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An effective means for damage detection of bridges using the contact-point response of a moving test vehicle

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ABSTRACT

To further the technique of indirect measurement, the contact-point response of a moving test vehicle is adopted for the damage detection of bridges. First, the contact-point response of the vehicle moving over the bridge is derived both analytically and in central difference form (for field use). Then, the instantaneous amplitude squared (IAS) of the driving component of the contact-point response is calculated by the Hilbert transform, making use of its narrow-band feature. The IAS peaks serve as the key parameter for damage detection. In the numerical simulation, a damage (crack) is modeled by a hinge-spring unit. The feasibility of the proposed method to detect the location and severity of a damage or multi damages of the bridge is verified. Also, the effects of surface roughness, vehicle speed, measurement noise and random traffic are studied. In the presence of ongoing traffic, the damages of the bridge are identified from the repeated or invariant IAS peaks generated for different traffic flows by the same test vehicle over the bridge.

1. Introduction

Integrated as parts of the land transportation systems, the bridge has been playing an irreplaceable role in ensuring the free and safe passage of pedestrians and vehicles. Regardless of its vital role in lifelines, a bridge may suffer from varying degrees of damages due to degradation of stiffness in structural members, connections, supports, or in material strength, which may be caused by overloaded vehicles, weathering, or natural disasters such as earthquakes and typhoons. Obviously, there is a strong demand to develop efficient and mobile techniques for the damage detection of bridges so as to enhance the routine management and maintenance.

To monitor the working and/or damage conditions of the bridges, vibration-based methods have been adopted for half a century or longer [1–4]. In general, these methods require the installation of quite a number of sensors on the bridge to detect the dynamic properties of bridge, such as frequencies, mode shapes, and damping coefficients. They were referred to as the *direct approach* in that the vibration responses *directly* measured from the bridge were used in processing the physical data of concern. An enormous volume of researches has been carried out along these lines using the ambient vibration, traffic vibration, forced vibration, impact vibration, etc. [5–11]. One drawback with the direct approach is the requirement of numerous sensors to be installed on the bridge along with a data acquisition system, for which the deployment and maintenance is generally *expensive*. Another drawback is that the vast amount of data generated, the so-called *sea-like data*, may

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not effectively used. It should be added that the monitoring system tailored for one bridge can hardly be transferred to the other bridges, resulting in the so-called *lack of mobility*.

To circumvent the drawbacks of the direct approach, a moving vehicle technique known as the *indirect approach* was proposed by Yang et al. in 2004 [12]. With this technique, the vibration data collected by one or few sensors installed on the moving test vehicle were used to extract the physical parameters of the supporting bridge, as schematically shown in Fig. 1. No sensors are needed on the bridge. Compared with the direct approach, the indirect approach shows great potential in economy, mobility and efficiency, although further research in software and hardware is required to make it robust to field applications.

The idea of the vehicle-based measurement proposed by Yang et al. [12] was validated in the field tests [13]. Since then, numerous researches have been inspired and conducted along these lines, including the theoretical studies [14], damage assessment [15–17], techniques for improving recognition results [18], experiments [13,19], mode construction [20,21], damping identification [22,23], damage detection of the bridges [24,25], and reviews of relevant works [26,27].

From the above review, it is known that the vehicle (body) response has been used frequently for identifying the modal parameters and damages of the bridge. This is mainly due to the fact that the vehicle response can be easily recorded by sensors mounted on the test vehicle. In this paper, however, the response of the vehicle's contact point with the bridge will be studied, which is shown to be a better measure for detecting the damages of the bridge, as it is born to be free of the vehicle frequency. For illustration of the basic idea involved, only simply supported beams will be considered, future study will be considered to consider other types of bridges.

The contents of the paper are outlined as follows. First, the moving vehicle's contact-point response (acceleration) is derived both analytically and in central-difference form for field use. Central to the damage detection is the calculation of the instantaneous amplitude squared (IAS) for the low-frequency driving component of the contact-point response by the Hilbert transform, making use of its narrow-band feature. In the finite element simulation, a damage (crack) is modeled by a hinge-spring unit. Using the IAS peaks, it is demonstrated that the location and severity of a damage or multi damages of the bridge can be clearly identified. Also, a parametric study is conducted for the effects of the key factors, such as surface roughness, vehicle speed, measurement noise and random traffic, on damage detection. In the presence of ongoing traffic, the damages of the bridge are identified from the repeated IAS peaks generated for different traffic flows by the same test vehicle over the bridge. In this paper, repetition with previous related works has been kept to the minimum.

2. Dynamic response of the vehicle-bridge system

As shown in Fig. 1, an undamped *single-axle* test vehicle is modeled as a lumped mass m_v supported by a spring of stiffness k_v, and passing through a simple beam of length L. Such a *single-degree-of-freedom* model was the one used in the theoretical and field studies [12,13,27], which should not be regarded as a half or quarter vehicle, but as the trailer of a tractor-trailer system. All the dynamic properties of the test vehicle, including the frequency, are assumed to have been made available by an ambient or impact test in practice. The equation of motion for the vehicle is

$$m_v \ddot{y}_v + k_v (y_v - u_c) = 0, \tag{1}$$

where y_v = the vertical displacement of the vehicle measured from the static equilibrium position, u_c = the contact-point displacement of the vehicle on the beam, or of the beam under the vehicle's wheels, and $\dot{( )} = \mathrm{d}( )/\mathrm{d}t$. It should be noted that the contact-point response can be interpreted as the bridge response under the vehicle's wheels in the real case. The equation of motion for the beam is

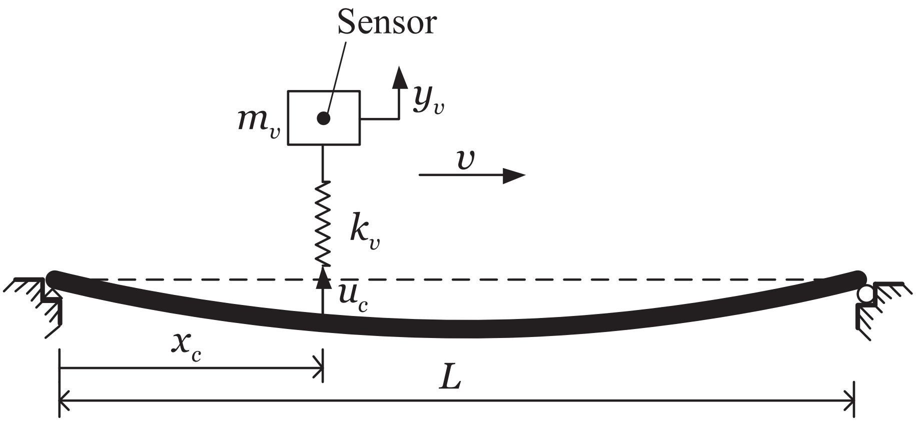

Fig. 1. Schematic of the vehicle-bridge interaction model.