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Damage detection in bridge structures under moving loads with phase trajectory change of multi-type vibration measurements

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ABSTRACT

This paper presents a non-model based damage detection approach for bridge structures under moving loads based on the phase trajectory change of multi-type vibration measurements. A brief theoretical background on the vibration of a simply-supported bridge with a crack under moving load is described. The phase trajectories of multi-type dynamic responses are obtained and a damage index is defined as the separated distance between the trajectories of undamaged and damaged structures to indicate the damage location. Numerical studies on a simply-supported beam structure are conducted to investigate the sensitivity and robustness of the proposed approach to accurately identify the damage location. Experimental studies demonstrate that the proposed approach can be used to successfully identify the shear connection failure in a composite bridge model subjected to moving loads.

1. Introduction

Dynamic responses of bridge structures subjected to moving loads could be measured from vibration tests and used for assessing structural health and safety conditions. Mazurek and Dewolf [1] examined the feasibility of detecting structural deterioration in highway bridges by analyzing the vibrational characteristics. Lee and Ng [2] and Mahmoud [3] investigated the effect of cracks on the dynamic response of a simply supported beam subjected to a moving load. Zhang et al. [4] proposed a method for simultaneous identification of moving masses and structural damage from measured responses. In practical applications, the properties of the moving vehicle are not easy to obtain, however, which is important to better understand the dynamic interaction behavior between the bridge and vehicles loads. Some researchers [5,6] paid their attention to identify the properties of the moving vehicles from the time history of the dynamic responses of the bridge. For structural damage detection, in some scenarios the moving vehicle properties have to be assumed as unknown parameters. Zhu and Law [7] performed the simultaneous identification of the moving forces and structural damage iteratively by using a two-step identification procedure. Later, Law et al. [8] conducted structural damage identification of a three-span box-section concrete bridge deck subjected to a three-dimensional moving vehicle model. In this study, the time-histories of the interaction forces and the system parameters are identified simultaneously in an iterative manner. To improve the accuracy in structural damage identification, which may be influenced by the accuracy of the identified moving loads, Li et al. [9] proposed an improved damage identification approach for the bridge structures subjected to moving loads with numerical and experimental validations, based on dynamic response reconstruction without the need to identify the moving

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forces as well as the properties of the moving vehicle. McGetrick et al. [10] presented an interesting study on using an instrumented vehicle to identify bridge dynamic parameters. The acceleration measured from a moving vehicle was used to identify the stiffness of the bridge model.

The above studies mainly investigate the damage detection problems with modal information or vibration testing measurements for bridge structures under moving loads, and an initial finite element model is required for the updating. Those methods are usually termed as model based methods. The main difficulty of model based methods is to obtain an accurate finite element model to well represent the real bridge structure. With the development of advanced signal processing techniques, there have been a growing number of studies in the recent two decades for non-model based damage detection in bridge structures. For example, numerous studies have been conducted by performing the time-frequency analysis, such as the wavelet transform [11,12] and Hilbert-Huang transform (HHT) [13] of displacement response, and wavelet transform of acceleration response [14,15]. Marchesiello et al. [16] used time-frequency map to identify the instantaneous frequency variations along the bridge with crossing loads. Li and Hao [17] applied continuous wavelet transform and HHT to analyze the measured relative displacement responses and successfully identified the damage of shear connectors in composite bridge models under moving loads. The ideas of the above-mentioned studies are based on the fact that the damage can be indicated by the abnormality or singularity in the dynamic responses and it is visualized through the appearance of a highlighted oscillation in the processed signal feature. The success of the methods therefore depend on that a singularity or oscillation in the response signals can be observed with advanced signal processing techniques when the moving load passes the location of the damage in the bridge structure.

Usually only an individual type of dynamic response quantity, i.e. displacement or acceleration, is used in the above-mentioned studies to detect the structural damage. This could limit the sensitivity and accuracy of damage identification. Law and Zhu [18] investigated the dynamic behavior of damaged concrete bridge structures under moving loads. The vibration “displacement-velocity” phase plane at the mid-span of a simply-supported beam subjected to a moving load is illustrated. It was observed that there is a clear difference in the phase plane plots between undamaged and damage structural states. This indicates that damage detection using multi-type vibration measurements may perform better than that only using a single type of response quantity. Pakrashi et al. [19] applied continuous wavelet transform to observe the significant distortion in wavelet coefficients and detect the presence of damages. The measured strain and its derivative were plotted in a phase plane to track the evolution of damage conditions. Nie et al. [20] analysed measured strain signals on a steel arch to reconstruct the phase space and detect structural local damage. Later, this method was used to process the acceleration response of a continuous reinforced concrete beam under a hammer impact load. A damage index termed as Change of Phase Space Topology (CPST) with multiple embedding dimensions is defined and used to identify the structural damage [21]. It is worthy to note that this method is very sensitive to the structural damage, and only a single type of vibration response, i.e., strain or acceleration is used. It is believed that the development of a good index to describe the distortion of the phase space is of great importance to identify the damage, however, this has not been fully discussed, particularly when multi-type vibration measurements are acquired from bridge structures under moving loads and used for damage detection.

This paper presents a non-model based damage detection approach for bridge structures under moving loads based on the phase trajectory change of multi-type vibration measurements. A brief theoretical background on the vibration of a simply-supported bridge with a crack under moving load is described. The phase trajectories of multi-type dynamic responses are obtained and a damage index is defined as the separation distance between the trajectories of undamaged and damaged structures to indicate the damage location. Numerical studies on a simply supported beam structure are conducted to investigate the sensitivity and robustness of the proposed approach to accurately identify the damage location. Experimental studies are also carried out to demonstrate that the proposed approach can be used to successfully identify the shear connection failure in a composite bridge structure model subjected to moving loads.

2. Dynamic response analysis of a damaged beam under a moving force

Considering a simply-supported beam as shown in Fig. 1 with the length L, width b and height h, respectively, when the moving load $P(t)$ crosses along the beam, the displacement response can be obtained by the modal superposition and expressed as follows [11]

$$u(x,t) = \sum_{i=1}^{\infty} \frac{\phi_i(x)}{M_i} \int_0^t h_i(t-\tau)P(\tau)\phi_i(\widehat{x}(\tau))d\tau \tag{1}$$

where $u(x,t)$ denotes the displacement of the beam at the location x and time instant t, $\phi_i(x)$ is the ith mode shape; $h_i(t) = \frac{1}{\omega'_i} e^{-\xi_i \omega_i t} \sin \omega'_i t$ with $\omega'_i = \omega_i\sqrt{1-\xi_i^2}$; ω_i,ξ_i, $M_i = \int_0^L \rho A \phi_i^2(x) \mathrm{d}x$ are the modal frequency, damping ratio and the modal mass of the ith mode, respectively.

If a crack occurs at the location x_c on the beam and the relative depth of the crack is a/h, in which a is the crack depth, the

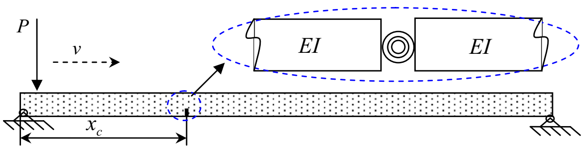

Fig. 1. A simply-supported damaged beam with a crack subjected to a moving force.