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MILLIMETER WAVE IMAGING OF CORROSION UNDER PAINT: COMPARISON OF TWO PROBES

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ABSTRACT. Critical aircraft structures are susceptible to harsh environmental conditions that cause corrosion of these structural components. It is of great importance to detect corrosion under paint, particularly in its early stages. Millimeter wave nondestructive evaluation methods have shown great potential for detecting corrosion under paint and evaluating its properties. This paper presents and compares the results of using two distinct millimeter wave detection methods; namely a standard single probe and a newly developed differential probe for detecting corrosion under paint.

Keywords: Millimeter wave, corrosion, data fusing, differential probe
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INTRODUCTION

Aircraft structures are susceptible to harsh environmental conditions that cause corrosion of these critical structural components. Early detection of corrosion affects the required effort and cost associated with repair and maintenance of these structures. It is of great importance to detect corrosion under paint, particularly in its early stages before it causes blistering of paint, thinning of the plates, and the eventual structural failure [1-2]. Near–field millimeter wave nondestructive evaluation methods have shown great potential for detecting corrosion under paint and evaluating its properties [3-5]. However, at the early stages of corrosion process, the perturbation caused by corrosion on the reflected millimeter wave signal may be small and strong clutter may mask this signal. A standard millimeter wave single probe in its near-field is highly sensitive to changes in dielectric properties of the specimen under test, including the presence of corrosion and its thickness [3]. However, this probe is also very sensitive to standoff distance (distance between the probe and the specimen under test) variation which is one of the primary sources of clutter that may potentially mask corrosion detection [5]. This paper presents and compares the

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results of using two distinct detection methods for imaging several corroded aluminum panels, namely a standard single probe and a differential probe that coherently removes the effect of clutter. The panels were corroded in a salt fog chamber per ASTM B117 test conditions, with varying exposure times that resulted in a progressive increase in the amount of corrosion. These panels were subsequently painted and tested using the two methods mentioned above. The imaging attributes of each method along with a quantitative measure of detection capability of each method is also presented.

THE PROBES

Many types of probes at several frequency bands have been used in previous investigations to detect corrosion under paint [5]. This paper presents the results and a comparison between two V-band (50 – 75 GHz) probes; a single open-ended waveguide probe and a differential probe. A standard millimeter wave probe, which in this paper is referred to as a single probe, consists of a CW signal source (Gunn oscillator) at a millimeter wave frequency, a power splitter, and a diode detector as shown in Figure 1a. A power splitter is used to extract a portion of the source signal to be used as a reference. The rest of the signal is used to irradiate the specimen under test through a radiating aperture. The reflected signal is subsequently picked up through the same aperture and mixed with the reference signal which is subsequently fed to the detector to produce a DC voltage proportional to the phase of the reflected signal. To produce an image, the specimen is then raster scanned. The resulting matrix of DC voltages is normalized (with respect to its range) and plotted as a greyscale image. A single probe utilizing an open-ended waveguide aperture produces images with relatively fine spatial resolution and is sensitive to the presence of corrosion under paint. However, the primary disadvantage associated with this probe is its high sensitivity to variations in standoff distance [5].

To overcome this disadvantage, a probe utilizing two apertures was designed and built. The output of this probe represents the coherent difference between the reflected signals picked up by each aperture. Since the two apertures are closely spaced, both of them face an equivalent amount of standoff distance change. Therefore, the output of the differential probe is not affected by changes in this parameter as much as a single probe would [6].

As shown in Figure 1b, this probe consists of a millimeter wave source, a 3dB power divider, two identical waveguide aperture probes, a power combiner, and a detector. A magic-tee may be used as a power divider as well as a power combiner to obtain the difference signal. A CW oscillator, such as a Gunn oscillator, is used to generate a signal in the V-band frequency range which is then fed to the sum port of the magic tee. The magic tee divides the signal from the oscillator into two equal in phase and magnitude signals at its collinear arms, each of which are connected to identical open-ended rectangular waveguide apertures via two identical transmission lines. These apertures irradiate immediate areas beneath them and pickup reflected signals from the specimen under test. These reflected signals subsequently travel back to the magic tee through the same two transmission lines. Consequently, the coherent difference of the reflected signals is measured by the diode detector resulting in a DC voltage that represents local variations in the specimen properties.

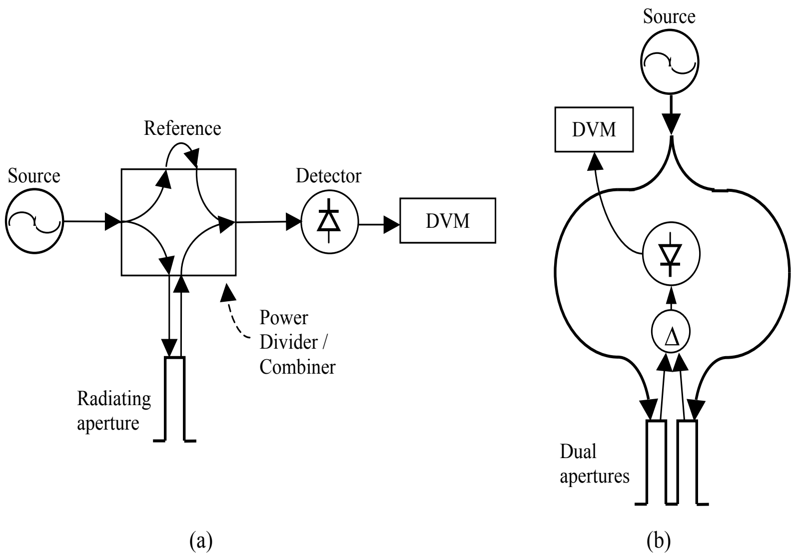


FIGURE 1. Millimeter wave probes; a) single probe, and b) differential probe.

RESULTS

Several aluminum 7075-T6 and 2024-T3 alloy plates were corroded in a salt fog chamber with varying exposure times from one day to five days resulting in varying corrosion levels. The plates were masked to produce square corrosion patches with dimensions ranging from 1" to 0.125" as shown in Figure 2. Some patches were placed in proximity to test the probe's spatial resolution. These plates were raster scanned using the two probes mentioned above to produce corrosion images. To illustrate the difference between the two probes, first images of exposed corrosion patches will be shown. Finally, a few examples of imaging corrosion under paint will be presented.

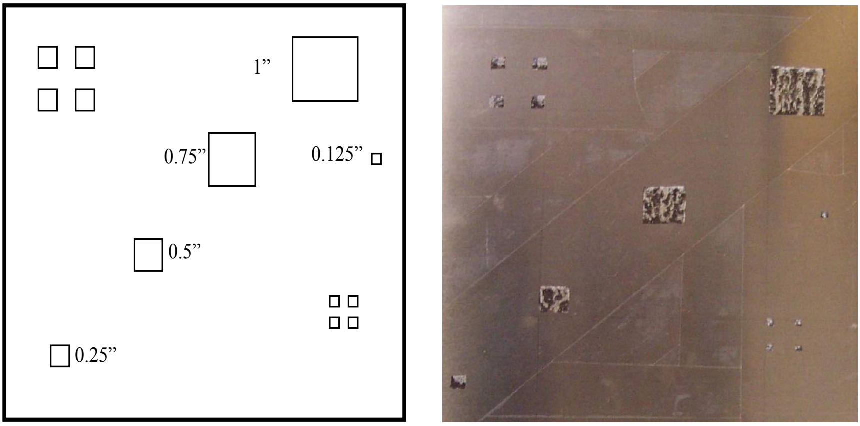
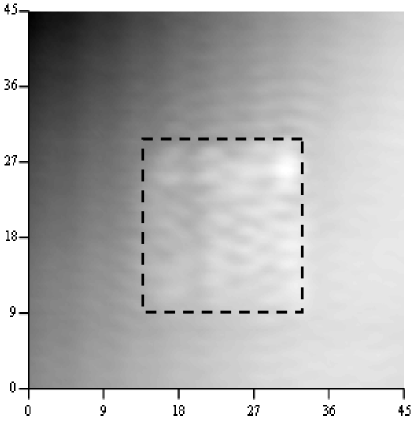


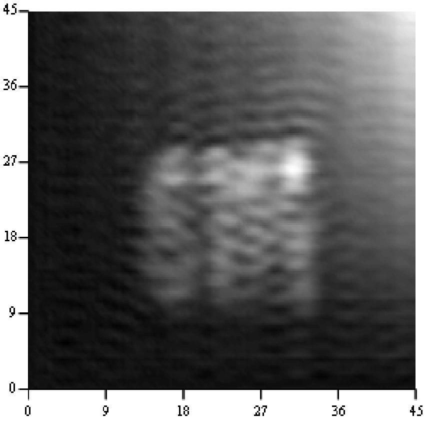
FIGURE 2. A schematic and a picture of the corrosion specimen.

Figure 3 shows an image of a 0.75” x 0.75” corrosion patch (corroded for three days in the salt fog chamber) obtained using the V-band single probe at 71 GHz. The raw data represented in Figure 3a has a non-uniform background caused by standoff distance changes which overshadows the corrosion signal. Subsequently, this image was processed to remove non-uniformity in the image background. The processed image (Figure 3b) clearly shows the square corrosion patch. In this image one may notice that the corrosion is not uniform throughout the patch. Furthermore, the resolution of the V-band probe is adequate to confine the corrosion signal within the area that has corrosion (i.e. no spatial spreading of the image which allows the operator to accurately determine the boundaries of the corroded patch). Since the clutter produced by the change in standoff distance usually may mask the corrosion signal, all of the single probe images that are presented in this paper have been processed to remove the non-uniform background signal due to the standoff distance variation.

Since the single probe and the differential probe use similar probing apertures (i.e. open-ended rectangular waveguide), their imaging properties are somewhat similar. However, the differential probe produces images with unique features and properties. These features depend on few factors, such as the spacing between the apertures, the distance of the probe to a defect, and most significantly the relative dimensions of the defect compared to the combined aperture size of the probe. If the object being imaged is spatially larger than the combined apertures of the probe, the differential probe system behaves as an edge detector. When both of the probes are irradiating a clean area on the specimen or both are irradiating the corrosion patch, the output of the differential probe is nearly zero since both apertures pickup similar reflections which are consequently subtracted from each other. On the other hand, when the differential probe is transitioning from a clean area to the corrosion patch, one of the apertures senses the clean aluminum plate and the other senses the corrosion patch. The diode detector translates this difference to a non-zero output voltage. Consequently, by using this method the exact location of the edges of the patch can be determined. To illustrate this point, a steel specimen was corroded and painted. This specimen was scanned using the single and differential probes and the results are as shown in Figure 4. While the single probe (Figure 4a) shows clearly



(a)



(b)

FIGURE 3. Intensity image of an exposed 0.75” x 0.75” square corrosion patch using a V-band single probe at a standoff distance of 1.5 mm; (a) raw data, (b) processed image.

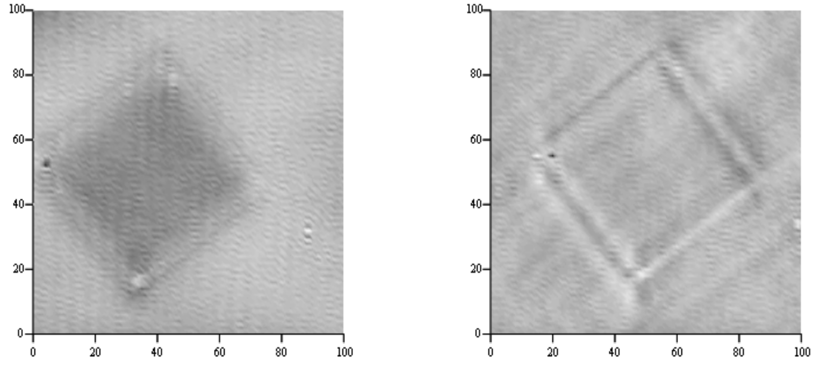


FIGURE 4. Intensity image of a uniform corrosion patch on painted steel using V-band; a) single probe and b) differential probe.

a uniform corrosion patch, the differential probe (Figure 4b) on the other hand, shows only the boundaries of that corrosion patch. If the corrosion patch does not have uniform thickness (e.g. aluminum corrosion) the differential probe will output a non-zero value. Figure 5 shows an image of the same corrosion patch shown earlier (Figure 3). Two vertical edges of the corrosion patch are registered in the image as a white and a black line at the left and right side of the patch respectively. The upper and lower edges were not detected since the orientation of the apertures causes both of them to sense equal reflections from the patch. As was noticed in the image obtained by the single probe, this corrosion patch is not uniform in its thickness. This causes a mixture of black and white spots, with lesser intensity than the edges to be apparent in the middle of the patch image.

If the defect size is smaller than the combined aperture of the probe, the probe produces two indications of the defect in the image [6]. Figure 6a shows the image of the single square corrosion patch (three days in the salt fog chamber) with dimensions of 0.125” x 0.125” obtained using a V-band differential probe at 71 GHz. Two indications representing the patch may be seen in this image. Each of these indications is similar to patch images obtained using a single probe. In this image the patch appears as two indications with

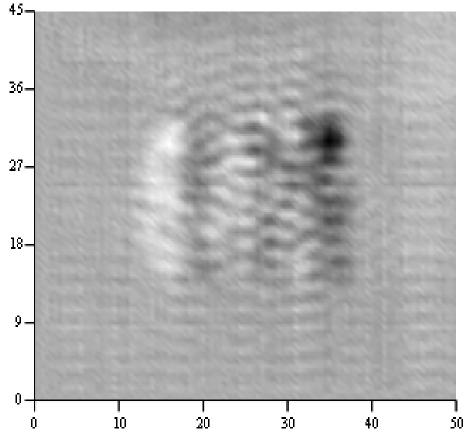


FIGURE 5. Intensity image of an exposed 0.75” x 0.75” square corrosion patch using a V-band differential probe at a standoff distance of 1.5 mm.

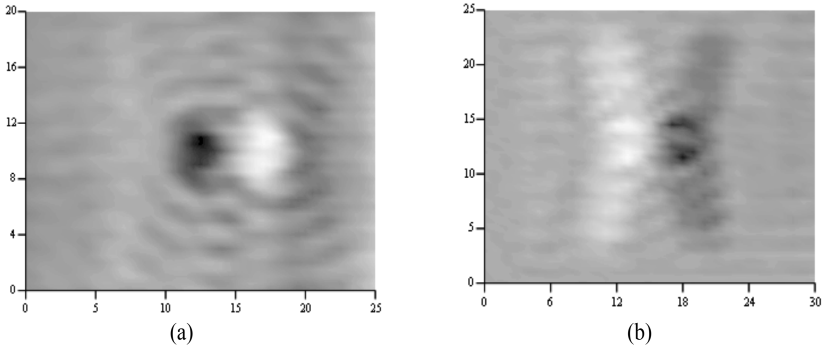


FIGURE 6. Intensity images of an exposed 0.125" x 0.125" square corrosion patch using a V-band differential probe at a standoff distance of; (a) 1 mm, and (b) 0.5 mm.

reverse color/intensity, i.e. one indication is brighter than the image background and the other is darker, as expected since from the detector point of view the apertures are 180° out of phase [6]. Some ringing indications are seen at the top and bottom of the patch indications due to the standing wave setup on the surface of the specimen between the flange of the probe aperture and the edge of the patch. At lower standoff distances (Figure 6b) the intensity of these rings increases which appears as spatial spreading of the corrosion signal.

As the size of the corrosion patch becomes smaller (i.e., pitting or early corrosion stages), the need for a robust imaging system which is insensitive to clutter becomes more crucial. A thin and small corrosion patch causes a very small perturbation to the reflected signal and may be easily masked by clutter. Figure 7 shows the images of the cluster of four corrosion patches each of dimensions 0.125" x 0.125" obtained using the V-band single and differential probes at 71 GHz. Although these patches were corroded for three days in the salt fog chamber, only one of them had severe corrosion and the other three were lightly corroded. In the single probe image, three of the patches are hardly visible. These corrosion signals may have been lost in the cleaning process or being masked by the remaining clutter in the image. On the other hand, the differential probe with its unique black and white signature clearly shows all four corrosion patches.

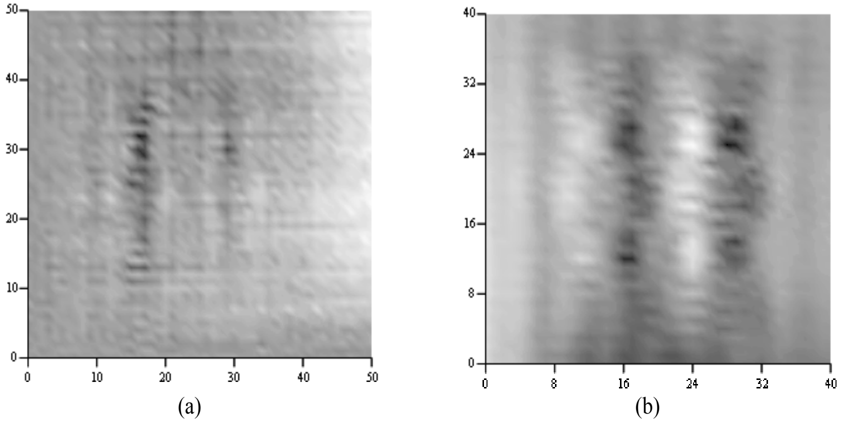


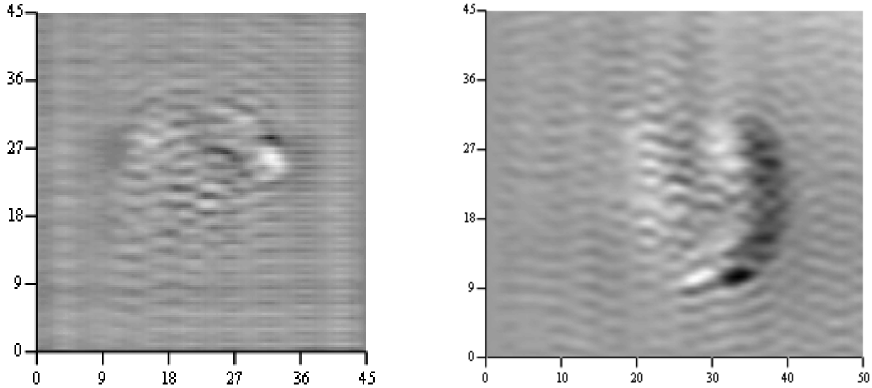
FIGURE 7. Intensity image of four exposed 0.125" x 0.125" square corrosion patch using the V-band probes at a standoff distance of 0.5mm; (a) single probe, (b) differential probe.

Since paint is generally a low loss dielectric material, signals at millimeter wave frequencies penetrate it without being highly attenuated. Thin layers of paint do not affect the operation of the millimeter wave probes mentioned. If the paint is lossless, the layer of paint appears as an additional standoff distance. Figure 8 shows a single probe and a differential probe image of a very thin patch of corrosion under paint. This specimen was corroded for two days in the salt fog chamber. The specimen was painted with a blank primer with a thickness of 25 micrometers and cured in air. Overall, the signal measured by both probes is very weak. Since the paint was uniform and the specimen was fairly flat, the single probe could produce a weak corrosion signal without being affected by strong clutter. The differential probe produced only one edge of the patch since most of the corrosion was concentrated on one side of the patch. Overall, the differential probe image contains stronger corrosion signal and is more indicative of the corrosion presence.

SUMMARY

Imaging properties of a single and a differential millimeter wave probes were presented. These probes were used to detect corrosion on aluminum structures. Millimeter wave open-ended waveguide probes are sensitive to the presence of corrosion and produce images with high spatial resolution. However, they are also sensitive to slight changes in standoff distance. Standoff distance variation causes clutter which mask weak corrosion signal. These images may be processed to remove the clutter at the cost of possible loss of information.

The differential probe is highly insensitive to clutter sources such as standoff distance variation. On the other hand, its sensitivity to the presence of corrosion is preserved since it uses similar probing aperture to the single probe. Furthermore, the unique black and white signature produced by the differential probe enables the user to distinguish corrosion from unwanted clutter or noise. Since it is very unlikely that large areas of a structure will be uniformly corroded, the differential probe will detect not only the edges of the corroded area, it will also detect the inner parts of the corrosion patch. The differential probe is a highly reliable detection probe. For further thickness evaluation of corrosion, a single probe is a better candidate. The output of the differential probe depends on at least two reflected signals from adjacent areas. On the other hand, a single probe output depends only on the reflection properties of the immediate area beneath the probe.



(a) (b)

FIGURE 8. Intensity image of a very thin corrosion patch under paint using the V-band single probe at a standoff distance of 1.5mm and frequency of 71GHz; (a) single probe, (b) differential probe.

ACKNOWLEDGMENT

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