CAPACITIVE PROBE ARRAY MEASUREMENTS AND LIMITATIONS

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INTRODUCTION

This paper reviews the use of electrostatic capacitive probes for detections and evaluations of dielectric material properties and flaws. Interest in using both inductive and capacitive arrays for proximity sensing, surface feature characterization, material properties evaluation, and flaw detecting has increased steadily since the mid-1980's [1-7]. Two other papers [6,7] in this proceedings also discuss the present state of the art, particularly with regard to the measurement of lossy dielectrics (complex permittivity). In traditional dielectrometry measurements (as well as in eddy-current measurements of material properties evaluation) varying the probe frequency has long been used as a tool for extracting information about dispersion and loss mechanisms. Use of a spatially periodic array probe interrogates the material, or flaw, with a field that penetrates into the sample to a degree determined by the periodicity. This controllable penetration phenomenon (artificial-skin effect or zoom effect) has been successfully exploited by Melcher, Zaretsky [5], and Goldfine [6] in what they call imposed w-k magnetometry and dielectrometry, using interdigital probes of different periodicities. Details are given in these proceedings. Gammell's paper [7] gives a progress report on complex permittivity measure-ments using probes of more conventional type.

Our paper focuses on the design and operation of capacitive probes for manufacturing process control. Attention is focused on process and quality control in the production of ceramics. As in all manufacturing, the reject

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cost rises steadily through the sequence of process steps: green-state material preparation, rolling, stamping, firing, polishing, and plating. Since prior processing errors cannot be corrected after firing, it is imperative to ensure that the initial green-state preparation be carefully controlled, on-line, before proceeding. A second monitoring should be performed after firing and before the final polishing, cladding, and plating steps. The purpose of this second control procedure is to ensure that the dielectric constant ϵ (where $\epsilon = \epsilon_0 \epsilon_r$, ϵ_0 is the permitivity of free space, ϵ_r is the relative permitivity of the material) which changes with firing and porosity is within specifications, as well as to detect cracks, inclusions, and other flaws.

A capacitive probe designed for evaluating the green-state ceramic material by measuring ϵ is shown in Figure 1. This probe consists of a four-electrode array connected in the bridge circuit shown in the insert. It is designed to give a change in output when placed near a dielectric material. In this arrangement, the probe output is sensitive to the liftoff distance between the dielectric and the probe, just as in the case of an absolute eddy-current probe.

Figure 2 illustrates a probe designed for post-firing process inspection, intended to reject samples for inhomogeneities in ϵ and density, cracks, and inclusions. As in eddy-current practice, this is a differential probe, designed to minimize the effect of liftoff while enhancing and localizing the response to internal inhomogeneities of the material. It uses a through-transmission geometry for optimum sensitivity to deeply buried defects.

PROBE-MATERIAL INTERACTIONS

Figure 3 illustrates schematically the two probe configurations introduced above, where the sensor capacitor electrodes (bold) of the absolute probe are all placed on one face of the ceramic sample, as shown in Fig. 1. The probe's

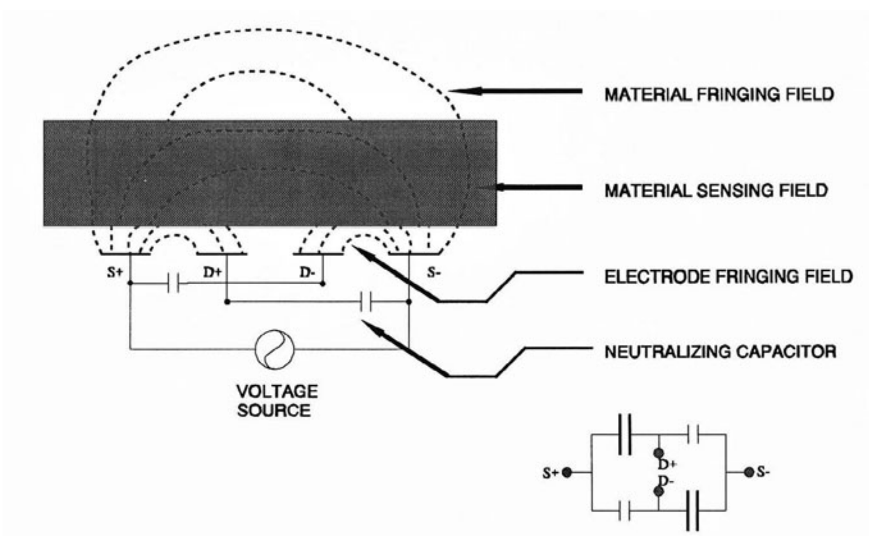

Figure 1. One-sided absolute capacitive bridge probe.

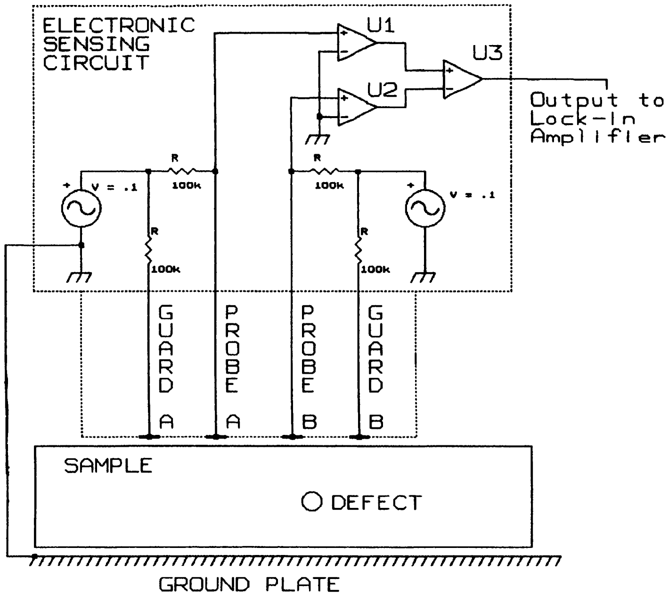

Figure 2. Feed-through differential capacitive probe.

performance can be evaluated by first evaluating the changes in the sensor capacitors due to the introduction of dielectric material, and then calculating the probe output signal from circuit theory. Changes in the sensor capacitances may be obtained: (1) exactly by the finite-element method, or (2) approximately by reciprocity theorem analysis [2]. The second approach provides valuable physical insight into the influence of various parameters and the effects of changing probe and defect geometries.

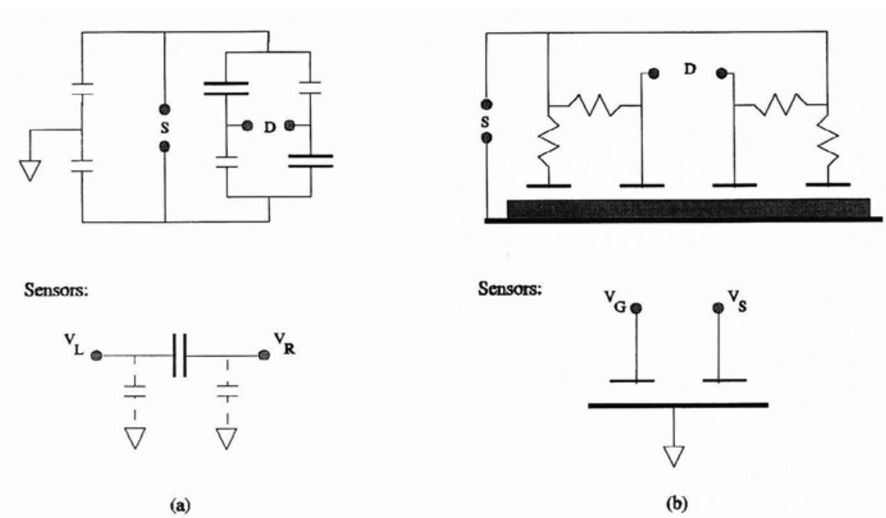

Figure 3. Equivalent circuit modeling: (a) one-sided absolute probe and (b) feed-through differential probe.

In the lower part of Figure 3a, the sensor depicted for the absolute probe represents each of the bold capacitors in the bridge circuit. For the differential probe, the sensor depicted in Figure 3b is a guard/signal electrode pair as shown in either the left or right arms of the full schematic. We can show from the ΔY theorem [2], that the change in sensor capacitance ΔC for the absolute probe placed over a sample of dielectric permittivity ϵ is

$$\Delta C = \varepsilon_0 \int_{sample} (\varepsilon_r' - \varepsilon_r)\, E_R \cdot E_L dv, \ \Delta\varepsilon < \varepsilon \tag{1}$$

with the R subscript denoting the probe field E_R with unit voltage on the R electrode and zero voltage on the L electrode, while the L subscript corresponds to reversed voltages (Figure 3). Where $\Delta\epsilon = \epsilon_r' - \epsilon_r$, ϵ_r' is the perturbed episilon, and the r subscript denotes relative. For the differential probe over a crack, the change in sensor capacitance is [2]

$$\Delta C = \varepsilon_0 (\varepsilon_r' - \varepsilon_r)\, E \cdot M \cdot E\, V_{crack} \tag{2}$$

with the electric field E evaluated in an unflawed sample at the position of the crack when unit voltage is applied to the signal electrode (S) and zero voltage to the guard electrode (G). The crack is modeled as a flat ellipsoidal void in the dielectric. In Equation (2), the quantity M is a matrix relating the vector electric field inside the ellipsoid to the vector electric field applied externally. In a coordinate system aligned with the principle axes of the ellipsoid M is a diagonal matrix. For the coordinate directions in the plane of the void, M is approximately unity. This shows that the interrogating electric field should be applied in the plane of the crack for optimum sensitivity. In this direction, the electric field lines are forced to traverse the void in its long direction, so that the presence of the void introduces maximum change in the overall capacitance. Equation (2) also shows that the capacitance change due to a crack is proportional to the square of the electric field interrogating the crack. From the above discussion, it may be concluded that a capacitive probe designed for crack detection should generate a maximum electric field at the position of the target crack and directed in the plane of the crack. It should be emphasized that the crack detection model, Equation (2), is implicitly based on the assumption that the crack is small, so that the interrogating field is essentially uniform over the region of the crack.

From Equation (2), the crack signal is proportional to the square of the electric interrogating field produced by unit voltage applied to the electrodes. It is therefore clear that the sensitivity can be improved by decreasing the inter-electrode spacing, or in Figure 2 by decreasing the thickness of the test sample. These scaling changes can also be seen from the figures to increase the liftoff effect. For crack detection both probe types are operated in the differential mode, where liftoff signals are canceled by the circuit connections. In practice, differential circuit connections are never completely balanced and a residual liftoff signal always remains. A significant part of this residual is due to tilting of the electrode array relative to the surface.

In eddy-current probes, circuit noise is completely dominated by liftoff noise, or clutter, as the probe is scanned over the sample. We anticipate that the same situation will prevail with respect to capacitive probes. Estimation of minimum detectable crack size, therefore, requires a comparison of the maximum value of ΔC for the crack with the value of ΔC for liftoff. To completely evaluate capacitive probes for detecting cracks in dielectrics requires detailed numerical modeling of both crack and liftoff signals, as well as systematic measurements of these signals. Simple analytic models can provide order-of-magnitude estimates and guidelines for such an evaluation program.

MATERIAL CHARACTERIZATION AND FLAW DETECTION

Using the one-sided absolute probe of Figure 1, a series of permittivity measurements were made on production green state ceramic, compressed into samples and tested at NIST. Sample thicknesses were typically in the range of 0.025 to 1.53 mm. The composite curve shown in Figure 4 plots measured density versus predicted density for the complete set, corrected for different thicknesses. Inset is the fitted density calibration formula (error $\leq 0.2\%$). Future probe improvements required for test automation include monitoring of liftoff and evaluation of sample thickness using multidimensional scalings of the probe structure to vary the field penetration into the sample (Figure 1).

To test the flaw detection capabilities of the feed-through differential probe in Figure 2, a set of artificial "penny-shaped" voids was machined in PMMA. These voids were in the form of disks or rectangular parallel pipes with vertical and horizontal orientations, five different geometries in all. The flaws were all machined into one face of a thick PMMA block. By stacking this block in various combinations with an unflawed block (thick layer on top or bottom, flaw down or flaw up) various flaw depths could be tested (Figure 2). Figures 5 and 6 show measured results for a horizontal disk-shaped void.

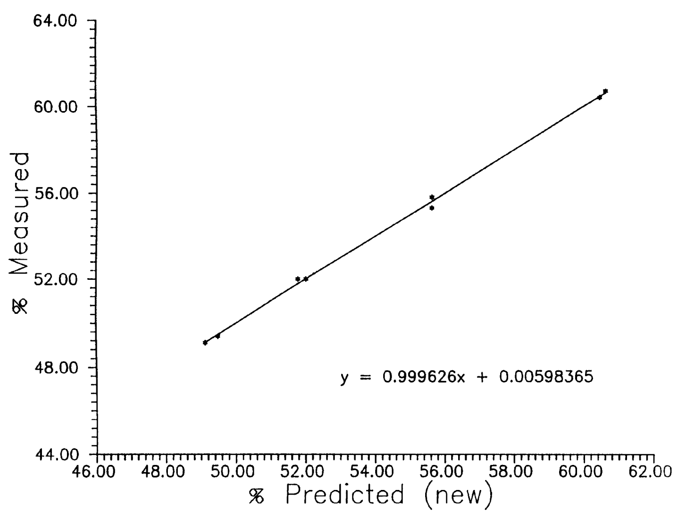

Figure 4. Density calibration curve for ceramic green-state compaction measurements with the one-sided absolute probe (Figure 1).

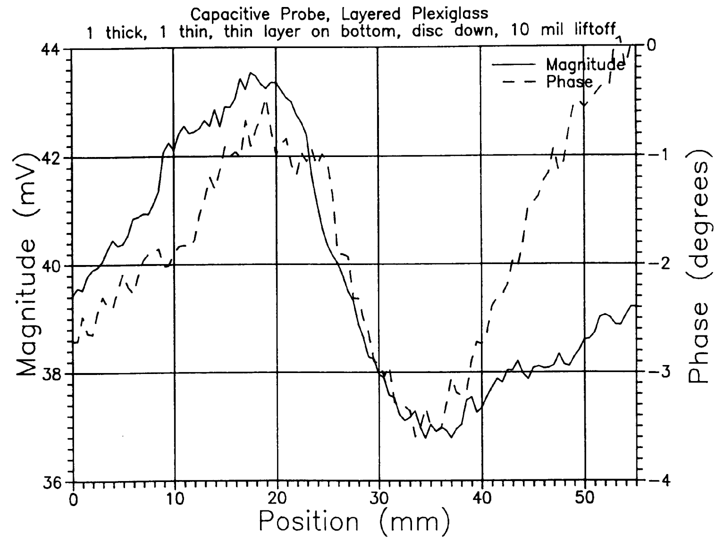

Figure 5. Surface scan of a horizontal penny-shaped void (6.35 mm radius by 1.02 mm thickness in acrylic plastic (PMMA) at 0.00 mm depth and 0.25 mm liftoff with the feed-through differential probe, Figure 3).

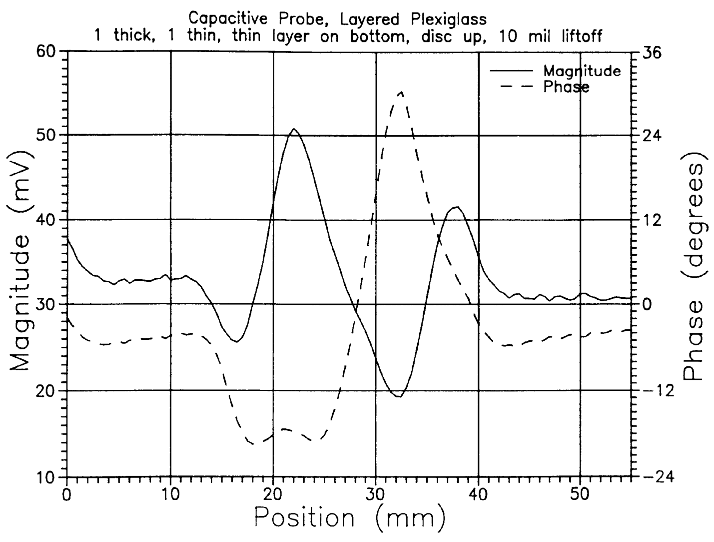

Figure 6. Surface scan of the same defect at 12.7 mm depth and 0.25 mm liftoff with the same probe as used in Figure 5.

The signal from the deeper flaw (Figure 6) is substantially smaller than that of an identical surface flaw (Figure 5). Since the flaw is horizontal the increased detection sensitivity at the surface is plausible on the basis of the discussion regarding Equation (2). The small-flaw condition assumed in deriving Equation (2) is not well satisfied in the experiment. Since the PMMA material has a very small loss tangent at the test frequency (100 kHz), the phase angle changes in Figures 5 and 6 are the result circuit phase shifts created by purely capacitive changes in the sensors (Figure 3).

According to Equation (2), the capacitive change due to a void is proportional to the volume of the void. The flaw measured in Figure 6 had a volume of 12.9 mm^3 and gave a peak-to-peak signal of 6.75 mV. A typical crack in a ceramic has a volume of approximately 1 mm^3 and should produce a (scaled) signal of 0.523 mv. An estimated circuit noise RMS voltage of 7 μV predicts a voltage S/N ratio of approximately 100. The observed clutter in Figure 6 has peaks of about 2 mV, sufficient to mask the signal from the typical 1 mm^3 flaw cited above. This clutter is judged to be due to liftoff variations during scanning, material variations and various types of electromagnetic interference. As in eddy current practice, the clutter signal is many times the voltage of the signals from flaws that are to be detected. Successful implementation of capacitive probe crack detection will require a better understanding of the sources of the scan clutter and a search for effective electronic discrimination measures.

ADVANTAGES AND LIMITATIONS

Capacitive probes have the capability of detecting density variations, porosity, inclusions and cracks in insulating materials. By varying the probe geometry material properties can be separated from sample thickness and liftoff height. In low-loss insulating materials there is no natural skin depth. The depth of penetration can be controlled by the probe geometry. Fabrication is simpler and more precise than in the case of eddy-current probes.

By contrast with eddy-current probes, capacitive probes respond to the open volume of a crack and cannot detect tight cracks. In materials with small permittivity the detection sensitivity is reduced. In materials with large permittivity the field penetration tends to decrease. For small liftoff and relative permittivity up to 10, the effect is negligible. There is no phase discrimination against liftoff noise. Some other method, such as liftoff sensing by a fine-scale periodic array, must be implemented in order to achieve ultimate detection sensitivity.

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