Development of an indirect bridge health monitoring approach using moving sensors

by

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CERTIFICATION OF ORGINAL AUTHORSHIP

I, Jiantao Li, declare that this thesis is submitted in fulfilment of the requirements for the award of Degree of PhD., in the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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LIST OF PUBLICATIONS

Journal papers

1. Li J.T., Zhu X.Q., Law S.S. and Samali B. (2019) Indirect bridge modal parameters identification with one stationary and one moving sensors and stochastic subspace identification. *Journal of Sound and Vibration* 446: 1-21.

2. Li J.T., Zhu X.Q., Law S.S. and Samali B. (2019) Drive-by blind modal identification with singular spectrum analysis. *Journal of Aerospace Engineering ASCE* 32(4): 04019050.

3. Li J.T., Zhu X.Q., Law S.S. and Samali B. (2019) A two-step indirect bridge damage detection using vehicle axle responses by Dual Kalman Filter. *Mechanical Systems and Signal Processing* (submitted on 16 May 2019)

4. Li J.T., Zhu X.Q., Law S.S. and Samali B. (2019) Time-varying characteristics of bridges under passage of vehicles. *Mechanical Systems and Signal Processing* (submitted on 8 July 2019)

Conference papers

1. Li J.T., Zhu X.Q. and Samali B. (2017) "Extraction of bridge modal parameters using a moving instrumented vehicle by SSI technique." *Proceedings of the 8th International Conference on Structural Health Monitoring of Intelligent Infrastructure*, 5-8 December 2017, Brisbane, Australia.

2. Zhu X.Q., Li J.T. and Samali B. (2018) "Estimation of bridge frequency from the vibration measurements of a moving vehicle by using blind source separation technique."

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3. Li J.T. and Zhu X.Q. (2018) "Condition assessment of highway bridges under traffic loadings." *Proceedings of the 15th International Symposium on Structural Engineering*, 24-27 October 2018, Hangzhou, China.

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ABSTRACT

The inevitable deterioration and damage of bridge infrastructures due to repeated and excess traffic loading, environmental erosion and ageing are of great concern worldwide. Bridge structural health monitoring (SHM) is critical to obtain structural health information and early warning for potential damage. Most of the current SHM strategies measure vibration responses from sensors installed at different locations on the bridge. This direct approach poses several challenges, such as the high cost of the installation and maintenance of sensors, the need for extensive data processing and the insufficient spatial information. To seek a more economical and flexible way to monitor bridges, an indirect approach that measures responses of a passing vehicle has recently drawn great attention. This strategy involves the use of instrumented vehicles as a moving sensory system to capture bridge dynamic information via vehicle-bridge interaction (VBI). Sensors are installed on the vehicle axles or body. However, the responses from sensors on a moving vehicle are nonstationary, noisy and significantly affected by the surface roughness of the bridge. Therefore, most of the classical output-only system identification approaches based on the assumption of white noise excitation may fail to extract accurate structural dynamic properties.

This research aims to establish a framework for bridge SHM using vehicle-based mobile sensory systems. Indirect structural identification methods that consider the intrinsic nonstationary characteristics of VBI responses are proposed to extract the bridge dynamic parameters from vehicle acceleration responses. Firstly, a Short-time Stochastic Subspace Identification (STSSI) strategy was proposed to identify bridge modal frequencies and mode shapes. This method combines conventional SSI with a rescale procedure to estimate the bridge modal parameters using the responses of two instrumented vehicles.

Secondly, based on the sequential implementation of singular spectrum analysis (SSA) and blind source separation (BSS), a method named drive-by blind modal identification with singular spectrum analysis (SSA-BSS) was proposed to extract the response components from a single set of vehicle vibration responses. The bridge frequencies can be identified from the obtained bridge related components.

Numerical and experimental results clearly demonstrated the feasibility and effectiveness of the proposed methods for indirect identification of bridge modal frequencies and mode shapes. To gain insight on the time-dependent features of VBI system, a time-frequency (TF) analysis method called Synchroextracting transform (SET) was used to analyse the vehicle and bridge responses in TF domain. The instantaneous frequencies (IFs) of the system revealed the time-varying characteristics of the VBI system. Besides the indirect bridge modal identification, a two-step drive-by bridge damage detection strategy using vehicle axle responses was proposed. Dual Kalman filter (DKF) was applied to identify the interaction forces between vehicle and bridge. With the interaction forces, a sensitivity analysis was performed with regularization technique to identify the bridge damage. The proposed two-step damage detection method effectively identified the location and extent of the damages using vehicle axle responses, which demonstrated its great potential for drive-by bridge damage detection. Moreover, the SSA-BSS and the TF analysis strategy were successfully applied to analyse the responses from an in-situ VBI system.

In summary, an indirect bridge SHM technique using vehicle-based moving sensing system was developed in this study. Bridge modal identification and damage detection were conducted successfully using vehicle responses. Results further demonstrated that it can be a convenient and cost-effective alternative or a promising complement to conventional bridge SHM.

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LIST OF ABBREVIATIONS

SHM	Structural Health Monitoring
VBI	Vehicle-Bridge Interaction
SSI	Stochastic Subspace Identification
STSSI	Short-Time Stochastic Subspace Identification
SSA	Singular Spectrum Analysis
BSS	Blind Source Separation
TF	Time-Frequency
TFA	Time-Frequency Analysis
SET	Synchroextracting Transform
IFs	Instantaneous frequencies
DKF	Dual Kalman Filter
FDD	Frequency Domain Decomposition
RDT	Random Decrement Technique
DOFs	Degrees of Freedom
PCA	Principal Component Analysis
FFT	Fast Fourier Transform
HHT	Hilbert-Huang Transform
HT	Hilbert Transform
EMD	Empirical Mode Decomposition
IMFs	Intrinsic Mode Functions
CWT	Continuous Wavelet Transformation
STFT	Short-time Fourier Transform
NExT	Natural Excitation Technique
IMFs	Intrinsic Mode Functions
IAS	Instantaneous Amplitude Squared
Ref-SSI	Reference-based SSI

SDOF	Single-Degree-of-Freedom
PSD	Power Spectral Density
MAC	Modal Assurance Criterion
DMF	Dynamic Magnification Factor
SOBI	Second-Order Blind Identification
BMID	Blind Modal IDentification
CS	Compressive Sensing
JAD	Joint Approximate Diagonalization
SVD	Singular Value Decomposition
SST	Synchrosqueezing Transform
TFR	Time-Frequency Representation
SNR	Signal-to-Noise Ratio
AKF	Augmented Kalman Filter
ZOH	Zero-Order-Hold
RPE	Relative Percentage Error

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