ESTIMATION OF CORROSION THICKNESS UNDER PAINT USING A SIMPLE MILLIMETER WAVE PROBE

Mohammad T. Ghasr¹, Reza Zoughi¹ and Gary Steffes²

¹Applied Microwave Nondestructive Testing Laboratory (amntl)
Electrical and Computer Engineering Department
University of Missouri-Rolla, Rolla, MO 65409
Email: zoughir@umr.edu

²Air Force Research Laboratory (AFRL), Wright Patterson, OH 45433

Abstract. Corrosion detection and damage estimation is a major concern in maintenance of critical structures and aircraft. Damage tolerance approaches which minimize maintenance costs require accurate knowledge of corrosion thickness or in other words accurate quantitative information about metal loss. A millimeter wave probe is an inexpensive and robust tool for detecting corrosion under paint and along with theoretical modeling it may also be used to estimate the thickness of the corroded region and subsequently translating that information into metal loss. This paper presents an approach to characterize such a probe, and to use it to obtain a quantitative measure of corrosion thickness under paint.

Keywords: Corrosion, Thickness, Millimeter wave, Estimation

1 INTRODUCTION

When considering maintenance of aging commercial and military aircraft, corrosion detection and damage estimation are important cost reducing issues. The damage tolerance approach is recently adopted among aircraft maintenance community for its ability to minimize costs while maintaining structure’s health. An important factor in monitoring the health of a structure is to accurately measure the metal skin thickness on different locations on the structure in particular in structurally critical regions. These data along with structural analysis tools, can provide a clear perspective about the load bearing capabilities of the structure.

Since millimeter wave signals do not penetrate inside metals, they cannot be directly used to measure the metal thickness as Eddy Current techniques do. However, millimeter wave techniques have shown high precision in measuring dielectric coating thickness [1-3]. Therefore, millimeter wave techniques may be used to measure corrosion thickness and from there, determining the material loss which later may be translated to remaining metal thickness in the structure. Several millimeter wave probes may be used to robustly detect and qualitatively assess the severity of corrosion [4]. However, accurate quantitative measurement of corrosion thickness requires characterization of these probes to link the measurement to theoretical modeling of the structure. This paper presents a model and a method of characterizing a millimeter wave probe for accurate estimation of corrosion thickness under paint.
2 THE PROBE

Accurately measuring complex reflection coefficient at millimeter wave range frequencies requires sensitive and expensive equipment such as a vector network analyzer. Therefore, it is preferable to use a small, inexpensive, and robust probe for in-field measurements. A millimeter wave reflectometer \[4\] is a good candidate, which outputs a voltage proportional to magnitude and/or phase of the reflected signal. However, to incorporate and correlate the results of models that predict the thickness of corrosion, phase and magnitude of reflection coefficient must be measured. Since a reflectometer does not directly provide information about these parameters, then the calibration of the reflectometer becomes necessary. Figure 1 shows the schematic of the reflectometer used for this purpose. The millimeter wave signal generated by the source is split equally into ports 1 and 2 of the magic-tee where the open-ended waveguide and a reference load are attached respectively. The reflected signal from the sample which is picked up by the open-ended waveguide and the reflected signal from the reference load are coupled into the detector through the magic-tee. Finally the detector outputs a voltage proportional to the difference of the aforementioned reflected signals. According to the schematic shown in Figure 1, the signal \(S\) at the detector may be found using the following equation:

\[
S = S_{43} + S_{41} \frac{S_{13} S_{51} \Gamma + S_{12} S_{23} S_{62} R}{1 - S_{12}^2} + S_{42} \frac{S_{23} S_{62}^2 R + S_{12} S_{13} S_{51} \Gamma}{1 - S_{12}^2}
\]  (1)

Where; \(\Gamma\) is the complex reflection coefficient at the aperture of the probe, \(R\) is the reflection from the reference (usually a short), and \(S_{mn}\) are the system S-parameters linking ports \(n\) to \(m\). These parameters should either be measured using a vector network analyzer or found using a calibration procedure as will be described in the next section. Finally, the output of the detector is found using Equation (2) where; \(P_s\) is the source power.

\[
V_d = P_s |S|^2
\]  (2)

Figure 1. Schematic of the single probe.
Equation (1) is an approximate expression and involves a few assumptions. For example, all the components making the circuit are assumed to be matched to each other (i.e. $S_{ii} = 0$) which is a valid assumption given that connecting waveguide components produce small return losses. $S_{51}$ and $S_{62}$ are the characteristics of the sections of transmission lines (waveguides) connecting the magic-tee to the radiating aperture and the reference short respectively. These sections of transmission line are lossless, therefore $S_{51}$ and $S_{62}$ will only represent a phase shift given by $e^{-j\beta d}$, where $d$ is the length of that particular waveguide section and $\beta$ is the wave propagation constant in the waveguide.

The largest obstacle in using these equations is finding the magic-tee S-parameters ($S_{12}$, $S_{13}$, $S_{23}$, $S_{43}$, $S_{41}$, and $S_{42}$). An ideal magic-tee is balanced and does not have coupling between its collinear arms and its E- and H-plane arms. In other words for an ideal magic-tee $S_{13} = S_{23} = 0.5$, $S_{41} = -S_{42} = 0.5$, and $S_{12} = S_{43} = 0$. However, no commercial magic-tee is ideal, subsequently these parameters should either be measured using a vector network analyzer or found using a calibration procedure which involves measuring the output of the probe for known loads such as a matched load or a short.

3 RESULTS

In order to measure corrosion thickness in practice, first the corrosion area is scanned using the millimeter wave probe (Figure 1). An example image of a 0.75 inch squared corrosion patch on aluminum (2024 alloy) substrate and under 69 μm-thick paint is shown in Figure 2. The intensity in the image is directly related to the voltage output of the probe which is in part is related to complex reflection coefficient as seen by the open-ended waveguide probe irradiating the paint, corrosion, and metal structure. The voltage output of the probe will subsequently be used to estimate the thickness of corrosion. The complex reflection coefficient is simulated using an electromagnetic model that calculates reflection coefficient at the aperture of a waveguide irradiating a multi-layered dielectric structures backed by a conductor (paint, corrosion, aluminum) [5]. The simulated result is then converted into voltage using the model described by Equations (1) and (2). Consequently, the thickness for the corrosion patch is found by iteratively comparing the results of the simulated data to the measurement. The probe model (Equations 1 and 2) is only reliable when all parameters are known. The most important part of that model which is the magic-tee is far from ideal and has to be characterized. The best approach for the characterization of the various model elements is to use a vector network analyzer. On the other hand, when one is not available at the desired frequency band, an alternative method of using two known loads (a match and a short) may be used, as was done here. For a V-band (50 – 75 GHz) probe, the response of the probe to each load for the reference short distance of 0 to 6 mm was measured, as shown in Figure 3. This figure shows that the response of the probe is far from ideal, for example; ideally the response to the match load must be a constant.
Few assumptions were made before characterizing the probe. First, the magic-tee was assumed to be balanced and reciprocal (i.e. $S_{13} = S_{23} = \sqrt{0.5(1 - S_{43}^2)}$, $S_{41} = -S_{42} = \sqrt{0.5(1 - S_{43}^2)}$).

Second, the waveguide sections linking the magic-tee to the reference short and the load were assumed to be lossless. The characterization was performed using an iterative search algorithm on five dimensions, namely; the magnitude and phase of $S_{12}$ and $S_{43}$, and the source power $P_s$.

Although the source power was given in its data sheet, the search helped in accounting for the losses in the probe (which was not modeled) and the data sheet inaccuracy. After characterizing the probe, the simulated probe responses to a match and a short load were determined, as also shown in Figure 3.

![Figure 3. Characterizing the single probe circuit.](image-url)
For a given paint thickness a curve may be generated that links the voltage output of the probe to the corrosion thickness. Using the electromagnetic formulation in [5] the reflection coefficient as seen by a V-band open-ended waveguide irradiating a structure consisting of a 69 μm-thick layer of paint and a layer of corrosion with varying thickness from 0 to 100 μm on top of an aluminum plate was simulated at the frequency of 74 GHz. The relative dielectric constant of paint was chosen to be 3.37-j0.1 and that of corrosion was 3.49-j0.35 [6]. Figure 4a shows the magnitude of reflection coefficient plotted vs. corrosion thickness. As expected, there is a very little change in the magnitude, which renders it useless in estimating the corrosion thickness. On the other hand, the phase of reflection coefficient (Figure 4b) shows a substantial response to the changes in corrosion thickness. The complex reflection coefficient (phase and magnitude) was fed to the calibrated probe model to obtain the voltage data. The reference short here was set to obtain maximum phase sensitivity out of the probe. Figure 5 shows the voltage data referenced to the case when no corrosion is present. For 100 μm change in corrosion thickness, this curve is linear and shows a substantial change of 150 mV. Consequently this curve can serve as a calibration curve for directly measuring the corrosion thickness. Taking the image of Figure 2 as an example, the average voltage reading of the corrosion area (dark) minus the average voltage of the clean, paint only area (bright) yields approximately 14 mV which using the information in Figure 5 translates to approximately 9.2 μm of corrosion thickness.

4 CONCLUSIONS

The millimeter wave reflectometer, is a relatively inexpensive tool for the detection and quantitative thickness evaluation of a corrosion layer under paint. This probe may be easily modeled and characterized using a simple procedure. Consequently, the characterized probe may be used in conjunction with theoretical modeling to accurately estimate the thickness of corrosion layer under paint. For a given structure of known paint thickness and dielectric constant, the probe exhibits linear corrosion thickness to voltage relationship.
Figure 5. Simulated probe output voltage vs. corrosion thickness.

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