Measurement of Dielectric Constant of paint coated aluminium panel through Microwave Non Destructive Testing at frequency 18GHz to 26GHz (K band)

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Abstract—**Microwave non-destructive testing of paint and primer in components commonly used in moist and salty environment are very crucial in the investigation of signs of corrosion. In this paper, we present a method for measuring the dielectric properties and loss factor of paint coated aluminium panels using the metal-backed method. Complex reflection coefficient (S_{11}) is measured for Plexiglas container backed by metal plate. Dielectric constant and loss factor were measured for corrode and non-corrode paint coated aluminium panel in the frequency range of 18 to 26GHz (K-Band). The thru, reflect and line (TRL) calibration technique were used to eliminate the effect of undesirable multiple reflections. The dielectric constant for corrode paint coated aluminium panels is 2.9± 0.1 and for non-corrode paint coated aluminium panel is 2.5±0.1, showing that the dielectric constant of corrode samples are higher than non-corrode ones. The loss factor for corrode aluminium panels is ranged from -0.02 to -0.01 and for non-corrode aluminium panels, the loss factor is from -0.083 to -0.008. Loss factor for corrode aluminium panel is higher than that of non-corrode aluminium panel. The differences could be due to errors in the magnitude and phase of S_{11}, surface of the paint coated aluminium panel and the air-gap effect during the assembly of the sample.**

Keywords— Corrosion, Paint Coated Aluminium Panel, Free space Microwave Measurement (FSMM), Gaussian Optic Lens (GOA) antenna, Thru, Reflect, Line (TRL), Vector Network Analyzer (VNA), Microwave Non-destructive Testing (MNDT)

I. INTRODUCTION

In recent years, much attention has been given to the problems of improving the inspection of the strength state of materials and structures and assessing their durability in developing rockets and spacecraft technologies. This therefore requires the development of improved techniques and instruments.

Microwave non-destructive testing (MNDT) techniques are being used to evaluate the quality of anti-corrosive protective coatings and paints on metal surfaces [1]. A free-space microwave measurement (FSMM) system is used for MNDT of protective coatings [1].

It has been reported that many techniques such as cavity resonant technique, coaxial line and waveguide were employed to evaluate dielectric properties of many substances.

Non-destructive testing (NDT), also called non destructive examination (NDE) and non-destructive inspection (NDI), is testing without destroying the test object. This method definitely provides unique non-destructive approaches to material testing. However, it requires a lot of skill and expertise to handle usage of microwave for material flaw detection. Moreover, the cost and complexity which applies to microwave makes it quite hard for people to get used to it.

In this paper, the MNDT of paint coated aluminium panels using metal back method is depicted. The complex reflection coefficient (S_{11}) is measured for Plexiglas container backed by metal plate. We used the free-space implementation of reflection-transmission method for simultaneous determination of complex permittivity (ε^*) and complex permeability (μ^*) of the aluminium panels. Dielectric constants and loss factors were measured for corrode and non-corrode paint coated aluminium panels within the frequency range of 18 to 26 GHz.

To minimize errors which can be due to diffraction, the use of the spot focusing horn lens antennas is necessary [2]. The use of free-space TRL calibration and time domain gating, which is a feature of VNA are also required to eliminate/minimize errors due to multiple reflections between antennas.

II. THEORY

For metal back method, we first measure the reflection coefficient (S_{11}), which can be used to compute the complex permittivity (ε^*) of the sample. Figure 1 shows the schematic diagram for metal back technique of the samples of coated aluminium panels.

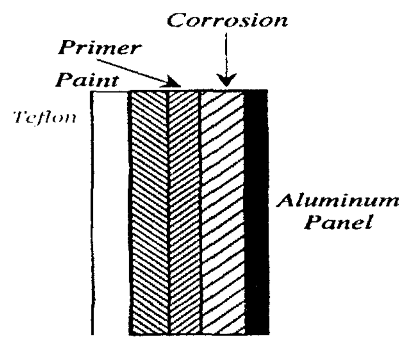

Figure 1: Schematic diagram for metal back method.

Complex permittivity (ε^*) of the sample can be computed from measured reflection coefficient (S_{11}). From transmission line theory, $S_{11}$for normal incidence plane is related to the complex relative permittivity $\varepsilon^* = \varepsilon' - j\,\varepsilon'' = \varepsilon'\,(1-j\tan\delta_{\varepsilon})$ by the following relationship [2]

$$S_{11} = \frac{jZ_{dn}\tan(\beta_d d) - 1}{jZ_{dn}\tan(\beta_d d) + 1} \quad (1)$$

where Z_{dn} is normalized impedance in the unknown material and d is the thickness of the sample.

For non-magnetic materials, Z_{dn} is given by

$$Z_{dn} = \frac{1}{\sqrt{\varepsilon^*}} \quad (2)$$

The phase constant is given by β_d is given by

$$\beta_d = \frac{2\pi}{\lambda_0}\sqrt{\varepsilon_d^*} \quad (3)$$

where λ is the wavelength of free space. The complex permittivity ε* is found iteratively from (13)- (15). This is done by using a zero finding technique which finds the zeros of the error function. The error function is defined as:

$$E = \left| S_{11}^{m} - S_{11}^{c} \right| \quad (4)$$

where S_{11}^{m} and S_{11}^{c} are measured and calculated complex reflection respectively. The muller method with deflation is used for calculation of zeros of the error function [4].

III. CALIBRATION AND MEASUREMENT SET UP

Before the calibration of the VNA, the thickness of the paint coated layer on each sample and the thickness of the aluminium panels had to be determined. The thickness was measured using sheen gloss meter from SIRIM Berhad as shown in figure 2 below.

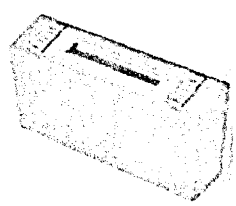

Figure 2: SHEEN gloss meter from SIRIM Berhad used to measure the thickness of paint coating and aluminium panels.

The whole measurement is done using a GOA Gaussian optics lens antennas that form well-defined Gaussian beams through the use of corrugated feed horns and efficient dielectric lenses. In Gaussian optics transmission, the propagating signal is not confined by metal or by dielectric walls, but travels in free space, resulting in a very low loss system. Figure 3 shows the GOA optic lens antenna

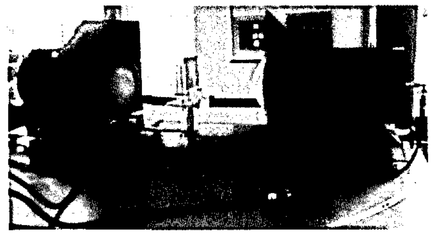

Figure 3: GOA Gaussian Optic Lens Antenna

GOA antennas are available in waveguide bands from 18 to 220 GHz. In Gaussian optics transmission, the propagating signal is not confined by metal or by dielectric walls, but travels in free space, resulting in a very low loss system. The series GOA is available in single or dual polarization. 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 one is moveable).

This project is implemented using half-wave at mid-band. The mid-band for the K-band frequency is 22GHz. For all the S-parameter measurements, we used the Wiltron 37269B vector network analyzer system. Initially, we do calibration of the VNA. Afterwards, we measure Teflon and Plexiglas to ensure that the results are indeed accurate. Following this, we then measured the samples one by one by placing it together with the Teflon in front in the sample holder i.e. between the plates. Network Analyzer measures the two-port scattering parameters of a device under test (DUT).

Multiple reflections between coaxial-to-rectangular waveguide adapters, rectangular-to-circular waveguide transition and the antennas can be very troublesome. Hence, it is necessary to calibrate the equipment in free space for S-parameter measurements. Here, we implemented the free-space TRL calibration technique. The calibration techniques together with the time domain gating feature of the network analyzer enhance the results and also eliminate unwanted effects of multiple reflections.

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. Free-space LRL calibration is implemented by establishing three standards, namely, a through connection, short circuit connected to each port and a transmission line connected between the test ports. The complete schematic diagram of the free-space microwave measurement system is shown below in figure 4.

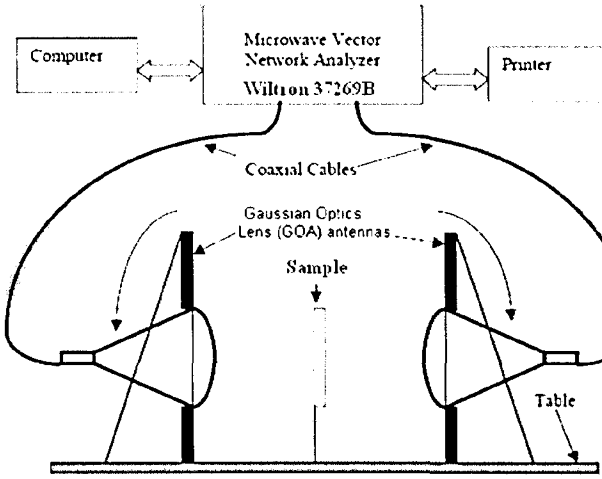

Figure 4: Schematic diagram for Non destructive Testing (NDT) techniques in free-space measurement

For thru concept of the calibration technique, the first device is set to 0.00mm whereby there is nothing in between the plates. Then, the distance shown on the micrometer is moved behind by 3.409mm from the centre of the middle reference plates. This process is designed for the line concept of calibration technique. For the reflection concept, the distance must be moved behind depending on the thickness of the metal plate used (3.18mm in our case).

It is necessary for the focal distance to antenna diameter (F/D) of the lens to be equal to one and D to be approximately 30.5 cm.

The VNA of label Wiltron 37269B network analyzers utilize synthesized-frequency sources to provide a known test stimulus that can sweep across a range of frequencies or power levels. The vector network analyzer measures the amplitude and phase of reflected or transmitted signal in any transmission media such as coaxial line, rectangular waveguide, micro strip line and free-space. The equipment can also perform rationalised measurements (including phase), which require multiple receivers. It can give us large amount of data from the device under test (DUT), including its magnitude, phase, and group-delay response. After TRL calibration, the thru connection was measured.

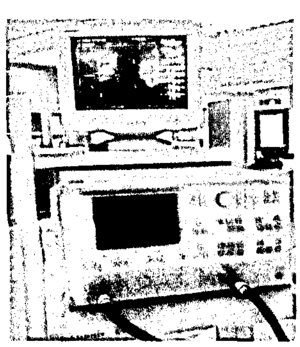

Figure 5: Vector Network Analyzer (VNA)

Figure 5 shows the Vector Network Analyzer Wiltron 37269B used for the calibration and measurement system. This network analyzer is used to make accurate reflection and transmission (S-parameters) measurements in free-space using line-reflect-line calibration model.

After LRL calibration, we measured the dielectric properties of Teflon and Plexiglas respectively at 22GHz to verify whether the calibration was accurate or not. The measured dielectric constants of Plexiglas and Teflon sample are 2.609 and 2.046 respectively and correct to 3 decimal places. In literature [5], Plexiglas and Teflon value are reported as 2.59 and 2.08, respectively. The values obtained are very much similar to the values reported in literature [5].

Figure 6 below depicts clearly the different layers of the sample, namely the aluminium panel, the primer, the paint and the corrosion layer (for corrode samples only).

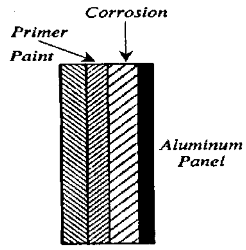

Figure 6: Layers of the sample of the aluminium panel

IV RESULTS

For measurement of complex transmission coefficient (S_{21}) and complex reflection coefficient (S_{11}) of composite material sample, the reference planes corresponding to transmit and receive antennas were located at the front and back face of the sample which is Plexiglas. The residual post calibration errors can be further reduced by using time domain gating or smoothing function of VNA.

The amplitude and phase of S_{11} were 0.0 ± 0.1 dB and $180^\circ \pm 0.2^\circ$, while the amplitude and phase of S_{21} were 0.0 ± 0.02 dB and $0^\circ \pm 1^\circ$ respectively. The theoretical value for the magnitude and phase of S_{11} are 0dB and 180° respectively. The magnitude and phase of S_{21} the theoretical values of are 0dB and 0° respectively. Measurements and theoretical values of S_{11} and S_{21} show extreme resemblance. This implies that calibration was successful.

We then measured Plexiglas followed by Teflon. The measured dielectric constants of Plexiglas and Teflon sample are 2.64 and 2.046, respectively. In the literature [5], Plexiglas and Teflon value are reported as 2.59 and 2.08, respectively. The values obtained are very much similar to the values reported in literature [5]. The Plexiglas quarter wavelength was 3.409mm.

By using the computer simulation based on the equations (1) to (4), the result of the complex permittivity of the aluminium panels can be calculated. When doing the measurement of the ten samples, the Teflon which is of thickness (0.0975mm) is placed in front of the sample. This is the metal back method used as the thickness of the aluminium panel is too thin to get accurate results. Hence we use Teflon in front of the sample in the sample holder and adjust the distance regarding to the thickness of the Teflon as well. Hence, the total thickness is the summation of the thickness of Teflon and that of the aluminium panel.

In all, ten samples were used for this measurement in order to get a more accurate result, five of which are non-corrode samples and the other five are corrode paint coated aluminium panel. The dielectric constant (ε'), the loss factor and the loss tangent for corrode and non-corrode paint coated aluminium panels at a frequency of 22GHz are shown in table 1. We choose 22GHz, as it the centre frequency and it is most stable compared to the other frequencies.

Table 2 and table 3 show the dielectric constant (ε'), the loss factor and the loss tangent for corrode and non-corrode paint coated aluminium panels across various frequencies within 17.5GHz to 26.5 GHz

Table 1
The dielectric constant (ε'), loss factor (ε") and the loss tangent for both corrode and non-corrode paint coated aluminium panels at 22GHz are shown in the table below.

Samples	Dielectric Constant (ε')	Loss Factor (ε")	Loss tangent (tan δ)
C1	2.9629	-0.0198	0.0067
C2	2.9397	-0.0169	0.0058
C3	2.9695	-0.0172	0.0058
C4	2.9326	-0.0153	0.0052
C5	2.8134	-0.0144	0.0051
N1	2.3676	-0.0080	0.0034
N2	2.4411	-0.0083	0.0034
N3	2.3332	-0.0093	0.0040
N4	2.4447	-0.0087	0.0036
N5	2.4161	-0.0095	0.0040

Table 2
The dielectric constant (ε'), loss factor (ε") and the loss tangent for corrode paint coated aluminium panels across frequencies are shown in table 2 below.

Frequency (GHz)	Dielectric Constant	Loss factor	Loss Tangent
17.5	3.6624	-0.2195	0.0599
19.12	1.6741	-0.0054	0.0032
19.3	1.8197	-0.0052	0.0028
22	2.9341	-0.0173	0.0059
23.26	2.0734	-0.0137	0.0066
24.88	3.9620	-0.0248	0.0062

Table 3
The dielectric constant (ε'), loss factor (ε") and the loss tangent for non-corrode paint coated aluminium panels across frequencies are shown in table 3 below.

Frequency (GHz)	Dielectric Constant	Loss factor	Loss Tangent
17.5	1.1429	-0.0572	0.0500
19.12	1.3436	-0.0021	0.0016
19.3	1.2941	-0.0030	0.0023
22	2.4363	-0.0216	0.0089
23.26	2.3008	-0.0161	0.0070
24.88	4.2893	-0.0223	0.0052

The relative to free-space dielectric properties (or constant) of a material is generally a complex parameter ($\varepsilon_r = \varepsilon_r' - j\varepsilon''$) whose real part (relative permittivity) indicates the ability of the material to store microwave energy (i.e., material's tendency to be polarized), while its imaginary part (relative loss factor) indicates the ability of the material to absorb microwave energy [6]. According to literature [6], the dielectric properties of paint and primer were measured to be ε_r=3.48-j0.12. However theoretical investigation involving simulating painted aluminium panel with and without corrosion shows a value of dielectric constant of 2.290 –j0.024 at Ku band and 2.489-j0.078 at G band. So according to literature [6], the dielectric constant must be approximately 3 for corrode paint coated aluminium panels.

Measured dielectric constant for corrode and non-corrode paint coated aluminium panel is almost similar to the published data in literature [6].

Figure 7 below depicts a graph which shows the comparison of the dielectric constant against frequency of the average results obtained for corrode and non-corrode samples respectively.

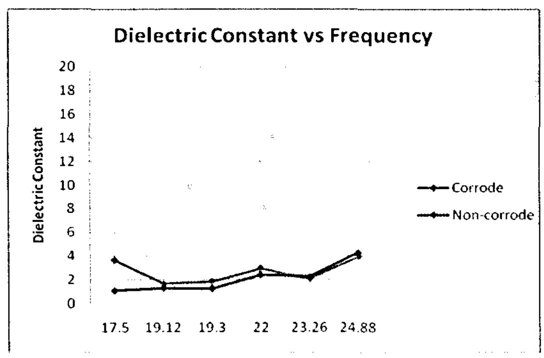

Figure 7: Comparison of the dielectric constant against frequency for corrode and non-corrode aluminium panels.

Figure 8 shows a graph of the comparison of the loss factor against frequency for corrode and non-corrode samples respectively.

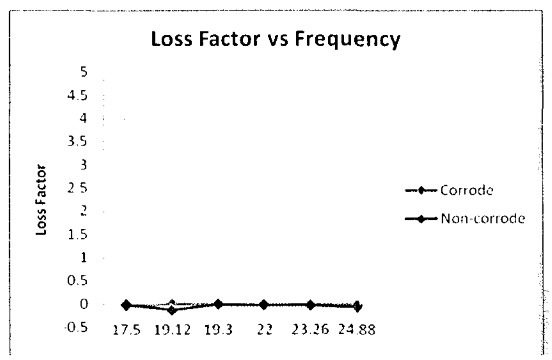

Figure 8: Graph comparison of the loss factor against frequency for corrode and non-corrode samples

Figure 9 shows a graph of the comparison of the loss tangent against frequency for both corrode and non-corrode samples respectively.

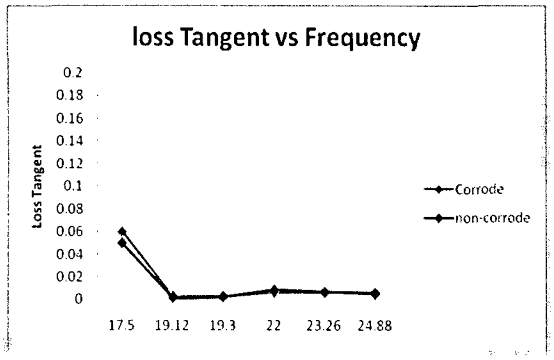

Figure 9: Graph comparison of the loss tangent against frequency for corrode and non-corrode samples

V. DISCUSSION

From the results obtained, the dielectric constant for paint coated corrode and non-corrode aluminium panels is noticed to be close to 3 as reported by literature [6].

At 22GHz, the corrode samples have an average dielectric constant of 2.9341, a loss factor of -0.0173. The values for the dielectric constant of the corrode samples ranges from 2.8134 to 2.9695. As for the loss factor, the values ranges within -0.0198 and -0.0144. The calculated average value for the loss tangent of the corrode samples is 0.0059 and varies from .0051 to .0067.

For the non-corrode samples, we obtained an average dielectric constant of 2.4363 and a loss factor of -0.0216. The calculated average value for the loss tangent is 0.0089. The values for the dielectric constant of the non-corrode samples range from 2.3332 to 2.4447. As for the loss factor and the loss tangent, the values range from -0.0095 to -0.080 and from 0.0034 to 0.034.

From my results at 22GHz, I can deduce that the dielectric constant for corrode aluminium panel is higher than that of a non-corrode one. The loss factor of both of them is almost the same with non-corrode samples having a slightly lower loss factor than corrode samples and the loss tangent for corrode is slightly higher than that of non-corrode paint coated aluminium panels. .

Averaging is done by choosing proper values of the dielectric constant and loss factor from the measurements taken. An investigation is carried out to determine their variation with frequency as shown in figure 7, 8and 9. Within a range of 17.5GHz to 25GHz, the dielectric constant can be seen to increase as frequency increases. The values of the dielectric constant can be seen to fluctuate within the frequency range. From 22GHz, there is a decrease in the dielectric constant until 23.26GHz, and then an increase again. The dielectric constant ranges from 1 to 4.5 approximately as seen in figure 7. Overall, the dielectric constant is increasing with an increase in frequency.

As for figure 8, we can deduce that the loss factor is almost constant across frequency. There is very slight variation. Point to be noted that for most of the values, the loss factor of corrode samples is slightly higher than that of non-corrode samples as shown in figure 8. The loss factor and dielectric constant for corrode samples are higher than that of non-corrode paint coated aluminium panels. This implies that higher is the dielectric constant and the loss factor, higher is the loss and higher is the degree of corrosion.

The loss tangent is calculated and plotted against frequency as shown in figure 9.

Loss tangent is the ratio of the loss factor to the dielectric constant.

The formula for loss tangent is

$$\text{Loss tangent } (\tan \delta) = \left|\frac{\varepsilon''}{\varepsilon'}\right| \qquad (12)$$

ε" refers for loss factor and ε' is dielectric constant. From this equation, loss tangent is always positive.

Again, it can be noticed that the loss tangent is higher for corrode samples than that of non-corrode ones. Point to be noted that the loss tangent must always be greater than zero that is it must be positive. There is a decrease in loss tangent from 17.5 GHz to 19.12 GHz and then the values of the loss tangent starts to increase again slowly onwards. The higher is the loss tangent, the higher is the loss of the material and therefore the more exposed is the material to corrosion.

In order to get the most accurate results, the calibration must be done very effectively and efficiently. Calibration results should be the same as theoretical results which are a magnitude of 0dB for S_{11} and a phase angle of 180°. S_{21} magnitude must be around 0 dB with a phase angle of 0°. Another factor that can affect the measurements is the environment within which the measurement is being done. Dealing with microwave needs much care and sensitivity as any unneeded action can abrupt the readings.

VI CONCLUSION

In this paper, FSMM has been used for the MNDT of the samples of corrode and non-corrode paint coated aluminium panels. From the samples being measured, we obtained the dielectric constant and the loss factor for corrode and non-corrode coated aluminium panels. The loss tangent was calculated using the formula (12).

For the non-corrode samples, we obtained an average dielectric constant of 2.4363, a loss factor of -0.0216 and a loss tangent of 0.0045. As for the corrode samples, the dielectric constant is 2.9341, the loss factor is -0.0173 and the loss tangent is 0.0059.

The dielectric constant for non-corrode and for corrode paint coated aluminium panels are respectively (2.42 to 2.61) and (2.81 to 2.99) adjusted to two decimal places. The average dielectric constant for corrode and non-corrode aluminium panels are respectively 2.93 and 2.44 correct to two decimal places.

At a frequency of 22GHz, the dielectric constant for corrode samples are higher than non-corrode ones. This can be noticed at the other different frequencies as well, which is denoted by figure 7. Loss factor for the corrode samples is slightly higher than the non-corrode paint coated aluminium panels as seen in figure 8. The variation of the loss tangent with frequency can be seen in figure 9.

The loss tangent of corrode samples are higher than that of non-corrode samples. Dielectric constant and the loss factor can be said to be directly proportional to the degree of corrosion of the aluminium plate as with corrode panels, the dielectric constant and the loss factor are higher than with non-corrode panels. Due to the low loss nature of these layers, the magnitude of reflection coefficient was not of much use. From the calculated values of the loss tangent, it can be deduced that the loss tangent is directly proportional to the degree of corrosion, as for corrode samples, the loss tangent is higher than for non-corrode samples.

Free space non destructive material and contactless method is developed at microwave frequency which gives accurate values of dielectric properties of paint coated aluminium panels. Although the primary results are rather promising, other factors should be included to improve the accuracy of the measurements.

The microwave properties of corrode and non-corrode samples have been measured and are satisfactory. MNDT has been implemented as the investigation method to verify the parameters of the samples. The metal back method has been implemented. The different properties of corrode and non-corrode samples have been analyzed and discussed. Hence, we can say that we have achieved our objectives for this project.

In the future development, we have to simulate the sample measurement by using CST software. Moreover, we have to use a larger number of samples in order to get better accuracy in the results. Third, we can classify the degree of corrosion into different stages for e.g. early, mid and final stages for a better analysis of each stage of corrosion.

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