DETECTION OF CORROSION USING MILLIMETER WAVES

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ABSTRACT

Corrosion in metallic structures leads not only to a loss of metal, but also to changes in physical properties leading to a degradation of its mechanical strength. In occasions where the metallic structure is covered, the corrosion process is invisible and it is necessary to employ nondestructive testing (NDT) methods for the detection of the degree of the developed corrosion.

A technique for the detection of the corrosion degree using millimeter and sub-millimeter waves is presented. It is based on the electromagnetic wave reflection properties of the metallic structure. Illumination the structure by millimeter waves, the power reflection is measured for several different incident angles. The dielectric and magnetic properties of the material are evaluated using the Fresnel equations, revealing the electrical conductivity of the metal in the presence of corrosion.

Based on a theoretical study, a computational solver is developed for the analysis of different metallic structures. We demonstrate the technique using electromagnetic radiation in several frequencies in the millimeter wavelengths.

I. INTRODUCTION

Recently, deterioration of infrastructure is becoming a serious problem in the world. Among the biggest problems is the development of corrosion in oil and the gas pipelines. Maintenance and inspection of aging infrastructures becomes important. Non-destructive tests identifying corrosive defects in crude oil pipelines and storage tanks, are required during maintenance procedures.

Tera-Hertz waves has been receiving increasing attention in many engineering applications. THz waves penetrate dielectric materials and are reflected from metallic ones. They are considered to be safe for remote sensing and imaging. Different materials have their own fingerprint reflection spectrum [1]. The quasi-optical properties of THz waves enables developing inspection techniques for the substrate metallic material, such as iron oxide (Fe_2O_3) and iron oxide (Fe_3O_4), and evaluate their corrosion rate.

Metals are known for having high reflectivity for electromagnetic (EM) radiation. High reflectance of EM wave in lower frequencies is associated to high conductivity, following the Hagens-Ruben relation. In the present study, we consider electromagnetic wave in millimeter and sub-millimeter wavelengths, illuminating conducting plane metallic surface in different incident angles, and study the corresponding reflections for different corrosion degrees.

II. THEORETICAL BACKGROUND

The power reflectance (R) of electromagnetic wave from a material is defined as the efficiency of a material to reflect incident light [2]. This value depends on the complex refractive index (n_R) and the damping constant (n_I):

$$\hat{n} = n_R + jn_I = \sqrt{1 + i\frac{\sigma}{2\pi\varepsilon_0 f}} \tag{1}$$

$$(\hat{n})^2 = {n_R}^2 - {n_I}^2 + j2n_R n_I = 1 + i\frac{\sigma}{2\pi\varepsilon_0 f}$$

These two sets of constants are most applicable depends on the material under investigation. Reflection and transmission by bulk media are best described using the complex refractive index. The media with which we are concerned have complex refractive indices that depend on wavelength. Using (1), the following relations are derived:

(2)
$$n_R{}^2 - n_I{}^2 = 1$$
$$2n_R n_I = \frac{\sigma}{2\pi\varepsilon_0 f} \rightarrow n_R = \frac{\sigma}{4n_I\pi\varepsilon_0 f}$$

Positive root is taken for the quadratic solution, because both the refractivity and damping index are real quantities:

(3)
$$n_I = \frac{1 + \sqrt{1 + 4(\frac{\sigma}{4\pi\varepsilon_0 f})^2}}{2}$$

When media are semi-infinite and transparent, the transmission and reflection angles are given by Snell's law. Fresnel's equations describe the reflection and transmission coefficients for both polarization types; transverse electrical (TE) and transverse magnetic (TM) [3]:

(4)
$$\rho_{TE} = \frac{cos(\theta_0) - \sqrt{n_R{}^2 - n_I{}^2 - \sin^2\theta_0 + j2n_R n_I}}{cos(\theta_0) + \sqrt{n_R{}^2 - n_I{}^2 - \sin^2\theta_0 + j2n_R n_I}}$$
$$\rho_{TM} = \frac{-[n_R{}^2 - n_I{}^2 + j2n_R n_I]\,cos(\theta_0) + \sqrt{n_R{}^2 - n_I{}^2 - \sin^2\theta_0 + j2n_R n_I}}{[n_R{}^2 - n_I{}^2 + j2n_R n_I]\,cos(\theta_0) + \sqrt{n_R{}^2 - n_I{}^2 - \sin^2\theta_0 + j2n_R n_I}}$$

Substitution of Equation (2) into (4) results in:

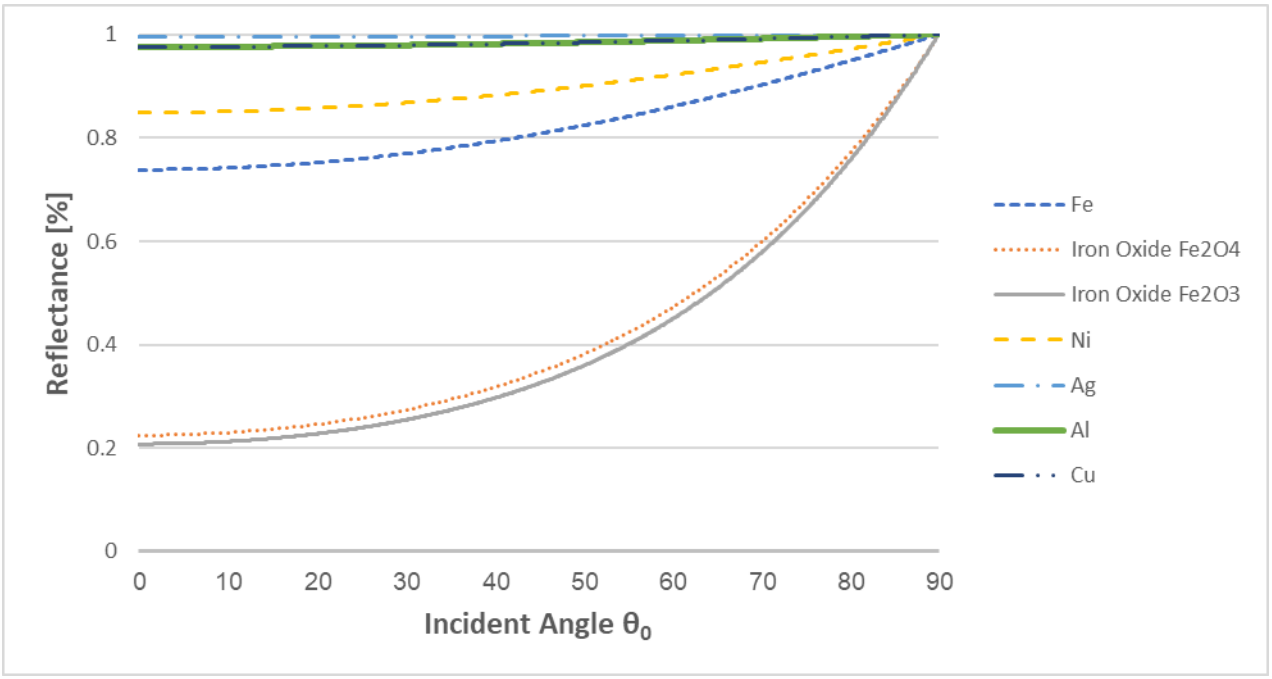
(5)
$$\rho_{TE} = \frac{cos(\theta_0) - \sqrt{cos^2(\theta_0) - j\frac{\sigma}{2\pi\varepsilon_0 f}}}{cos(\theta_0) + \sqrt{cos^2(\theta_0) - j\frac{\sigma}{2\pi\varepsilon_0 f}}}$$

$$\rho_{TM} = \frac{-\left[1 + j\frac{\sigma}{2\pi\varepsilon_0 f}\right]cos(\theta_0) + \sqrt{cos^2(\theta_0) + j\frac{\sigma}{2\pi\varepsilon_0 f}}}{\left[1 + j\frac{\sigma}{2\pi\varepsilon_0 f}\right]cos(\theta_0) + \sqrt{cos^2(\theta_0) + j\frac{\sigma}{2\pi\varepsilon_0 f}}}$$

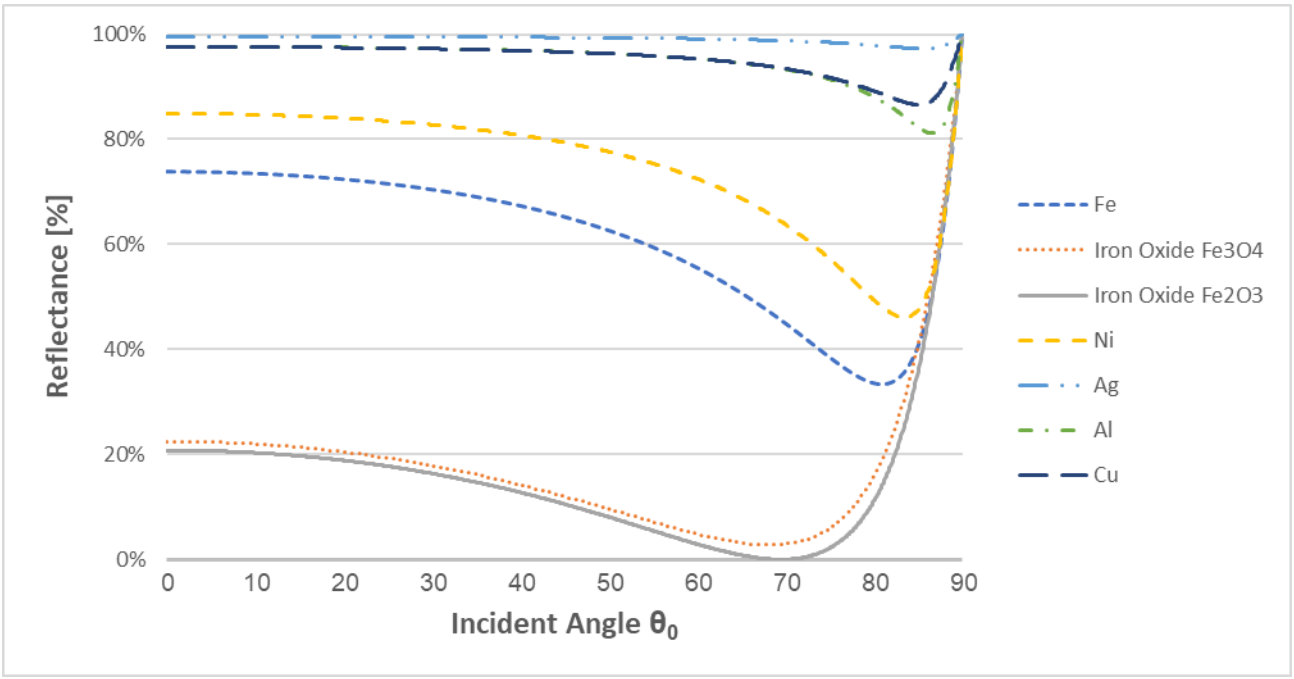
Power reflection from metals is given by $R = |\rho|^2$. Table 1 summarizes refractive characteristics for different metallic and semi-conducting materials. The corresponding power reflection for normal wave incidence is also shown. Figure 3 shows the power reflectance for both TE and TM polarizations for several known metals [5], [7].

Table 1: Typical optical constants and reflectance (normal incidence) of metals and semi-conductors in air.

Material	Wavelength [mm]	n_R	n_I	R(%)
Aluminium	0.22	0.14	2.35	91.8
	0.546	0.82	5.99	91.6
	1.0	1.4	9.5	94.2
	10.0	25.4	67.3	98.1
Silver	0.55	0.055	3.32	98.2
	10.0	10.7	69.0	99.1
Gold	0.55	0.33	2.32	81.5
	1.0	0.27	7.07	97.9
	10.0	7.4	53.4	99.0
Rhodium	0.546	1.62	4.63	77.1
Chromium	0.546	2.51	2.66	48.2
Nickel	0.54	1.85	3.27	60.7
Copper	0.55	0.76	2.46	66.8
Steel	0.55	2.4	3.4	58.5
Silicon	0.546	4.05	0.03	36.5
	1.50	3.48	0	30.6
	5.0	3.422	0	30.0
Germanium	0.545	5.15	2.15	51.5
	1.50	4.28	0	38.6
	10.0	4.003	0	36.0
Gallium arsenide	0.55	4.04	0.3	36.6
	1.5	3.38	0	29.5
	5.0	3.30	0	28.6
Indium phosphide	0.55	3.65	0.4	33.0
	1.5	3.17	0	27.1
	5.0	3.09	0	26.1



(a)



(b)

Figure 3: Reflectance in different polarizations; (a) TE (b) TM.

III. PREPARATION OF CARBON STEEL SAMPLES

The tested materials were 3mm carbon steel samples. Four samples have been in different NaCl solutions to accelerated corrosion rate differently. The fifth plate was a clean plate and used as a non-corrosive reference. All samples have been dipped in solution for seven days. After seven days the samples went throughout cleaning and brushing to get a uniform surface avoiding further corrosion. At the end of the cleaning process the samples wad dipped in ultrasonic tube to get high resolution of cleaning and to get the highest uniform cleaning (see Figure 4).



(a)



(b)

Figure 4: Sample preparation: a) in different solutions,

b) An example of 3.5 % NaCl sample

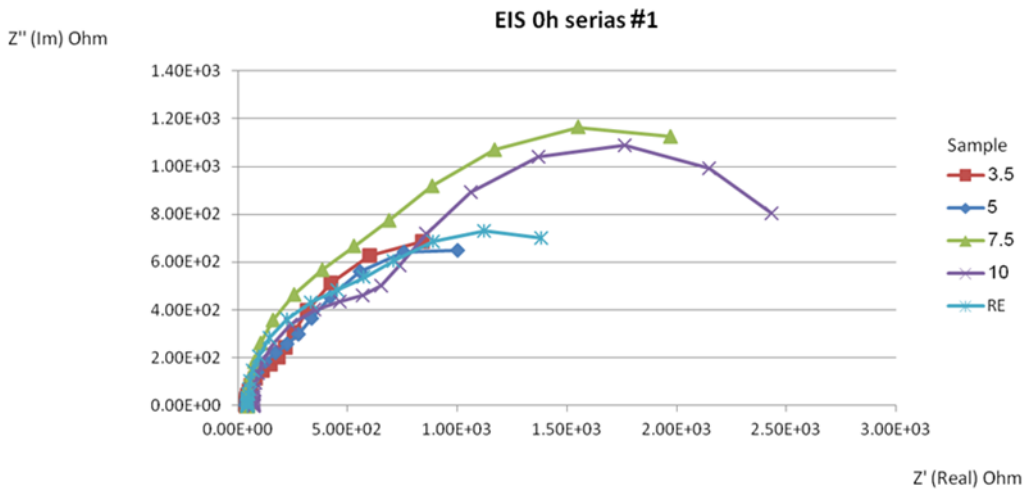
IV. ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY (EIS)

Weight loss and penetration measurements are the most common ways of assessing the corrosion resistance. However, electrochemical techniques such as polarization

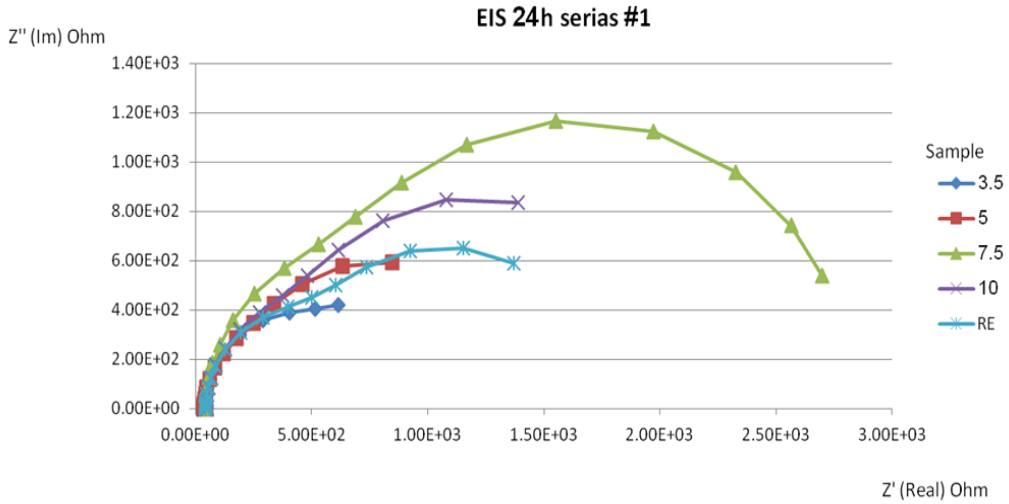
methods or electrochemical impedance spectroscopy are often used to supplement weight loss measurements and to evaluate corrosion mechanisms.

Electrochemical Impedance Spectroscopy EIS analysis is done in order to characterize the sample corrosion degree. The impedance of the samples is recorded as a function of frequency of the applied alternating current (AC) signal at a fixed (E,i) working point of polarization curve. This working point is often Ecorr (E=Ecorr, i=0). Usually a very large frequency range has to be covered to obtain the complete impedance spectrum. This frequency range is from 100KHz up to 1MHz, which is the upper limit of commonly used frequency response analyzers (FRAs). Measurements at lower frequencies are time consuming. Impedance data are usually determined employing three electrodes, although it is possible to use only two electrodes of the same material. In this case the EIS data are collected at E=0. The FRA is programmed to apply a series of sine waves, varying in frequency with constant amplitudes, small enough to remain in the linear regime. Impedance values are measured by the FRA at each frequency and stored in its memory. Because of the large number of data points have to be collected, displayed and analyzed, it is a essential to use adequate software for the processing. Such software is available from all major manufacturers of FRAs.

Information obtained with EIS differs from that determined using other techniques previously describe, because the corrosion system is analyzed at a fixed potential (or current) [8]. Properties of the material at this potential can then be determined via frequency response analysis of the measured impedance. One of the advantages of the EIS technique is that very small signals are applied, making it a nondestructive technique. In many cases, it demonstrates more reliable results than that obtained using existing models for corrosion based on direct current (DC) measurements.



(a)



(b)

Figure 5: EIS Nyquist mesuring: (a) after one hour (b) after 24 hours

for different corrosion rate

V. POTENTIO-DYNAMIC TECHNIQUE

Potentio-dynamic polarization curves can be obtaining as a single sweep, that is, the applied voltage $E_{Applied}$ is increased at a constant scan rate, S= d $E_{Applied}$ /dt, between a starting potential, E_s, which is often E_{corr} or possibly below, and a final potential, E_f. Sometimes the scan is reversed when E_f or a preset maximum current density is reached, and stopped when the previous E_{corr} or a new value of E_{corr} is reached. Great care has to be taken in choosing an appropriate value of the scan rate [9]. In general, less distortion of the true polarization curve occurs at the lowest scan rate. The results obtained with the dynamic potential techniques is shown in Figure 6 for the different samples examined.

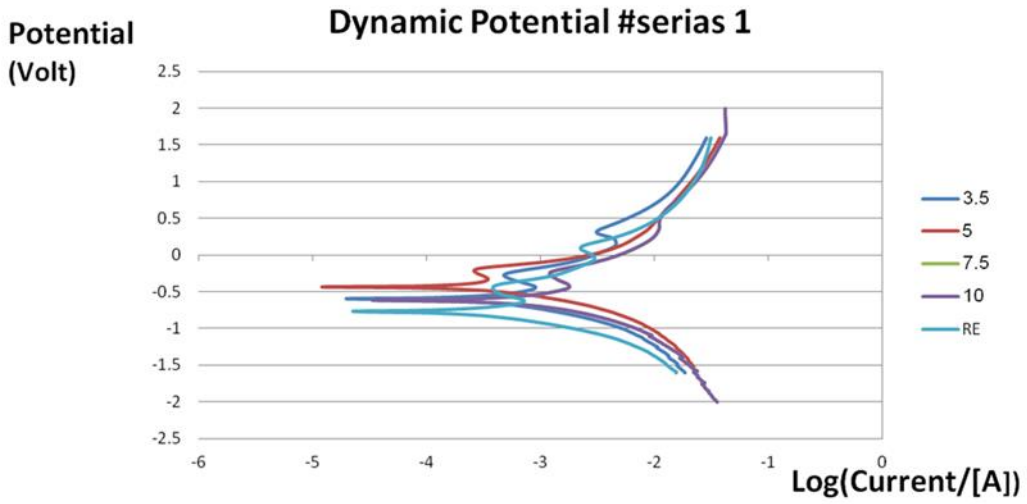


Figure 6: Dynamic potential for different corrosion rate

VI. EXPERIMENTAL SETUP

Figure 7 shows the schematics of sub-millimeter RF chain used in the experiment for the characterization of carbon steel metal at a frequency of $f = 330\,GHz$. It consists of the X-band Synthesizer with a power amplifier at its output that drives multi-stage multiplier (four sections) with a total multiplication factor of 4x2x2x2=32. The signal power at the output is 10mW and it is fed to a horn-lens antenna as shown in Figure 7. The signal reflected from the metal is captured by a pyroelectric detector [4]. The direction of the transmitted power is set to two different illumination angles 30 and 60 degrees.

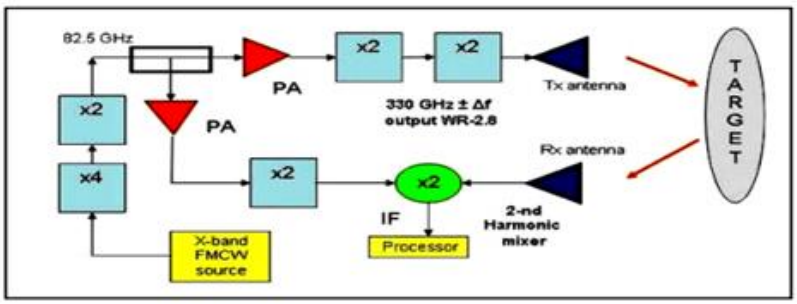


Figure 7: Transmitter and receiver RF chains schematics



Figure 8: Experimntal setup

VII. EXPERIMENTAL RESULTS

Millimeter and sub-millimeter wave can be used to predict corrosion rate. Reflectivity measurements are shown to correspond to corrosion degree as measured by Electrochemical Impedance Spectroscopy and from dynamic potential techniques. Table 2 summarizes sub-millimeter wave reflectivity measured for two incident angles, 30 degrees and 60 degrees. Same predictable differences between the samples with a different corrosion rate are revealed also in electromagnetic characterization technique. As corrosion rate increases, the reflection coefficients value become lower.

Table 2: Normalized reflection coefficients for the TE polarization

Corrosion	3.50%	5%	7.50%	10%
$\theta_0 = 30°$	0.214	0.151	0.038	0.027
$\theta_0 = 60°$	0.177	0.136	0.029	0.025

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