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# On the use of a passing vehicle for the estimation of bridge mode shapes

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**Abstract**

This paper presents a novel algorithm for the estimation of bridge mode shapes using the response measured on a passing vehicle. A truck-trailer system is assumed, equipped with an external excitation at a frequency close to one of the bridge natural frequencies. The excitation makes the bridge response dominant at its natural frequency. The acceleration responses are measured on two following axles of the vehicle. It is shown that the amplitude of the signal includes the operational deflected shape data which can be used to estimate the bridge mode shapes. The energy of the responses measured on two following axles is obtained using the Hilbert Huang Transform. It is shown that the bridge mode shape can be estimated with high resolution and accuracy using a rescaling process. The presence of road roughness introduces additional contributions to the response measured on the vehicle, in addition to the bridge response. The concept of subtraction of the responses measured from two identical axles is used to remove the effect of road roughness.

**Key words:** Bridge mode shape; Indirect method; Vehicle bridge interaction; Hilbert Huang Transform

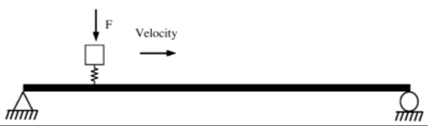
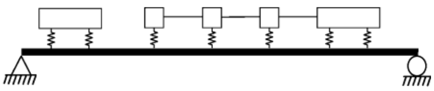
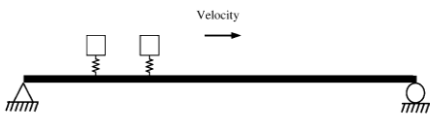
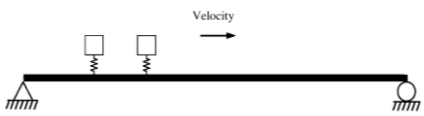
## 1. Introduction

Bridge health monitoring plays an important role in the maintenance and assessment of transportation infrastructure. Visual inspection is still the most common method used but vibration-based methods have attracted a lot of attentions in recent years. The idea is that any change in the bridge health condition causes a detectable change in its dynamic properties [1]. Many of these methods employ some means to identify the bridge modal parameters (natural frequencies, damping ratios and mode shapes) through vibration experiments. Many sensors need to be installed directly on the bridge to identify its modal parameters. The idea has been studied by many researchers through numerical [2, 3] and experimental [4-6] approaches.

Recently a new idea of bridge monitoring using indirect measurement has been considered [7, 8]. The concept is to identify bridge dynamic properties using the response measured indirectly on a passing vehicle [9]. Through vehicle bridge interaction, the vehicle suspension system is excited by the bridge displacement as well as the road or rail surface profile. Providing there is enough measurement time and good surface profile, it is possible to identify the bridge modal parameters from the indirect measurements. A considerable literature has been published on these methods and there is an increasing interest in them. Several investigations have been carried out targeting identification of the bridge natural frequencies [10-12]. Damping is considered using the indirect methods by González et al. [13] and Keenahan et al. [14]. More recently the feasibility of identifying the bridge mode shapes using indirect measurements has been investigated [15-19]. A knowledge of bridge mode shapes is very valuable in a dynamic investigation of a bridge. Bridge mode shapes can be used for damage detection purposes as there are discontinuities at the damage points in the mode shapes of a damaged bridge, including slope discontinuities at cracks [20, 21]. Structural finite element model updating is another application for which bridge mode shapes can be used [22].

Table 1 provides a summary of some of the attempts that have been proposed for the estimation of bridge mode shapes from indirect measurements. The earliest attempt is proposed by Zhang et al. [16] for the purpose of damage detection. A moving vehicle called a 'tapping vehicle', equipped with an accelerometer and a shaker to control the applied force artificially, is passed over the bridge. A point impedance is constructed using the applied force and the response, both measured at a moving coordinate. It is shown theoretically that the amplitude of the spectrum obtained from the point impedance is approximately proportional to the square of the mode shape. The mode shapes are constructed using the response and the applied force together, which needs the measurement of applied force.

Table 1: A summary of proposed methods for indirect identification of bridge mode shapes (STFFT= Short Time Fast Fourier Transform; SVD= Singular Value Decomposition; STFDD= Short Time Frequency Domain Decomposition).

| | Method | VBI | Mode shape obtained from |
|---|---|---|---|
| 1 | Zhang et al 2012 [16] |  | The amplitude of STFFT at different locations. |
| 2 | Oshima et al. 2014 [17] |  | SVD of the response measured from three (or more) trailers. |
| 3 | Yang et al. 2014 [23] |  | Hilbert amplitude of the filtered response. |
| 4 | Malekjafarian and OBrien 2014 [18] |  | STFDD of the response measured from the following axles. |
| 5 | OBrien and Malekjafarian 2016 [19] |  | Improved STFDD of the response measured from the following axles. |

Oshima et al. [17] propose a damage detection procedure which uses the bridge mode shapes identified from the measurements on a passing vehicle. The authors propose a convoy truck-trailers system for two main reasons; firstly to excite the bridge and secondly, to measure the response at three or more moving points (depends on how many mode shape points are needed) at the same time. As shown in the second row of Table 1, the first and the last trucks excite the bridge and the middle trailers measure the response. For example, if three mode shape points are going to be identified, the spaces between trailers should be adjusted in a way that each trailer passes over one third of the bridge. As a result, three segments of bridge response are recorded at the same time at different locations on the bridge. By applying Singular Value Decomposition (SVD) to these signals, a mode shape vector containing three members, corresponding to the defined areas, are identified for each mode. If greater mode shape resolution is needed, the number of trailers and their spacings should be adjusted accordingly.

In a theoretical study, Yang et al. [15] discuss the possibility of constructing the bridge mode shapes directly from the measured response on a passing vehicle. The authors consider a moving sprung mass on a bridge and theoretically show that the energy of the measured signal at a frequency equal to the bridge natural frequency, is the bridge mode shape corresponding to that frequency. The authors use bandpass filtering to get the distilled signal corresponding to a specific frequency and apply the Hilbert Transform to get the amplitude of the filtered signal. It is stated that the amplitude is the bridge mode shape for the corresponding mode. If the bridge is considered as a system, the idea is based on a single-input-single-output concept where the bridge is excited at only one point (which is a moving point) under the wheel and the response is measured at the same point. Although it is theoretically proven that the amplitude of the signal at the first natural frequency provides the first mode shape of the bridge, a more complicated case including more axles and many source of excitations, is not discussed.

Malekjafarian and OBrien [18] propose using a method called Short Time Frequency Domain Decomposition (STFDD) to identify bridge mode shapes from the response measured on a moving vehicle. Similar to the method proposed by Oshima et al., the bridge needs to be divided into a number of segments corresponding to the number of required mode shape points. However, instead of having one moving sensor for each segment, the authors propose using the response measured on two following vehicles. In a multi-step measurement process, short signals are measured from the following segments on the bridge. The local mode shape values corresponding to each step are identified using Frequency Domain Decomposition (FDD). A rescaling process is used to correlate the identified mode shapes at different locations, step by step. This method provides greater resolution and needs less equipment compared to the method proposed by Oshima et al. Nevertheless both methods provide an approximate mode shape which is the average of the mode shape values for the segment of the bridge where the response is measured. OBrien and Malekjafarian [19] improve the STFDD method by modifying the segmentation to include some overlapping , thereby providing improved resolution. The most important advantage of the improved version is that it provides better resolution of the identified mode shapes which is necessary for the purpose of damage detection. However it still gives only approximate mode shape values because of the averaging process.

Together these studies provide important insights into the indirect identification of bridge mode shapes. In this paper a new algorithm is proposed, that builds on the previously proposed methods. A vehicle equipped with an exciter is suggested, combining the ideas of Zhang at al. [16] and Oshima et al. [17]. The excitation device, which can apply a controlled force, is installed on an excitation vehicle which is not the same vehicle where the response is measured. The energy of the measured responses on two following axles are extracted using the Hilbert Huang Transform (HHT) in a process similar to that proposed by Yang et al. [23]. However, while it is shown that the obtained Hilbert amplitude includes mode shape information, for such a complex excitation, it is operational deflected shape which is an approximation of the true mode shape. Finally a rescaling process similar to that proposed by Malekjafarian and OBrien [18] is used to construct the mode shapes from the HHT amplitudes of two following axles. It is shown that, to estimate each mode shape of the bridge, the excitation frequency needs to be adjusted close to the corresponding natural frequency of the bridge. The sensitivity of the estimated mode shapes to the excitation frequency is investigated. The presence of road profile and its effect on the effectiveness of the method is also studied. The numerical simulations confirm the capability of the proposed algorithm to approximate the bridge mode shapes using signals measured on a passing truck.

## 2. The proposed algorithm using an exciter

A general view of the algorithm proposed in this paper is shown in Fig. 1. The first step is to define a specialized vehicle. It is proven that the axle response for good road conditions includes some information on the bridge dynamic properties including natural frequencies [24], mode shapes [18] and damping ratios [13]. One of the most important challenges is the ratio of the bridge response to the vehicle response [25] which is mostly a small number. This causes the vehicle response to be dominant in most cases which overshadows the bridge dynamic properties [9]. Some ideas have been used to improve this ratio such as using ongoing (ambient) traffic [18] or a vehicle equipped with an exciter [16]. The first one may be feasible as ongoing traffic would be expected in most highways, but there is little information available about the frequency content of the excitation coming from it. In some cases it could excite the vehicle frequency more than the bridge frequency in the response measured on the axle which is not helpful for the mentioned ratio. The second idea may be difficult and expensive to implement, but it provides many advantages. It is possible to excite the bridge at a desired frequency by controlling the applied force. A similar idea has been used in [16, 26, 27], where the excitation is applied at the point of measurement. Zhang et al. [16] apply a controlled load to the passing vehicle in a laboratory scale experiment using a shaker mounted on the vehicle. Li [26] also employs a mechanical exciter mounted on a vehicle model in a laboratory scale experiment. In these cases, although the bridge vibration could be improved, but again the vehicle response to the external excitation is measured not to the excitation caused by the bridge vibration under the vehicle wheel. To overcome this drawback, it is suggested here to apply the external force in a different axle or even a different vehicle from that where the response is measured (Fig 2).

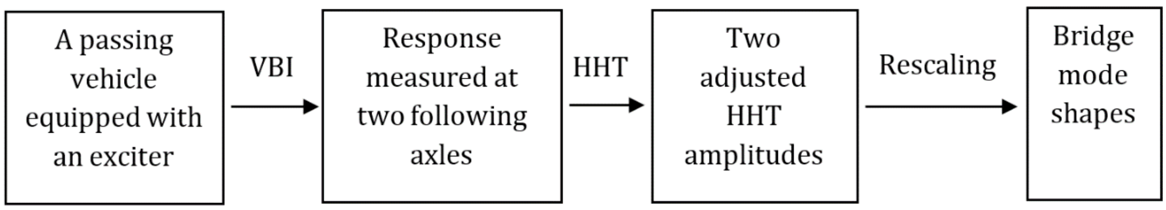



Figure 1: The algorithm (HHT= Hilbert Huang Transform).

Referring to Fig. 2, the excitation is applied to the fourth axle and the measurement is done at the sixth and seventh axles. This approach provides the possibility of controlling the bridge vibration before the measurement. It means that, by applying a force with a frequency close to the first natural frequency of the bridge, it is possible to extract good information on the first mode shape.

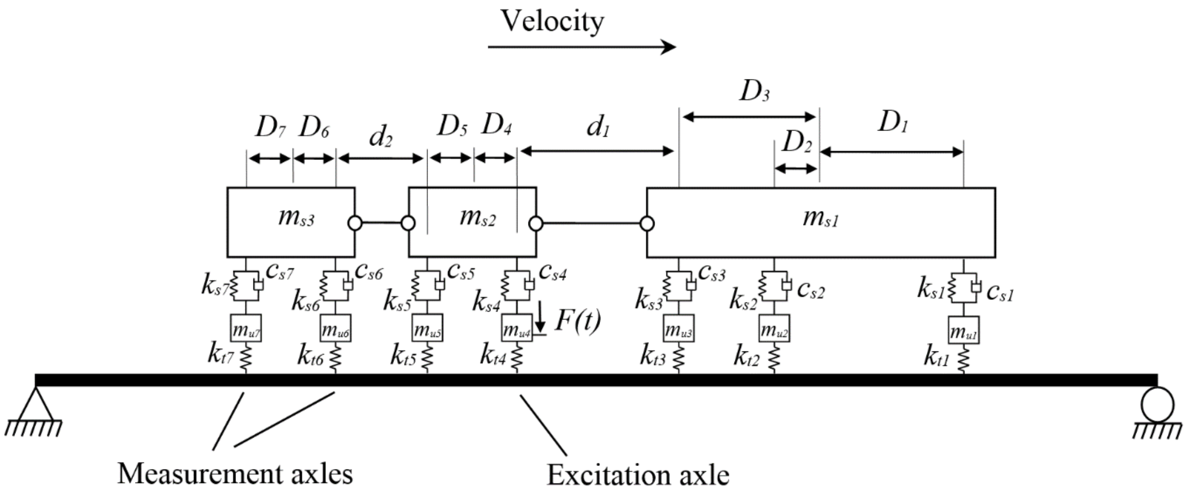



Figure 2: The truck-trailer model.

In the second step of Fig. 1, the response should be measured simultaneously at two following axles. It is necessary to have the bridge response corresponding to the first natural frequency at two different locations at a same time. These responses will be used in the last step, called rescaling, to construct the global bridge mode shape from the HHT amplitudes.

The energy of each response at each natural frequency gives the bridge deflected shape at a particular location which is correlated with the corresponding bridge mode shape. Hence the responses are first decomposed to different modes using Empirical Mode Decomposition

(EMD), and then the Hilbert amplitude of each Intrinsic Mode Function (IMF) represents the energy of the signal for the corresponding frequency. As a result, two HHT amplitudes from the two following axles are obtained.

The following axle amplitudes include the bridge mode shape information, but they are not mode shapes. They actually represent the energy of the bridge response at its natural frequency for different locations on the bridge at each time. To extract the bridge mode shapes from the amplitudes, a rescaling process is employed. The idea is based on the reference-based approach proposed in [28] where some reference sensors are needed when different tests are carried out with different setups to cover all locations along a structure. The purpose of using the reference sensors is to establish a link between the setups. The two following moving sensors here are collecting data from different locations on the bridge at a constant distance from each other. Therefore through a multi-step procedure, one of them is always the reference sensor to construct the global mode shape approximation [18, 19].

## 3. Theoretical background

### 3.1. Hilbert Huang Transform

The Hilbert-Huang transform (HHT) was first proposed by Huang et al. [29] for analysing nonlinear and nonstationary signals. It is used for damage detection in structures under a moving load [30]. The method introduces the concept of instantaneous frequency (IF) which provides the frequency of each mode in the signal as a function of time. It includes two main parts; EMD and the Hilbert Transform. Firstly a finite number of IMFs is obtained by applying the EMD. Once the signal has been decomposed, the IFs are determined by applying the Hilbert Transform to each of the IMFs. Each IF represents the frequency content of the corresponding IMF. The energy content of each IMF can also be found by calculating its Hilbert amplitude.

#### 3.1.1 Empirical Mode Decomposition

EMD is an adaptive method which has been proposed for decomposing signals. It has been used for damage detection through vehicle bridge interaction [31]. It uses a sifting process to extract a series of IMFs. The decomposition process is based on two conditions; (i) the number of extrema and the number of zero crossings must be equal or differ by at most one and (ii) at any point the mean value of the envelopes defined by the local maxima and local minima must be zero. The sifting process can be performed using the following steps [29]. First, connect the local maxima and minima of the original signal using a cubic spline to define the upper and lower envelopes. Then, subtract the envelope's mean from the original signal to generate the first IMF. The original signal is then decomposed into the first IMF and a residual. By repeating this procedure on the residual, the successive IMF's are constructed. The sifting process ceases when the last IMF has no more than one extremum.

### 3.1.2 Hilbert transform

The Hilbert transform of the $i^{th}$ IMF, $x(t)$ is [29]:

$$y(t) = \frac{1}{\pi} P \int \frac{x(\tau)}{t-\tau} d\tau \tag{1}$$

where P presents the Cauchy principle value of the singular integral. The analytic signal of $x(t)$ is defined by:

$$z(t) = x(t) + jy(t) \tag{2}$$

where j is $\sqrt{-1}$. The polar form of $z(t)$ is:

$$z(t) = a(t)e^{i\eta(t)} \tag{3}$$

The instantaneous amplitude $a(t)$ and phase $\eta(t)$ are calculated as:

$$a(t) = \sqrt{x^2(t) + y^2(t)} \tag{4}$$

$$\eta(t) = \tan^{-1}\left(\frac{y(t)}{x(t)}\right) \tag{5}$$

The instantaneous frequency is determined as [32]:

$$\omega(t) \frac{d\eta(t)}{dt} \tag{6}$$

By applying the Hilbert transform to the IMFs, a series of IF's, and their amplitudes, are calculated.

## 4. Numerical validation

Vehicle bridge interaction (VBI) is modelled using the Finite Element (FE) method. The bridge is defined here as a simply supported beam and a half car model is used for the vehicles. Discretized beam elements including 4 degrees of freedom (2 per node) with constant mass per unit length, m, modulus of elasticity E and second moment of area J are employed. A half car model with three axles is used to represent the truck and two half car models with two axles each are used for the trailers. The vehicle body has two independent degrees of freedom corresponding to body mass translation and rotation and each axle has a translational degree of freedom. $\mathrm{m_s}$, $\mathrm{m_{u1}}$ and $\mathrm{m_{u2}}$ represent the vehicle body and axle component masses respectively. $\mathrm{k_t}$ is the stiffness of the tyre which connects the axle masses and the road surface. The mass and stiffness matrices of the bridge and the vehicle are constructed separately. Considering the fact that they are connected at the tyre contact points, a coupled VBI system of the equations of motion is constructed by imposing equilibrium of the interaction forces. The VBI is implemented in MATLAB. The excitation force is applied externally to the translational degree of freedom corresponding to the 4$^{\text{th}}$ axle at $m_{u4}$ in the coupled system.

### 4.1. Example of a truck-trailer equipped with an exciter on a smooth profile

A truck-trailer system is employed consisting of a three-axle truck towing two trailers (Fig. 2). The bridge and vehicle properties are given in Tables 2 to 4 respectively. The first three natural frequencies of the bridge are 5.65, 22.62 and 50.89 Hz respectively.

Table 2. Properties of the bridge.

| | Unit | Symbol | Value |
|---|---|---|---|
| Length | m | L | 15 |
| Mass per unit length | kg/m | m | 28125 |
| Modulus of elasticity | MPa | E | 35000 |
| Second moment of area | $\mathrm{m^4}$ | J | 0.5273 |

Table 3. Properties of the truck.

| | Unit | Symbol | Value |
|---|---|---|---|
| Body mass | kg | $m_{s1}$ | 27100 |
| Axle mass | kg | $m_{u1}$ | 700 |
| | | $m_{u2} = m_{u3}$ | 1100 |
| Suspension stiffness | N/m | $k_{s1}$ | $4\times10^5$ |
| | | $k_{s2} = k_{s3}$ | $1\times10^6$ |
| Suspension damping | Ns/m | $c_{s1}$ | $10\times10^3$ |
| | | $c_{s2} = c_{s3}$ | $20\times10^3$ |
| Tyre stiffness | N/m | $k_{t1}$ | $1.75\times10^6$ |
| | | $k_{t2} = k_{t3}$ | $3.5\times10^6$ |
| Moment of inertia | kg m$^2$ | $I_{s1}$ | $1.56\times10^5$ |
| 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 4. Properties of the trailers.

| | Unit | Symbol | Value |
|---|---|---|---|
| Body mass | kg | $m_{s2}$ | 4000 |
| Axle mass | kg | $m_{u4} = m_{u5}$ | 50 |
| Suspension stiffness | N/m | $k_{s4} = k_{s5}$ | $4\times10^5$ |
| Suspension damping | Ns/m | $c_{s4} = c_{s5}$ | $10\times10^3$ |
| Tyre stiffness | N/m | $k_{t4} = k_{t5}$ | $1.75\times10^6$ |
| 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 |

In order to identify the first two mode shapes of the bridge, two simulations with different excitations are carried out. The vehicle is first simulated passing over the bridge with an excitation of amplitude 3 kN and frequencies of 5.5 Hz and 22.9 Hz at a speed of 2 m/s (it is acknowledged that this speed is too slow to be implemented in practice). The acceleration responses are assumed to be measured at the sixth and seventh axles for both cases. The bridge related parts of the signals are extracted from the total measured signal using the times that the axles enter and exit the bridge. Fig. 3 (a) shows the acceleration response measured for the first case in which the first mode of the bridge is dominant in the response. The frequency content of the response measured at Axle 6 is shown in Fig. 3(b) using a Fast Fourier Transform (FFT). It shows that the dominant frequency in the response corresponds to the first natural frequency of the bridge. The amplitudes of the signals, which represent their energies, look like the first mode shape, but they are not exactly the mode shape for two main reasons. Firstly, the first mode shape in this case must be symmetric and its peak should be at midspan, but it is clear in Fig. 3(a) that the peaks of both responses are located close to 6.5 m in the 15m bridge. Secondly, there are significant differences between the amplitudes of the two signals at different locations whereas, if they were the bridge first mode shape, they should be the same, or at least very similar. A more clear trend is observed in Fig. 3 (c) where the second mode is dominant. In this case, the energy of the two signals are not similar and they do not look like the bridge's second mode shape. The FFT of the response measured at Axle 6 in the second case is shown in Fig. 3(d). It shows that the dominant frequency of the response is closer to the second natural frequency of the bridge than the excitation frequency.

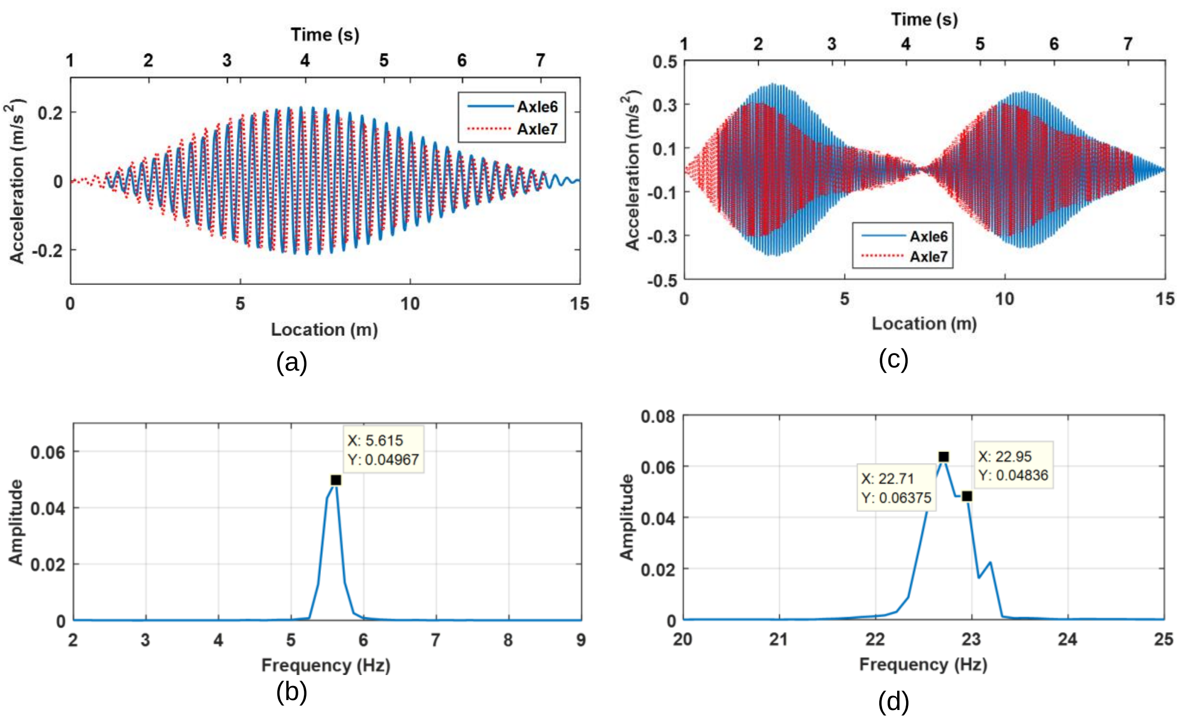
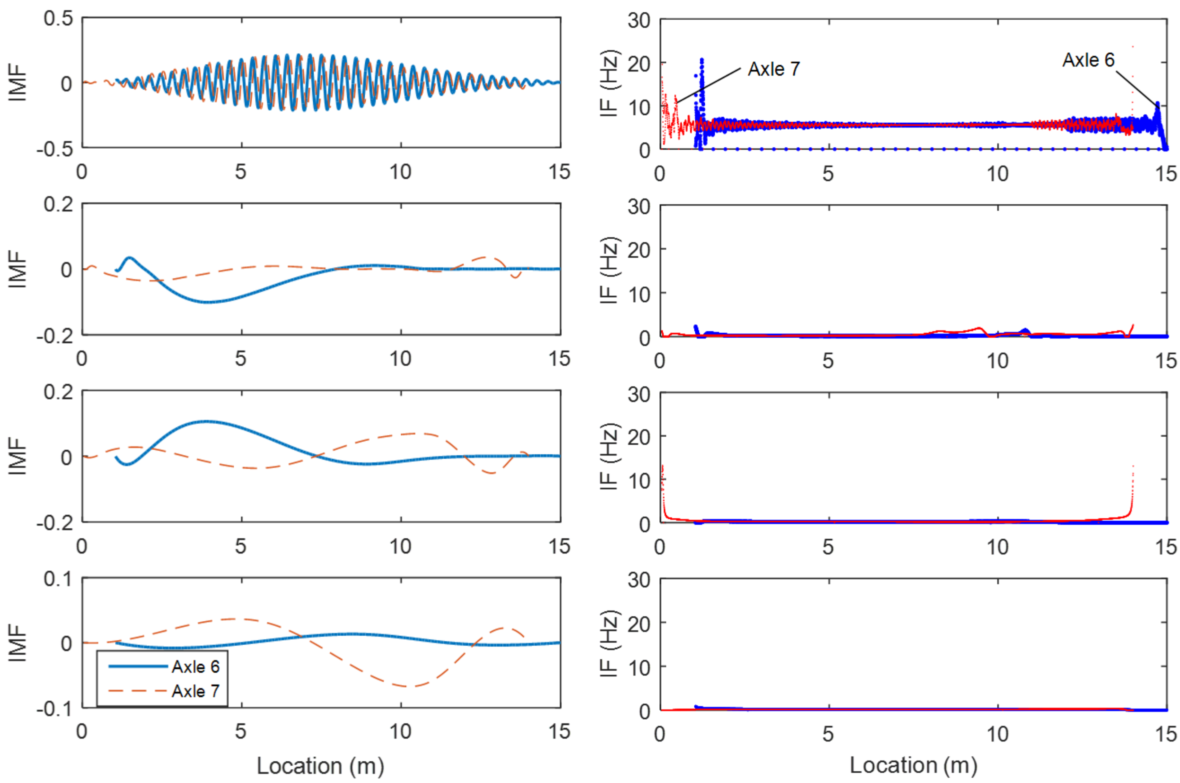


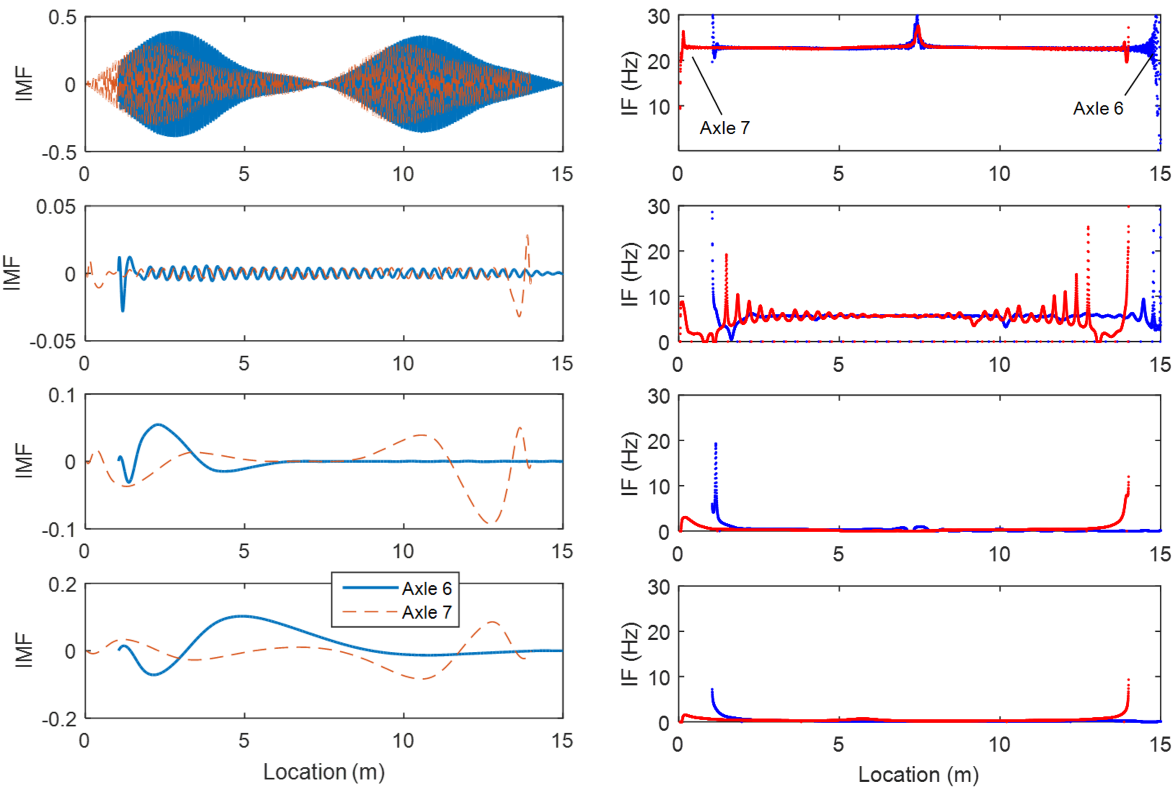

Figure 3: Acceleration responses for different excitations; (a) excitation at frequency of 5.5 Hz and (b) its frequency content (FFT), (c) excitation at frequency of 22.9 Hz and (d) its frequency content (FFT).

The HHT is applied to the responses measured in each case. As mentioned in Section 3.1, the first step includes the application of EMD. Figs. 4 and 5 show the IMFs and IFs obtained from applying EMD to the acceleration signals. Each IF shows the frequency content of the corresponding IMF. The first IF in Fig. 4(b) shows that the corresponding IMF in Fig. 4(a) is related to the bridge first natual frequency. It means that the first IMF includes the acceleration required for the first mode shape. A similar explanation can be given for the second mode. Figure 5(a) represents the acceleration part of the total acceleration which corresponds to the second mode shape.



(a) (b)

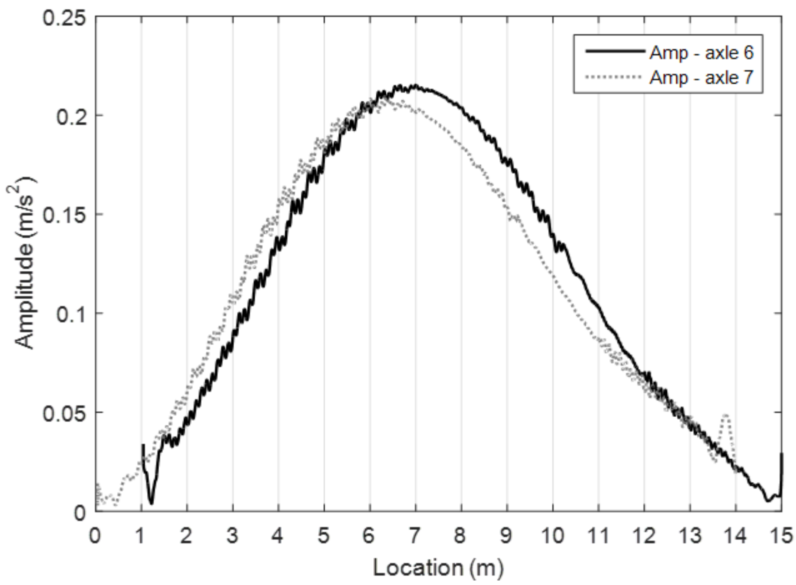
Figure 4: HHT for first case (excitation at frequency of 5.5 Hz), (a) IMFs, (b) IFs.



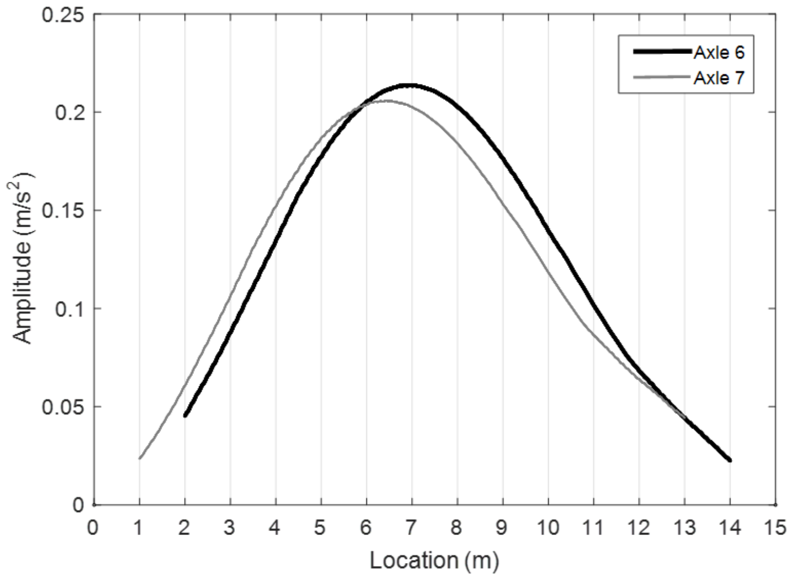

(a) (b)

Figure 5: HHT for second case (excitation at frequency of 22.5 Hz) (a) IMFs, (b) IFs.

The HHT amplitudes for the first case are shown in Fig. 6 (a). A moving average of each amplitude is calculated to smooth the curve (Fig. 6(b)). It can be seen that the amplitudes obtained from the two following axles are not the same (they would be the same if they were the bridge mode shape) and their peaks are not located at the bridge mid-span (where the peak of the first mode shape of the bridge is located). The first average amplitude is trimmed at 2 and 14 m and the second one at 1 and 13 m. This provides enough information to obtain the bridge mode shape in an interval between 1 to 14 m. The amplitudes are a measure of the energy of the bridge response corresponding to the first mode at each location.



(a)



(b)

Figure 6: Amplitudes obtained from two following axles, (a) Calculated raw amplitudes, (b) Smoothed and trimmed amplitudes.

As the spacing between the sixth and seventh axles is 1 m, the Axle 7 amplitude for location x correlates to Axle 6 amplitude for location x+1. This concept is illustrated in Fig. 7 which is a zoomed view of Fig. 6(b). To construct the global bridge mode shape, several points starting from x=2m for the sixth axle and x=1m for the seventh axle are selected with 1 metre spacing. Each of these points are marked as $\psi_{ij}$ and are the local mode shapes that are obtained from the HHT amplitude at the i$^{th}$ axle and the location of x=j m. For example $\psi_{23}$is the local mode shape at x=3 m and measured at the 7$^{nd}$ axle. The important point is that $\psi_{21}$ and $\psi_{12}$ are measured at a same time which is called $t_1$ here. It means that they give the ratio of the bridge response at the first natural frequency for two locations at the same time which is exactly the concept of mode shape. The same explanation can be presented for $t_2$, $t_3$ and $t_4$ in Fig. 7. Therefore, the process starts by considering $\psi_{21}$ and $\psi_{12}$ as the global bridge mode shape values, $\phi_1$and $\phi_2$ at x=1 and x=2, respectively. Then two local mode shapes, $\psi_{13}$ and $\psi_{22}$ at time $t_2$ are considered which include the ratio of the bridge global mode shapes at x=2 and x=3. As $\psi_{12}$ is already considered as the global bridge mode shape at 2 m, consequently the bridge global mode shape at x=3m can be obtained as:

$$\phi_3 = \psi_{13}\frac{\phi_2}{\psi_{22}} \tag{7}$$

The first global mode shape of the bridge is obtained by continuing this process for the other points. The result is illustrated in Fig. 8.

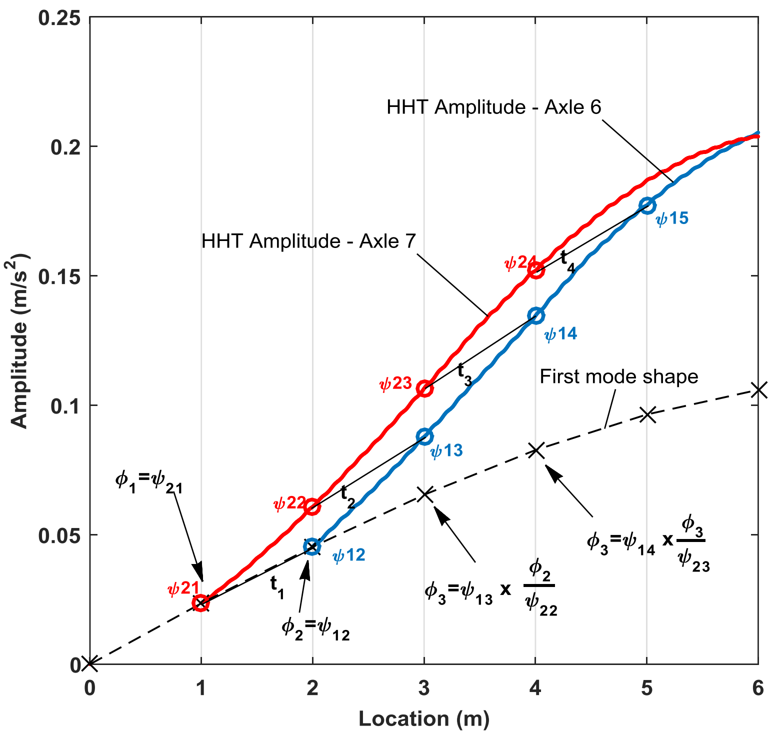



Figure 7: The rescaling process.

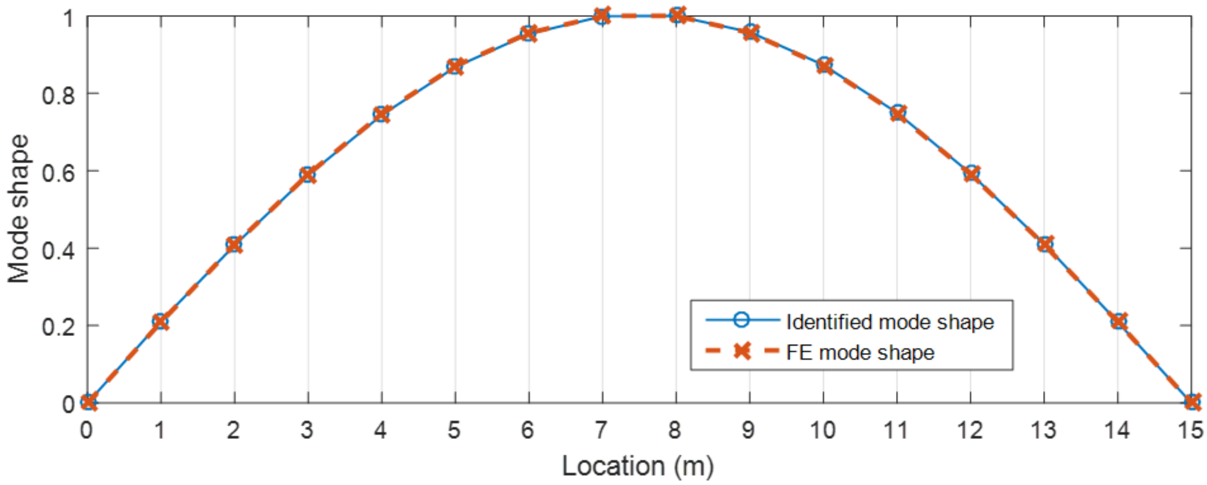



Figure 8: The first normalized mode shape of the bridge.

As can be seen in Fig. 7, the process of rescaling started from x=1m and continued in intervals of 1m up to 14 m. Assuming there is a high quality amplitude over all the bridge, the process can start from any other point between 1 to 2 m and continue, again at 1m intervals, to a point between 13 and 14m. This results in the same mode shape at new locations. For example, instead of starting the process from x=1m, it can be started from x=1.2 or x=1.4. Consequently a high resolution mode shape of the bridge can be constructed.

The frequency of excitation plays an important role in this method. Several excitation frequenices around the first natural frequency of the bridge are used. Fig. 9 shows that when the excitation frequency is in the range of 5.4 to 5.8 Hz, the method provides the first mode shape with acceptable accuracy. It is obsereved that when the excitation frequency is out of this range, the response amplitude correponding to the first mode of the bridge is not well seperated from the total response which casues an inaccurate mode shape.

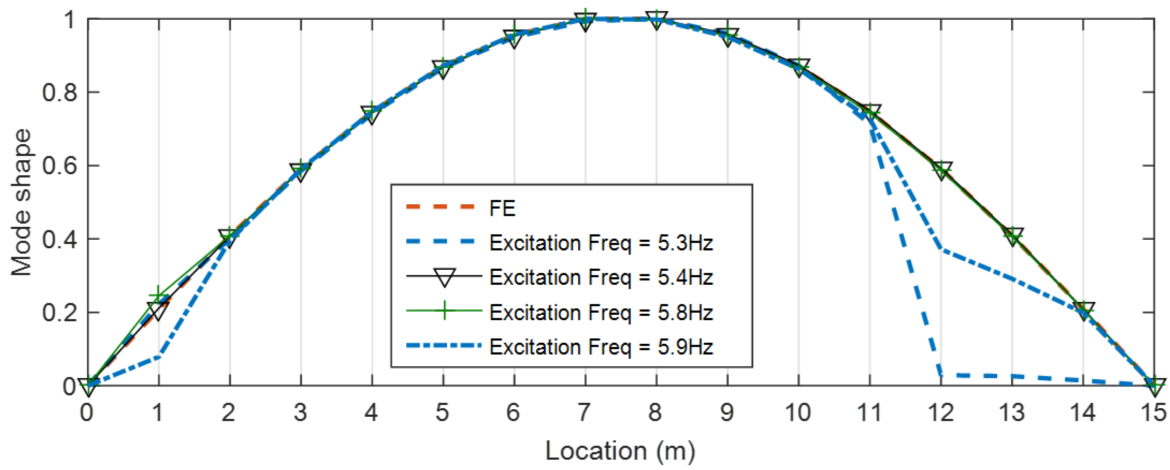
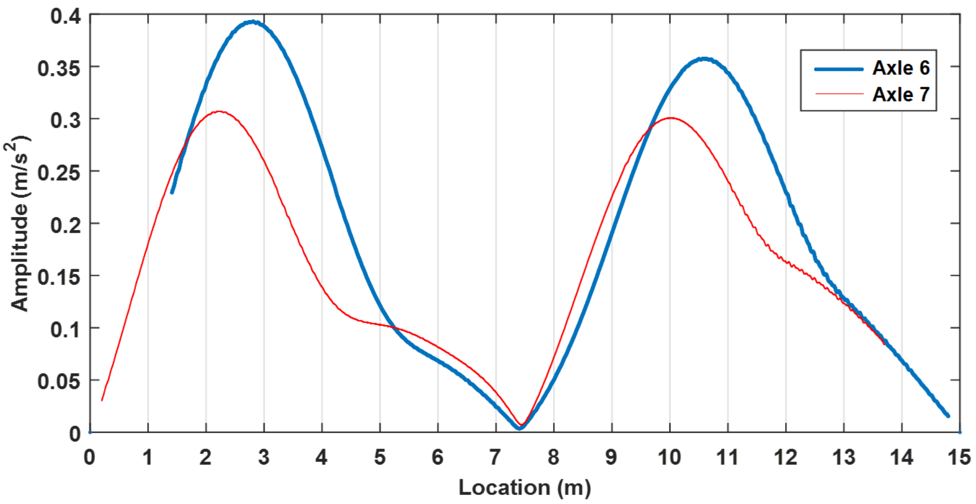
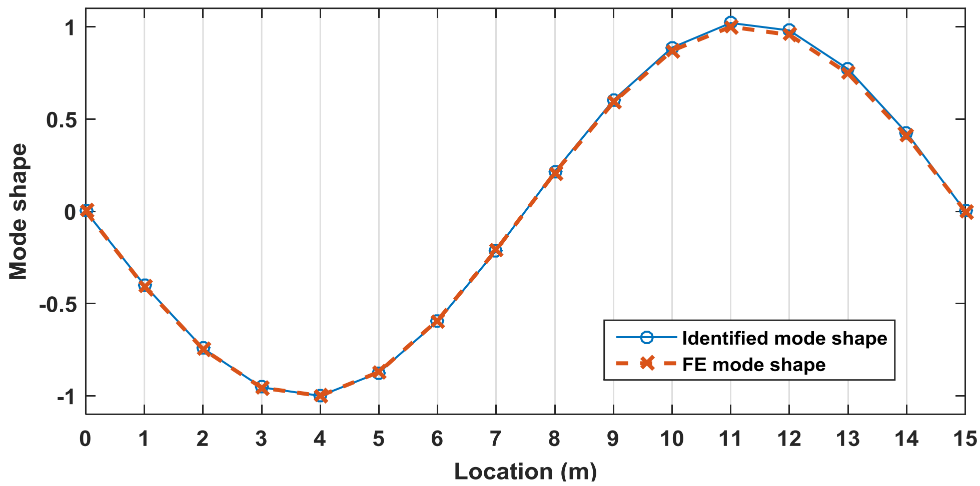



Figure 9: The first normalized mode shape of the bridge with different excitation frequencies.

The same procedure illustrated in Fig. 7, as explained for the first mode, is applied to the results from the second mode. The HHT amplitude obtained from the second case is obtained and shown in Fig. 10 (a). In contrast to the case of the first mode, it is much more clear here that this is not the bridge mode shape. The procedure starts at $x$=1 for Axle 7 and $x$=2 for Axle 6 and fiishes at $x$=14. It means there is enough data in Fig. 10(a) to cover all points of interest. The bridge second mode shape is obtained using the same rescaling process that is used for the first mode and is shown in Fig. 10(b). The modal amplitude obtained from the HHT amplitude (Fig. 10(a)) has a positive sign for all points. This means that the proposed method identifies a positive modal amplitude for all points of the second mode. In this case, engineering judgement is used to identify the right sign of the inferred second mode shape.




(a)




(b)

Figure 10: Second mode shape: (a) The HHT amplitudes, (b) Inferred and true (FE) mode shapes.

The effect of excitation frequency on the proposed method is studied also for the second mode. It is observed that an excitation frequency within a range of 22.0 to 23.2 Hz provides the second mode shape with acceptable accuracy. It is of note that the identified shapes shown with blue points in Figs. 8 and 10(b) are operating deflection shapes. Since an external excitation is used in each to excite the natural frequency of the bridge, the estimated shape is very close to the corresponding bridge mode shape. In a case with closely spaced modes, the method may face difficulties in distinguishing mode shapes from operating deflection shapes. As a result, the method may only work for cases where the bending modes of the bridge are well separated and there is no other bridge mode (e.g. torsional) close to them. In addition, the vehicle speed in this case is 2 m/s which is much lower than real traffic speeds in a highway. Increasing the speed reduces the time in which the vehicle is on the bridge which means a shorter acceleration signal measured on the vehicle. This causes a low resolution HHT amplitude which results in reduced accuracy in the identified mode shape. Further research is needed to get similar results with higher vehicle speed.

### 4.2. Example of a truck-trailer equipped by an exciter on a class A road profile

A road roughness is generated using the ISO standard for a class 'A' profile, is added to the bridge (shown in Fig. 11(a)). A simulation similar to that used in Section 4.1, is employed here. The passes over the bridge were with an excitation of amplitude 30 kN and frequencies of 5.5 Hz and 22.5 Hz at a speed of 2 m/s. Greater excitation was found to be necessary in the presence of a profile.

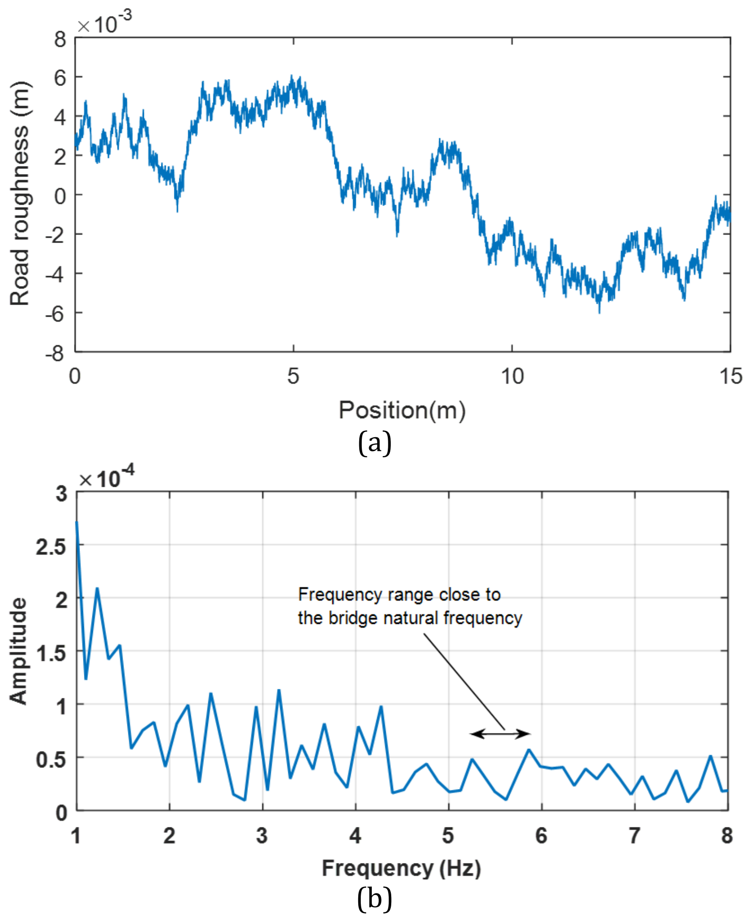
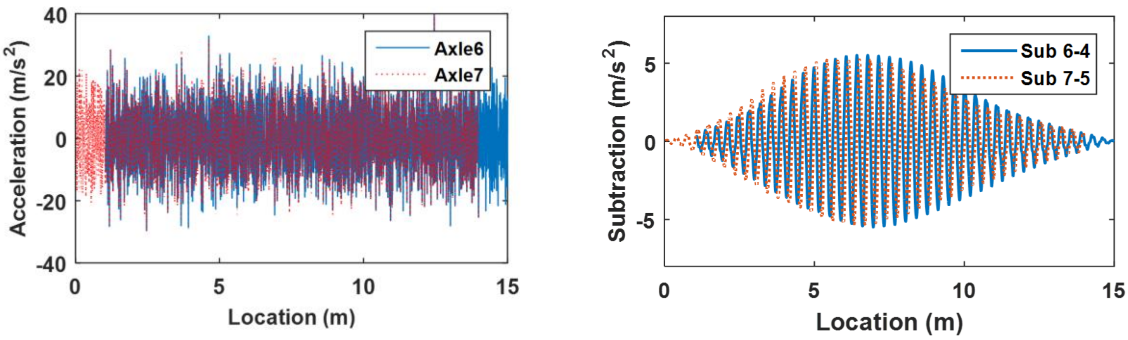



Figure 11: Class 'A' road profile, (a) road profile, (b) FFT of the profile.

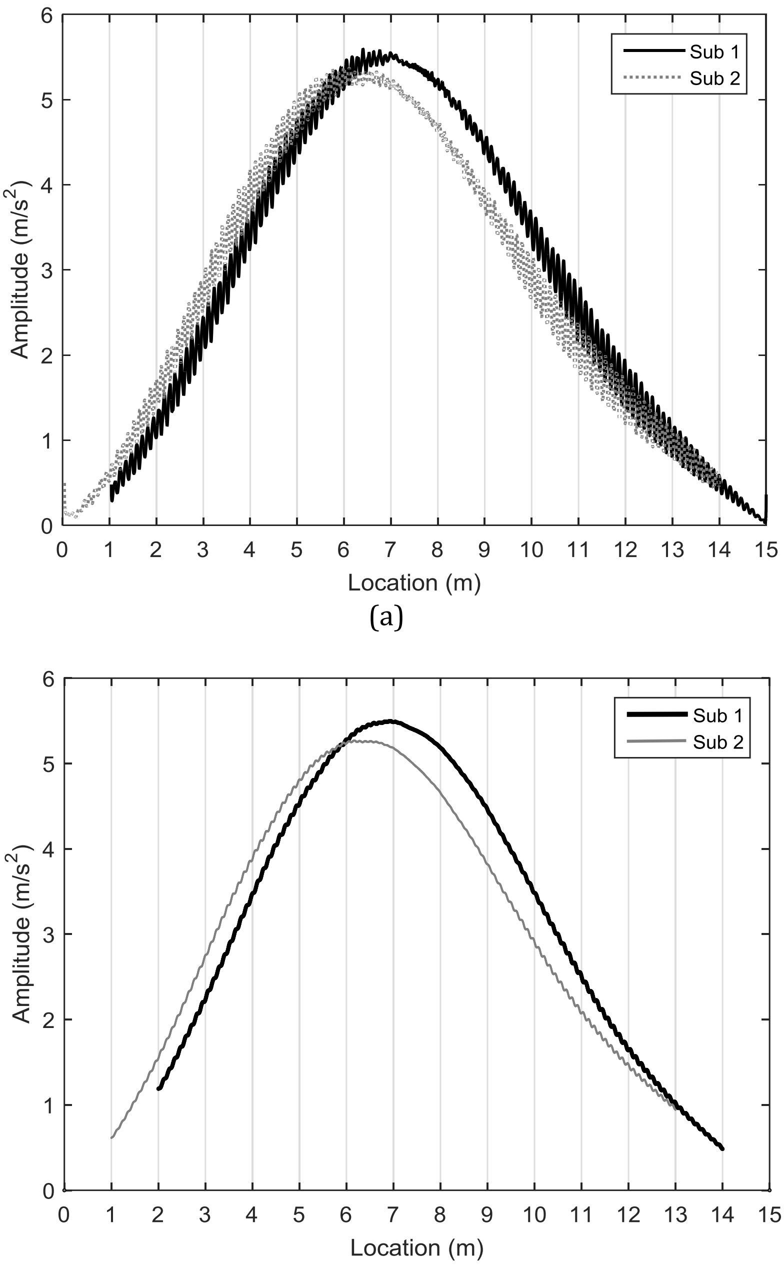
The road roughness constitutes an extra source of excitation for the moving vehicle in addition to the sources discussed. The frequency content of the roughness is shown in Fig. 11(b) using its FFT around the bridge natural frequency. The road roughness includes many frequencies that may appear in the vehicle response. This causes a problem, particularly in a range close to the bridge natural frequency. In this case, the idea of subtraction which is proposed in [14, 33], is used to totally remove the effect of road profile. Although this idea has shown promising results in numerical studies, there has not been any experimental validation. The acceleration responses of Axles 4, 5 and 7 are measured in the presence of external excitation adjusted to frequencies close to the bridge natural frequencies. Fig. 12(a) shows the acceleration response measured at Axle 4 in the presence of a road profile. Two difference signals are constructed as $\ddot{x}_1 = \ddot{y}_6 - \ddot{y}_4$ and $\ddot{x}_2 = \ddot{y}_7 - \ddot{y}_5$ to remove the effect of road profile. The first subtraction is shown in Fig. 12(b).




(a) (b)

Figure 12: (a) Acceleration response measured at Axles 6 and 7, (b) the differences.

A similare procedure to that explained in Section 4.1, is used here. The HHT is applied to the differences for the first and second modes. The HHT amplitudes for the first mode are shown in Fig. 13(a). The calclulated HHT amplitudes include some fluctuations. This may be due to the subtraction process. The smoothed HHT amplitude is calculated using a moving averge process (Fig. 13(b)).

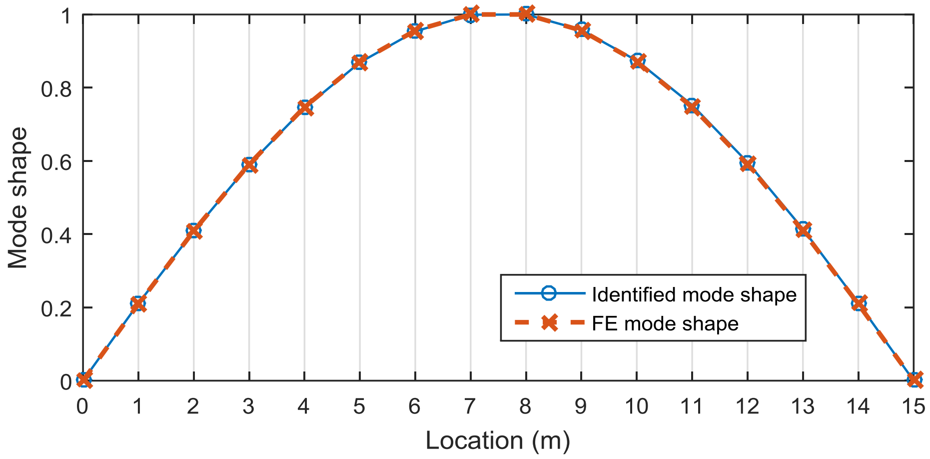


(a)

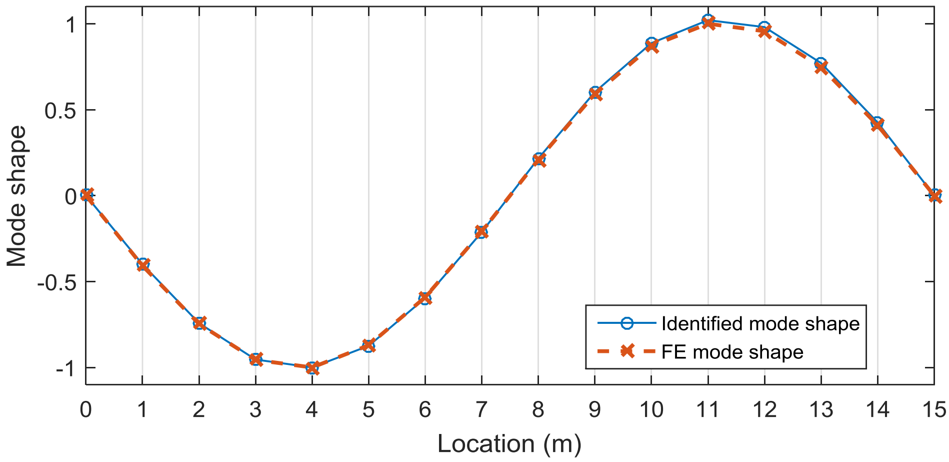

(b)

Figure 13: Amplitudes obtained from two following differences, (a) Calculated raw amplitudes, (b) Smoothed and trimmed amplitudes.

The rescaling process explained in Section 4.1 is repeated here. The first and second mode shapes of the bridge are obtained (Fig. 14). It is shown that the mode shapes are identified with good accuracy.



(a)



(b)

Figure 14: The normalised bridge mode shapes, (a) the first mode, (b) the second mode.

The simulation is repeated for two additional road roughness classes, B and C, to study the effect of roadway roughness on the results. The first amplitude subtraction is calculated when the truck travels over a bridge with those road roughness classes (Fig. 15(a)). It is shown that the difference includes more oscillation as the road roughness increases. It means that road roughness may contribute more in the calculated amplitude which makes it hard to identify the bridge mode shape. Fig. 15(b) shows the comparison of the first mode shape of the bridge identified in the presence of three classes of road roughness. It shows that the identified mode shape in the presence of a class C road is of poor accuracy. It can be concluded that the proposed method only provides acceptable accuracy in the presence of a good quality of road profile.

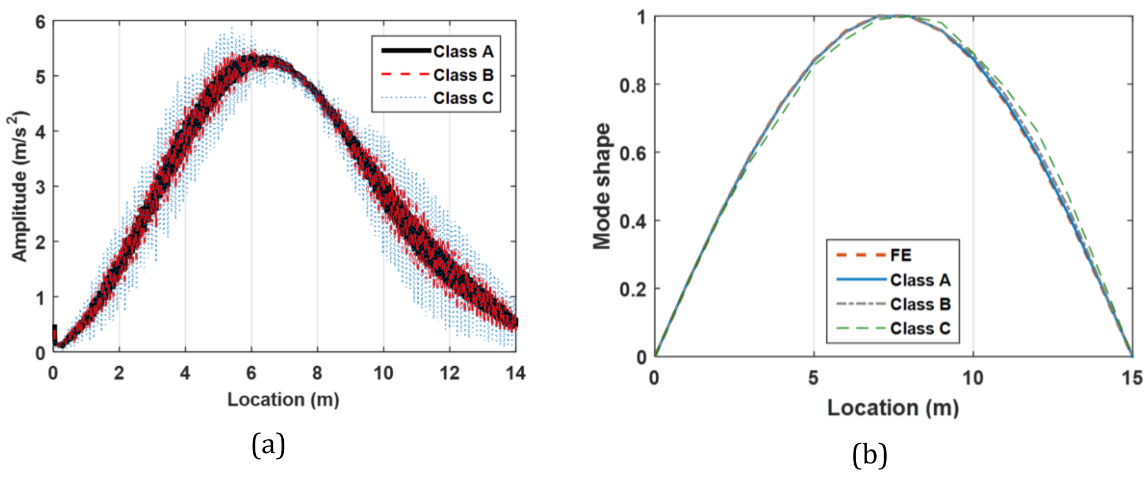



Figure 15: (a) The calculated raw amplitudes and (b) the estimated first mode shape of the bridge when the truck passes over different road roughness classes.

Although the numerical simulations show promising results, the application of such a method in a real bridge case study requires further work. An important factor affecting the accuracy of the results is the accuracy of the operational deflection shape which is estimated from the difference response. It is shown in recent studies [18, 19] that subtraction is sensitive to measurement noise and variation of the vehicle speed. A Traffic Speed Deflectometer (TSD) [34] is a vehicle instrumented with laser vibrometers which is used to measure the deflection 'basin' in a pavement, that is, the depression in the road pavement under a heavy axle as it passes. The inferred displacement has a resolution of tens of microns. It has been shown numerically that TSDs could provide sufficient accuracy for drive-by bridge monitoring [35]. Using a special truck like the TSD may be the practical implementation of the proposed method. TSDs provide real time vehicle velocity which can be used to map the measured signal to the location in order to minimize the effect of vehicle speed variation.

## 5. Conclusion

This paper describes an approach for indirect identification of bridge mode shapes from the response measured on a passing vehicle. A truck-trailer system equipped with an actuator is proposed. It is shown that the external excitation is beneficial for getting access to the energy of the bridge response at the key frequencies. It is shown that, unlike in the previous studies, this energy is not the bridge mode shape, but is correlated to the bridge mode shape at the time of measurement. A rescaling process is proposed to construct the bridge mode shapes using the amplitude of the responses measured on two following axles. The possibility of using the approach in presence of road profile is also studied. The concept of subtraction is employed to remove the effect of road profile in the measured responses.

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