EXPERIMENTAL TECHNIQUES IN MICROWAVE NDE

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INTRODUCTION

The objectives of this paper are to provide a historical perspective of microwave NDE and to review the associated experimental techniques by discussing them in the context of specific applications. The application examples are drawn from the published literature and the author's own experience. The applications discussed include measurements of layer thicknesses and material parameters, detection and quantification of internal flaws inside dielectric objects, detection and quantification of surface flaws on conductors, and imaging of flaws inside material media. The discussion will seek to clarify the potential advantages and disadvantages of various microwave NDE techniques.

DEFINITION AND CHARACTERISTICS OF MICROWAVE NDE

Microwave NDE may be defined as the inspection of materials and structures using high-frequency electromagnetic energy. The microwave frequency region, although not rigidly defined, is generally taken to lie between a few hundred megahertz and a few hundred gigahertz. The corresponding wavelengths in free space lie between 100 cm and 1 mm. The wavelength is usually chosen to maximize interaction of the electromagnetic energy with dielectric layers, voids, inclusions, surface flaws, material variations, and molecules such as water. An important feature of this type of electromagnetic inspection is that the transducer (antenna) need not be in contact with the object being inspected, thus permitting inspection of hard-to-reach areas or moving parts. However, only dielectric objects can be inspected internally; inspection of conducting objects is limited to their surfaces.

Microwave inspection generally consists of measuring the waves scattered by, or transmitted through, an object. In the case of monostatic (co-located source and receiver) reflection, one can also think of the measurement as being one of changes in transducer impedance. Specific characteristics of microwave measurements worth noting are: (1) incident and reflected waves are readily separated, (2) electrical phase varies rapidly with distance or frequency, (3) wave polarization can have a strong influence on interaction with a flaw, (4) the angular distribution of the scattering can contain useful information, and (5) broad-bandwidth measurements are often possible. Spatial resolution along the direction of a scan is either determined by the wavelength for far-field inspection, or by the dimensions of the transducer for near-field inspection. The spatial resolution normal to the scan direction is determined by the bandwidth of the measurement.
Since microwave wavelengths are relatively small, the circuits used for signal transmission and analog processing tend to be distributed (in space) rather than lumped. In particular, hollow waveguides, coaxial lines, and printed microstrip lines are common. Also, like optical or ultrasonic waves, microwaves can be formed into beams and propagated between transducers. The transducers in this case are antennas, and their size is dictated by whether or not they are required to radiate efficiently. Efficient radiators have a size on the order of a wavelength, while antennas used for close-proximity inspection can be smaller. In the latter case, microwave and eddy-current inspection are very similar, except that eddy-current instruments operate at much lower frequencies.

EVOLUTION OF MICROWAVE NDE

One of the earliest examples of microwave NDE was discussed in a 1948 patent by C. L. Liskow, wherein he describes a microwave technique for inspecting dielectric materials for moisture content [1]. This has been an important application of microwave NDE up through the present time because of the large changes in microwave dielectric constant produced by the presence of water molecules in a material. The application of microwaves to NDE developed slowly, but a number of papers began to appear in the 1960s whose titles linked the words “microwave” and “nondestructive testing” [2-3]. The applications discussed in these papers were primarily related to missile development and manufacturing. Applications during this period tended to be very specialized and limited, mainly because of inflexibility in the microwave instrumentation of the day and the need for specialized skills to design and operate a microwave NDE system. As we will discuss, modern microwave instrumentation has partly alleviated this situation.

A partial list of microwave NDE applications examined during the 1960s and early '70s would include the following: testing for delaminations in rocket casings, detecting defects in rocket propellants, measuring the burn rate of solid-propellant rocket motors, measuring the thicknesses of ablative shields for reentry vehicles, detecting voids in honeycombed ablative materials, detecting inclusions and porosity in ceramics and molded rubber, detecting surface cracks in artillery shells, measuring epoxy-resin cure rates, measuring moisture content in dielectric materials, and measuring density variations in lumber. As mentioned above, most of these applications were in aerospace.

The modern era in microwave NDE was ushered in by the development of the microwave network analyzer in the early 1970s. This instrument provides the flexibility required for testing the use of microwave NDE in particular applications. In particular, it incorporates microprocessors that permit calibration and customization for each application, and which make it easy to use. Another important instrumentation advance that occurred at this time was the development of stable, high-resolution, microwave-frequency synthesizers. These sources exhibit high spectral purity (which is important, for example, when it is necessary to maintain a background null) and are readily controlled by a separate computer. Finally, microwave signal-processing devices such as hybrid couplers, amplifiers, etc., have become smaller and cheaper due to advances in microwave integrated-circuit technology.

Microwave network analyzers are available in two types: scalar and vector. The scalar network analyzer measures reflected or transmitted amplitude ratios, and thus replaces the old-fashioned reflectometer. The vector network analyzer measures complex two-port scattering parameters, and thus measures both the amplitude and phase of scattered and transmitted waves. Phase data are essential when a vector subtraction between two measurements is required to increase dynamic range. These instruments are available for a wide range of frequencies (45 to 110 GHz), are very accurate and stable, and have a digital
interface built in to facilitate external control and data acquisition. Prices range from tens to hundreds of thousands of dollars, with the scalar instrument being the least expensive.

TYPICAL MICROWAVE TRANSDUCERS

Typical far-field transducers (antennas) are sketched in Figure 1. Of course, any kind of antenna could be used. However, if it is important to achieve a small beam size in the far field, an antenna array (real or synthetic) or lens would be used. One of the examples in this paper illustrates the use of a plastic lens at millimeter wavelengths. Similarly, some near-field transducers (probes) are sketched in Figure 2. For this type, interaction takes place with the quasi-static fields that fringe away from the end of the probe. Since these fringing fields die away rapidly, the probe must be scanned in close proximity with the work piece.

Note that the microstrip slot and loop shown in Figure 2 are actually resonant probes, where the resonator is formed by a length of microstrip line coupled to the feed line by a gap. The use of resonance enhances the sensitivity of the probe, but narrows its bandwidth. Additional examples of resonant transducers are depicted in Figure 3 [4-6]. Note that three of these examples are so-called “open” resonators that permit easy interaction with the material under test.

MEASUREMENT ISSUES

Measurement issues in microwave NDE are similar to those which are important in other types of NDE. One always needs the highest signal-to-noise ratio possible. To achieve this, one maximizes the field strengths incident on the work piece (for example, by maximizing the efficiency of the transmit antenna) and the signals that are received (for example, by choosing the operating frequency so that flaw scattering is maximized). Also, as in eddy current testing, it is often required in microwave NDE to suppress a strong coherent background signal so that a much smaller flaw signal can be detected.

Background suppression is, in fact, a major measurement issue in microwave NDE much of the time. The main sources of unwanted background signals are (1) transmit-receive coupling, (2) multipath scattering, (3) other electromagnetic sources in the vicinity (EMI), and (4) drift in the background-suppression electronics. Transmit-receive coupling can be reduced by using directional couplers or circulators, shielding between the antennas, or orthogonally polarized antennas. Multipath scattering can be reduced by pulsing and time gating, spatial filtering, or electronic background subtraction. EMI is basically controlled by frequency filtering unless the interfering frequency is too close to the operating frequency. Finally, background drift is minimized by using very stable frequency sources, controlling the temperature of the environment, using phase-stable cables, and controlling the lift-off between the sensing probe and the work piece.

EXPERIMENTAL EXAMPLES

An example of a microwave NDE system [7] is the 100-GHz cross-polarized reflectometer shown schematically in Figure 4. This a homodyne system that measures both amplitude and phase of the scattered field. The lens-focused horn achieved a spot size on the flat work piece of about 3 mm. The background reflection was reduced 50 dB by using a tuned orthomode coupler to suppress the orthogonally polarized reflected wave. However, using this type of polarization filtering makes the system sensitive to crack orientation and work-piece alignment. Because this system produces both in-phase (I) and quadrature (Q)
Figure 1 Far-field microwave transducers.

Figure 2 Near-field microwave transducers.
Figure 3 Resonant transducers.

Figure 4 100-GHz cross-polarized reflectometer.
signals, the response of a linear flaw appears much like that produced by a conventional eddy current system, except that this system operates in the far field at 100 GHz. This flaw response is illustrated in Figure 5 for a series of six electro-discharge machined (EDM) slots. The top photograph shows the responses of the 2.54-mm-long slots, while the bottom photograph shows the responses of slots half as long. These two sets of responses have quite different characters: the longer slots are “cut on” and energy can propagate into the slot, while, in the case of the shorter slots, energy cannot propagate into the slot and the slot response is 90 degrees out of phase with the reflection from the surrounding surface (which facilitates lift-off discrimination). Thus, for the longer slots both the amplitude and the phase of the scattering contain information about the depth of the slot, whereas for the shorter slots only the amplitude is affected by the depth.

This same system was used to generate a microwave cross-polarized C scan of several different types of inclusions in a silicon nitride plate. The result is shown in Figure 6. This display is a contour plot obtained by setting the threshold slightly above the background clutter. Since the front-surface reflection from this plate is large (ε = 7), this measurement requires a large amount of background suppression and is limited by the capability of the polarization filter. The strongest signals were obtained from the iron inclusions, while those from carbon were the weakest. It is interesting to note that some of the inclusions generate a characteristic cloverleaf pattern. This is indicative of quadrupolar-mode scattering from a spherical inclusion.

![Figure 5 100-GHz responses of EDM slots.](image)
A 1-GHz eddy-current system that used a differential probe composed of two microstrip-loop probes (Figure 2) has also been built and tested on EDM slots and fatigue cracks [7]. Compared with a 100-kHz commercial eddy-current probe, the microwave system was 45 dB more sensitive to EDM slots in titanium. However, the microwave system was less sensitive to closed fatigue cracks. We attribute this result to the short-circuiting of the crack by displacement currents at high frequencies. The microwave probe was also more sensitive to lift-off because its active area was smaller than that of the commercial probe.

RECENT APPLICATIONS AND FUTURE TRENDS

Some recent applications of microwave NDE have involved an interesting combination of microwave sensing and laser excitation. The photoconductivity lifetime in semiconductors [8] and photothermal images of magnetic structures in recording tapes [9] have both been realized in this way. Other recent applications have involved corrosion detection [4], level sensing of molten metals [10], thickness and variation measurement in lossy dielectric slabs [11], and thickness measurement of very thin coatings [12].

Spurred by better instrumentation, the current trend in microwave NDE is definitely toward the use of millimeter-wave frequencies, particularly for imaging. Other trends (common to most NDE) are the increased use of sensor fusion, adaptive sensors, and digital signal processing.
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REFERENCES

12. M. T. Lusk, personal communication.