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Microwave Non-Destructive Testing of Coatings and Paints Using Free Space Microwave Measurement

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ABSTRACT

Microwave nondestructive testing (MNDT) techniques are applied to evaluate quality of anti-corrosive protective coatings and paints on metal surfaces. A tree-space microwave measurement (FSMM) system is used for MNDT of protective coatings. The FSMM system consists of transmit and receive spot-focusing horn lens antennas, a vector network analyzer, mode transitions and a computer. Diffraction effects at the edges of the sample are minimized by using spot-focusing horn lens antennas. Errors due to multiple reflections between antennas are corrected by using free-space LRL (line, reflect, line) calibration technique. We have measured complex reflection coefficient of polyurethane based paint which is coated on brass plates.

Introduction

Microwave nondestructive testing (MNDT) of materials is an important science which involve development of sensors/probes, methods and calibration techniques for detection of flaws, cracks, defects, voids, inhomogeinities, moisture content (MC), etc. by means of microwaves [1]. They are increasing being used for quality control and condition assessment of concrete structures [2, 3]. Recently, a MNDT technique

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has been used for the measurement of slope-of-grain of timber for grading applications [4].

Since the penetration of microwaves in good conducting materials is very small, MNDT techniques are mainly used for nonmetallic materials. The spatial resolution of these techniques depends \on the wavelength of the electromagnetic wave. For the microwave band of 3-100 GHz, wavelength varies from 100 mm to 3 mm. These techniques have advantages over other NDT methods (such as radiography, ultrasonics and eddy current) regarding low cost, good penetration in nonmetallic materials, good resolution and contactless feature of the microwave sensor (antenna).

For MNDT techniques, the measured parameters are reflection coefficients, transmission coefficients, dielectric constants, loss factors, and complex permeabilities as a function of frequency (microwaves) and temperature. These measured parameters can be related to material parameters of interest (*e.g.*, flaws, inhomogeinities, moisture content, etc.) by suitable modeling and calibration. There are two classes of MNDT methods which are (1) free-space methods operating in the farfield region employing spot-focusing horn lens antennas and (2) waveguide methods operating in the near-field region which employ open-ended coaxial lines, rectangular waveguides, microstrip lines and cavity resonators as probes.

However, in the waveguide methods, it is necessary for the composite material to be in close contact with the probe. So, these methods are not contactless. In this paper, free-space methods are used which are nondestructive as well as contactless.

The free-space microwave measurement (FSMM) system consists of a pair of spot-focusing horn lens antennas which are connected to a vector network analyzer Wiltron 37269B via coaxial cables and spot focusing horn lens antennas. The inaccuracies in free-space measurements are due to two main sources of errors.

1. Diffraction effects at the edges of the sample.
2. Multiple reflection between horn lens antennas and mode transitions via the surface of the sample.

The diffraction effects are minimized by using spot focusing horn lens antennas as transmit and receive antennas. The effect of multiple reflections is eliminated by implementing free-space LRL (Line, Reflect, Line) calibration method.

Previously, microwave radiations (8 - 12 GHz and 53 - 78 GHz ranges) were used for diagnosis of protective coatings [5]. In this paper, it was suggested that MNDT can be used for measurement of defects, thickness and structure of protective coatings. Protective coating non-uniformities and pipe corrosion were detected by using microwaves in the wavelength range of 5 - 8 mm for oil and gas pipelines [6]. MNDT technique used in this paper consists of complex reflection coefficient measurements of brass plates coated with a polyurethane based paint using FSMM system in 8 - 12 GHz frequency range.

Measurement System

Figure 1 gives a schematic diagram of the free-space microwave measurement system. A pair of spot focusing horn lens antennas have been mounted on a large table (1.83 m × 1.83 m) of 2.54 cm thick wood. These antennas (model no. 857012X-950/C) were manufactured by Alpha Industries, Woburn, MA (USA). These antennas have two-equal plano-convex lenses mounted back to back in a conical horn antenna. One plano-convex lens gives an electromagnetic plane wave and the other plano-convex lens focuses the electromagnetic radiation at the focus.

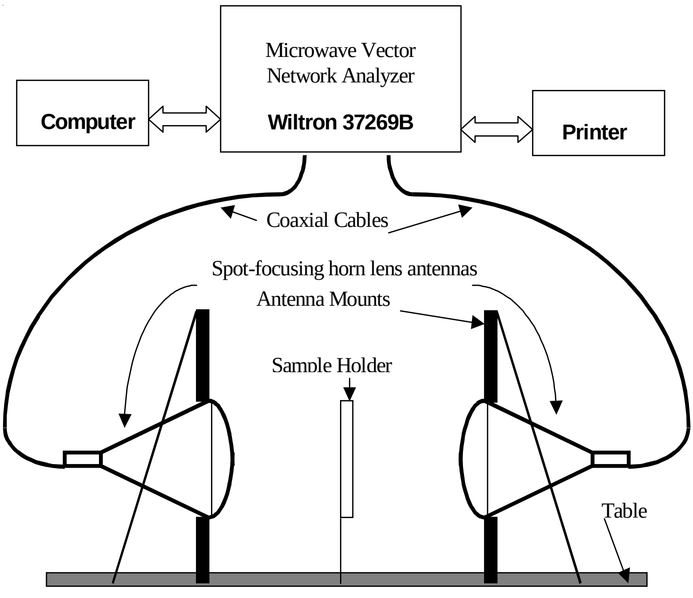

Figure 1: Free-space Microwave Measurement System

For these antennas, the ratio of focal distance to antenna diameter (F/D) of the lens is equal to one and D is approximately 30.5 cm.

A specially fabricated sample holder is mounted at the common focal plane for holding planar samples. The sample is sandwiched between. two perspex plates (one plate is fixed and the other is moveable). The transmit and receive horns are mounted on a carriage and the distance between' them can be changed with an accuracy of 25.4 μm. by using a dial indicator. From measured radiation patterns supplied by the manufacturer, the 3 dB and 10 dB E-plane beamwidths can be calculated. These beam widths will vary in proportion to wavelength in free space (Ao). The 3 dB and 10 dB beamwidths are approximately λ_0 and 1.9 λ_0 respectively. The depth of focus for these horn lens antennas is approximately 10 λ_0. Because of spot focusing action of antennas at the focus, the diffraction effects are negligible if the minimum transverse dimension of the sample is three times the 3-dB E-plane beamwidth (which is approximately 3 λ_0) This measurement set up covers a frequency range of 8.0 - 14.0 GHz . But, the same setup can be used in the frequency range of 8.0 - 40 GHz by appropriate change of mode transitions.

The focused antennas are connected to the two ports of the Wiltron 37269B vector network analyzer by using precision coaxial cables, rectangular-to-circular waveguide adapters and coaxial-to-rectangular waveguide adapters. The receive antenna can be rotated from co-polarized position in steps of 10° between – 70° to + 70°. The polarization of transmit and receive antennas depend on polarization of the wave in rectangular waveguide used in coaxial-to-rectangular waveguide adapter. Vector network analyzer measures amplitude and phase of reflected or transmitted signal in transmission media such as coaxial line, rectangular/ circular waveguide, microstrip line and free-space. A complete VNA system consists of a fast sweeping synthesized signal source, auto-reversing S-parameter test set, display unit and a controlling computer. This network analyzer is used to make accurate reflection and transmission (S-parameters) measurements in free-space using line-reflect-line calibration model.

Because of multiple reflections between coaxial-to-rectangular waveguide adapters, rectangular-to-circular waveguide transitions and horn lens antennas, there is a need to calibrate the measurement system in free-space for S-parameter measurements. We have implemented free-space LRL calibration technique [7, 8]. This calibration technique along with smoothing or time domain gating feature of the network analyzer, can eliminate effects of multiple reflections. It is known that

LRL calibration technique can produce the highest quality calibration available. Also, it is easier to realize. LRL calibration standards in free-space as compared with open, short and matched termination standards used in coaxial and waveguide media. So, LRL calibration is the best calibration technique for the free-space medium.

Free-space LRL calibration is implemented in free-space by establishing three standards. The reference planes for port 1 and port 2 are located at the focal planes of transmit and receive antennas. The through standard is realized by keeping the distance between two antennas equal to twice the focal distance. It means that there is a common focal plane for the through standard. The line standard is achieved' by separating the focal planes of the two antennas. The distance between focal planes is approximately a quarter wavelength at mid-band, The reflect standards for port 1 (transmit horn) and port 2 (receive horn) are obtained by placing a metal plate (15.24 cm × 15.24 cm × 2.1 mm) on sample holder at the reference plane.

LRL calibration kit for coaxial line of the vector network analyzer is modified by defining LRL standards regarding wave impedances and line lengths. Because of the characteristics of spot focusing horn lens antennas, the electromagnetic fields in the neighborhood of common focal plane are plane wave in character, so the use of modified coaxial calibration kit is justified. The error model for LRL calibration includes error terms for directivity, isolation, source impedance match, load impedance match, transmission frequency response and reflection frequency response. This error model has 12 error coefficients which are evaluated from measured data for the LRL standards. By performing the LRL calibration using the free-space calibration standards, two-port free-space LRL calibration is obtained.

For measurement of complex reflection coefficient (S_{11}), and complex transmission coefficient (S_{21}) of composite material sample, the reference planes corresponding to transmit and receive antennas were located at the front and back face of the sample, respectively. The residual post calibration errors can be further reduced by using time domain gating or smoothing function of VNA. It is observed that magnitude and phase of S_{11} are within ± 0.2 dB and ± 2° of the theoretical value of 0 dB and 180° for the metal plate.

For the through connection, the measured magnitude and phase of S_{21} are within ± 0.05 dB and ± 0.2° of the theoretical values of 0 dB and 0°.

Experimental Results

Five brass plates were coated with epoxy primer. Then, coated with polyurethane based paint of thickness 0.07 to 0.48 mrn. All brass plates have a thickness of 3.32 mm and have a cross section of 15.24 cm × 15.24 cm.

Table 1: Variation of Phase of Complex Reflection Coefficient with Paint Thickness

Paint thickness (mm)	Phase (Degree)
0.07	180
0.21	180
0.31	176
0.48	175

After performing free-space LRL calibration, the complex reflection coefficients (S_{11}) were measured for brass plates coated specimens. The accuracy of measurement of metal plate for magnitude and phase of S_{11} is 0.0 ± 0.2 dB and 180° ± 20 respectively. Measured magnitudes of complex reflection coefficient for all brass plates were within 0.0 ± 0.2 dB. So, they are within measurement errors. But, there is considerable variation of phase of $S_{11}$with paint thickness. Tables 1 give variation of phase of complex reflection coefficient as a function of paint thickness.

Conclusions

From Table 1, it is observed that phase of the complex reflection coefficient decreases with increase in paint thickness. So, phase of 811 can be used to detect corrosion under paint.

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