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# Structural damage detection using a parked vehicle induced frequency variation

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ABSTRACT

Natural frequencies are attractive in structural damage detection as they can be conveniently measured and are usually less contaminated by experimental noise. However, generally natural frequencies alone are not sufficient for a unique solution when applied in finite element model (FEM) updating based damage detection. In view of this, a damage detection method by using a parked vehicle induced frequencies variation is proposed in this paper. Firstly the phenomenon of frequency variation caused by a parked vehicle is illustrated via a simulated simply supported beam. Then a FEM updating based damage detection method is proposed by using measured frequencies of the vehicle-bridge system with the vehicle parked at different locations. Numerical and experimental examples with different damage scenarios are conducted to verify the feasibility of the proposed method. The results indicated that it possesses the ability of taking advantage of the high accuracy and overcomes the insufficient quantity of the natural frequencies for damage detection.

## 1. Introduction

Damage detection of existing bridge structures is an essential and challenging task. Tremendous vibration-based damage detection techniques have been developed during the past decades [1–4]. Such methods are normally based on the fact that structural damage causes changes in natural frequency, mode shape, and damping [5,6]. Compared to mode shapes and damping, natural frequencies are more attractive as they can be conveniently measured from just a few accessible points on the structure and are usually less contaminated by experimental noise [3,7–9]. Adams et al. presented a damage detection method for one-dimensional components, including straight prismatic bars, doubly-tapered bar, and automobile camshaft, based on the natural frequencies of longitudinal vibrations [10]. Nandwana and Maiti proposed a two-stage crack detect method for stepped cantilever beam [11]. The crack location was visualized by the point of intersection of the three curves related to the natural frequencies, and then the crack size was estimated via the standard relation between stiffness and crack size. This method was further extended to identify cracks in segmented beams by Chaudhari and Maiti [12] and variable cross-section beams by Chinchalkar [13]. Messina et al. employed the statistical correlation between the analytical and measured frequency changes to estimate the location and size of damages [14]. A single crack in a vibrating rod and two cracks of equal severity in a simply supported beam were identified by using the knowledge of the damage-induced shifts in a pair of natural frequencies by Morassi and his collaborator [15,16]. Lele and Maiti developed a frequencies based crack detection method for short beams in which the effects of shear deformation and rotational inertia were considered [17]. Patil and Maiti established a linear relationship explicitly between the changes in natural frequencies and the damage parameters, and employed it to detect multiple open cracks in a slender Euler-Bernoulli beam [18]. Kim and Stubbs formulated two models, i.e., crack location model and crack size model by relating fractional changes in modal energy to natural frequencies changes, and applied it to identify cracks in beam-type structures [19]. Zhong et al. adopted the derivatives of natural frequency curve for damage detection of beam-like structures based on auxiliary mass spatial probing [20]. Yang and Wang constructed a damage feature database by natural frequency vectors of an intact structure with different damages and then defined a damage index named natural frequency vector assurance criterion accordingly to identify damages [21]. Wang et al. put forward the concept of frequency shift path which combined the effects of frequency shifting and amplitude changing into one space curve to detect local stiffness reduction [9].

As a typical inverse problem, structural damage identification normally requires the number of available measurements to be great enough. Otherwise it becomes an underdetermined problem in mathematics [22]. However, the number of accessible natural frequencies which are suited for damage detection is very limited. In other words, natural frequency changes alone may not be sufficient for a unique

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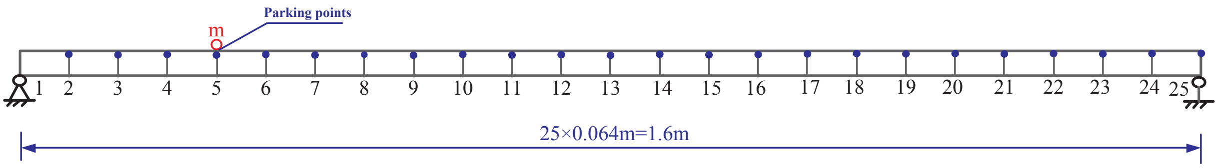


**Fig. 1.** A simply supported bridge with a parking mass.

solution of the structural damage [7]. Therefore mode shapes are further employed to provide more information for vibration based damage detection [23,24]. However, compared to natural frequency, mode shape identification has obvious disadvantages in the aspects of the complexity of signal processing technique and the sensitivity to noise. The limited identification accuracy of mode shape would lead to unreliable damage detection results.

This paper aims to propose a new damage detection method for bridge structures based on a parked vehicle induced frequencies variation. This method possesses the ability of taking advantage of the high accuracy and overcome the insufficient quantity of the natural frequencies for damage detection. Bearing vehicle load is the essential property of bridge. As the presence of a parked vehicle introduces additional mass to the bridge, the natural frequencies of the bridge vibrating alone are different from that vibrating along with a parked vehicle [25–28]. This phenomenon can be used to provide more frequency information with a vehicle parked at different locations of the bridge for damage detection. Firstly the phenomenon of frequency variation caused by a parked vehicle is illustrated via a simulated simply supported beam. Then a finite element model (FEM) updating based damage detection method is proposed by using measured frequencies with a vehicle parked at different locations. Numerical examples of a two-span continuous beam and a simply supported truss with different damage scenarios, and experimental example of a simply supported beam are analyzed to verify the feasibility of the proposed method.

## 2. Basic theory

Bearing vehicle load is the essential property of bridge. The presence of a vehicle introduces additional mass to the bridge, thus the natural frequencies of the bridge vibrating alone are different from that vibrating along with a parked vehicle [25–28]. In this section, this phenomenon is illustrated by a simulated simply supported bridge. FEM is employed to calculate the natural frequencies. For a linear structural system with $n$ degree-of-freedoms (DOFs), the eigenvalue problem in FEM can be written as

$$\mathrm{K}\ \Phi_i = \lambda_i \mathrm{M}\ \Phi_i \quad (i = 1,2,\cdots n) \tag{1}$$

where K and M are the global stiffness matrix and mass matrix of the bridge, respectively; $\lambda_i$ and $\Phi_i$ are the *ith* eigenvalue and the corresponding eigenvector of the bridge, respectively.

When the bridge is bearing an additional vehicle, the vehicle and the bridge will formulate a vehicle-bridge system. For simplicity, the vehicle is assumed as a point mass in this section. The damping effects for both the vehicle and bridge are neglected since only frequencies are investigated in this study. Furthermore, the road surface roughness is not taken into consideration for its non-contribution to the frequencies when a vehicle is parked on the bridge. Thus the vehicle mass can be added in the corresponding DOF in the global mass matrix M, then Eq. (1) changes into

$$\mathrm{K}\ \Phi_i^m = \lambda_i^m \mathrm{M}^m \Phi_i^m \quad (i = 1,2,\cdots n) \tag{2}$$

where $\mathrm{M}^m$ is the global mass matrix of the mass-bridge system, $\lambda_i^m$ and $\Phi_i^m$ are the *ith* eigenvalue and eigenvector of the mass-bridge system, respectively.

The *ith* natural frequency of the bridge ($f_i$), and natural frequency of the vehicle-bridge system $f_i^m$ can be obtained as

$$f_i = \frac{1}{2\pi}\sqrt{\lambda_i} \tag{3a}$$

$$f_i^m = \frac{1}{2\pi}\sqrt{\lambda_i^m} \tag{3b}$$

Fig. 1 shows the simply supported bridge with a parked mass. The main parameters of the bridge and the mass are as follows: length $L = 1.6$ m, elasticity modulus $E = 2.1 \times 10^{11}$ Pa, constant mass density $\rho = 7800$ kg/m$^3$, constant cross section $A = 0.2 \times 0.01$ m$^2$, the additional mass $m = 5$ kg.

The nodes (NO. 1 to 25) are selected as parking points for the mass gradually. The first three natural frequencies of the mass-bridge system with the mass parked at different locations are calculated via FEM. The bridge is divided into 25 finite beam elements equally. And the point mass is added to the DOF in the bridge FEM according the parking location. Modal analysis is performed 25 times to consider the 25 different conditions. Then they are normalized to the natural frequencies of the bridge without the parked mass. The normalized natural frequencies of the system with the parked mass at different locations are shown in Fig. 2. It can be observed that the frequencies of the system are different from that of the bridge alone, and the changes vary along with the parking locations. Similar to the bridge alone, structural damage will cause changes to the frequencies of the mass-bridge system. Fig. 3 shows the changes of the first three natural frequencies caused by a local damage on element 15 with the severity of 40%.

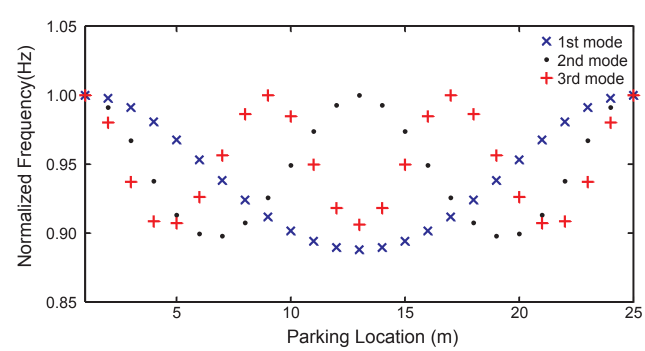


**Fig. 2.** Natural frequencies of a bridge with a mass parking at different locations.

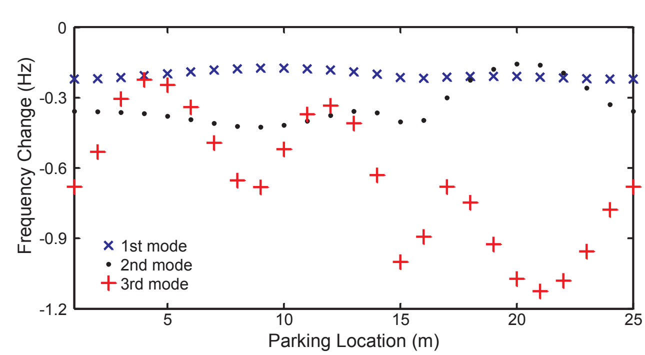


**Fig. 3.** Natural frequencies changes of a bridge caused by local damage.