Journal of Sound and Vibration 415 (2018) 111–127

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

# Damage identification of supporting structures with a moving sensory system

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ARTICLE INFO

*Article history:*
Received 9 May 2017
Received in revised form 6 November 2017
Accepted 15 November 2017
Available online 24 November 2017

*Keywords:*
Moving sensor
Damage identification
Homotopy iteration algorithm
Interaction force

ABSTRACT

An innovative approach to identify local anomalies in a structural beam bridge with an instrumented vehicle moving as a sensory system across the bridge. Accelerations at both the axle and vehicle body are measured from which vehicle-bridge interaction force on the structure is determined. Local anomalies of the structure are estimated from this interaction force with the Newton's iterative method basing on the homotopy continuation method. Numerical results with the vehicle moving over simply supported or continuous beams show that the acceleration responses from the vehicle or the bridge structure are less sensitive to the local damages than the interaction force between the wheel and the structure. Effects of different movement patterns and moving speed of the vehicle are investigated, and the effect of measurement noise on the identified results is discussed. A heavier or slower vehicle has been shown to be less sensitive to measurement noise giving more accurate results.



## 1. Introduction

The non-destructive approach for identifying local damages in a structure has been a hot research topic in the past few decades. Most literature in this area are based on the characteristic dynamic parameters and responses [1] of structures. Sensors are often installed on the bridge deck for direct measurement of the responses of structure under load. Since the local damages are not known, a dense array of sensors should be used at different positions of the structure in practice to estimate the location and extent of the structural damage. Incorrect identification may occur when the sensor is far away from the local damage as local responses are sensitive to local damages. This phenomenon will be illustrated in Section 4.2.1 of this paper. Also, the design life of structure is usually much longer than the reliable lifespan of most sensors. The centralized long-term monitoring system requires costly onsite sensor maintenance due to the harsh operational environments. There is also a large stock of short and medium bridges, and most of them do not have such a system in practice. These form the main obstacles for general application of most existing damage detection algorithms.

Sensors have been installed on the axle or the vehicle body instead of the bridge deck [2,3] to enable the vehicle to serve as both an exciter and a sensory system. Yang et al. [4] extracted the natural frequencies of a bridge deck directly from

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https://doi.org/10.1016/j.jsv.2017.11.032

accelerations obtained from the axle of a passing vehicle. The accelerometers and velocity meters were vertically installed near the center of the vehicle. Experimental verification has been conducted [5] using a four-wheel commercial light truck towing a small two-wheel cart. Two identical trailers were instrumented with sensors to capture the ambient vibration of the bridge, and the modal parameters are extracted by applying the short-time frequency domain decomposition [6] on the difference of signals from the two trailers. Yang and Chen [7] presented a method to identify the bridge natural frequencies from the dynamic response of a test vehicle using the stochastic subspace identification technique. Kong et al. [8] conducted field tests to extract bridge modal properties using a specialized test vehicle consisting of a tractor and two trailers. The tractor was used as the exciter and the trailers were instrumented with sensors. The responses of the trailers were used to extract the modal parameters of the bridge deck.

The above idea of a moving sensory system is for extracting the fundamental bridge frequency and mode shape. This indirect approach has also been adopted for damage detection in the last two decades. Bu et al. [9] proposed a method to assess the conditions of a bridge deck using dynamic response of the passing vehicle with acceptable results. Kim and Kawatani [10] proposed a pseudo-static formulation of the vehicle-bridge interaction to identify the elemental stiffness changes of a bridge structure experimentally [11]. A truck-based mobile wireless sensory network has also been proposed to capture the vehicle-bridge interaction [12]. The wireless monitoring system is time-synchronized with the permanent wireless monitoring system installed on the bridge. Cerda et al. [13] collected data from passing vehicles over a bridge in an indirect approach of bridge health monitoring. The acceleration signals are wavelet decomposed. An instrumented truck-trailer vehicular system has been used to detect damping changes in a bridge deck with accelerometers fitted to the axles of the trailer [14,15]. Miyamoto and Yabe [16] studied the feasibility of the indirect approach to extract the bridge dynamic properties using an accelerometer mounted on the chassis of a public bus. The target bridge performance is evaluated from the measured acceleration data for the formulation of rational maintenance strategies. Zhang et al. [17] obtained damage information of a bridge deck using only one sensor mounted on a moving robot with a tapping device serving as an exciter. The operating deflection shape of the bridge deck was also estimated using information from a moving device [18], and its curvature can be obtained from wavelet-based filtering of the information for damage detection.

The above review shows that the use of a moving sensory system is feasible and reliable for damage identification. The moving sensory system proposed in this paper collects dynamic responses along its moving path and this is equivalent to measuring responses from a dense array of sensors along the structure. Local damage in a region trespassed by the vehicle can be accurately identified by the local responses collected. Accelerometers located on the axle and body of the moving vehicle collect the dynamic responses of the vehicle. The dynamic interaction force between the vehicle and structure can then be determined from these responses.

The identification equations from the above methods are usually solved iteratively in the inverse analysis using regularization method [9]. This and other methods of optimization are locally convergent depending on the initial values. There are, however, algorithms for solving nonlinear sets of equations that are globally convergent without this constraint. The essence of these algorithms is the construction of an appropriate homotopy map and the tracking of solution sets on curves in this homotopy map. He [19] developed a new homotopy perturbation technique from the traditional perturbation method for solving different linear and nonlinear problems. Liao [20] proposed a homotopy analysis method which is capable to solve problems with highly nonlinear systems. Alexander and Yorke [21] developed a homotopy continuation method to solve bifurcations problems in nonlinear systems with fixed points and singularities in the vector fields.

In this paper, the homotopy map in the damage detection problem studied is formulated according to the general homotopy method [19–21]. The solution of the homotopy equation is based on the homotopy continuation method [21]. However, successful solution of the homotopy equation depends on the smooth tracking of the solution in the homotopy path. Choi et al. [22] have employed both the Euler method and Newton method to track the solution. Both approaches do not perform well in the system identification of a structure due to the presence of a singular matrix resulting in a set of non-realistic result. Other researchers [23] estimated the homotopy parameter from the homotopy equation with improved solution in the homotopy path using Newton iterative method. The Newton's iterative method is adopted to track the correct solution path in this study. The proposed method of analysis based on interaction force has been shown to yield more accurate identified result than the regularization technique based on vehicle responses [9]. The interaction force under the wheel is shown much more sensitive to local damages in the structure than measured accelerations from either the structure or the moving vehicle. Different patterns of vehicle movement on deck, vehicle speed and measurement noise level on the identification are numerically investigated.

## 2. Theory

### 2.1. Determination of interaction force from vehicle responses

The moving vehicle is modeled as a five-parameter two degrees-of-freedom (DOFs) system as shown in Fig. 1. It moves on the beam bridge at a uniform speed $v$ from left to right. Two accelerometers are installed on the axle and body of the vehicle to collect the responses of the two masses. The physical properties of the vehicle are: an upper mass $m_{v1}$ of the suspension, a lower mass $m_{v2}$ of the bogie and axle connected to the suspension damper $c_v$ and a suspension spring $k_{v1}$, together with another spring $k_{v2}$ to model the stiffness of the tire. The equation of motion of the vehicle can be written as