NON-DESTRUCTIVE CRACK DETECTION TECHNIQUE BY MEANS OF MICROWAVE IMAGING

By

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DEDICATION

I, dedicate this project to:

The Lord God Almighty

My beloved wife: Hannah Gogo Jiya

And daughter: Fidelia Yebosoko Jiya

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LIST OF ABBREVIATIONS

2-D	Two-Dimensional
3-D	Three-Dimensional
ABC’s	Absorbing Boundary Conditions
BW	Bandwidth
DAS	Delay And Sum
DB	Decibel
FCC	Federal Communication Commission
FDTD	Finite-Difference Time Domain
GHz	Giga Hertz
Lab VIEW	Laboratory Virtual Instrument Engineering Workbench
PML	Perfectly Matched Layer
SNR	Signal-to-Noise Ratio
Rx	Receiver
Tx	Transmitter
UWB	Ultra Wideband
VNA	Vector Network Analyser
VSWR	Voltage Standing Wave Ratio

LIST OF SYMBOLS

f_c	Centre frequency
f_h	Upper band frequency
f_l	Equal to Lower band frequency
c	Speed of light in free space
λ	Wave Length
S_{11}	Input Reflection Coefficient
S_{22}	Reverse Reflection Coefficient
S_{12}	Reverse Transmission Coefficient
S_{21}	Forward Transmission Coefficient
p_r	Range Resolution in Concrete
$\in_r$	Real part of the complex permittivity of concrete.
ΔR	Range resolution

TEKNIK MENGESAN KERETAKAN TANPA MEMUSNAH MENGGUNAKAN PENGIMEJAN GELOMBANG MIKRO

ABSTRAK

Bangunan-bangunan dan struktur awam selalunya terbeban dengan beban melebihi had sehingga membawa kepada kemerosotan dan kelemahan struktur penahanan dan mengakibatkan keretakan. Keretakan dalam konkrit atau bahan berasaskan simen membawa ancaman besar kepada mana-mana struktur awam: ianya sangat berbahaya dan telah membawa kepada banyak kemusnahan dan kerosakan. Walaupun satu keretakan kecil yang kelihatan tidak penting boleh membesar sehingga akhirnya menyebabkan kegagalan struktur yang serius. Selain daripada pemeriksaan manual yang tidak efektif dan memakan masa, beberapa teknik ujian penilaian tanpa musnah pernah digunakan untuk mengesan keretakan. Contohnya, ultrasonik, getaran dan teknik regangan, namun ada di antara penderia yang digunakan samada terlalu besar ataupun beresolusi rendah. Objektif utama adalah untuk mengkaji kemungkinan pengesanan keretakan di dalam konkrit atau simen menggunakan gelombang mikro bersama dengan algoritma lengah-dan-campur. Pertama sekali model pelbagai jenis keretakan di dalam bata disimulasikan menggunakan teknik FDTD. Keputusan dari simulasi digunakan untuk menentukan parameter persediaan eksperimen. Bata dan struktur konkrit dengan keretakan telah digunakan sebagai bahan ujikaji. Daripada keputusan eksperimen, didapati isyarat dengan frekuensi 1 hingga 7 GHz menghasilkan resolusi dan penembusan yang optimum. Keretakan sekurang-kurangnya sebesar 5 mm telah berjaya dikesan dengan resolusi $\lambda/4$, yang membolehkan pengesanan keretakan tahap awal. Kesimpulannya

teknik pengimejan gelombang mikro mempunyai potensi untuk mengesan keretakan di dalam konkrit atau bahan berasaskan simen dengan resolusi yang tinggi.

NON-DESTRUCTIVE CRACK DETECTION TECHNIQUE BY MEANS OF MICROWAVE IMAGING

ABSTRACT

Building and civil structures are often overburdened with load above their threshold value that led to deterioration and weakening of the supporting members, and resulted in cracks. Cracks in concrete or cement based materials present a significant threat to any civil structures; they are very dangerous and have caused much destruction and damages. Even small cracks, which look insignificant grow and eventually lead to severe structural failure. Besides manual inspection that is ineffective and time-consuming, several non-destructive evaluation techniques have been used for crack detection. For instance, ultrasonic, vibration and strain-based techniques, however some of the sensors used are either too big or limited in resolution. The main objective is to study the possibility of crack detection in concrete or cement based materials using microwave imaging with Delay-and-Sum, (DAS) algorithm. First, models of various crack types in bricks were simulated using finite difference time domain method (FDTD) method. The simulation results were used to determine the design parameters for the experimental setup. Single brick and a constructed concrete structure with cracks were used as phantoms. From the experimental results, signal with frequency of 1 to 7 GHz gave an optimum resolution and signal penetration. Cracks of at least 5 mm in size were detected with a resolution of $\lambda/4$ that enabled crack detection at the early stage of development. In conclusion, microwave imaging technique showed the potential to detect cracks in concrete or cement-based materials with high-resolution image.

CHAPTER 1

INTRODUCTION

1.1 Overview

Many buildings and civil structures consist of reinforced concretes or cement based materials. These structures are designed to carry a certain amount of load under a particular condition(s) and for a given period. Environmental exposure and various coupling effect of loading among others are different ways through deterioration and damage can be presented or introduced into a functioning civil structure or cement based materials during service. For example, civil structures are often overburdened with the load above their carrying capacity. This gradual deterioration and damage to this material(s) usually appears in the form of a crack. Cracks present a significant threat to any civil structures, they are very dangerous and have caused much destruction and damages in this area. Even small crack grow and eventually lead to severe structural failure. Cracks irrespective of their type and source they extensively affect the structural integrity of buildings and civil structures. Also, their mechanical behavior, integrity, and permeability characteristics are affected (M.A. Glinicki and Litorowicz., 2003, H.R. Samaha and Hover., 1992, C.-M. Aldea et al., 1999, H. Mihashi et al., 2003, N. Gowripalan et al., 2000, P.P. Win et al., 2004). Therefore, cracks reduced the actual strength of civil structures, whereas, residual strength cannot support the structure for an extended period of attending services.

Un-attended micro cracks can rapidly deteriorate the support member to eminent collapse of the affected structure. Therefore, lack of efficient crack monitoring and detection methods can be detrimental to the sustainability of the structure and human life. The cracks sizes and their patterns on reinforced concrete are critical to the viability of existing civil structure. Thus, attention has to be dedicated to forestalling costly structural damage. Litorowicz., (2006) reported that quantitative technique can assess deterioration of reinforced concrete. It is imperative to devise and adopt a robust, reliable, and efficient alternative crack detecting method that can save the consequential damage of crack to concrete or cement based material (Litorowicz., 2006).

Recently, microwave imaging was regarded as a promising tool for non-destructive evaluation crack detection approach. The technique is cost effective, avoids the use of ionizing radiation and give a high definition image than ultrasonic technique. It provides clearer images of the object under detection and can be easily applied to the peripheral areas of the material under test (Zastrow et al., 2008, Fear et al. 2002a). Largely, microwave radiation is a non-ionizing nature and does not change both the molecular and atomic structure of any material. Whereas, it reduces the harmful effect of both the user and the device under test (Hinrikus and Riipulk, 2006).

Since the allocation of the frequency band from 3.1 GHz - US Federal Communications Commission (FCC) has used 10.6 GHz within the microwave spectrum for ultra-wideband (UWB) in the commercial application. There has been a growing passion in the development of UWB system for several applications. A UWB signal as a short, sub-nanosecond pulse, and falls in the electromagnetic spectrum below the acceptable noise level. As the pulses are shorter than the target dimension and propagate over shorts distance at high speed, it is an attractive tool for non-destructive applications for industries as well as biomedical imaging. It can resolve an object with dimension exceeding the Rayleigh's limit, leading to an accuracy approaching sub-millimeter resolution in dielectric materials (Gilmore et al., 2010). Its strong multipath resolving capabilities are ideal for the localization and detection of defects or abnormalities in several objects or materials (Pan, 2007). Hence, UWB microwaves imaging for non-destructive evaluation of structural cracks has proved to be a promising method among others. The imaging technique is widely popular among researchers; they use antennas as sensors and imaging the cracks based on delay and sum reconstruction (DAS).

1.2 Problem Statement

To-date there are several methods that have been devised and used for crack detection in civil structures. Due to extreme events, civil structures are often carrying more loads than they were designed for while their condition deteriorates with years. Because of this, cracks are most of the time seen on their surfaces. Cracks are form of damage that emanate because of surface breaking, de lamination and discontinuity to an existing structure (Nadakuduti et al., 2006).

According to Yamaguchi and Hashimoto (2006) one of the techniques that have been used for crack detection to draw up a details sketch of the distribution of cracks. Moreover, at the same time measuring the data for each and every crack to acquire the knowledge about the condition of the concrete that is determined by the specialist as contained in the manual. The major drawback of the visual inspection include lacks of objectivity for quantitative analysis, requires many efforts and also time-consuming. In addition, Sorncharean and Phiphobmongkol (2008) stated that human inspectors need too many professionals for just a single task; it is financially restrictive. Another downside is that two inspectors could give different results of distress information even when studying the same problem or defects.

Semi-empirical model, X-band (8.2–12.4 GHz) frequency model was used with a probe. This method involves computing the reflection coefficient for both the starting and the middle point. The downside of this technique is that, to evaluate the reflection coefficient for these points, especially the central point, an electromagnetic model need to be developed which may be difficult to design. Though, another technique was used to measuring the magnetic field around the device under test. The result shows that the calculated positions in the absence of crack was found to be correct but in the presence of crack. The calculated position and the actual position does not agree on which give rise to a broader distribution. Therefore, the technique required a new parameter in order to be able to resolve this difference (Nonaka et al., 2001).

The performance of these crack detection techniques could be divided into the vital characteristics such as, crack precision, position, the computational time, cost of measurement equipment and setup. Therefore, a very robust method is required that reduces the computational time, reconstruction technique that principally leads to qualitative images. Moreover, the method should enhanced data acquisition system that gives an extremely precise position of the crack with less cost.

However, we aimed at reducing the burden of very long computational time and also to maintain the precision of crack detection in this study. Ultra wideband (UWB) sensor at low frequencies of less than X-band can give high resolution via good signal penetration to have precise data for the study. In this case, the computational time and precision of the crack detection are the important factors in the crack detection analysis. These methods start by using the newly designed P-Shaped Wide-slot antenna as sensor for automatically extracting the values from the image using lab-view and applying DAS algorithm for final image reconstruction. For the validity and practical application of this project, a real brick phantom, and a small model building structure was used in validating the method and procedures experimentally.

1.3 Objective

The primary purpose of this research work is to detect cracks in civil structures using non-destructive microwave imaging techniques with P-Shaped Wide-slot antennas as the sensor. The intention, for this reason, is to use an efficient means that is simple, easy, low cost and fast with good signal penetration for data acquisition and better image resolution through multistatic arrangement. Therefore, to achieve the objective, the research is aimed to achieve the following:

i. To experimentally assess the performance of the P-Shaped Wide-slot antenna as a sensor for cement based application;
ii. To determine the suitable frequency range that gives a better signal penetration depth through the brick structure;
iii. To model the time domain propagation of UWB pulses using the finite difference time domain method (FDTD);

iv. To construct the ultra-wideband experimental data acquisition hardware arrangement; and

v. To validate this method and procedure using a brick through simulation and experiment.

1.4 Scope and Limitation of Study

The scope of this work is to detect crack in a civil structure (brick) using non-destructive evaluation by means of microwave imaging. The ultimate goal of the study is to produce a working product, which could be used to detect crack in a civil structure. More information regarding the materials used can be found in subsequent chapters.

Firstly, prior to observation and analysis, before the actual measurements, the bricks are modeled and simulated with FDTD. The conditions relevant to the analysis are specified that include: Permeability, brick size, thickness, electrical delays and other related parameters.

Secondly, the actual experiment will be carried out at SERC with the actual or real materials including concrete brick with different crack sizes and orientations, sensors, VNA, and multiplexers. These devices were combined in order to help in data acquisition processes. In addition, an appropriate platform is needed in this design to hold the sensors in place, provides a suitable position for the brick phantom for testing and easy handling of the system. Besides, since the sensors will be in fixed position, this increases the measurement accuracy for UWB crack detection system.

Thirdly, image reconstruction will be implemented using delay and sum (DAS) algorithm from the information obtained during data acquisition in order to establish the position and the orientation of the crack on the phantom.

Finally, this experiment will be concluded by carrying out measurement using different design parameters. Different frequencies will be used ranging from 1 GHz to 7 GHz. Also, different array configuration and sensor setups will be used for this work with full view scan geometry utilizing sixteen number of sensors.

The study is not without its limitation; the project focused on the construction of a two-dimensional image only. However, the reconstruction of three-dimensional image is not included in this work. The reason is that the work is based in the dielectric of the plane, not the volume.

In addition, the antenna design will not be included in this work because it will be too time-consuming and challenging due to shortness of the period designated for Mixed ESDE project. Therefore, a newly designed P-Shaped Wide-Slot antenna for breast cancer will be experimentally used for the investigation of this work to determine its efficiency and performance in cement based materials.

1.5 Thesis outline

The arrangement of the thesis write-up consists of five main chapters. Chapter 1 gives a brief introduction of the basic concepts and motives behind the work. Besides that, it also describes the purpose of the project, problem statement, objectives and the scope of the work as well.