from the target to the ground return connector on the Accumeasure amplifier. When measuring thickness of dielectric materials, a fixed gap is established between the probe face and the grounded return plate. The dielectric material to be measured is placed in the fixed gap, or placed in contact with the surface of the ground return plate. If the material to be measured is moving, it may be passed through the gap without contact. The MTI Instruments KD-CH-IIID, a precision calibration micrometer fixture

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Principle

The Accumeasure System operates on the basic principle that $C_p = K(A/D)$ where C_p = the capacitance formed between the face of the capacitance probe sensing element and the target surface; K =the dielectric constant of the air, plus other physical constants; A = the area of the sensing electrode at the face of the probe, and, D = the distance between the sensing electrode and the target surface. A more complete description of the Accumeasure operation and circuitry can be obtained by referring to the Users Manual for the Accumeasure amplifier in use.

Since the Accumeasure operates as a constant current supply, then:

$V_o \alpha (I/C_p)$ where V_o = amplifier output voltage
$C_p \alpha (1/D)$
then V_o D

A block diagram of the Accumeasure circuitry and sensing technique is shown in Figure 2. An active guarding current is used to cancel the coaxial cable capacitance and to prevent divergence of the electric field at the probe face.

If an insulating material having a dielectric constant greater than air (1.0) is inserted into the sensing gap, then the capacitance C_p will be changed even if the gap between the probe face and the ground plane remain constant. This effect can be used to measure the thickness of a test sample.

If the dielectric constant K of the test material is known, then the thickness can be measured using the following procedure:

Since $C_p = K(A/D)$, if A and D remain constant, then $C_p \alpha K$. Also, since $V_o \alpha (1/C_p)$, then $V_o \alpha 1/K$. This effect can be seen in Figure 3, which shows the output voltage versus gap (or D) when the gap is completely filled with air, having a dielectric constant of 1.0, or completely filled with some other nonconducting material such as oil or plastic having dielectric constant greater than 1.0.

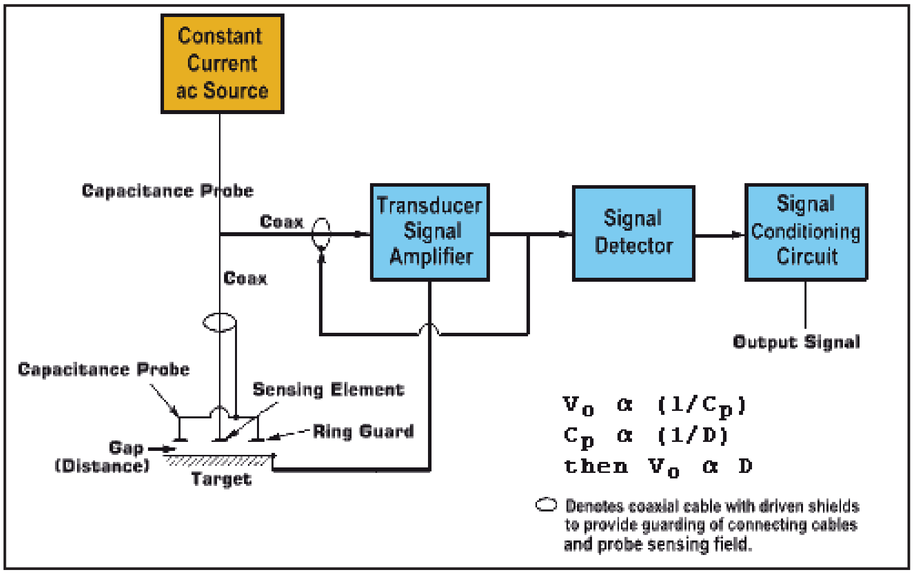


Figure 2

Method A

When dielectric constant of material to be measured is known:

If an Accumeasure amplifier and capacitance probe are set up at any air gap within the operating range of the system, the Thickness Sensitivity Factor for a material having a particular dielectric constant can be calculated as follows:

$$\text{Thickness Sensitivity Factor} = \frac{\text{Operating gap}}{V_o\text{Air} - (V_o\text{Air} \div K)}$$

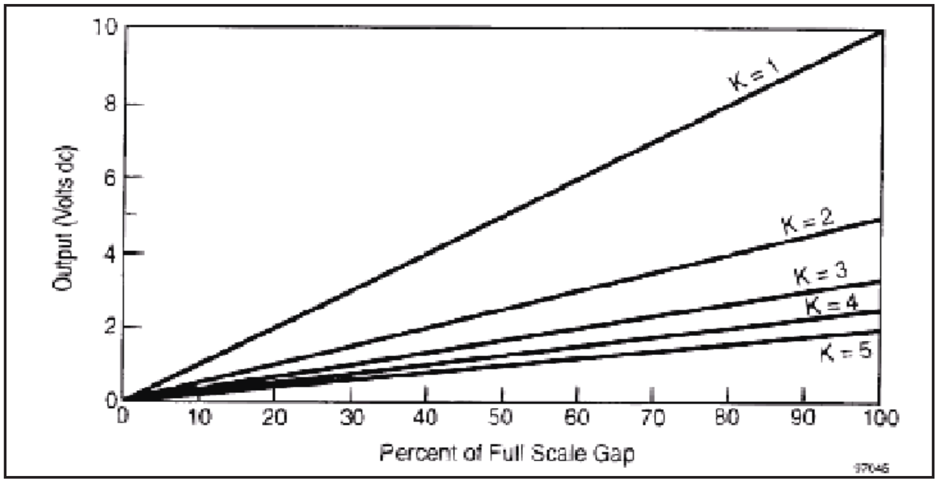
Example A1:

If the fixed operating gap is 0.020” and the V_o(AIR) is 10.00 volts, and the dielectric constant K of the material to be measured is known to be 3.00, then:

$$\text{Calculated Thickness Sensitivity Factor} = \frac{0.020''}{10.00 - (10.00 \div 3.00)} = 0.003'' / \text{Volt}$$

Therefore, if a test sample of the same dielectric constant of 3.00 but having an unknown thickness were to be introduced into the same gap, the thickness could be calculated as follows:

Figure 3



Test sample thickness = Thickness Sensitivity Factor x (Vo Air - Vo Sample)If the output voltage with the test sample in place reads, for example, 6.50 volts, then:

Test sample thickness = 0.003” / Volts x (10.00 - 6.50) = 0.01050”

Example A2:

If the operating gap was 0.008”, the V_o AIR was 9.00 volts, and the dielectric constant K was known to be 2.30, then the Sensitivity Factor could be calculated as follows:

$$\text{Sensitivity Factor} = \frac{0.008''}{9.00 - (9.00 \div 2.30)} = 0.00157'' / \text{Volt}$$

If a test sample of the same dielectric constant of 2.30, but having an unknown thickness were introduced into the same 0.008” operating gap, and the voltage then dropped to 7.30 volts, then:

Sample thickness = 0.00157” / Volt x (9.00-7.30) = 0.00267”If the dielectric constant of the material to be measured is unknown, or cannot be determined by contacting the manufacturer or referring to handbook references, then there are two methods to measure it using the Accumeasure equipment.

Method B

When the dielectric constant is unknown, but a sample of known thickness is available or can be measured by independent means:

Insert the sample into the operating gap and measure the change in the output voltage. The sensitivity factor can then be calculated as follows:

$$\text{Sensitivity Factor} = \frac{\text{Sample Thickness, in inches}}{(10.00 - 7.63)} = 0.0021'' / \text{Volt}$$

The thickness of additional pieces of continuous strips of the same material can now be measured without contact by multiplying the sensitivity factor by the change in the output voltage due to the presence of the material being measured. If the change in voltage was 3.1, then the thickness would be: (0.0021”/ VOLTS) X 3.1 VOLTS = 0.0065” thickness.

Method C

When the dielectric constant is unknown and a sample of known thickness is unavailable

If the dielectric constant is unknown or uncertain, then it can be measured with the Accumeasure equipment by placing a sample of the material in the operating gap and then adjusting the gap until the test material completely fills the gap. A reading of the output voltage is taken and the material carefully removed without changing the gap setting. The reading of the output voltage is now taken without the material in the same gap. The dielectric constant can be calculated as follows:

K= V_o AIR V_o SampleAfter the dielectric constant is established, then Method A can be used to measure additional samples of the same material.

Some thin film dielectric materials may be slightly conductive or may be coated on one or both sides with very thin films of conductive material. If this is the case, then care should be taken before using the Accumeasure System to measure thickness or dielectric constant to insure that the results are valid. This can be done by placing the test material in the operating gap and then moving it so that it alternately touches the probe face and the ground return reference plate while noting the change in output signal. Another check that can be made is to reverse the test material sides within the operating gap and noting the change in output voltage. In either case, if the output voltage changes more than about ±10 millivolts, the material may have some bulk conductivity or thin film plating on one or both sides.

The output voltage variations, due to positional changes or reversals of the test material within the operating gap, can then be multiplied by the Sensitivity Factor to determine the uncertainty or possible error in the thickness reading. If the dielectric is coated on one side only, then the coated side should be placed in contact with the grounded reference plate to obtain proper thickness measurements.

Dielectric Materials

1. Dielectric materials are those materials which behave more like insulators than conductors.

They are classified as having very few electrons available for conduction in contrast to metals which have an abundance of free electrons which can travel over large distances inside the metal. Inserting a dielectric material between two capacitor plates has the effect of increasing the capacitance between the two plates.

The following is a list of the dielectric constant of some common gases:

Material	Temperature °C	Frequency (Hz)	Dielectric Constant
Air	0	$< 3 \times 10^4$	1.000590
Helium	140	$< 3 \times 10^4$	1.000684
Nitrogen			1.000580
Oxygen	100	$< 3 \times 10^4$	1.000523
Vacuum (free space)			1.000000

The following is a list of dielectric constant for some common plastics, rubber, glasses and liquids:

Material	Temperature °C	Frequency (Hz)	Dielectric Constant
Polyamide	25	1×10^6	3.3
Polyethylene	-12	1×10^6	2.3
Polyvinyl Chloride	25	1×10^6	3.3
Polyesters	25	1×10^6	3.1 to 4.0
Epoxy Resins	25	1×10^6	3.5
Neoprene	25	1×10^6	6.2
Silicone Rubber	25	1×10^6	3.1
Alumina			4.5 to 8.4
Silica Glass (clear)			3.8
Water			80
Motor Oil (SAE 30)			2.5 to 3.0

*The dielectric constant and the conductivity of water is very dependent on the mineral content and impurities. It is not recommended as a gap medium for use with capacitance probes.

Conclusion

1. Most gases have a dielectric constant very close to 1.000 and therefore have little effect on the output signal of a capacitance probe when operated as a displacement sensor relative to a conductive target.

2. Most plastics, glasses, and oils have dielectric constants in the order of 2 to 5 times higher than air and are therefore good candidates for capacitance based thickness measurements, or for use in the operating gap of capacitance displacement sensors, but the exact dielectric factor must be known or measured if accurate thickness or displacement information is required.

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