APPLICATION OF LASER MEASUREMENT TO THE DRIVE-BY INSPECTION OF BRIDGES

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Abstract. *This paper introduces the application of laser vibrometer measurements to the drive-by inspection of bridges. Drive-by methods usually process the acceleration response measured from an accelerometer installed on a vehicle passing over a bridge. In this paper, two laser vibrometers and two accelerometers are installed on the vehicle to measure a relative velocity between the bridge and vehicle and the vehicle acceleration. The vehicle velocity is removed from the relative velocity by subtracting the time integration of the vehicle acceleration. It is shown by subtracting two following bridge spatial velocities at moving coordinates, that the spatial velocity of the road roughness can be removed. As a result, the bridge velocity at the moving coordinate is obtained. By applying the FFT to the bridge velocity, the fundamental frequency of the bridge is visible in the spectrum.*

1 INTRODUCTION

In recent years, in monitoring transport infrastructures, Structural Health Monitoring (SHM) is becoming more prevalent. Vibration-based methods are among the most significant methods within the field of SHM of bridges. Generally, these methods are based on changes in modal parameters (natural frequencies, damping ratios and mode shapes) of the structure, due to the occurrence of damage in the bridge [1]. Traditionally, in what are called direct methods, many sensors are installed on the bridge to detect changes in the bridge modal parameters. Providing such equipment for all bridges is a financial challenge, particularly for small bridges where a mains power supply may not be available and the cost of installation is considerable.

In recent years, a number of researchers have sought to overcome the difficulties of direct methods by introducing a new concept of bridge monitoring called indirect methods or drive-by methods using sensors installed on a specialist vehicle passing over the bridge. Drive-by approaches have many advantages in terms of simplicity, economy, efficiency and mobility. The idea was first proposed by Yang et al. [2] in which the fundamental frequency of the bridge is estimated from the acceleration response measured on a passing vehicle. Several researchers have now developed methods to identify the bridge fundamental frequency from the acceleration signal measured on a passing vehicle [3-6] and to prove the idea in an experimental case study [7-9]. In addition, several studies have been carried out to identify the bridge damping using the signal measured on a passing vehicle [10, 11]. In most the recent studies, the possibility of estimating the bridge mode shapes from indirect measurement has been investigated [12-14]. Consideration of the road surface profile in indirect methods is a critical issue as it can excite vehicle-related frequencies to a much higher amplitude level than bridge-related ones, making it difficult to identify the bridge frequencies. Some authors have developed methods to overcome this challenge, such as; (1) using the excitation due to ongoing traffic to increase the relative influence of the bridge in the vehicle response [9, 15] and (2) subtracting the signals from successive trailer axles – provided those axles have identical properties [16, 17]. In the view of all that has been mentioned so far, there is a great potential for drive-by methods for the purpose of bridge inspection [18].

In this paper, the idea of using a laser vibrometer on the vehicle is proposed to overcome the issues associated with road profile. It is suggested that by mounting a laser vibrometer beside the accelerometer on the vehicle, the relative velocity between the axle and the bridge can be measured. By integrating the acceleration signal, the axle velocity can be obtained. Subtraction these two velocity signals, the bridge velocity at the moving coordinate (at the point of vehicle bridge interaction) can be calculated with high accuracy. A numerical case study is investigated using Finite Element (FE) models of vehicle bridge interaction (VBI) and is used to validate the effectiveness and performance of the concept. The simulations confirm the capability of the proposed approach to remove the vehicle frequency from the response measured on the vehicle.

2 FINITE ELEMENT OF VBI

González [19] describes coupled and uncoupled vehicle bridge interaction (VBI). A coupled Finite Element (FE) model similar to that used by [14] is employed for the numerical analysis. The half-car system shown in Fig. 1 is used here to represent the vehicle. The vehicle body and axle component masses are represented by m_s and m_u (sprung and unsprung). The axle mass connects to the road surface via a spring with linear stiffness k_t which represents the tyre. By imposing equilibrium of all forces and moments acting on the masses and

expressing them in terms of the degrees of freedom, the equations of motion of the vehicle model are obtained:

$$M_v \ddot{y}_v + C_v \dot{y}_v + K_v y_v = f_{int} \tag{1}$$

where M_v, C_v and K_v are the respective mass, damping and stiffness matrices of the vehicle and $\ddot{y}_v$, $\dot{y}_v$ and y_v are the respective vectors of nodal acceleration, velocity and displacement. f_{int} is the time-varying dynamic interaction force vector applied to the vehicle degrees of freedom.
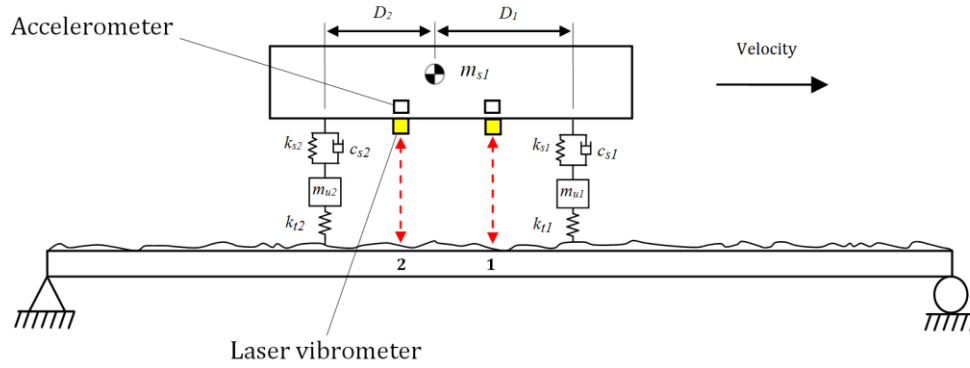
Figure 1: The half-car model on the bridge.

The bridge is represented by a simply supported beam of total span length L, flexural rigidity EI and mass per unit length m^*, using the finite element method. The model consists of 20 discrete beam elements, each with 4 degrees of freedom (2 per node). The response of the beam model to a series of moving time-varying forces is given by the system of equations:

$$M_b \ddot{y}_b + C_b \dot{y}_b + K_b y_b = f_{int} \tag{2}$$

where M_b, C_b and K_b are global mass, damping and stiffness matrices of the beam model, respectively and $\ddot{y}_b$, $\dot{y}_b$ and y_b are the vectors of nodal bridge accelerations, velocities and displacements, respectively.

The dynamic interaction between the vehicle and the bridge is implemented in MATLAB. The vehicle and the bridge are coupled at the tyre contact points via the interaction force vector. Combining equations (1) and (2), the coupled equation of motion is formed as:

$$M_g \ddot{u} + C_g \dot{u} + K_g u = F \tag{3}$$

where M_g and C_g are the combined system mass and damping matrices, respectively, K_g is the coupled time-varying system stiffness matrix and F is the system force vector. The equations for the coupled system are solved using the Wilson-Theta integration scheme [20]. The optimal value of the parameter $\theta = 1.420815$ is used for unconditional stability in the integration scheme. The initial condition of the solution is considered to be zero displacement, velocity and acceleration in all simulations.

3 DRIVE-BY BRIDGE INSPECTION

3.1 Numerical case study

A bridge is modelled using the FE method with the properties given in Table 1. The first two natural frequencies of the bridge are 4.97 and 19.88 Hz. A half-car model (Fig. 1) with the properties given in Table 2 is investigated travelling over a bridge at a speed of 4 m/s.

Properties	Unit	Symbol	value
Length	m	L	16
Mass per unit	kg/m	m	28125
Modulus of elasticity	MPa	E	35000
Second moment of area	m^4	J	0.5273

Table 1: Properties of the bridge.

| Property	Unit	Symbol	Value
Body mass	kg	m_{s1}	16200
Axle mass	kg	m_{u1}	700
		m_{u2}	1100
Suspension stiffness	N/m	k_{s1}	4×10^5
		k_{s2}	1×10^6
Suspension damping	Ns/m	c_{s1}	10×10^3
		c_{s2}	20×10^3
Tyre stiffness	N/m	k_{t1}	1.75×10^6
		k_{t2}	3.5×10^6
Moment of inertia	kg m^2	I_{s1}	1.56×10^5
Distance of axle to centre of gravity	m	D_1	2.5
		D_2	2.5
Body mass frequency	Hz	$f_{body,1}$	1.58
Axle mass frequency	Hz	$f_{axle,1}$	8.83
		$f_{axle,2}$	10.21

Table 2: Properties of the half-car.
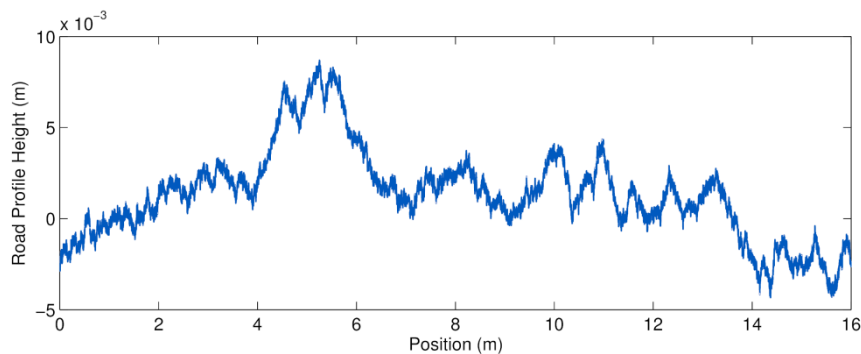
Figure 2: Class "A" road profile.

A road profile (shown in Fig. 2) is included in the simulations. The irregularities of this profile are randomly generated according to the ISO standard [21] for a road class 'A' (very good profile, as expected in a well maintained highway). The simulation is carried out using the FE method programmed in the MATLAB software environment. The sampling time in-

terval is selected to be 0.001 s. The total length of the acceleration response of the vehicle is 4 s.

3.2 Drive-by inspection using acceleration measured on the vehicle axle

Drive-by bridge monitoring is usually based on the acceleration response measured on the axle of the vehicle passing over the bridge. The acceleration response measured at the first axle of the vehicle is shown in Fig. 3(a). In order to analyse the axle response, a Fast Fourier Transform (FFT) is performed on the simulated vehicle response. The obtained FFT spectrum of the vehicle response is shown in Fig. 3(b). As expected, there is a small peak due to the fundamental frequency of the bridge and there is a dominant peak related to the axle frequency.
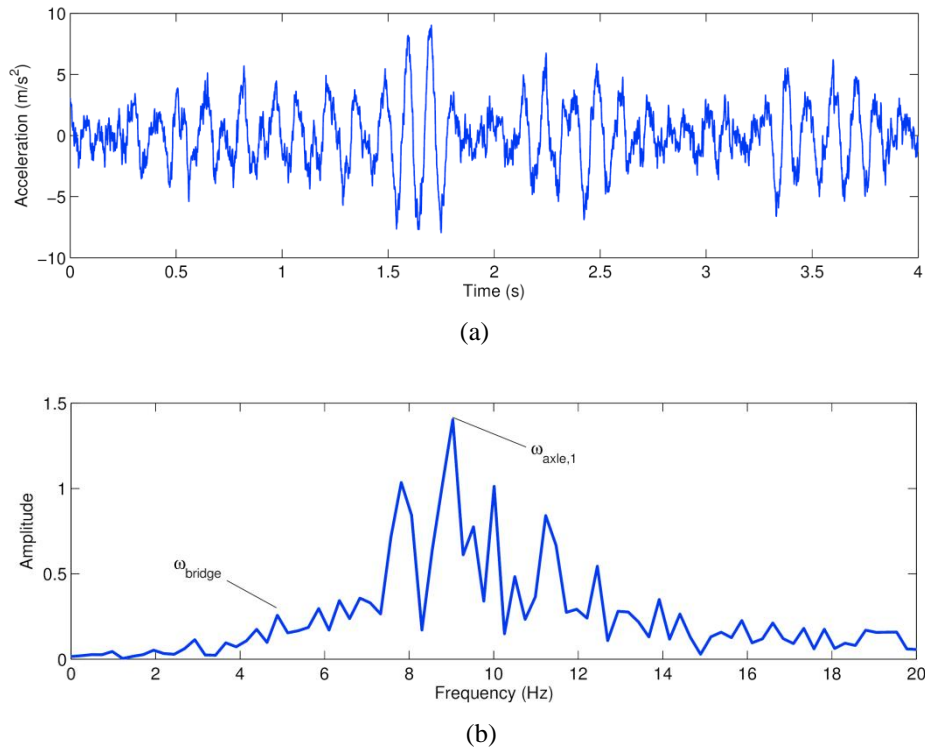

(a)

(b)

Figure 3: Response measured at the first axle; (a) acceleration, (b) FFT spectrum.

3.3 Drive-by inspection using laser measurement on the vehicle

In this section the concept of using laser vibrometer measurement on the vehicle to remove the vehicle frequency from the spectrum is introduced. A vehicle instrumented with two laser vibrometers and two accelerometers (Fig. 1) is used. Relative velocities among the bridge surface and the vehicle body are measured using two measurement points:

$$\dot{y}_{relative,i}(t) = \dot{y}_{body,i}(t) - \dot{y}_{bridge,i}(t), \ i = 1,2 \qquad (4)$$

The body acceleration is measured using the accelerometer installed at exactly the same location as the laser vibrometer. The velocity of the bridge is calculated by integration of the body acceleration (Fig. 4). Therefore, the bridge spatial velocity $\dot{y}_{bridge}^{i}(t)$ can be obtained by subtracting the body velocity from the relative velocity.
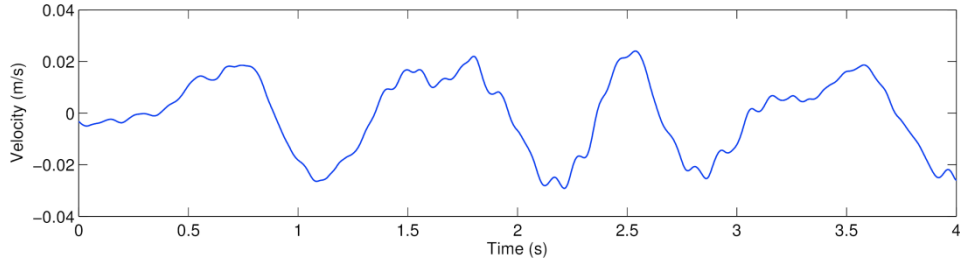
Figure 4: Body velocity measured at the first accelerometer ($\dot{y}_{body,1}(t)$).

The spatial velocity includes two parts. The first part is the bridge response relative to the moving reference and the second part is the spatial velocity of the road profile (Fig. 5), i.e., the road profile converted to velocity relative to the moving reference:

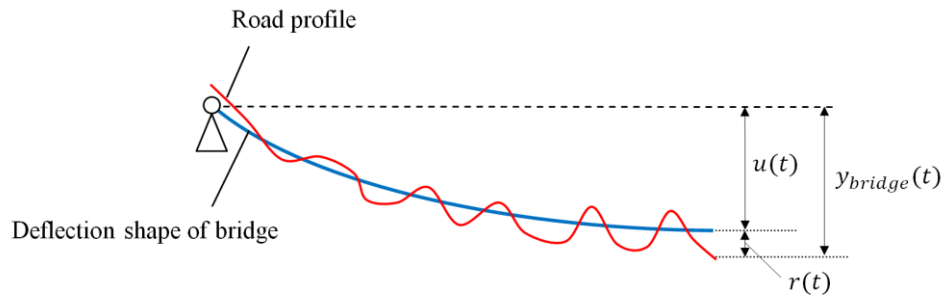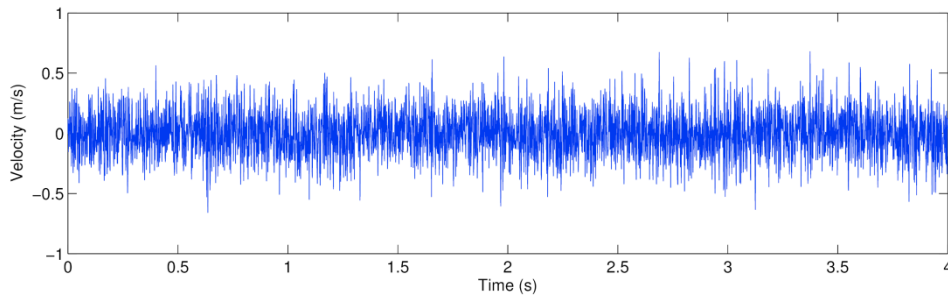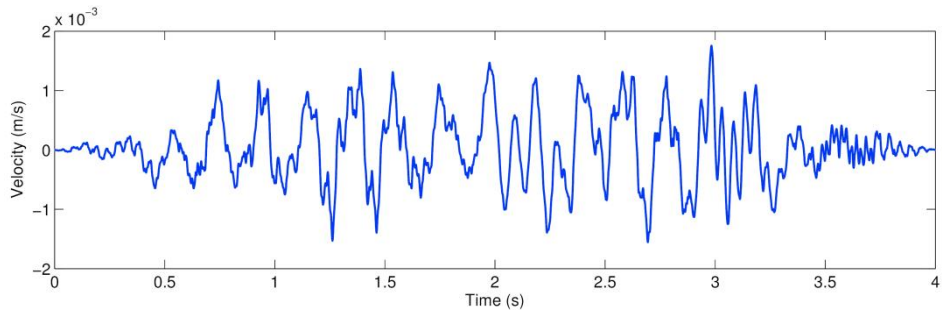$$\dot{y}_{bridge,i}(t) = \dot{u}_i'(t) + \dot{r}_i(t), \qquad i = 1,2 \tag{5}$$

Figure 5: Bridge vibration under the laser vibrometer.

Figure 6: Relative velocity measured at the first laser ($\dot{y}_{relative,1}(t)$).

Figure 7: Velocity difference ($\Delta\dot{y}$).

The spatial velocities at two following points on the vehicle are measured (Fig. 6). In order to remove the spatial velocity of the road profile from the response, the second response is subtracted from the first with a time shift to allow for their relative positions.

$$\Delta\dot{y} = \dot{y}_{bridge,2}(t + \Delta t) - \dot{y}_{bridge,1}(t)$$

$$= \dot{u}_2(t + \Delta t) + \dot{r}_2(t + \Delta t) - \dot{u}_1(t) - \dot{r}_1(t) \tag{6}$$

where Δt is the time interval between two measurement points. If Δt is selected to that $r_2(t + \Delta t) = r_1(t)$, the road profile is removed from the response and a time shifted difference of the bridge response is obtained:

$$\Delta\dot{y} = \dot{u}_2(t + \Delta t) - \dot{u}_1(t) \tag{7}$$

The velocity differences obtained from Eq. 7 are shown in Fig. 7. As a result, a bridge response at the moving coordinate is obtained which can show the most important characteristics of the bridge dynamics. The frequency spectrum of the obtained bridge response is shown in Fig. 8. A dominant peak is observable in the spectrum which is related to the bridge fundamental frequency. This can be expected to be damage sensitive.
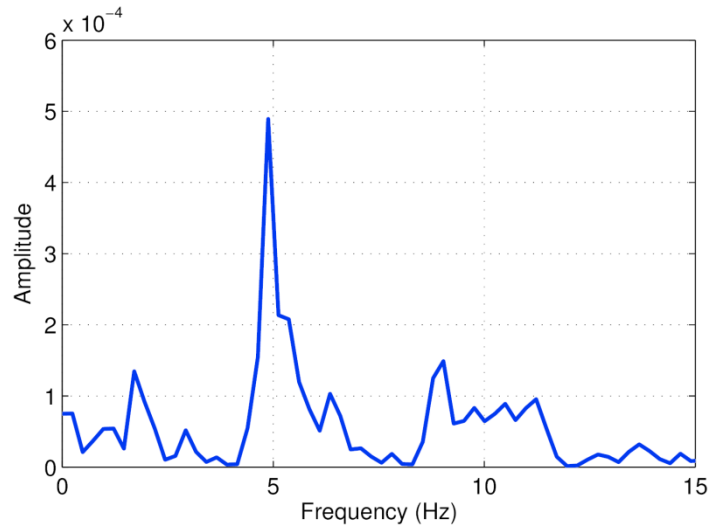

Figure 8: Frequency spectrum of the bridge response.

4 CONCLUSIONS

This paper describes the application of laser measurement to the drive-by bridge inspection problem. Subtraction of responses measured using laser vibrometers and accelerometers is used to obtain the bridge spatial velocity. Finally, spatial velocity of road roughness is removed by subtraction of the bridge spatial velocities measured at two following laser vibrometers. It is shown that the FFT spectrum of the differences response shows a dominant frequency which is corresponds to the bridge fundamental frequency.

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