

**A REFINED LAMB WAVE TIME-REVERSAL
METHOD FOR BASELINE-FREE STRUCTURAL HEALTH
MONITORING OF THIN-WALLED STRUCTURES**

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MAY 2017**

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METHOD FOR BASELINE-FREE STRUCTURAL HEALTH
MONITORING OF THIN-WALLED STRUCTURES**

by

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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2017

*Dedicated to
my mother (Pushpa Devi) and father (Ganga Prasad Agrahari)*

Certificate

This is to certify that the thesis entitled “**A Refined Lamb Wave Time-Reversal Method for Baseline-Free Structural Health Monitoring of Thin-Walled Structures**” being submitted by **Mr. Jitendra Kumar Agrahari** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in Applied Mechanics is a record of original bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirements for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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Acknowledgements

The past five years have been the most educational and exciting years in my life. There are many people I would like to thank for their support and help in my research. Without them, I would not have been able to accomplish this study. I am extremely fortunate to have Prof. S. Kapuria as my esteemed supervisor. He has always been supporting me and provided whatever resources necessary to accomplish my goals. He has not only guided me through study related difficulties, but also helped me grow the skill of study. I am sincerely thankful to the members of my research committee, Prof. S. Ahmad, Prof. J. K. Dutta, and Dr. M. K. Singha for their observations and comments. I owe a huge debt of gratitude to Dr. Poonam Kumari, Dr. Yaqoob Yasin, and Mr. Adnan Ahmed for their immense help during T.A. duties and kind support at the critical phases. I wish to express my gratitude to all the staff of the Department of Applied Mechanics for their generous help during the course of this work.

I enjoyed working with so many intelligent colleagues and sincere friends. I would like to extend very special thanks to all my colleagues Aswani Kumar, Emrati, Dhanesh N, Sandeep Singh, Shreya Banerjee, Vishwanath, Mohit Gupta, Amit Yadav, Shashank Pandey, Gaurav Watts, Anurag Singh, Gargi Jaiswal, Bishweshwar Babu, Prakhar Gupta, PMG Bashir, Sriram K, Md. Hasan, Pramod Kawade, Bhuvnesh Kalwar, Nitin Khandelwal and Ajinkya Dahale for their help and support. I wish to give my special thanks to Dr. Rajneesh Shrama, Dr. Nitin Sharma, Dr. Shivdayal Patel and Mr. H. Nirjhar Das for their motivational support.

I wish to dedicate this thesis to my father, Ganga Prasad Agrahari and mother, Pushpa Devi. I also thank my sisters, brother, and other family members for their continuous support, patience and understanding.

Jitendra Kumar Agrahari

Abstract

Structural health monitoring (SHM) is a prime concern in engineering community for preventing catastrophic failure of critical structures such as aircrafts, ships, nuclear reactors, pressure vessels and pipelines. Ultrasonic Lamb waves excited and sensed by surface-bonded thin piezoelectric wafer patches have shown great potential in detecting small localized damage in thin-walled structures. However, the need to compare the sensor signals to a prerecorded baseline of the healthy structure in the conventional methods present several complications. This work focuses on the development of a damage detection technique without involving comparison with baseline data, based on the time reversal process (TRP) of Lamb waves. The study involves numerical simulations, experiments as well as development of new analytical solutions for this purpose.

The effectiveness of the time-reversed Lamb wave based baseline-free damage detection technique is critically examined for block mass and notch-type of damages in thin metallic plates, through finite element (FE) simulation of an integrated actuator-plate-sensor system as well as experiments. The frequency of best reconstruction has been determined experimentally as well as through FE simulations of the actuator-plate-sensor systems by performing the TRP for a range of frequency. It is shown that the single-mode tuning at the so called sweet spot frequency, hitherto recommended for improving performance of the TRP based technique, does not generally lead to the best reconstruction of the original input signal. The results of the TRP in the presence of damage show that the damage indices (DIs) computed using the conventional main wave packet of the reconstructed signal do not show any significant change with an increase in damage size, which is consistent with some recently reported experimental results by other groups. A new method of computing the DIs with extended signal length is proposed capturing the extra bands around the main wave packet, which are generated due to interactions of the propagating Lamb waves with the damage. The new refined DIs show excellent sensitivity

to damage, and also ensure a low threshold for the undamaged case, when used at the best reconstruction frequency. Refined DIs based on correlation and similarity of the reconstructed signal reflect the true severity of the damage.

To design an SHM system based on the proposed refined TRP based method, it is essential to develop a good understanding of the parameters that affect the amplitude dispersion and consequently the time reversibility of the Lamb wave signal. With this objective, the effects of adhesive layer between the transducers and the host plate, the tone burst count of the excitation signal, the plate thickness, and the piezoelectric transducer thickness on the time reversibility of Lamb waves in metallic plates are studied using experiments and finite element simulations. The effect of adhesive layer on the forward propagation response and frequency tuning has been also studied. The results show that contrary to general expectations, the quality of the reconstruction of the input signal after the TRP may increase with the increase in the adhesive layer thickness at certain frequency ranges, and narrower band of the signal does not necessarily enhance the time reversibility at all frequencies.

It is important to provide a theoretical estimate of the best reconstruction frequency for a given actuator-plate-sensor system for the design of a SHM system based on the proposed refined TRP method. With this objective, a two-dimensional (2D) shear-lag model for the stress transfer between rectangular piezoelectric wafer transducer and orthotropic host plate bonded through an adhesive layer is developed, using the recently developed mixed-field multiterm extended Kantorovich method. Both actuation and sensor modes are accounted for through appropriate boundary conditions. The effects of various parameters on the interfacial shear stress distribution are illustrated. The results from the 2D shear-lag solution reveal that for an isotropic plate with square piezoelectric transducers, the interfacial shear stress distribution matches well with the 1D plane strain solution. Accordingly, an analytical solution is presented for the time-reversed response of Lamb wave in an actuator-plate-sensor system for the plane strain case, considering the shear-lag effect. The solution is compared with the experimental and numerical results for both forward and time-reversal responses, and also for the best reconstruction frequency. The shear-lag effect on the time reversibility of the reconstructed signal is studied for varying bonding layer thickness, transducer thickness, plate thickness and the tone burst count of excitation.

सार

इंजीनियरिंग समुदाय में स्ट्रक्चरल हेल्थ मॉनिटरिंग (एसएचएम) एक मुख्य चुनौती है, जिससे विमानों, जहाजों, परमाणु रिएक्टरों, दबाव वाहिकाओं और पाइपलाइन जैसे महत्वपूर्ण संरचनाओं की विपत्तिपूर्ण विफलता को रोका जा सके। अल्ट्रासोनिक लैम्ब तरंगों ने जो की सतह-बंधुआ पतली पीज़ोइलेक्ट्रिक वफ़र पैच द्वारा उत्साहित और संवेदित हैं, ने पतली दीवारों वाली संरचनाएं में छोटे स्थानीयकृत क्षति का पता लगाने में काफी संभावना दिखायी है। हालांकि, संवेदक संकेतों की तुलना स्वस्थ संरचना के पूर्ववर्ती आधारभूत संकेतों से करने की आवश्यकता से परंपरागत तरीकों में कई जटिलताएं मौजूद हैं। यह काम लैम्ब तरंगों की टाइम रिवर्सल प्रोसेस (टीआरपी) के आधार पर आधारभूत संकेतों के साथ तुलना किए बिना क्षति खोज तकनीक के विकास पर केंद्रित है। इस उद्देश्य के लिए वर्तमान अध्ययन में संख्यात्मक सिमुलेशन, प्रयोग और साथ ही साथ नए विश्लेषणात्मक समाधान की परिवृद्धि शामिल है।

टाइम रिवर्सेड लैम्ब तरंगों पर आधारित आधारभूत-मुक्त क्षति का पता लगाने की तकनीक की प्रभावशीलता को पतली धातु प्लेटों में ब्लॉक-द्रव्यमान और दर्रा-जैसे नुकसान के लिए एक एकीकृत एकट्यूएटर-प्लेट-सेंसर सिस्टम के फाइनाइट एलिमेंट (एफई) सिमुलेशन और प्रयोगों के माध्यम से अच्छी तरह से जांच की गयी है। आवृत्ति की एक सीमा के अंदर, टाइम रिवर्सल प्रोसेस के द्वारा सबसे अच्छा पुनर्निर्माण की आवृत्ति प्रयोगात्मक रूप से साथ ही साथ एक एकीकृत एकट्यूएटर-प्लेट-सेंसर सिस्टम के फाइनाइट एलिमेंट (एफई) सिमुलेशन के माध्यम से निर्धारित की गई है। यह दिखाया जाता है कि तथाकथित स्वीट स्पॉट पर एकल-प्रकार की ट्यूनिंग आवृत्ति होने से टीआरपी आधारित तकनीक के प्रदर्शन में सुधार के लिए सिफारिश की गई है, परन्तु आम तौर पर उस आवृत्ति पर मूल इनपुट सिग्नल का सबसे अच्छा पुनर्निर्माण नहीं होता है। क्षति की उपस्थिति में टीआरपी के परिणाम यह दर्शाते हैं कि क्षति सूचकांक जिनकी गणना पारंपरिक मुख्य लहर पैकेट का उपयोग करके की जाती है, क्षति के आकार में वृद्धि के साथ कोई महत्वपूर्ण परिवर्तन नहीं दिखाते हैं जो कि हाल ही में दूसरे समूह द्वारा रिपोर्ट किए गए प्रायोगिक परिणामों के अनुरूप है। विस्तारित संकेत लंबाई के साथ क्षति सूचकांक की गणना करने की एक नई पद्धति के उपयोग करने का प्रस्ताव है जो कि मुख्य तरंग पैकेट के आसपास अतिरिक्त बैंड, जो कि क्षति से पारस्परिक प्रभाव के कारण उत्पन्न होते हैं, को समाधान की विवेचना में लेता है। सबसे अच्छे पुनर्निर्माण आवृत्ति के लिए, नया परिष्कृत क्षति सूचकांक क्षति के प्रति उत्कृष्ट संवेदनशीलता को प्रस्तुत करता है, और साथ ही साथ

अक्षत संरचना मामले में कम थ्रेशोल्ड सुनिश्चित करता है. सहसंबंध और समानता के आधार पर परिष्कृत क्षति सूचकांक क्षति की वास्तविक गंभीरता को दर्शाते हैं।

प्रस्तावित परिष्कृत टीआरपी आधारित पद्धति के आधार पर एक एसएचएम प्रणाली को डिजाइन करने के लिए, यह आवश्यक है आयाम फैलाव और जिसके फलस्वरूप लैम्ब तरंग संकेत की समय प्रत्यावर्तन को प्रभावित करने वाले पैरामीटर्स की अच्छी समझ विकसित कि जाए। इस उद्देश्य के साथ होस्ट प्लेट और ट्रांसड्यूसर के बिच एडहेसिव परत, उद्दीपन तरंग की बर्स्ट संख्या, प्लेट और पीज़ोइलेक्ट्रिक ट्रांसड्यूसर की मोटाई का प्रभाव धातु प्लेटों में लैम्ब तरंग का समय प्रत्यावर्तन के ऊपर, प्रयोगो और फाइनाइट एलिमेंट (एफई) सिमुलेशन के माध्यम से किया गया है। अग्रिम संचरण अनुक्रिया और आवृत्ति समस्वरण पर एडहेसिव परत के प्रभाव का अध्ययन भी किया गया है। परिणाम बताते हैं कि सामान्य अपेक्षाओं के विपरीत, कुछ फ्रीक्वेंसी श्रेणियों पर आगत सिग्नल के पुनर्निर्माण की गुणवत्ता टीआरपी के बाद एडहेसिव परत की वृद्धि के साथ बढ़ सकता है और संकुचित बैंड वाले संकेत जरूरी नहीं है सभी आवृत्तियों पर समय प्रतिरूपता बढ़ाएं।

प्रस्तावित परिष्कृत टीआरपी विधि के आधार पर दिए गए एक एकट्यूएटर-प्लेट-सेंसर सिस्टम के लिए एसएचएम प्रणाली को प्रारूप देने के लिए सबसे अच्छा पुनर्निर्माण आवृत्ति का सैद्धांतिक अनुमान प्रदान करना महत्वपूर्ण है। इस उद्देश्य के साथ, एक दो-आयामी (2 डी) शियर-लैंग मॉडल, आयताकार पीज़ोइलेक्ट्रिक वफ़र ट्रांसड्यूसर और ऑर्थोट्रोपिक होस्ट प्लेट जो कि एडहेसिव परत से चिपके हुए है, के बीच तनाव हस्तांतरण के लिए विकसित किया गया है, जिसमें हाल ही में विकसित मिक्स-फील्ड मल्टिटर्म एक्सटेंडेड कंटोरोविच का उपयोग किया गया है। दोनों क्रियान्वयन और सेंसर मोड को उचित सीमा शर्तों के माध्यम से लिया जाता है। इंटरफेसियल कतरनी तनाव वितरण पर विभिन्न मापदंडों के प्रभाव व्याखित हैं। 2 डी कतरनी-लंप समाधान के परिणाम से पता चलता है कि स्क्वेयर पीज़ोइलेक्ट्रिक ट्रांसड्यूसर के साथ एक आइसोट्रोपिक प्लेट के लिए, इंटरफेसियल कतरनी तनाव वितरण 1 डी प्लेन स्ट्रेन समाधान के साथ अच्छी तरह से मेल खाता है। कतरनी-अंतर प्रभाव को देखते हुए, एक विश्लेषणात्मक समाधान प्लेन स्ट्रेन-तनाव के मामले के लिए एकट्यूएटर-प्लेट-सेंसर सिस्टम में लैम्ब तरंग की टाइम रिवर्सल प्रोसेस के लिए प्रस्तुत किया गया है। फॉरवर्ड और टाइम रिवर्सल प्रोसेस दोनों द्वारा प्राप्त किये गए परिणामों की प्रयोगात्मक और संख्यात्मक परिणामों से तुलना की गयी है, और सबसे अच्छी पुनर्निर्माण आवृत्ति के लिए भी तुलना की गयी है। इस पुनर्निर्धारित सिग्नल के समय प्रतिवर्ती पर कतरनी अंतर प्रभाव का अध्ययन विभिन्न एडहेसिव परत मोटाई, ट्रांसड्यूसर मोटाई, प्लेट मोटाई और उद्दीपन तरंग की बर्स्ट संख्या के लिए किया गया है।

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