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ON THE ESTIMATION OF BRIDGE MODE SHAPES FROM DRIVE-BY MEASUREMENTS

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Abstract. *This paper summarizes the latest approaches proposed on indirect bridge monitoring and provides recommendations for future development. The possibility of the estimation of bridge mode shapes from indirect measurements, is investigated. The Hilbert transform is applied to the responses measured from two following axles to extract the amplitudes of the signals. The global bridge mode shapes are constructed by applying a re-scaling process to the local mode shapes obtained from the amplitudes. The performance of the proposed method is demonstrated using a numerical case study.*

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1 INTRODUCTION

Improved condition monitoring of bridges is an important issue all over the world. The use of structural vibration data is one of the most popular Structural Health Monitoring (SHM) approaches. The concept is that if damage occurs in a structure, it causes measurable changes in its dynamic properties. In most vibration-based bridge health monitoring techniques, sensors are installed on the structure to monitor the dynamic properties. The on-site instrumentation tends to be costly, time-consuming, and may even have safety implications, depending on the location and type of bridge.

Bridge SHM using indirect measurements has been studied by many researchers in recent years [1, 2]. The concept is to instrument a vehicle passing over the bridge and identify bridge dynamic properties using the response measured on the vehicle. Malekjafarian et al. [3] provide a critical review of indirect methods published up tp 2015.

Identification of the bridge natural frequencies using indirect measurements has been extensively investigated by many researchers [4-6]. Yang and Chen [7] propose a modified version of the Stochastic Subspace Identification (SSI) method for estimating the bridge natural frequencies from the responses measured on a vehicle. It is shown that the method is more effective compared to conventional methods. Nagayama et al. [8] propose using a cross-spectrum of the accelerations measured from multiple vehicles to find the common vibration component. It is shown that the cross-spectrum provides a higher peak corresponding to the bridge natural frequency compared to the power spectral density (PSD) of the accelerations measured on a single vehicle.

Several attempts have been made for bridge damage detection using drive-by measurements. OBrien et al. [9] use empirical mode decomposition (EMD) of the accelerations measured on a passing vehicle for damage detection. It is shown that some components of the signal include the damage information. Hester and González [10] investigate using a wavelet transform of the drive-by measurements for the localization of bridge damage.

Estimation of the bridge mode shapes using indirect measurements has been investigated in a few studies [11-17]. Oshima et al. [13] propose a convoy truck-trailer system for estimating the bridge mode shapes. The estimated mode shapes are then used for bridge damage detection. The authors employ the truck to excite the bridge at a high level and a few trailers to measure the bridge response at many moving coordinates. The mode shape vectors of the bridge are identified from Singular Value Decomposition (SVD) of the measured signals. Short Time Frequency Domain Decomposition (STFDD) is proposed by Malekjafarian and OBrien [14] for identifying bridge mode shapes from a moving vehicle. In this method, the bridge is divided into a number of segments and the responses are measured on two following vehicles. Frequency Domain Decomposition (FDD) is applied to short signals related to each segment to identify the local mode shapes. The global bridge mode shapes are then obtained by a rescaling process. The STFDD method provides a better resolution of mode shapes compared to the method proposed by Oshima et al. The STFDD is improved by OBrien and Malekjafarian [15] to provide more resolution. The authors illustrate that the estimated mode shapes can be used for bridge damage detection. Yang et al. [11] theoretically prove that the vehicle response contains bridge mode shape information. The authors investigate the amplitude of the theoretical response of a moving sprung mass on a bridge using the Hilbert transform. It is shown that this amplitude at a frequency close to the bridge natural frequency, is an approximation of the bridge mode shape corresponding to that frequency.

Malekjafarian and OBrien [16] summarize the most recent methods for drive-by identification of bridge mode shapes. They conclude that a truck-trailer system equipped with an actuator can be an optimum vehicle for this case. In this paper, a recent method proposed by the authors in [16], is explained and a discussion is elaborated about its limitations. An external excitation is employed to provide access to the energy of the bridge response at the key frequencies. It is discussed that this energy is not the bridge mode shape, but is correlated to the bridge mode shape at the time of measurement. It is shown that a rescaling process needs to be applied to obtain the bridge mode shapes from the Hilbert amplitudes. The first two mode shapes of the bridge are estimated with good accuracy and high resolution. This study provides important insights into the indirect identification of bridge mode shapes.

2 THE VBI MODEL

The truck-trailer vehicle shown in Fig. 1 is employed to excite the bridge and measure its responses. It consists of a truck towing two trailers. It is assumed that a controlled force, *F(t)*, can be applied to the fourth axle of the vehicle. The properties of the vehicle are given in Tables 1 and 2.

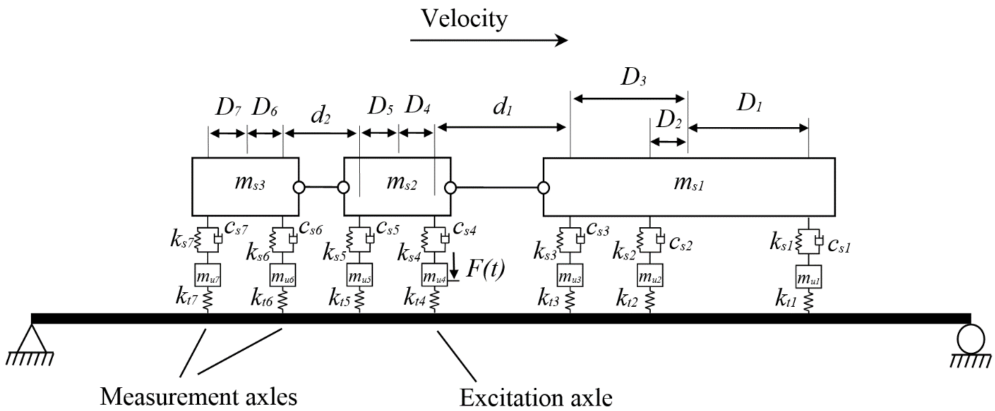


Figure 1: The truck-trailer model.

	Unit	Symbol	Value
Body mass	kg	m_{s1}	27100
Axle mass	kg	m_{u1}	700
		$m_{u2} = m_{u3}$	1100
Suspension stiffness	N/m	k_{s1}	4×10^5
		$k_{s2} = k_{s3}$	1×10^6
Suspension damping	Ns/m	c_{s1}	10×10^3
		$c_{s2} = c_{s3}$	20×10^3
Tyre stiffness	N/m	k_{t1}	1.75×10^6
		$k_{t2} = k_{t3}$	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	4.57
		D_2	1.43
		D_3	3.23
Body mass frequency	Hz	$f_{body,1}$	1.32
Axle mass frequency	Hz	$f_{axle,1}$	8.82
		$f_{axle,2}$	10.17
		$f_{axle,3}$	10.20

Table 1. Properties of the truck.

	Unit	Symbol	Value
Body mass	kg	m_{s2}	4000
Axle mass	kg	$m_{u4} = m_{u5}$	50
Suspension stiffness	N/m	$k_{s4} = k_{s5}$	4×10^5
Suspension damping	Ns/m	$c_{s4} = c_{s5}$	10×10^3
Tyre stiffness	N/m	$k_{t4} = k_{t5}$	1.75×10^6
Moment of inertia	kg m^2	I_{s2}	2401.67
Distance of axle to centre of gravity	m	$D_4 = D_5$	1.25
Body mass frequency	Hz	$f_{body,2}$	2.02
Axle mass frequency	Hz	$f_{axle,4}$	33.01
		$f_{axle,5}$	33.04
Gaps, truck-to-trailer and trailer-to-trailer	m	$d_1 = d_2$	1

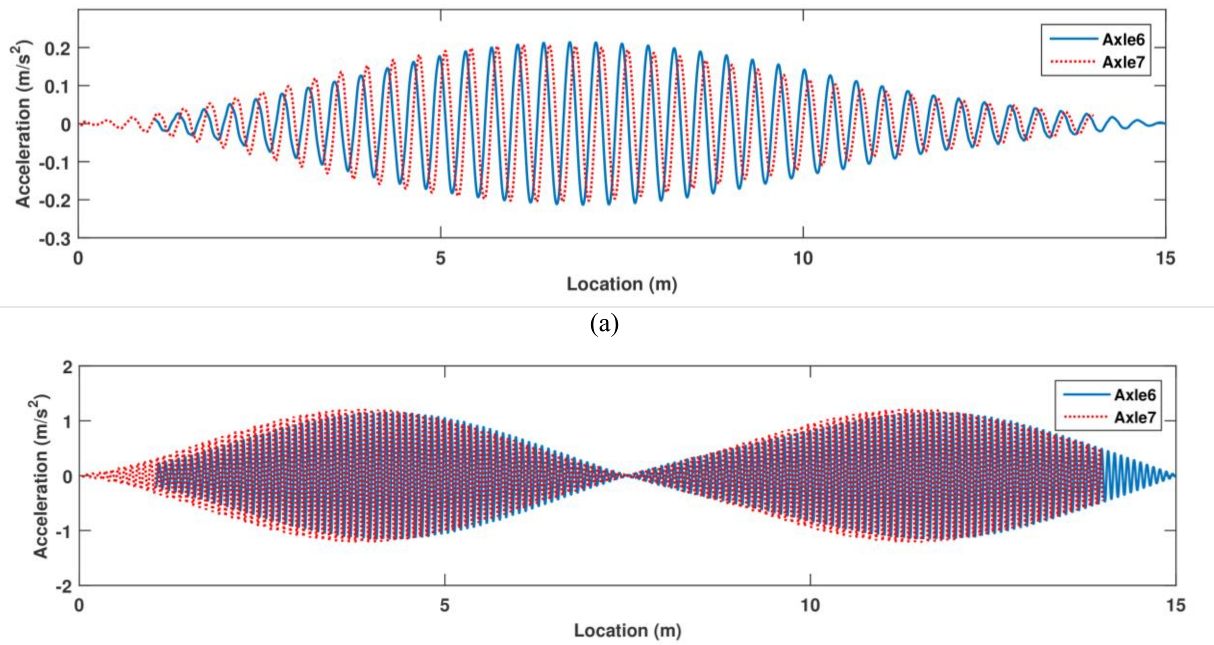
Table 2. Properties of the trailers.

The bridge is a 15 m simply supported beam with a modulus of elasticity of 35000 MPa and second moment of area of 0.5273 m^4. The first two natural frequencies of the bridge are 5.65 and 22.62 Hz. The bridge is modeled using the finite element (FE) method using 20 beam elements. The global mass and stiffness matrices of the coupled vehicle bridge interaction (VBI) model are constructed at each time step.

3 NUMERICAL SIMULATIONS

The vehicle is assumed to pass over the bridge at the speed of 2 m/s. Two simulations are implemented with different excitation frequencies. An excitation force with an amplitude of 3 kN and frequency of 5.5 Hz is applied to the vehicle in the first simulation. This frequency is close to the first natural frequency of the bridge. The simulation is repeated with a new excitation frequency of 22.5 Hz. The acceleration responses are measured at the axles of the second trailer (Axles 6 and 7). The responses measured from the two simulations are shown in Fig. 2. It can be seen that the first mode of the bridge is dominant in the response shown in Fig. 2(a), while Fig. 2(b) shows a response where the second mode is dominant. The amplitudes of the measured signals correspond to the energy in them. As the bridge is excited at frequencies close to its natural frequencies, the energy of each signal is correlated to the bridge mode shapes. Although the amplitudes look like the bridge mode shapes, they are not exactly the mode shapes. For example, Fig. 2(b) gives different amplitudes for the same location from the two axles.

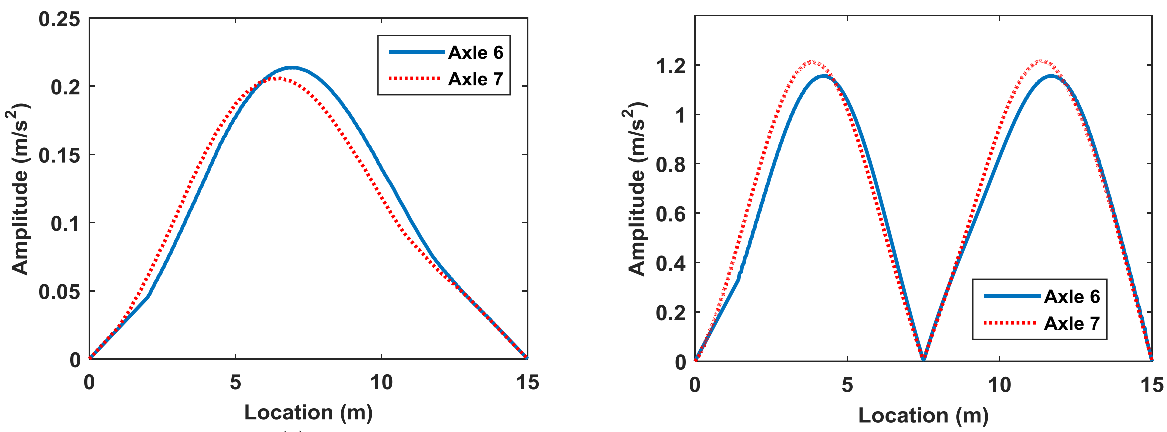
The amplitudes of the measured accelerations at two following axles are obtained using the Hilbert transform (Fig. 3). This figure clearly shows the difference between the amplitudes measured by different axles at the same location. For example, Fig. 3(a) shows the amplitudes of two following axles. They represent two different shapes which are not exactly the bridge first mode shape, but are correlated with it. Fig. 3(b) shows the amplitudes of the axles when the second mode is dominant in the responses.



(a)

(b)

Figure 2: Acceleration responses measured at Axles 6 and 7; (a) excitation frequency of 5.5 Hz and (b) excitation frequency of 22.5 Hz.

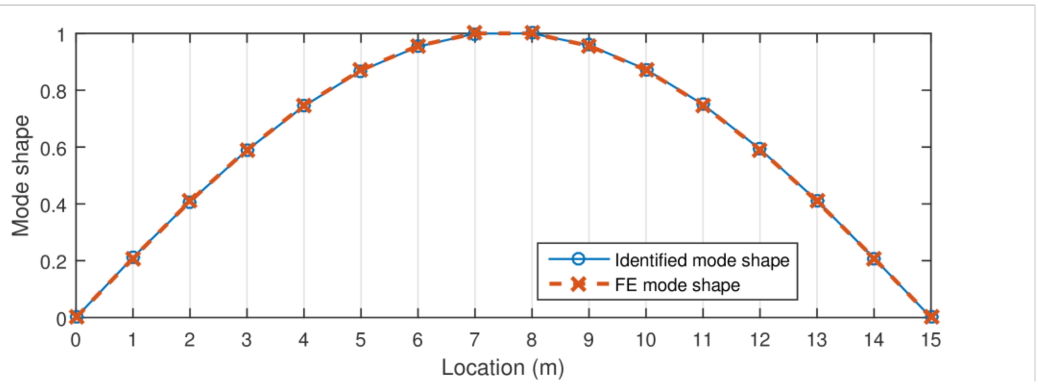


(a)

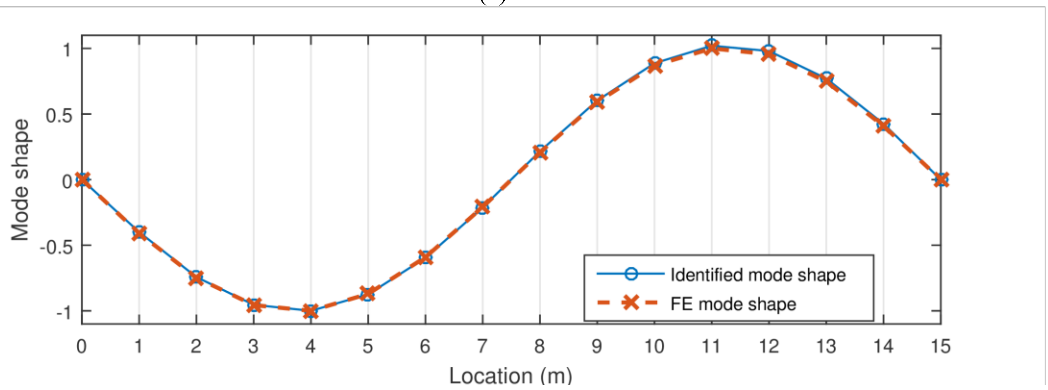
(b)

Figure 3: Amplitudes obtained from two following axles; (a) excitation frequency of 5.5 Hz and (b) excitation frequency of 22.5 Hz.

The amplitude for each axle represents how much the bridge is excited at the frequency of excitation. They are represented at two moving coordinates corresponding to the axle locations. However, as they are measured at the same time at different coordinates, the rescaling process proposed in [14] is used to find the global mode shape values. The bridge first and second mode shapes are estimated and compared to the FE mode shapes in Fig. 4. Fig. 4 (a) shows the first mode shape which is estimated by applying the rescaling process to the amplitudes shown in Fig. 3 (a). A similar procedure is used for the second mode shape shown in Fig. 4 (b). As the amplitude values shown in Fig. 3(b) have a positive sign, engineering judgment is used to infer the correct sign of the second mode shape components. It is shown that the mode shapes are estimated with good accuracy and high resolution.



(a)



(b)

Figure 4: The normalized bridge mode shapes (a) the first mode, (b) the second mode.

4 DISCUSSION AND CONCLUSION

This paper provides a numerical study on the identification of bridge mode shapes with high resolution. It suggests using a truck-trailer system equipped with an actuator to artificially excite the bridge. It is proposed that the external excitation is useful for getting access to the energy of the bridge response at the key frequencies. Some of the previous studies assumed that this energy is a normalized bridge mode shape. In contrast, it is shown that the energy is not the bridge mode shape, but is correlated to the bridge mode shape at the time of measurement. To obtain the bridge mode shapes, a rescaling process is employed using the amplitude of the responses measured on two following axles. The study has gone some way towards enhancing understanding of the contribution of the bridge mode shapes to the measured response in a vehicle. There are many challenges that need to be tackled to use the idea in practice. More research is needed to overcome the challenge of the influence of road profile. In addition, the current work is based on acceleration measurements on the vehicle axle which is usually contaminated by measurement noise. On the other hand, using laser measurements on the vehicle provides many advantages compared to accelerometers. Therefore, future research should examine using such a measurement system. A Traffic Speed Deflectometer (TSD) device seems to be a promising instrumented vehicle which could be used successfully for indirect bridge monitoring.

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