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# Nondestructive testing of marine protective coatings using terahertz waves with stationary wavelet transform

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ABSTRACT

Terahertz wave propagation in marine protective coatings and its non-destructive testing (NDT) capability were studied by the finite difference time domain (FDTD) method. The FDTD model was used to calculate the propagation and reflection of THz radiation from marine protective coatings. The reflected terahertz waves could be employed in coating thickness analysis of the paint layers. In order to clearly identify the interface between antifouling and anticorrosive coatings, stationary wavelet transform (SWT) approach was applied to decompose the obtained terahertz impulse functions into approximation and detail coefficients; SWT detail coefficients were used for the feature extraction of the coating thickness. SWT provides a more accurate identification of salient features in a signal, such as the weak feature between antifouling and anticorrosive coatings. We found that the developed model and SWT-based algorithms could be used to evaluate the occurrence of defects beneath the coatings (e.g., paint-off and corrosion defects). The proposed method provides the solution for coating thickness of marine protective coatings and it would benefit the effective maintenance to avoid coating failure and facilitate marine protective coating design. Therefore, non-destructive testing and evaluation of marine protective coating system by terahertz waves with SWT could be recommended for engineering applications.



## 1. Introduction

Protective coating is usually applied for marine structures and offshore plants as a corrosion protection. However, deterioration, aging or failure occurs in the harsh marine environment, especially the corrosion deterioration. During the corrosive process, the chemical and physical characteristics changes in the coating system and thus forms various defects, such as bubbling, rust, cracking, shedding etc. (Soares et al., 2009; Khobaib et al., 2001; Sørensen et al., 2009; Akpan et al., 2002). Severe corrosion degradation may lead to the replacement of a complete ship panel (deck, side, bottom, etc.). Thus the monitoring of the degradation of paint layers is of great importance for the long term use of the marine protective coatings (Deardorff, 2009). In addition to general (uniform) corrosion which reduces the plate thickness uniformly, there are other types of more localized corrosion, such as corrosion, pitting, and detachment, blistering, etc. A fast, reliable detection method to detect possible coating defects and to evaluate coating performance can provide timely and effective maintenance to avoid serious consequences due to coating failure. Corrosion processes beneath organic coatings are usually monitored by using conventional electrochemical techniques, such as electrochemical impedance spectroscopy (EIS), electrochemical noise measurements (ENM) and so on, which allow both the evaluation of corrosion rates and the identification of corrosion mechanisms (Heyer et al., 2014; Láng et al., 2012; Mansfeld et al., 1998; Moshrefi et al., 2011). EIS uses an external voltage or current source; for this reason, corrosion processes can be disturbed, and the results may not be perfectly reliable. Furthermore, it can only provide the assessment of uniform corrosion of interface, which was difficult to give the local corrosion inspection (Rodriguez et al., 2013). The application of ENM method does not involve the artificial disturbance of the system and data analysis could be performed in the electrochemical noise records to capture information about the type of corrosion damage. However, because of the very small voltages and currents involved, most systems are characterized by a high number of overlapped transients, thus ENM data can sometimes be affected by extraneous signals (although normally the results are changed by only a factor

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of two or less) which make it need to be performed using adequate mathematical tools and not so suitable for monitoring or quality control (Aballe et al., 1999; Mabbutt et al., 2007). Other commercially available thickness measurement techniques for protective coatings including ultrasonic testing (Zhang et al., 2014) and eddy-current testing (He et al., 2012) etc. Furthermore, some optical probing methods such as eddy current pulsed thermography (He et al., 2014) and infrared thermography (Sfarra et al., 2012) are also adopted for the defect measurement of paint film.

Time Domain Terahertz (TD-THz) technology provides the capability for standoff inspection of coatings that are otherwise opaque and cause strong scattering at visible and infrared wavelengths. Recent advances in TD-THz technology has been extensively used in the sensing and imaging fields because of its many merits such as non-contact, non-destructive and that many materials are relatively transparent to THz waves (Yun-Shik, 2008). Besides, the photon energy of terahertz radiation is in the range of a few meV (one thousand times smaller than that of UV light and one million times smaller than that of X-ray) (Yun-Shik, 2008), which makes TPI technology much safer than X-ray testing although X-ray can give high-precision and accurate measurement, regarding to the safe operating procedures (Chantler et al., 2001). When a terahertz pulse is incident on a multilayered medium, the reflected or transmitted signals would record information whenever there is a change in the refractive index or the optical absorption coefficient of the material (caused by either chemical or structural changes in the medium). The structural information can be ultimately extracted by analysis of the recorded terahertz wave in the time domain. So far, terahertz pulsed imaging (TPI) has become an established powerful non-destructive testing tool to characterize a range of multilayered samples, for example, pharmaceutical solid dosage forms (Zhong et al., 2011), dental tissues (Crawley et al., 2003), layered polymer composites (Stoik et al., 2010) and other extensive investigation for industrial application such as detecting materials under coating layers (Geltner et al., 2002; Anastasi and Madaras, 2005; Zimdars et al., 2005; Lopato and Chady, 2013), detecting defects within the sprayed on foam insulation (Zhong et al., 2005), and detecting corrosion under metallic source material (Jackson et al., 2011). It showed that for thick samples such as the multilayer medium above, the detected echoes of the terahertz signal, which are caused by multiple reflections in the sample, can be time separated well.

To our best knowledge, there were some researches about TPI technique testing for protective coatings. The utility of time-domain terahertz technology for automobile paint thickness measurements has previously been demonstrated in the laboratory by Yasui et al. (2005) and Izutani et al. (2012). Fukuchi et al. (2013) determined refractive index and thickness of the topcoat of a thermal barrier coating from the reflected waveforms of terahertz waves. Kurabayashi et al. (2012) studied corrosion detection under paint films using a specific frequency of THz-wave in THz transmitted imaging system. Kurabayashi et al. (2012) found the mechanical defects and through holes were visualized, but corrosion areas were not. Cook et al. (2007, 2008) discussed the applicability of terahertz non-destructive testing for marine protective coatings and took a laboratory investigation to measure the dry film thickness of organic coatings. Cook et al. (2007, 2008) were developing a standoff sensor for the real-time thickness measurement of wet (uncured) marine paints for the purpose of providing feedback to an automated system for painting ships in dry-dock. The research showed that TPI technology could be an excellent complimentary means to the protective coating testing.

So far, to our best knowledge, the above researches on TPI technique testing for protective coatings are focused on experimental aspects. However, there were few theoretical studies about terahertz radiation interacts with protective coatings numerically and theoretically. Advanced numerical modeling and further theoretical analysis of the interaction of terahertz radiation with marine protective coatings will be extremely valuable for the better application of TPI technology in ship, especially for rapid hidden defect detection (such as peeling, blistering and corrosion, etc.) and quantitative analysis, which will provide timely and reliable information for ship maintenance work. Indeed, some theoretical analysis have already been reported to study the propagation of terahertz radiation in various multilayered media. For terahertz pulsed imaging in which a transient terahertz pulse is used, a time-domain method, such as the finite difference time domain (FDTD) method, is more applicable than a frequency-domain method because a differential equation is simpler to solve than an integral equation. The FDTD algorithm is a proven numerical method to model electromagnetic scattering problems, which solves the Maxwell's equations directly and obtains the solution of the electric field of electromagnetic waves (Tirkas et al., 1993). It analyses continuous electromagnetic problems by using finite difference and obtains the electric field value at the sampling point. The FDTD method offers several advantages, such as robustness and the ability to study dispersive, nonlinear, or anisotropic materials (Kumar et al., 2008; Larsen et al., 2011). In our previous works, a theoretical model based on the FDTD method for pharmaceutical-coated tablets was investigated and the simulated results were found to be in good agreement with the experimental results (Tu et al., 2013, 2014). It has been demonstrated that FDTD-model could be capable of calculating the propagation and reflection of THz radiation from a multilayered flat or curved structure.

In the present work, non-destructive testing of marine protective coatings was investigated by TPI technology with reflection-type detection mode using FDTD method combined with stationary wavelet transform approach. A FDTD-based three-dimensional (3D) model used to calculate and analyze the reflected THz wave from marine protective coatings was proposed. The numerical modeling and theoretical analysis of the interaction of terahertz radiation with marine protective coatings was investigated. This is not only valuable for the better application of TPI technology in marine protective coatings, but also for analysis of other non-metallic coatings on metal substrate. Current TPI technique provides few quantitative information (such as the thickness of paint layer) and possible defect testing of marine protective coatings, especially for the paint-off and corrosion defects which need to be detected when the ship was under period maintenance. We carried out theoretical analysis of coating thickness analysis for each paint layer of marine protective coatings and non-destructively evaluation of the occurrence of defects in the coatings. Different protective coating systems with different paint layer thickness were modeled and computed using the FDTD method with the broad-band terahertz radiation. Besides, multilayered samples to mimic the occurrence of various defects (paint-off defect and corrosion defect) in coating were investigated. Furthermore, stationary wavelet transform approach was used to terahertz impulse functions for quantitative coating analysis and defect identification of marine protective coatings.

## 2. FDTD modeling of terahertz wave propagation in marine protective coatings

FDTD is a direct solution of Maxwell's time-dependent curl equations. It applies simple, second-order accurate central-difference approximations for the space and time derivatives of the electric and magnetic field directly to the differential operators of the curl equations. In a 3D Cartesian coordinate system, the