ELECTRICAL RESISTANCE TOMOGRAPHY FOR MORTAR WITH MULTIPLE REBARS STRUCTURE INVESTIGATION

by

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LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
CCD	Charge-Couple Device
CFD	Circulating Fluidized Bed
CNN	Convolutional Neural Network
ECT	Electrical Capacitance Tomography
ERT	Electrical Resistance Tomography
EIT	Electrical Impedance Tomography
EMT	Electromagnetic Tomography
ET	Electrical Tomography
GREIT	Graz Consensus Reconstruction Algorithm for EIT
kHz	Kilohertz
LBP	Linear Back Projection
MSSIM	Mean Structural Similarity Index
NOSER	Newton's One Step's Error Reconstructor
NDT	Non-Destructive Testing
SHM	Structural Health Monitoring
TV	Total Variation

Tomografi Rintangan Elektrik untuk Penyiasatan Struktur Mortar dengan Pelbagai Tetulang

ABSTRAK

Konkrit bertetulang telah digunakan secara meluas sebagai bahan struktur di setiap pelosok dunia seperti di empangan, reaktor nuklear, stadium dan turapan. Jenis konkrit lain ialah mortar tetapi tanpa agregat kasar. Kehadiran tetulang dalam konkrit atau mortar memainkan peranan penting untuk mengelakkan struktur mudah pecah. Ujian tidak merosakkan (NDT) adalah kaedah yang terkenal dalam memeriksa dan memantau keadaan struktur konkrit dan mortar kerana tidak ada kesan kerosakan pada struktur. Teknik NDT terdiri daripada elektromagnetik, radiografi dan teknik elektrik yang mampu mencari tetulang. Walau bagaimanapun, teknik elektrik adalah yang paling sesuai kerana teknik ini tidak berbahaya, tidak invasif, dan tindak balas yang cepat berbanding dengan teknik elektromagnetik dan radiografi. Penyelidikan sebelumnya telah menunjukkan bahawa kaedah elektrik seperti kaedah tomografi menggunakan tomografi rintangan elektrik (ERT) masih belum digunakan untuk mengambarkan beberapa tetulang untuk struktur mortar. Oleh itu, dalam tesis ini, sistem ERT dicadangkan untuk melakukan pengimejan beberapa tetulang untuk struktur mortar. ERT tergolong dalam tomografi medan lembut dan sifat tomografi medan lembut mempunyai masalah balikan yang menghasilkan imej resolusi ruang rendah. Algoritma pembinaan semula gambar berulang, seperti *Total Variation* (TV), telah dicadangkan untuk menyelesaikan masalah ini. Pembinaan semula gambar berulang bermanfaat untuk menawarkan gambar resolusi spasial tinggi. Algoritma TV dibandingkan dengan empat algoritma bukan berulang, yang terdiri daripada *Linear Back Projection* (LBP), *Laplace*, *Newton One-Step Error Reconstruction* (NOSER), dan *Tikhonov*, untuk membuktikan bahawa algoritma TV sesuai untuk pengimejan beberapa tetulang dan menyelesaikan resolusi ruang rendah. Semua algoritma diterapkan dan diuji di bawah empat profil yang berbeza. Semua gambar yang dihasilkan dianalisis menggunakan alat penilaian gambar seperti *Mean Structural Similarity* (MSSIM). Kaedah ambang global diadaptasi ke dalam semua gambar untuk meningkatkan lagi penglihatan tetulang. Kaedah koefisien korelasi (CoC) diperkenalkan untuk membantu kaedah ambang untuk mencari nilai ambang optimum. Sebagai perbandingan dengan algoritma bukan berulang, algoritma TV telah menunjukkan prestasi yang luar biasa dalam indeks MSSIM dari simulasi dan kajian eksperimen. Penggunaan ambang global bersamaan dengan pendekatan CoC telah terbukti memberikan kesan yang signifikan dalam menghilangkan artefak yang tidak perlu dan penglihatan tetulang untuk semua algoritma. Jika dibandingkan dengan algoritma bukan berulang, algoritma TV telah menunjukkan keunggulan dalam indeks MSSIM walaupun setelah pelaksanaan ambang. Algoritma TV yang dicadangkan telah menunjukkan kemampuan untuk berjaya mengambarkan tetulang dengan lebih baik berdasarkan trend indeks MSSIM yang ditunjukkan dari simulasi dan kajian eksperimen serta setelah penggunaan ambang. Disamping itu, algoritma TV telah terbukti menjadi penyelesaian untuk mengatasi sifat resolusi ruang rendah dalam pengimejan ERT dan mampu mengambarkan pelbagai tetulang untuk struktur mortar.

Electrical Resistance Tomography for Mortar with Multiple Rebars Structure Investigation

ABSTRACT

Reinforced concrete has been broadly used as structural material in every part of the world such as in dams, nuclear reactor, stadium and pavements. Another type of concrete is mortar but without a coarse aggregate. The presence of reinforcement bars (rebars) in concrete or mortar play an important role in preventing the structure from breaking apart easily. Non-destructive testing (NDT) has been well known methods in inspect and monitor the condition of concrete and mortar structure due to no damage effect on the structure. NDT techniques consist of electromagnetic, radiography and electrical technique are capable of locating reinforcement bars. However, electrical technique is the most suitable since this technique is non-hazardous, non-invasive, and fast response in comparison to electromagnetic and radiography technique. Previous research has shown that electrical methods such as tomographic modalities using electrical resistance tomography (ERT) have yet to be used to image multiple rebars for mortar structures. Therefore, in this thesis, ERT system is proposed to perform imaging of multiple rebars for mortar structure. The ERT belongs to soft-field tomography and the nature of soft-field tomography possesses ill-posed inverse problem that produce low spatial resolution image. Iterative image reconstruction algorithms, such as Total Variation (TV), have been proposed to solve this problem. Iterative image reconstruction is beneficial in offering high spatial resolution image. The TV algorithm was compared to four non-iterative algorithms, consist of Linear Back Projection (LBP), Laplace, Newton One-Step Error Reconstruction (NOSER), and Tikhonov, to prove that the TV algorithm is suitable for imaging multiple rebars and solving low spatial resolution. All the algorithms were applied and tested under four different profiles. All the images produced was analysed using image assessment tool such as Mean Structural Similarity (MSSIM). Global thresholding method was adapted into all the images to further enhance the visibility of the rebars. Coefficient of Correlation (CoC) method was introduced to assist the thresholding method to find the optimise thresholding value. In comparison to non-iterative algorithms, the TV algorithm has exhibited outstanding performance in the MSSIM index from the simulation and experimental studies. The use of global thresholding in conjunction with the CoC approach has shown to have a significant effect on eliminating unnecessary artefacts and the rebars visibility for all the algorithms. As compared to non-iterative algorithms, the TV algorithm has shown superiority in the MSSIM index even after the implementation of thresholding. The proposed TV algorithm has demonstrated the ability to successfully visualise the rebars better based on the MSSIM index trend developed from simulation and experimental studies as well as after thresholding deployment. Moreover, the TV algorithm has proven also to be a solution to overcome the nature of low spatial resolution in ERT imaging and capable to visualise the multiple rebars for mortar structure.

CHAPTER 1 : INTRODUCTION

1.1 Process Tomography Overview

Process tomography is used to acquire images from a three-dimensional object in a plane segment form. Process tomography method generates images in cross-section form to present internal character and behaviour in targeted interest region and offers a considerable benefit in process evaluation and verification.

Electrical tomography (ET) is categorised as one of the processes of tomography methods. The electrical tomography method was introduced in the 1980s by Barber and Brown (1984); Huang et al. (1988). The electrical tomography comprises of three separate modalities such as electrical capacitance tomography (ECT), electrical resistance tomography (ERT) and electromagnetic tomography (EMT). ET is known for measuring two-phase flow such as liquid-gas, liquid-liquid, and liquid-solid phase (Abdul Wahab et al., 2015).

There is two type of tomography modalities which are hard-field and soft-field. Hard-field tomography transmits the signal in a straight line and the medium along the path influences the strength of the signal despite the material's location (Soleimani, 2016; Wei & Soleimani, 2013). Example of hard-field tomography is x-ray tomography, ultrasonic tomography and positron emission tomography (PET). On the other hand, soft-field tomography does not transmit the signal in the straight-line pattern and the area of measurement influences the distribution of the signal (Soleimani, 2016; Wei &

Soleimani, 2013). Soft-field tomography consists of ECT, ERT and magnetic inductance tomography (MIT).

ERT is a tomographic technique to reconstruct the electrical conductivity distribution within a medium using boundary voltage measurement. This technique has extensively applied in medical (Sun et al., 2017), geophysics (Okpoli, 2013), and industrial application (Razzak et al., 2010). ERT technique offers various advantages as non-hazardous, non-invasive and NDT tool (Aw et al., 2014; Huang et al., 2016; Karhunen et al., 2010).

1.2 Background Research Problems

Concrete is a mixture of cement, aggregate and water. Concrete has extensively used as a structural or construction material. Reinforced concrete is frequently constructed on concrete structures, for instance, columns, beams, and walls that are subjected to humidity or moisture. Reinforced concrete is concrete that contained the presence of steel reinforcing bars that allows these concrete and steel reinforcing bars (rebar) counteract the tensile forces. This combination prevents concrete from cracking by stretching the steel tendons. Another type of concrete is mortar but without a coarse aggregate. Mortar consists of a mixture of sand, cement, and water. Concrete structures can be seen in every part of the world, and example of practical application is dams, pavements, nuclear reactor, stadium, sculpture and many mores (Mehta & Monteiro, 2003).

Exposure of reinforced concrete to mechanical loading and moisture degraded the durability and life service of the reinforced concrete structure. This exposures lead the reinforced steel bar to corrosion and cracking. Thus, condition assessment and structural health monitoring (SHM) of the reinforced concrete structure is crucial. NDT method is the SHM technique that can help to examine the condition of the reinforced concrete structure without damaging the structure. Numerous NDT methods were available to examine the condition of the concrete structure such as visual inspection, acoustic techniques, radiation techniques and microwave techniques (Snyder et al., 2013). Nonetheless, these NDT methods are costly, required skilled personal to inspect the concrete structure, hazardous, environmental conditions affect the results obtained and unable to provide quantitative information (Snyder et al., 2013; Verma et al., 2013).

Thus, alternate NDT tool such as tomography approach for concrete investigation is essential to provide quantitative information. In the previous works, ERT has been deployed beforehand as potential NDT tool for concrete (Karhunen et al., 2010) and mortar. The studies concentrated on the localisation of single rebar (Huang et al., 2016; Karhunen et al., 2009; Karhunen et al., 2010), moisture distribution (Hallaji et al., 2015; Jiang et al., 2019; Smyl et al., 2017; Suryanto et al., 2017), crack (Hallaji & Pour-Ghaz, 2014; Karhunen et al., 2010; Zhou et al., 2017), damage (Hallaji et al., 2014; Zhao et al., 2016) in concrete and mortar. Yet, there is no study conducted on the investigation of multiple rebars in mortar. Besides that, conducted studies have demonstrated low spatial resolution in the image produced due to nature of soft-field tomography. In order to deal with these problems, this thesis focuses on the feasibility study of using ERT technique to examine the multiple rebars in mortar. An iterative image reconstruction algorithm is

proposed to enhance the spatial image resolution. The proposed algorithm will be assisted by additional image enhancement tool to further improve the localisation of the rebars.

1.3 Problem Statements

The life service and durability of the reinforced concrete is relied on the presence of the reinforcement bar in the concrete to prevent crack. Further cracking in the concrete leads to corrosion risk in the reinforcement bar. Also, misplacement of rebar may also expose the rebar to the speedy growth of corrosion. This phenomenon will reduce the durability and life service of the reinforced concrete. According to American Concrete Institute (ACI Committee 318, 2014), a minimum number of eight reinforcement bars are necessary for the circular concrete arrangement. Previous studies focus only on single rebar imaging in concrete. Therefore, an NDT tool using ERT to visualise and localise the presence of multiple rebars in the mortar for SHM is proposed.

Moreover, ERT suffers low spatial resolution in reconstructing the conductivity distribution due to ill-posed problems. A better approach to deal with this problem is using the iterative image reconstruction method such as Total Variation algorithm. Total Variation algorithm capable of preserving discontinuities, sharp edges in the image and offers a high spatial resolution. Although iterative algorithm offer high spatial resolution image but the presence of the artefacts still exist. Therefore, this algorithm will be assisted with global thresholding technique to eliminate the artefacts in which further enhance the localisation of the rebar(s). Therefore, this study will employ the ERT system using the TV algorithm with global thresholding technique to localise the presence of multiple rebars.

1.4 Aims and Objective of the Study

This research aims to design and develop an electrical resistance tomography system for multiple rebar detection in mortar. The specific objectives of this research addressed in the following:

i) To perform a feasibility study of multiple rebar detection using Electrical Resistance Tomography system through simulation study.

ii) To design the iterative Total Variation image reconstruction algorithm and adapt the global thresholding technique for reducing the artefacts of multiple rebars.

iii) To evaluate the performance of the iterative Total Variation image reconstruction algorithm with non-iterative image reconstruction algorithms in multiple rebar reconstruction.

1.5 Scopes of the Study

The research scopes are listed into several parts as follows:

i) The electrical resistance tomography system will consist of 16 silver/silver chloride electrodes that mounted on the surface of the mortar.

ii) The mortar will be integrated with rebar of 1.5 cm in diameter and 21.5 cm in length, which made of mild steel.

iii) The performance of the iterative Total Variation image reconstruction algorithm will be assessed using MSSIM and compared with Linear Back Projection (LBP), NOSER, Laplace, and Tikhonov Regularisation algorithm.

1.6 Significant Research Contribution

The findings that contribute to the research field are listed as follows:

i) Detection of multiple rebars using iterative Total Variation image reconstruction algorithm.

ii) Enhancement on the reconstructed image using global thresholding technique with coefficient of correlation.

1.7 Organisation of the Thesis

Chapter 1 briefly introduces an overview of process tomography, the research problems, the aims and objectives of the research scopes of study and the research contribution.

Chapter 2 describes the process tomography, NDT methods for locating rebars in concrete and mortar structure and related literature surveys of this study.

Chapter 3 describes the modelling work in ERT, resistivity measurement for concrete, discusses the image reconstruction methods, the image quality assessment tool, the thresholding method and the optimal threshold tool for thresholding technique and lastly review of hardware development in ERT system.

Chapter 4 presents the result of reconstructed images from simulation and experimental studies. Besides, the result of thresholded images for simulation and experimental are also presented. The results obtained are tabulated and analysed.

Chapter 5 presents the conclusions of the study and future work suggestions.