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NSFC/RGC Joint Research Scheme
Joint Completion Report

(Please attach a copy of the completion report submitted to the NSFC by the Mainland researcher)

Part A: The Project and Investigator(s)

1. Project Title

Corrosion and Fatigue Damage Monitoring in Large Scale Tubular Structures Using Guided Ultrasonic Waves

2. Investigator(s) and Academic Department/Units Involved

	Hong Kong Team	Mainland Team
Name of Principal Investigator *(with title)*	Prof. ZHOU Li Min	Prof. MENG Guang
Post	Professor	Professor
Unit / Department / Institution	Mechanical Engineering/ HKPolyU	State Key Lab of Mech. System and Vibration/ Shanghai Jiaotong University
Co-investigator(s) *(with title)*	Prof. CHENG Li	Dr LI Fucai
	Dr. SU Zhongqing	Prof. LI Hongguang
		Prof. YE Lin

3. Project Duration

	Original	Revised	Date of RGC/ Institution Approval *(must be quoted)*
Project Start date	01-JAN-2011		
Project Completion date	31-DEC-2013		
Duration *(in month)*	36		

Part B: The Completion Report

5. Project Objectives

5.1 Objectives as per original application

1. Investigate propagation characteristics of guided ultrasonic waves in complex large-scale tubular structures with corrosion and fatigue crack damage, and evaluate the performance of different piezoelectric (PZT) transducers and their properties in the activation and acquisition of guided ultrasonic waves for damage detection.
2. Design active sensor networks integrated with optimized PZT transducers for detecting typical corrosion and fatigue crack damage in large-scale tubular structures.
3. Establish the framework for extracting signal signatures from complex wave signals and develop novel inverse algorithms for real-time and online damage identification and structural health monitoring.
4. Study the influence of adverse conditions in practical applications on the capacity and robustness of the proposed techniques.

5.2 Revised Objectives N/A

Date of approval from the RGC: _____

Reasons for the change: _____

6. Research Outcome

Major findings and research outcome
(maximum 1 page; please make reference to Part C where necessary)

Welded tubular structures with fatigue cracks exist widely in real engineering situations and usually play vital roles in the whole framework. Identification of a crack in such structures in operation is a highly challenging topic which deserves in-depth investigation. The GW-SHM technique, which can be regarded as the integration of actuators and sensors into structural components combined with automated advanced signal processing procedure for implementing a damage identification strategy, makes this challenging demand realizable.

The main target of the project was detection of non-fatigue damage and fatigue damage based on GW-SHM technologies in plate-like structures and complex structures. Damage identification strategies were demonstrated in simple to complex structures, from artificial damage to fatigue crack, using either pulse-echo or pitch-catch configuration by PZT pairs in this study. The GW S_0 at the central frequency of 150 kHz was initially explored for the detection of a weld in a 10 mm thick steel plate from a PZT pair in pitch-catch configuration. Several kinds of materials were filled within the notch as impurities to investigate the detection effects of impurities in damage on the characteristics of GW propagation. The identification technique using GWs was shown to be suitable for the detection of weld and damage in welded structures.

Characteristics of GWs in a WTSS with rectangular cross-section and relative thick wall, a true-scale model of a train bogie frame segment, were investigated. It was found that (i) GWs generated by surface-bonded PZT actuator on any facet of the WTSS would be confined within the same facet at first; (ii) when incident GWs reach boundaries (welding zones and original edges of different facets of WTSS), they would be scattered (including wave reflection, transmission and diffraction); (iii) all the scattered wave components continue their propagation in adjacent facets. A probability-based damage imaging approach in terms of a signal feature Time of Flight was used for estimation of presence, size and location of fatigue crack in metallic structures based on GWs generated by an active piezoceramic transducer network. Both simulation and experimental results show that a fatigue crack can reflect and transmit guided waves by reason of discontinuous contact of crack surfaces under cyclic fatigue loading, which demonstrate the effectiveness of the proposed method for real-time monitoring of fatigue cracks in metallic structures. Apart from damage detection, it is obviously important to develop appropriate methods to monitor and evaluate fatigue crack propagation and the integrity of such structures. Thus, two damage identification strategies based on GWs for monitoring fatigue cracks in metallic structures were demonstrated, in which two sensor networks, with eight and six PZT transducers respectively, were employed. It was found that the TRM combined with the DPP-based damage imaging approach was suitable for estimating the presence and propagation of fatigue crack in metallic structures. Moreover, the PCA-based damage classification method was capable of reducing the dimensions of a complex set of original data and classifying the different structural conditions due to crack growth.

Characteristics of guided waves propagation in thick-walled hollow cylindrical structure without and with variable cross-section were systematically investigated by using analytical and finite element analysis methods, to explore applicable PZT-induced guided wave-based structural health monitoring method for high speed train axle. It was found that because of the axisymmetric characteristics of the train axle, variable cross-sections of the structure can only reflect the propagating waves but cannot convert the wave modes. Defects change the axial symmetry of the

structure and, therefore, generate asymmetric wave, viz. flexural modes. Particles vibrate only in circumferential direction for flexural modes and damage detection can be realized by measuring the circumferential strain using sensor array boned at the other end of the train axle. The dispersion properties of GW propagations in the pressure vessel were studied. It was found that L mode is suitable for monitoring structural damages. By optimization of the excitation waveform parameters and excitation frequency, The excitation frequency of 150 kHz was found to be suitable for exciting the PZT actuators. A sensor network with fewer sensors was designed and optimized to carry out a full range of monitoring of the pressure vessel. The wave packet components of experimental signals were analyzed by means of ToF method. Both theoretical and numerical analyses were carried out to simulate the propagation of GWs in the structure and the interaction between guided waves and holes. It was found that the experimental results and theoretical analysis could verify the correctness of theoretical analysis and the feasibility of applying guided wave-based SHM techniques to monitor the pressure vessels. The work laid a solid foundation for the further damage identification in the pressure vessel using guided wave-based SHM techniques.

Potential for further development of the research and the proposed course of action
(maximum half a page)

7. The Layman's Summary

(describe in layman's language the nature, significance and value of the research project, in no more than 200 words)

In Hong Kong and the Mainland China, there are many large-scale engineering structures which are made of metallic tubular structures. Corrosion and fatigue damages can considerably lower the integrity of critical sections of tubular structures and potentially lead to catastrophic failure of the entire structure with disastrous consequences. Monitoring of damages is especially significant for prediction of remaining service life and for timely maintenance of aging engineering structures. In this project, we firstly studied the propagation characteristics of piezo-activated guided waves in welded steel plates and tubes of rectangular section using numerical simulations and experiments. The effectiveness of a probability-based damage imaging approach for identifying multiple damages in welded tubular steel structures were then investigated. Our methods were extended to study welded steel structures with fatigue cracks, guided wave propagation and damage detection for pressure vessel structures and damage detection for shaft of high speed train. The proposed methods can be used for online identification and assessment of corrosion and fatigue damages, driving down maintenance costs and extending the lifespan of engineering structures in Hong Kong and the Mainland China. The most important outcome of the project is the development of a framework with fundamental knowledge and algorithms of guided wave-based damage identification in engineering tubular structures with fatigue damages. It is expected that the developed technologies in this project will have great impact in the areas of structural health monitoring.

Part C: Research Output

8. Peer-reviewed journal publication(s) arising directly from this research project
(Please attach a copy of each publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference.))

The Latest Status of Publications				Author(s) *(**bold** the authors belonging to the project teams and denote the corresponding author with an asterisk*)*	Title and Journal/Book *(with the volume, pages and other necessary publishing details specified)*	Submitted to RGC *(indicate the year ending of the relevant progress report)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*
Year of publication	Year of Acceptance *(For paper accepted but not yet published)*	Under Review	Under Preparation *(optional)*					
2011				Xi Lu, Mingyu Lu, Limin Zhou*, Zhongqing Su, Li Cheng, Lin Ye and Guang Meng,	Evaluation of welding damage in welded tubular steel structures using guided waves and a probability-based imaging approach, **SMART MATER. STRUCT** Volume: **20** Issue: **1** Article Number: **015018** Published: **2011.**		Yes	No
2013				Ye Lu*, Ming Yu Lu, Lin Ye, Dong Wang, Li Min Zhou*, Zhong Qing Su	Lamb Wave Based Monitoring of Fatigue Crack Growth Using Principal Component Analysis, Key **ENGINEERING MATERIALS**, Vol. 558, pp260-267, 2013		Yes	Yes
		Yes		Mingyu Lu, Xi Lu, Limin Zhou*, Lin Ye, Zhongqing Su, Li Cheng and Fucai Li	Fatigue crack detection in steel plates using guided waves and an energy-based imaging approach, submitted to **SMART MATER. STRUCT, 2014**		Yes	Yes
		Yes		Mingyu Lu, Limin Zhou*, Fucai Li, Zhongqing Su, Li Cheng and Lin Ye	Monitoring of fatigue crack propagation using time reversal method and imaging approach, submitted to **ENGINEERING STRUCTURES, 2014**		Yes	Yes

		Yes		Mingyu Lu, Xi Lu, Fucai Li, Lin Ye, Zhongqing Su and Limin Zhou*	Failure detection on train bogie structures using guided waves and an image-based approach, submitted to **ADVANCES IN STRUCTURAL ENGINEERING, 2014**		Yes	Yes
		Yes		Fucai Li*, Xuewei Sun, Limin Zhou*, Hongguang Li, Guang Meng	Guided wave propagation in high speed train axle and damage detection based-on wave mode conversion, submitted to **STRUCTURAL CONTROL AND HEALTH MONITORING, 2014**		Yes	Yes

9. Recognized International conference(s) in which paper(s) related to this research project was/were delivered *(Please attach a copy of each delivered paper)*

Month/Year/ Place	Title	Conference Name	Submitted to RGC *(indicate the year ending)*	Attached to this report *(Yes or No)*	Acknowledged the support of this Joint Research Scheme *(Yes or No)*
December, 2011, Shenzhen, China	Monitoring of surface-fatigue crack propagation in a welded steel angle structure using guided waves and principal component analysis	Third International Conference on Smart Materials and Nanotechnology in Engineering (SMN 2011)		Yes	Yes
September, 2011, Stanford, USA	Fatigue crack detection using guided waves and probability-based imaging approach	The 8th International Workshop on Structural Health Monitoring, (IWSHM8)		Yes	Yes
September, 2011, Stanford, USA	Guided wave and probability based diagnostic imaging for detection of multiple welding damages in welded tubular steel structures	The 8th International Workshop on Structural Health Monitoring, (IWSHM8)		Yes	Yes
August, 2011, Jeju, Korea	Monitoring of fatigue crack propagation of engineering structures using time reversal method	18th International Conference on Composite Materials		Yes	Yes
July, 2011, Shenzhen and Hong Kong, China,	Failure detection on train bogie frames using guided waves and an image-based approach	1st International Workshop on High-speed and Intercity Railways (IWHIR 2011)		Yes	Yes
November 2012, Houston, Texas, USA	Propagation of Guided Waves in Pressure Vessel and Its Application for Damage Detection	International Mechanical Engineering Congress & Exposition IMECE2012		Yes	Yes

10. Student(s) trained *(Please attach a copy of the title page of the thesis.)*

Name	Degree registered for	Date of registration	Date of thesis submission/ graduation

11. Other impact *(e.g. award of patents or prizes, collaboration with other research institutions, technology transfer, etc.)*