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Size Evaluation of Corrosion Precursor Pitting using Near-Field Millimeter Wave Nondestructive Testing Methods

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SIZE EVALUATION OF CORROSION PRECURSOR PITTING USING NEAR-FIELD MILLIMETER WAVE NONDESTRUCTIVE TESTING METHODS

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ABSTRACT. Early detection of corrosion precursor pitting and estimation of its overall dimensions directly affects the required effort and cost associated with repair and maintenance of critical aircraft structural components. The magnitude and phase of a reflected signal from a pitting are directly related to its dimensions. This paper presents a millimeter wave probe and a sizing procedure used to detect and evaluate overall pitting dimensions.

INTRODUCTION

Critical aircraft structural components, such as wings and fuselages, are exposed to harsh environmental conditions that lead to corrosion of these components. The initiation of corrosion is preceded by the presence of corrosion precursor pitting [1]. Early detection of corrosion precursor pitting in these structures is an important practical issue when considering maintenance and repair. The size (area and depth) of a precursor pitting is very small (fractions of a millimeter), yet the depth may be considered a significant percentage of an aircraft panel thickness in which case rehabilitation and repair maybe required. Corrosion that is hidden under paint and primer may not always be visually detected. However, microwave and millimeter wave signals are capable of penetrating paint and primer and interacting with surface anomalies, and measurements can be conducted in a rapid, one-sided and non-contact fashion [2]. Microwave and millimeter wave nondestructive testing (NDT) techniques have shown great potential for detecting corrosion and precursor pitting under paint and other thin and thick dielectric laminates [3-6]. Furthermore, these NDT techniques have shown great potential for detecting tight surface breaking cracks and evaluating their dimensions [2,7]. Close estimation of pitting overall dimensions, in particular its depth, directly affects the required effort and cost associated with repair and maintenance of an affected region. This paper presents a millimeter wave probe and a sizing procedure for detection and evaluation of pitting dimensions.

2nd place winner in the student poster competition of 2004.

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APPROACH

To evaluate the size of a pitting using a millimeter wave probe, two approaches maybe considered, namely: *a*) measuring the reflection properties of a probe when it is placed in the middle of a pitting and comparing the results with reflection from a clean region on a panel, or *b*) obtaining a high resolution image of the pitting and analyzing the properties of the image to determine the pitting dimensions. In this paper the latter approach was used since the image of a pitting is expected to possess more information than a single measurements conducted in the center of the pitting.

Several millimeter wave probes maybe used to image a pitting namely, an open ended rectangular waveguide, a tapered waveguide, a dielectric-loaded waveguide and a dielectric waveguide. Previous investigation showed that a dielectric waveguide probe provides for high spatial resolution due to its relatively small aperture dimensions. Furthermore, it has a relatively higher immunity to signal clutter associated with a panel surface features (i.e. edges, curvature, weld joints, etc.) [8]. A picture of a dielectric waveguide probe is shown in Figure 1. A standard rectangular waveguide is used as a feed for the dielectric waveguide which concentrates the electromagnetic field across its aperture (which is smaller than the aperture of the feeding open-ended waveguide). The dielectric waveguide probe should be operated at small standoff distances since it is a poor radiator and most of the energy is concentrated around its tip (i.e., close to its aperture). A typical intensity image (i.e., raster scan showing the measured signal magnitude) of a pitting produced by a dielectric waveguide probe has a cone shape as shown in Figure 2. To produce this image and others shown in this paper, a phase sensitive reflectometer at V-band (50-75 GHz) was used along with a dielectric waveguide probe (aperture dimensions 1 mm x 0.5 mm) similar to that shown in Figure 2 but at V-band. The output of this reflectometer is a dc voltage proportional to the magnitude and phase of reflection coefficient measured at the probe aperture. Using a 2D computer controlled scanning table, raster scans of various pittings were produced. For this investigation a set of pittings were laser machined in an aluminum panel. The pitting dimensions (diameter and depth) were in the range of 200 – 400 µm. A schematic of this set of machined pittings is shown in Figure 3. The millimeter wave image of this set of pittings was produced at a frequency of 67 GHz. The resulting image was further enhanced to remove the effect of standoff distance variation, as shown in Figure 4. The results clearly indicate that all pittings were detected using this dielectric waveguide probe. Additionally, the overall signal attributes associated with each individual pitting may be used to evaluate its size, as described in the next section.

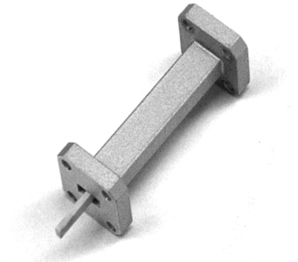

FIGURE 1. Dielectric waveguide at Ka-band (26.5 – 40 GHz).

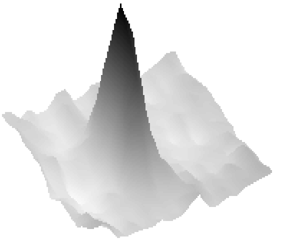

FIGURE 2. Microwave intensity image of a single pitting with a diameter of 250 μm and depth of 300 μm.

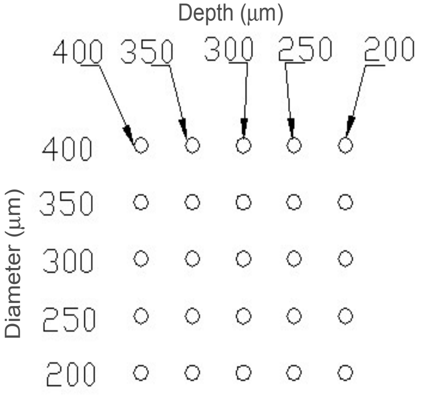

FIGURE 3. Schematic of an array of laser machined pittings.

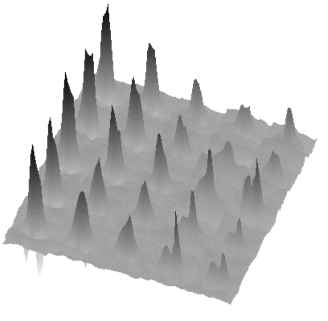

FIGURE 4. A microwave image of an array of pittings at 67 GHz.

SIZING RESULTS

As mentioned earlier, the results shown in Figure 4 clearly indicate the capability of the dielectric waveguide probe in distinguishing among closely spaced pittings (spacing of 0.25" in this case). Some of the pit indications possess double peaks. This deformation (from a nice cone shape) occurs in particular in the images of smaller pittings since a relatively small number of image pixels were recorded over them. This may be overcome by designing probes with smaller aperture dimensions and scanning with higher stepping resolution. Nevertheless, the image in Figure 4 clearly provides information about the relative size of the various pittings. It may be possible to extract relative size information from this image as well.

Originally, the relative probe output peak voltage associated with the pittings was considered as a sizing means. Figure 5 shows the peak signal level obtained from pits with a depth of 250 μm and diameters of 200, 250, 300, 350, and 400 μm. While this figure shows a correlation between the pit diameter and peak signal level, it also shows that one may not always distinguish among pitting sizes of 250-350 μm using peak signal level only. Furthermore, if the center of the probe and the center of the pitting do not coincide during scanning, especially for pittings with small diameters, the cone shaped image will be deformed (as shown in Figure 4) and this method of sizing is rendered ineffective. However, it is possible to use higher biased detectors to increase the output voltage. Also, one must keep in mind that in practice many measurement of a pitting peak signal voltage must be made and averaged and the statistics of the data should be used as a means for sizing. Figure 6a shows a plot of the integrated signal (integrated signal over individual cone shaped images) vs. pitting diameter, while Figure 6b shows the area on the image corresponding to a pitting vs. diameter. It is clear from this figure that the integrated signal and the area may be better indicators of the pitting diameter. One other factor to be considered is the average signal level which is the ratio of the integrated signal to the image area of a pitting (the area of the base of the cone). As it can be seen from Figure 7, the average signal correlates best to the pitting diameter, and the results shown in Figure 7 may be used as a calibration curve for estimating pitting diameter.

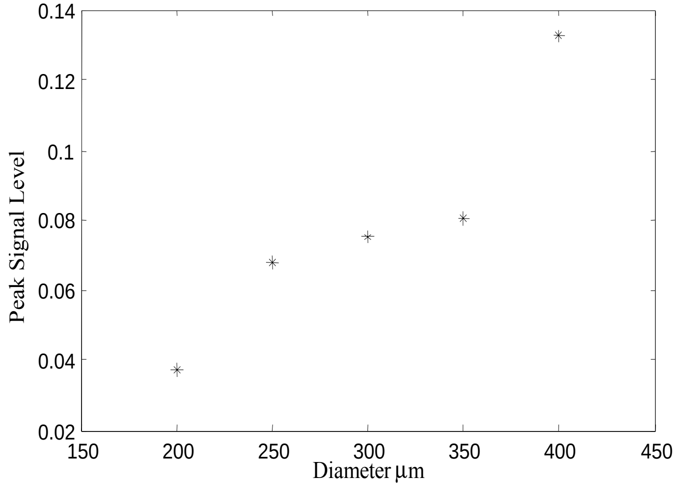

FIGURE 5. Peak signal level as a function of diameter for a set of pittings with a depth of 250 μm.

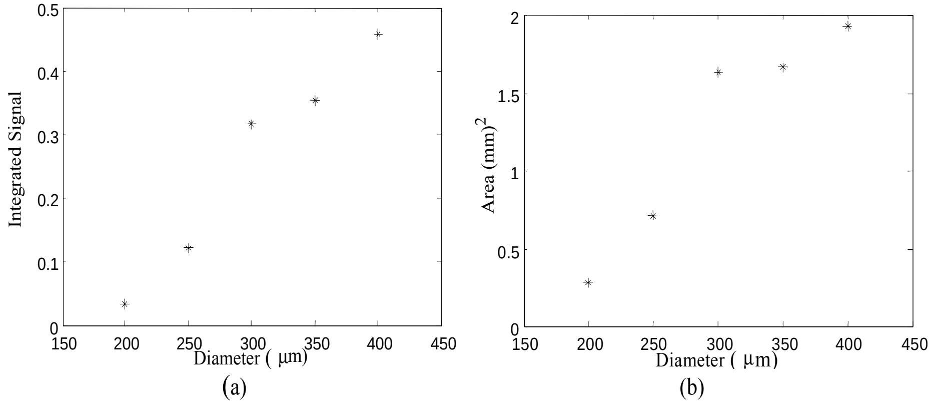

FIGURE 6. a) Integrated signal and b) image area of a pitting as a function of diameter, for an array of pittings all with a depth of 250 µm.

Figure 8 shows a plot of pitting integrated signal as a function of diameter for several depths. The effect of depth seems to be non-monotonic and with a small dynamic range. However, the error associated with measuring the diameter without having any knowledge of the depth of a pitting may not exceed a mere 50 µm. Once the diameter is estimated, several other independent measurements may be performed to determine depth and reduce uncertainty in evaluating the pitting diameter. Independent measurements may be performed at several frequencies, several standoff distances, and/or using other probes.

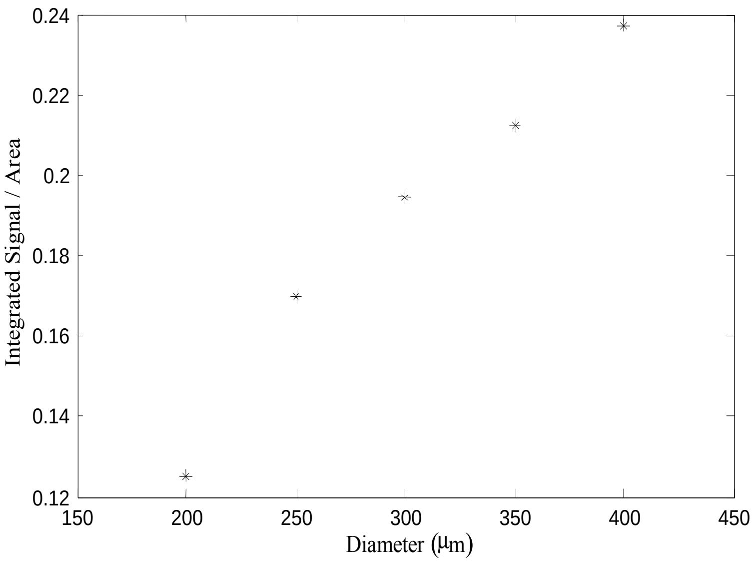

FIGURE 7. Integrated signal/area as a function of diameter for a set of pittings with a depth of 250 µm.

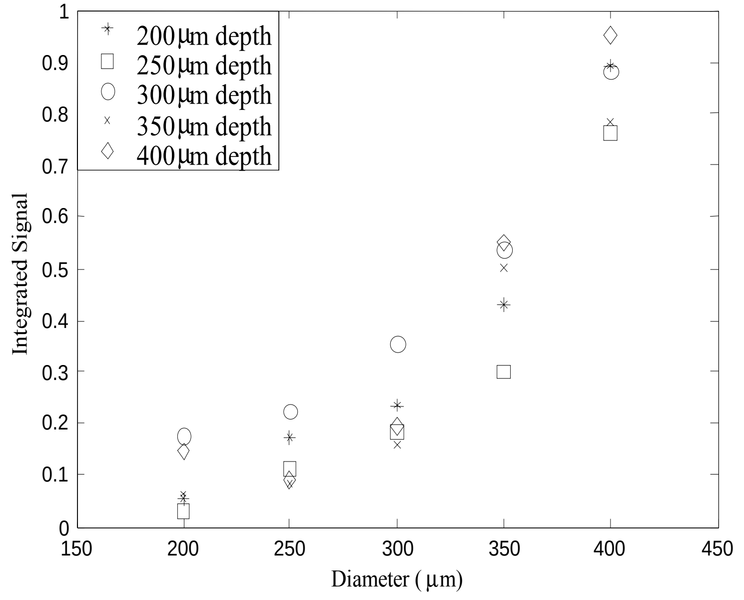

FIGURE 8. Integrated signal as a function of diameter for the pitting array shown in Figure 3.

SUMMARY

High resolution images (raster scans) of small pittings were obtained using dielectric waveguides operating at relatively high frequencies (V-band, 50-75 GHz). Pitting dimensions (diameter and depth) may then be evaluated using the attributes of the image associated with a pitting. In this way, calibration curves may be produced which can give a reasonable estimate of a pitting dimensions. The sensitivity of the measurement system to changes in pitting diameter was higher than the sensitivity to changes in depth especially for pittings with small diameters. Since the dielectric waveguide probe is not a good radiator, it is necessary to operate it at small standoff distances. Furthermore, the dielectric waveguide probe used was not completely optimal. Optimizing its dimensions and shape may provide for better matching to the feeder waveguide and better radiation, therefore improving the sizing accuracy. Also, independent measurements at different frequencies may increase measurement certainty.

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