EVALUATION OF MICROWAVE METHODS FOR THICKNESS MEASUREMENTS OF LIQUID SHIM MATERIAL

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INTRODUCTION

This paper describes the use of a microwave interferometer technique which measures the thickness of liquid shim material applied to composite surfaces. Liquid shim, which is a low dielectric material, is applied to spar cap surfaces in order to maintain wing skin mold-line tolerances while reducing stresses at the location of fastener holes. For this application, the thickness of the shim material must be controlled within specified limits. Microwave reflection techniques provide an alternative nondestructive approach to liquid shim thickness measurements.

Microwave nondestructive testing (NDT) methods have been applied successfully to specific testing problems for more than 40 years [1]. However, microwave techniques can be best classified as complementary or specialized techniques when compared to ultrasonic and eddy current inspection methods. Their general use has been limited and microwave NDT installations, as used by the aerospace industry, have typically been more experimental than full-scale production facilities [2].

Microwave NDT applications have been successfully applied to both non-metallic and metallic materials. A wider range of applications can be found for non-metallic, non-conductive materials as microwaves can freely penetrate these materials. Some applications for non-metallic materials include detection of delaminations and porosity, measurement of anisotropy and thickness, and determination of moisture content. Applications for metallic materials are limited to spatial measurements or surface imperfections as microwaves readily reflect from these materials. Some of these applications include measurement of displacement or detection of surface breaking anomalies [2].

BACKGROUND

Liquid shim, which is an epoxy-based material, is used to fill gaps located between the supporting substructure and wing skin, as shown in Figure 1. The material is applied to the spar cap using a pneumatic sealing gun and subsequently spread over the spar surface

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[3]. A release film is then placed between the shimmed structure and wing skin. Once the material has cured, the skin is removed and measurements are made to verify the thickness of the liquid shim material. The hole drilling technique currently used to measure shim thickness is labor intensive and somewhat inaccurate. This technique is based on drilling a hole with a depth that is equal to the thickness of the applied shim material. The measured depth of the hole is equivalent to the thickness of the shim material.

Ultrasonic and eddy current methods were evaluated as possible techniques for the required thickness measurements. Both methods yielded inconsistent results due to the structure of the carbon/epoxy wing spar surface. For this reason, the microwave reflection technique was considered for evaluation.

The term microwave is used to define all electromagnetic radiation waves whose frequencies lie between 0.3 and 300 GHz. These frequencies correspond to a range of free space wavelengths in a vacuum from one meter to one millimeter. In a vacuum or in air, microwaves travel at the speed of light ($2.997\ (10)^8$ m/s) [1]. The speed of a microwave is slowed as it passes through dielectric materials just as light is slowed as it passes through a lens.

The penetration of microwaves into a dielectric material depends on two physical phenomena: The reflection of the wave at the surface of the dielectric and the attenuation of the wave as it travels through the material. The primary physical mechanisms that attenuate microwaves in a material medium are wave interaction with conduction electrons, wave interactions with molecular dipoles, wave scattering from material discontinuities and beam spread.

The standard depth of penetration of microwaves into conducting materials is defined in the same way as the standard depth of penetration for eddy currents, as shown below:

$$\delta=1/\sqrt{\pi\sigma\mu f} \qquad (1)$$

where δ is the depth of penetration, μ is the total permeability, f is the frequency and σ is the conductivity of the material.

The sectional thickness of dielectric materials can be measured with microwave methods provided that the surfaces are parallel and that the dielectric properties of the material are constant. This measurement is made by generating an interference pattern, called a standing wave, between parallel surfaces of the material. When interference prevails, the reflection coefficient is a function of the sectional thickness and wavelength of the material [2]. Figure 2 shows how the amplitude of the reflection coefficient varies with respect to the thickness/wavelength ratio for materials with high and low dielectric constants backed by a conductive surface. Being a standing wave interference phenomenon, this response cycles every one-half wavelength (neglecting diffraction and loss effects).

Two different microwave techniques were evaluated during this investigation. The RF Probe, shown in Figure 3, is a single frequency device that will detect reflection amplitude changes as the thickness-to-wavelength ratio changes [4]. As shown in Figure 2, the amplitude of the reflection coefficient at a single frequency is more responsive to thickness changes when the thickness of the dielectric material is equal to integer multiples of one-half wavelength. Therefore, the measurement range is limited to one-quarter wavelength changes in equivalent thickness [2]. The microwave reflectometer, shown in Figure 4, utilizes an HP8720 Vector Network Analyzer for collection and processing of data. The reflectometer is a swept frequency device that detects the null frequency that corresponds to a thickness-to-wavelength ratio of 1/4 [5]. For this reason, the frequency range and the probe design must be selected to operate with the null in the measurement range of interest. This measurement requires more data processing but provides a method of removing random and systematic sources of noise.

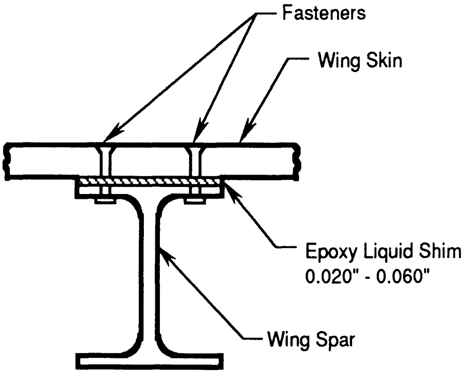

Fig. 1. Typical spar cap configuration

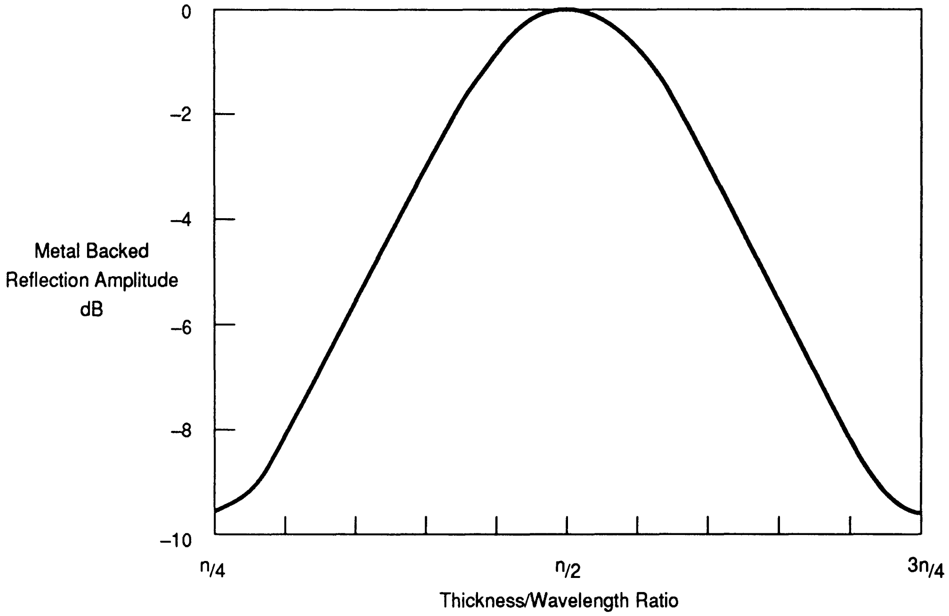

Fig. 2. Prediction of reflected power under measurement conditions

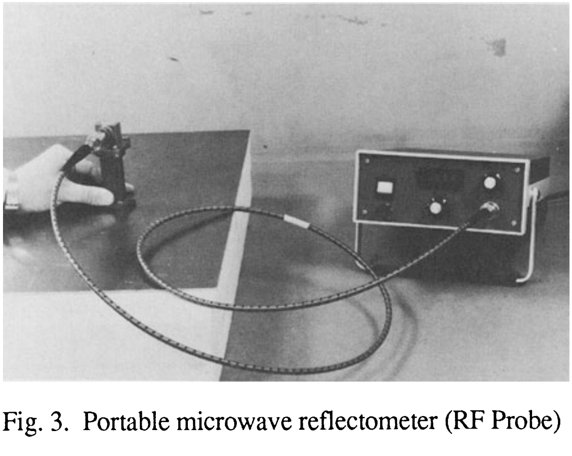

Fig. 3. Portable microwave reflectometer (RF Probe)

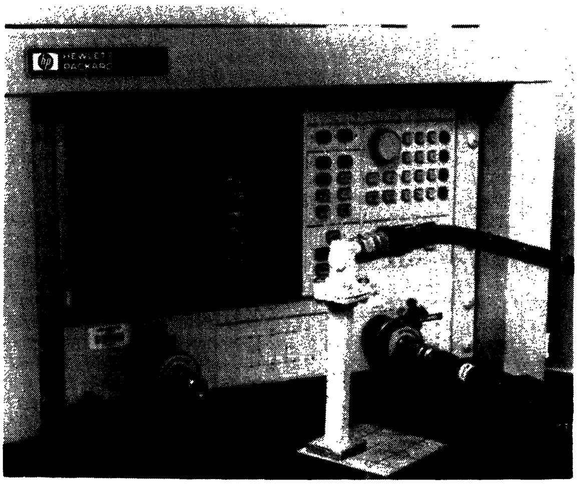

Fig. 4. HP8720 Vector Network Analyzer system with Ku-band waveguide probe

EXPERIMENTAL PROCEDURE

Liquid shim reference standards were fabricated to simulate coated spar caps. The thicknesses ranged from 0.005" to 0.100" in 0.005" increments [3]. These standards were fabricated by applying the liquid shim material to carbon/epoxy panels, which were similar in structure to actual substrate conditions. These standards were used to evaluate the performance of both the RF Probe and the microwave interferometer.

The performance of the RF Probe was optimized for these measurements by adding a fiberglass shoe to the X-band waveguide probe. As shown by the data presented in Figure 5, this fiberglass shoe significantly improved the sensitivity of the instrument to changes in liquid shim thickness over the 0.020" - 0.060" thickness range. Once the RF Probe was standardized, it was used to perform actual spar cap inspections. These inspections were not completely successful, requiring the introduction of the microwave interferometer to study the factors that were limiting the performance of the RF Probe.

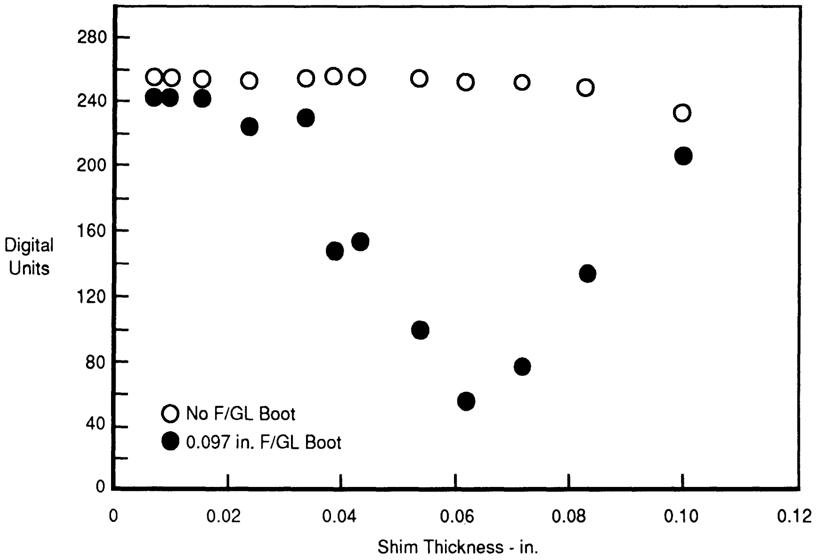

Fig. 5. RF Probe thickness measurements

The probe used for the microwave interferometer was designed to optimize thickness sensitivity and to reduce distortion caused by edges and holes. Sensitivity to thickness was optimized with a dielectric spacer made of the same liquid shim material. The thickness of this spacer was selected using an electromagnetic model that predicted the interference of microwaves reflected from the top surfaces of the shim material and the carbon/epoxy interface. The measured dielectric properties of the liquid shim, presented in Figure 6, were used for these predictions. The interference predictions are shown in Figure 7. The distortion caused by edges and holes was reduced by fabricating the probe flange using shim material and masking the probe with microwave absorber.

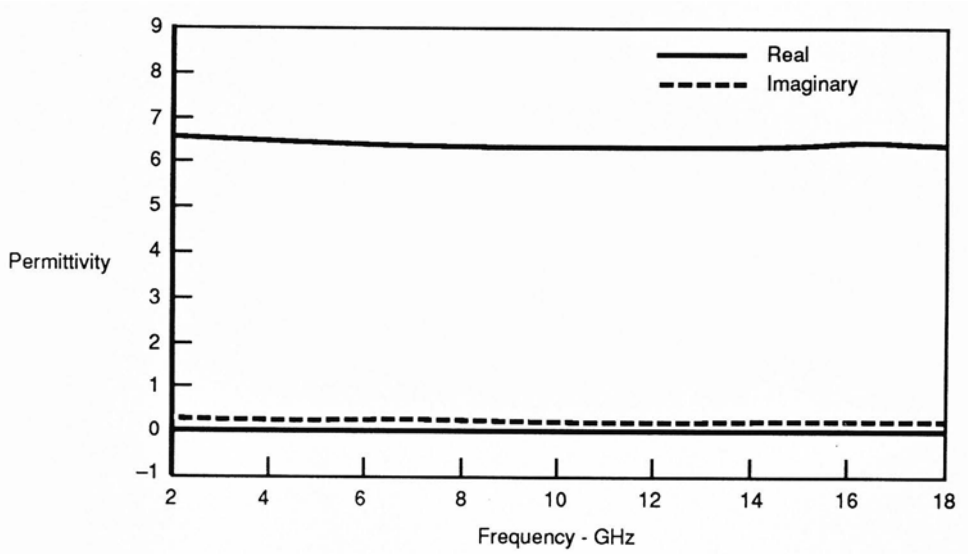

Fig. 6. Dielectric property data of liquid shim material over 2-18 GHz range

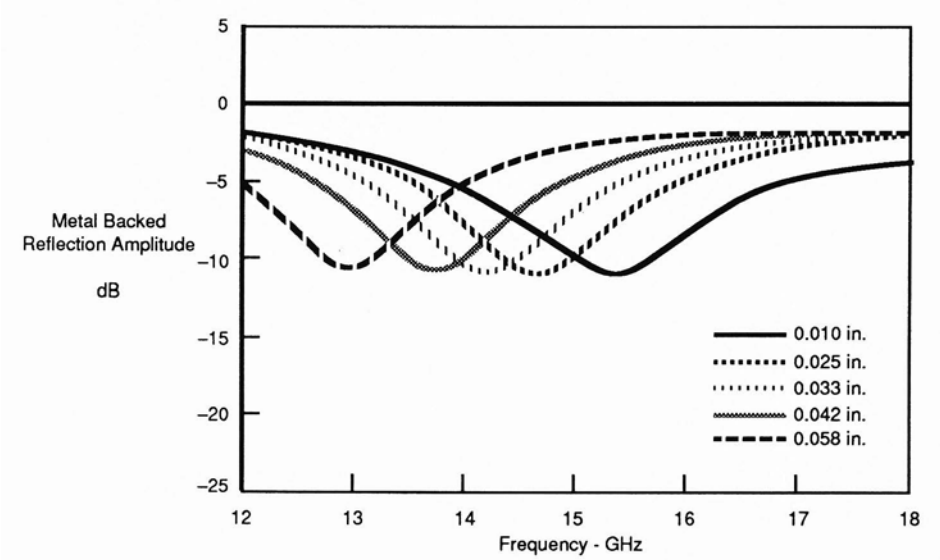

Fig. 7. Interference null predictions

The effects of polarization sensitivity, distortion caused by edges and holes and operator variability were evaluated using carbon/epoxy panels with shim material applied to the surface. The effects of polarization sensitivity were evaluated by rotating the probe while making shim thickness measurements on the standards. A carbon/epoxy panel with constant shim thickness was used to evaluate the effects of edges by taking thickness readings as the probe approached the edge of the panel. A 0.25" diameter hole was drilled into the center of a second panel and the effects due to the hole were quantified by measuring shim thickness as the probe approached the hole. Finally, operator variability was evaluated by having several independent operators collect shim thickness data on the same set of liquid shim standards.

RESULTS

Shim thickness data collected on spar caps using the RF Probe were too variable for acceptable evaluation of liquid shim thickness. This variability was due to noise signals from edges and holes, polarization sensitivity and random noise. With the exception of the polarization sensitivity, all of these sources of variability were reduced to acceptable levels through the use of a swept frequency microwave interferometer. The swept frequency technique offered significant advantages over the RF Probe. The frequency dependent response could be compared with the model used to design the probe and averaging could be used to eliminate random and systematic noise from the measurement. These sources of noise could not be removed from the RF Probe data since it is a single frequency measurement technique.

Polarization sensitivity, shown in Figure 8, was responsible for differences observed depending on probe orientation. These orientations are identified as PA (parallel) and PE (perpendicular) to the weave of the carbon fibers in the carbon/epoxy panel. The differences between these two perpendicular orientations of the probe ranged from 0.004" - 0.005". The polarization sensitivity was caused by the difference in conductivity of the carbon/epoxy panel surface when the electric field of the microwave is aligned differently with the carbon fiber axis. The use of a circularly polarized wave would remove this sensitivity. During a measurement, the circularly polarized wave would take all possible orientations of the carbon fibers into account. Under these conditions, the result would be an average of all possible orientations.

Figures 9 and 10 demonstrate the sensitivity of the microwave interferometer to edges and holes, respectively. These results represent a significant improvement over the RF Probe performance made possible by the removal of source of noise signal. These results clearly show that the center of the interferometer probe must be within 0.5" of an edge or a hole before an error greater than 0.002" is introduced into the measurement. This result could be improved by reducing the dimensions of the probe flange.

Measurement repeatability was found to be acceptable after the absorber was added to the design. The absorber prevented error signals from being reflected back into the probe when the operator's hand was placed near the flange. Operator variability data collected indicated that all but one of the 18 measurements taken were within 0.002" of the actual shim thickness.

CONCLUSIONS

In summary, it was determined that the RF Probe approach was too simplified to provide accurate thickness measurements. In contrast, the microwave interferometer technique shows definite potential as a repeatable method of measuring the thickness of liquid shim material. The sensitivity to curved surfaces and surface features such as holes

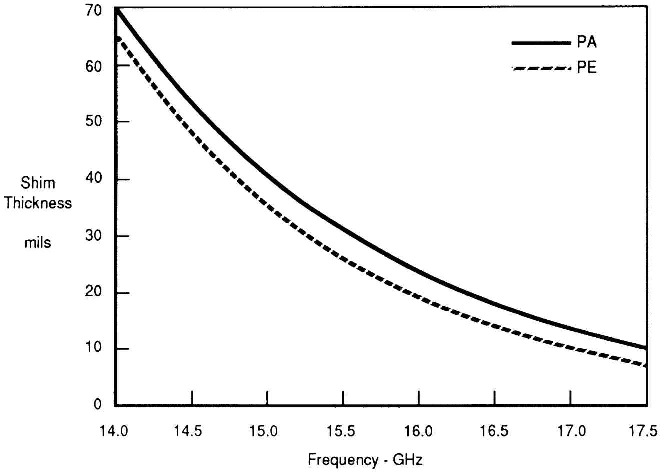

Fig. 8. Overlay of working curves demonstrating polarization sensitivity

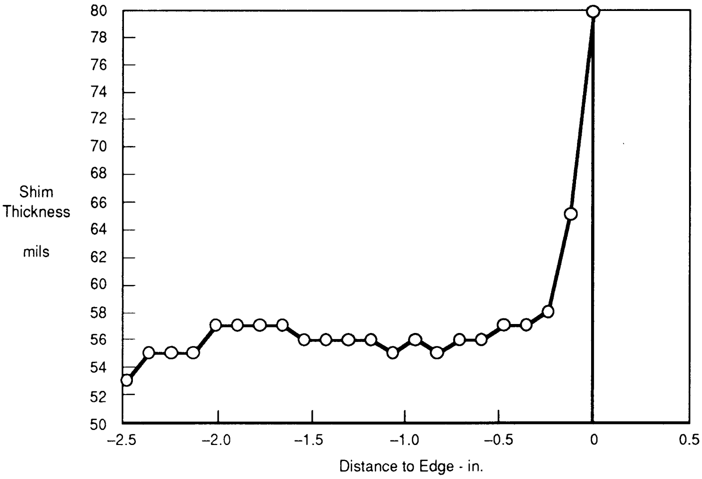

Fig. 9. Measurement errors due to edge effects

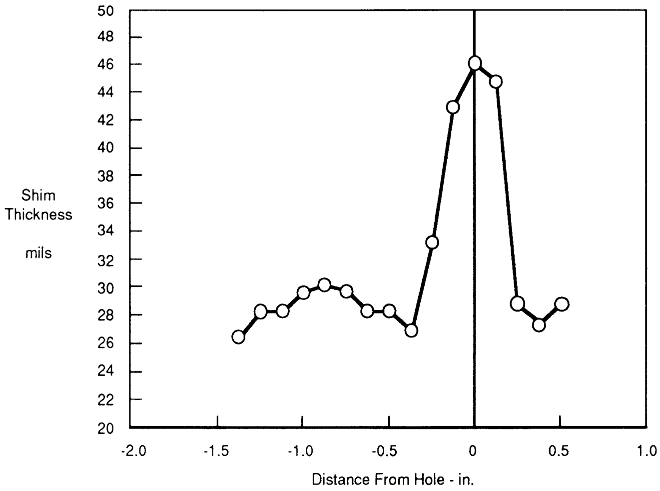

Fig. 10. Measurement errors due to the presence of holes

and edges could be reduced further by reducing the size of the waveguide and the dimensions of the flange and spacer used to fabricate the probe. Finally, the use of circularly polarized microwaves would remove the unwanted polarization sensitivity.

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