Modeling of Dynamic Behavior in Closed Crack and Nonlinear Ultrasonic Array Imaging

A DISSERTATION

SUBMITTED TO THE DEPARTMENT OF CIVIL ENGINEERING

AND THE COMMITTEE ON GRADUATE STUDIES

OF EHIME UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

DOCTOR OF ENGINEERING

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March 2017

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ABSTRACT

MODELING OF DYNAMIC BEHAVIOR IN CLOSED CRACK AND NONLINEAR ULTRASONIC ARRAY IMAGING

Ultrasonic testing (UT) utilizes the traveling time and amplitude of a scattered wave from cracks in a material. A distinct scattered wave can be obtained from a crack with opening faces. It is difficult, by contrast, to detect signals from closed cracks such as stress corrosion and fatigue cracks using the conventional UT. Since the crack faces are in contact due to a residual stress, most of the incident wave penetrates the crack faces and a little scattered wave will be generated. A nonlinear ultrasonic method based on contact acoustic nonlinearity (CAN) which utilizes the dynamic behaviors of the contact and separation states of the crack faces is a promising method. The clapping motion of the crack faces generates harmonics in the frequency spectrum. However, the generation of the harmonics from the crack faces is so sensitive that the voltage, angle, cycle, and frequency of the incident wave should be set in a well-chosen method.

In this thesis, a modeling of the generation of the harmonics wave from the closed crack was performed to enhance the reliability of the nonlinear ultrasonic method. Here, an elastodynamic finite integration technique (EFIT) was introduced to simulate a transient motion of the scattered wave from the closed crack. The EFIT adopted a set of split computational nodes at the interface of the closed crack to show the contact and separation depending on the stress and opening displacement of the interface. The numerical results for one-dimensional wave field showed good agreement with the analytical solutions. The simulation results revealed that a closing velocity of the interface was determined by the compressive pressure of the material and was validated by the experimental measurement with polymethylmethacrylate (PMMA) specimens. The appropriate conditions to obtain the nonlinear ultrasonic wave in the case of ultrasonic array testing were determined by performing two-dimensional simulations.

An imaging method of the closed crack using an array transducer was investigated using the EFIT simulation. The full waveforms sampling and processing (FSAP) was applied as the imaging technique. For the generation of the nonlinear ultrasonic wave from the closed crack, the FSAP was modified to an algorithm which can transmit a strong beam from the array transducer by setting the delay for all elements electronically. The second harmonic component which extracted from the scattered wave using a band-pass filter was used as the input to the FSAP imaging technique. From the results, it was found that the shape and the location of the closed crack can be reconstructed when the amplitude, frequency, cycle, and angle of the incident wave are set at appropriate values.

ACKNOWLEDGMENT

Praise to Allah. First of all, I would like to express my sincere gratitude and special appreciation to my advisor Dr. Kazuyuki Nakahata, Professor of Ehime University, for his continuous support, excellent guidance, constant motivation, and immense knowledge. His guidance helped me in all the time of research, writing of this thesis and also life in Japan.

I would like to thank Dr. Yamawaki Hisashi, Researcher of NIMS for shared knowledge, theoretical and technical guidance on measurement activities, also for Dr. Ikumu Watanabe, Researcher of NIMS for all supports throughout three months internship period in National Institute for Materials Science (NIMS).

Besides, I would like to thank the rest of my thesis committee: Prof. Dr. Mitao Ohga, Prof. Dr. Manabu Takahashi, and Assist. Prof. Dr. Pang Jo Chun for their insightful comments and encouragement. All these great guidance mainly directed to contribute an original research to the field. Also, great thanks to all fellow team in Structural Engineering Laboratory for the stimulating discussions and for all the fun we have had in the last three years. In particular, I thank to the secretary, Mrs. Yuko Katsura for assisting me throughout my academic session in Ehime University.

My appreciation also extend to Universiti Teknikal Malaysia Melaka (UTeM) and Malaysia Ministry of Higher Education for the financial support I received during the study. I would also like to thank all of my friends especially Malaysian community in Japan for their encouragement and companionship throughout the life in Japan and incented me to strive towards my goal.

Lastly and most importantly, I wish to thank my late father Ibrahim bin Abd Aziz (1949-2005), beloved mother Asiah binti Bikom, beloved husband Mohd Zaki bin Salehan and beloved daughter Asdaqul Afrah binti Mohd Zaki. They supported me, taught me, and loved me. Words cannot express how grateful I am for all of the sacrifices that you’ve made on my behalf. To them I dedicated this thesis.

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1 INTRODUCTION

(1) Purpose of Study

Non-Destructive Testing (NDT) has been widely used to evaluate a damaged state in a structural material without destroying or damaging it. The term 'Non-Destructive Evaluation' (NDE) has been used when the quantitative estimation is required to increase the reliability of the inspection[1, 2]. The main purpose of NDE is to determine the properties of materials such as fracture toughness, formability and microstructure characteristics[3]. NDT has been carried out using several techniques. Out of which ultrasonic testing (UT) is one of practical and popular methods. UT can be applied to detect the shape[4], size[5], orientation, and location[6] of the defect and the inclusion[7, 8].

When dealing with an interfacial problem, the evaluation of an imperfect interface is one of the challenging problems. At such the interface is partially bonding and temporary closing, the ultrasonic wave penetrates the interface and a little scattered wave will be generated. In order to overcome this problem, researchers have focused their efforts on exploiting nonlinear phenomena arising from the interaction of ultrasonic waves with imperfect interfaces. It has been experimentally proved that the frequency spectrum of a wave scattered by the imperfect interface had higher harmonics components. The ultrasonic method using the harmonics had been applied to the evaluation of closed cracks[9, 10] as well as the interface[11, 12] of materials.

A number of studies were carried out to understand the nonlinear wave generated in elastic solid material. There are several sources of generation when it comes to nonlinearity in solid material[13-15]. In the nonlinearity of elastic wave, the contact acoustic nonlinearity (CAN)[16] was exposed to exhibit a substantial departure for the higher harmonics generation and acoustic wave interaction. Hence, this has been a predominant subject for a majority of studies in classical nonlinear acoustics. These results were then supplemented by direct observation of efficient higher harmonics generation in bulk acoustic wave reflection from an interface between two nonlinear solids[17)]. The experiments revealed an increase in acoustic nonlinearity, by several orders of magnitude for both surface and bulk waves[18)] in a weakly bonded contact.

In spite of a great wealth of experimental results, the understanding of the mechanism responsible for the generation of nonlinear effects has lagged behind. This leads to the aim of this study which is to develop a numerical model based on the CAN concept and to apply it to a realistic simulation for the nonlinear ultrasonic testing of closed cracks. A numerical simulation using an elastodynamic finite integration technique (EFIT) is introduced to model the CAN and predict the ultrasonic signals from the closed crack. The research for appropriate conditions to generate the harmonics through the simulation would enhance the reliability of the UT for the closed crack.

(2) Background of Ultrasonic Testing

The UT utilizes the traveling time and amplitude of a scattered wave from the cracks in a material[5)]. A distinct scattered wave can be obtained from a crack with opening faces. However, it is difficult to detect signals from a crack with a closed face such as stress corrosion and fatigue cracks using a linear UT. Since most of the incident waves can penetrate the crack faces, a little scattered wave will be generated. Recently, nonlinear ultrasonic methods that use the CAN have been reported. The CAN is based on the dynamic behavior of contact and separation of the crack face when the incident wave with a large amplitude has been transmitted. The analytical model of the CAN was developed by Richardson[19)], followed by which several experimental studies were conducted to evaluate the closed crack[20-23)]. There have also been several numerical modeling studies to investigate the CAN. Notable techniques used were boundary element method (BEM), finite difference time domain (FDTD), and finite element method (FEM). Mendelsohn & Doong[24)] and Hirose[25, 26)] proposed the nonlinear interfacial model using the BEM and carried out the dynamic contact analyses in two-dimensional (2-D) out-of-plane and in-plane wave fields, respectively. Besides, the BEM was also utilized to model the generation of nonlinearity between solid-solid interfaces[27–29]. The FDTD technique was used to solve one-dimensional (1-D)[30] as well as 2-D[31–34] in-plane problems. The nonlinear behavior of the interacting interface[35–39] was studied in detail using the FEM analysis.

In this study, a numerical modeling using the EFIT[40, 41] is applied to model the dynamics of a nonlinear interface. The EFIT performs integration over volumes in the process of the discretization. This method results in staggered grids and provides very stable code, allowing easy and flexible treatment of various boundary conditions. This is also useful to model the elastic wave propagation in inhomogeneous material[42–46]. In the EFIT framework, digital 2-D and three-dimensional (3-D) images with a unified cell size are used as the input data for the simulation[47–49]. Using the image-based EFIT, the inhomogeneous cracks distributed in a material can be modeled with a small preprocessing cost. Since the CAN is based on a finite amplitude theory, the measurements are use the tone burst and continuous waves. A tone burst[50–52] creates an enveloped single frequency signal in the material.

To treat the interfacial problem strictly, a model with pressure-dependent nonlinear stiffness[53–55] was introduced. Besides, Solodov[56] proposed an interface friction model caused by sliding in the tangential direction. In this study, a measurement of harmonics is demonstrated to verify the simple CAN theory assuming the 1-D wave field. In the measurement, polymethylmethacrylate (PMMA) specimens with a smooth interface were used. By using the nonlinear ultrasonic wave, imaging methods were reported to show the location and height of the closed crack. A simulation model[33] using the FDTD method and its experimental[57–59] validation were carried out to obtain the image of the closed crack using subharmonics. Furthermore, the nonlinear effects by higher harmonics[60–62] were also used for the nonlinear ultrasonic imaging.

(3) Outline of the Dissertation

This thesis is arranged as follows:

- Chapter **1** describes the introductory concepts in the field of NDT, UT, and states the outline of the thesis by briefly describing the contents of each chapter.

- Chapter **2** explains the fundamental concept of the CAN. The generation of nonlinear ultrasonic wave at an interface in a linear elastic material is formulated. The analytical solution of interfacial displacement is formulated based on Richardson's theory.

- Chapter **3** proposes a 1-D numerical model of the CAN where the 1-D EFIT formulations are described. In the modeling, a set of split computational nodes is introduced to express the separation state of the interface. The numerical solutions are compared with the analytical solutions to check the accuracy of the proposed model.

- Chapter **4** reports the results of the experiment to measure the harmonics from an interface between two PMMA specimens. These experiments validate the 1-D interfacial model by the EFIT. According to the CAN, it is said a sawtooth wave is generated. The sawtooth wave that was generated by the clapping at the interface was experimentally observed using a laser doppler vibrometer for PMMA specimens. The characteristics of the sawtooth wave, in particular, the relationship between the compressive pressure at the interface and the closing velocity of the interface are discussed.

- Chapter **5** explains how the numerical model of the CAN is applied to 2-D wave field using EFIT. The 2-D simulation is performed to investigate the generation of harmonics from the closed crack. A phased array UT modeling is employed for the evaluation of the closed crack where the crack is located at the lower surface of the material. The characteristics of the harmonics generation are investigated by varying the incident angle and by studying the correlation between the compressive pressure and the incident stress amplitude.

- Chapter **6** describes the phased array imaging of the closed crack by using full-waveforms sampling and processing (FSAP) method. Here, the second harmonic extracted from the scattered wave from the closed crack is fed into the FSAP method. The simultaneous firing of array elements is employed to transmit ultrasonic waves with high amplitude and synthesize the scattered waves using the post processing of the FSAP. The simulation of the FSAP imaging is demonstrated using the scattered wave calculated with the EFIT.

- Chapter **7** concludes with the results obtained and also explains the conclusions of this research while highlighting the future works that are possible to be undertaken.