Effect of vehicle travelling velocity on bridge lateral dynamic response

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Abstract. Vibration-based Structural Health Monitoring (SHM) is an area of ongoing research and has received much attention from researchers in recent years. Online damage detection methods for bridges rely on placing sensors on the structure to detect anomalies in measured parameters such as acceleration, frequency or displacement among others. Changes in these parameters can be used to infer the presence of damage such as cracking in bridge beams, foundation scour etc. These methods mostly rely on using the signals arising on a bridge from ambient traffic or environmental loading. For foundation scour detection purposes, the lateral response of a bridge is of particular interest in that this has been shown to be particularly sensitive to the scour phenomenon. Vehicle-Bridge Interaction (VBI) effects can have a significant influence on the condition of output vibrations from a bridge element. In this paper, the effect of vehicle travelling velocity on the lateral response of a typical highway two-span integral bridge is investigated. It is shown that depending on the velocity of the vehicle relative to the oscillatory period of the bridge it traverses, the bridge's dynamic response is either amplified or diminished by varying degrees. This phenomenon could influence the accuracy of a particular damage detection method relying on output system vibrations to infer damage.

Keywords: Bridge Dynamics, Damage Detection, Vibration, SHM

1 Introduction

Vibration-based Structural Health Monitoring (SHM) is the art of monitoring the condition of a structure over its lifetime by monitoring dynamic properties with a view to preventing excessive damage from accumulating. Foundation scour is the term given to describe the process of soil erosion that can occur around bridge foundations due to adverse hydraulic action (Hamill 1999). Applying SHM techniques to scour detection has gained significant traction in recent years (Prendergast et al. 2013; Prendergast et al. 2015; Ju 2013; Foti & Sabia 2011; Prendergast et al. 2016; Klinga & Alipour 2015; Briaud et al. 2011; Elsaid & Seracino 2014). A common conclusion among researchers in this field is that the lateral response of a bridge sub-structural component (piles, pier) is the most sensitive to scour in terms of changes in modal properties (Prendergast et al. 2016; Prendergast et al. 2013; Elsaid & Seracino 2014; Briaud et al. 2011). It is therefore of interest to investigate phenomena that can affect the lateral dynamic response, or more specifically, impede the ability for a sensor located on the structure to effectively detect this response. The most practical way to excite a bridge (for vibration-based damage detection applications) is to use ambient traffic (Farrar et al. 1999). In this paper, the effect of vehicle travelling velocity as it traverses a bridge is investigated to highlight the significant effect that this can have via interaction with the bridge's own oscillatory motion. The type of bridge investigated is two-span integral bridges, due to their increasing popularity and prevalence.

2 Numerical Modelling

The issue relating to a vehicle travelling velocity across a two-span integral bridge is investigated using numerical modelling approaches in MATLAB. Various aspects of the model are discussed in the following sub-sections. Section 2.1 briefly describes different types of integral bridges and section 2.2 describes the mathematical approach taken to model the bridge, the foundation soil and the vehicle load in this paper.

2.1 Types of Integral Bridge

Integral bridges are becoming increasingly popular as they do not require a conventional expansion joint and this can reduce maintenance costs significantly. There are four main types of integral bridge (Prendergast et al. 2016): (1) Frame Abutment type; (2) Bank Pad Abutment type; (3) Flexible Abutment type and (4) Semi-Integral Abutment type. In this paper, type (3), a bridge with flexible support abutments, is modelled. A schematic of this type of bridge is shown in Fig. 1.

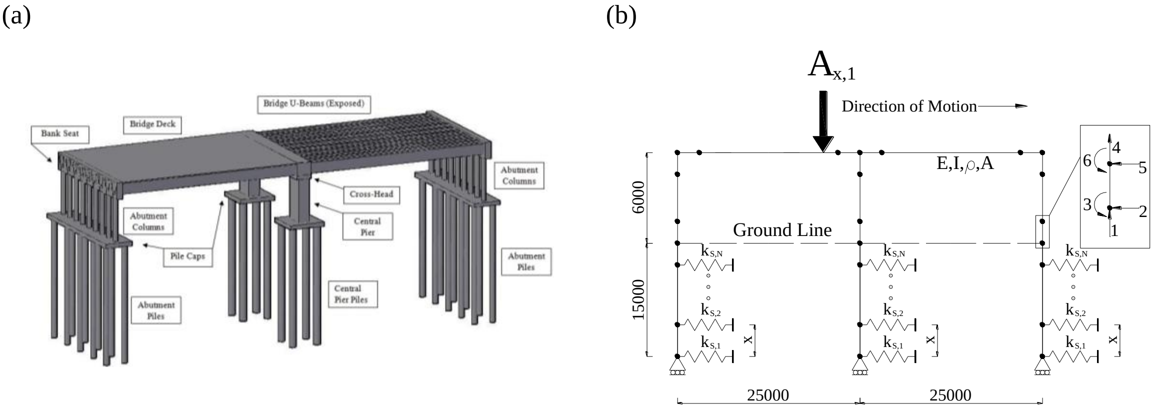

Fig. 1. Model schematics
a – bridge elements; b – numerical schematic

2.2 Mathematical Considerations

The bridge is modelled using 6-degree-of-freedom (6-DOF) Euler-Bernoulli (2D) frame elements, the mass $[\mathbf{M_b}]$ and stiffness $[\mathbf{K_b}]$ matrices are available in Kwon & Bang (2000). The foundation soil is modelled using a Winkler philosophy which models the continuous soil layers as discrete, mutually independent and closely spaced springs (Dutta & Roy 2002; Winkler 1867). Standard properties are adopted to model the integral bridge in this paper and these properties are available in Prendergast et al. (2016), see Fig. 1(b).

To model the foundation soil, the approach described by Prendergast et al. (2015); Prendergast et al. (2016) and Prendergast & Gavin (2016) is used. This approach considers each soil spring as a linear-elastic element (strain-independent $\boldsymbol{k_{s,i}}$) and uses small-strain soil stiffness parameters (G_0, E_0) to characterize the response. In this paper, the bridge is assumed to be founded in loose sand.

Global mass $[\mathbf{M_G}]$ and stiffness $[\mathbf{K_G}]$ matrices are assembled for the full structure according to the procedure in Kwon & Bang (2000). The dynamic response of the bridge structure can be obtained by solving the second-order matrix differential equation of motion, see Prendergast et al. (2016) using the Wilson-Θ integration scheme. The damping matrix $[\mathbf{C_G}]$ is determined assuming a Rayleigh damping approach (Yang et al. 2004) and a damping ratio ($\xi_1 = \xi_2 = \xi$) of 2% is assumed .

3 Velocity Effects

In this section, the interaction effects between a vehicle's travelling velocity over the bridge and the resulting impact on the bridge's own oscillatory motion is investigated. Section 3.1 presents an analysis of the mode shape of the bridge pertaining to lateral sway motion and section 3.2 investigates the effect of a single vehicle load traversing the bridge.

3.1 Global mode shape of bridge

An eigenvalue analysis is conducted in MATLAB to obtain the system eigenvalues and eigenvectors, which correspond to the un-damped frequencies and mode shapes of the model. The fundamental mode shape of the integral bridge is a global lateral sway mode, with a frequency of 1.5643 Hz and a corresponding period (*T*) of 0.639 seconds. The bridge modal shape at four vibration stages corresponding to 0.25 x *T*, 0.5 x *T*, 0.75 x T, and 1 x *T* is shown in Fig. 2. Fig. 2 provides a pictorial view of the displaced shape of the given mode at a particular stage of vibration over one cycle. The time it takes for the given shape to arise and the direction of motion is displayed in Table 1. Interaction effects between the bridge's dynamic motion and the rate of load traversing are investigated in the next section.

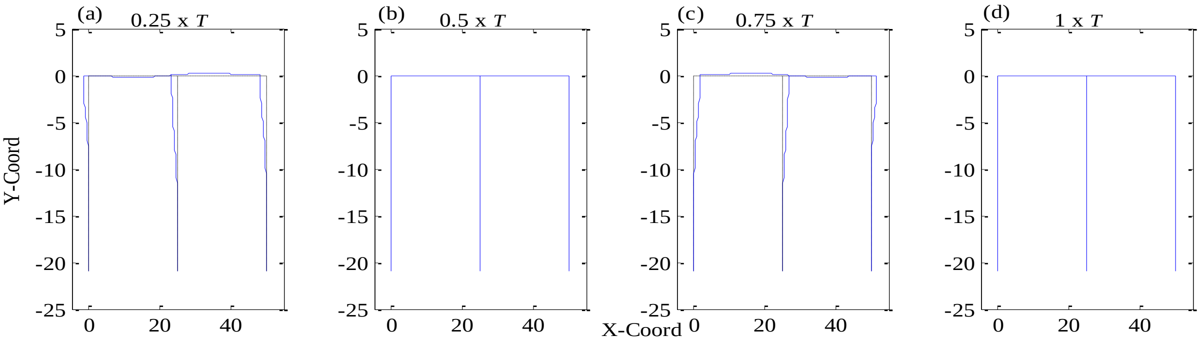

Fig. 2. Bridge mode at various ratios of natural period
a – 0.25 x *T*; b – 0.25 x *T*; c – 0.75 x *T*; d – 1 x *T*

Table 1. Bridge motion – direction and arrival times.

Fig. 2 Image Ref	Arrival Time (s)	Motion Direction
(a)	0.25 x 0.639 = 0.16s	Stationary (will move right)
(b)	0.5 x 0.639 = 0.32s	Swaying to right
(c)	0.75 x 0.639 = 0.4795s	Stationary (will move left)
(d)	1 x 0.639 = 0.639s	Swaying to left

3.2 Single traversing load

While the bridge undergoes global sway at the first natural frequency (see Fig. 2), it first sways to the left (say) with span 1 deflecting downward, then sways right with span 2 deflecting downward. If we consider a single load ($A_{x,1}$ = 100 kN) traversing the bridge while it undergoes motion at its own natural frequency, the rate at which the load traverses will interact with the amplitude of the bridge's lateral motion. It is postulated in this paper that maximum amplification of the response should occur if the load traverses the first span in the time it takes for the bridge to undergo one half of its vibration cycle (i.e. reaching the pier when the bridge is in condition (b) of Fig. 2). This means that the load will be on the left span when it naturally deflects downwards and on the right span when this naturally deflects downwards due to the bridge's periodic motion, thus amplifying this response. The opposite situation (maximum diminishing of signal) should occur if the load traverses span 1 in the time it takes for the bridge to undergo a full vibration cycle (i.e. condition (d) in Fig. 2). To investigate this, an analysis is conducted herein. For the analysis in this paper, only the free vibration signal after the vehicle (load) leaves the bridge is produced. A single load traverses the bridge with a velocity (v_s) such that it crosses the first bridge span (25 m) in a time that is a given ratio of the bridge's natural period, see Table 2. The results of this analysis should confirm that a load traversing the bridge span 1 in a time that equates to half of the bridge's natural period is the most beneficial in terms of signal amplification (free vibration) while a load traversing the span 1 in a time equating to the full bridge period will impede the vibration the most. Establishing the effect at multiples of the bridge period (i.e. ratios > 1) is also undertaken to observe if the effect is any different and also to see how the system reacts with more realistic loading velocities. Table 2 outlines the crossing times and required velocities for the analysis.

Table 2. Load velocities to traverse span 1.

Span (m)	*T* (s)	Time to cross Span 1 T_v (s)	Ratio T_v/T	Load v_s (m/s)
25	0.639	0.16	0.25	156.43
25	0.639	0.32	0.5	78.22
25	0.639	0.4794	0.75	52.14
25	0.639	0.639	1	39.11
25	0.639	0.799	1.25	31.29
25	0.639	0.959	1.5	26.07
25	0.639	1.118	1.75	22.36
25	0.639	1.278	2	19.56

The results for the analysis are shown in Fig. 3. Fig. 3(left) shows the lateral pier top displacement and acceleration responses in free vibration for velocity ratios ≤ 1. Fig. 3(right) shows the lateral pier top displacement and acceleration responses in free vibration for velocity ratios ≥ 1. Five seconds of free vibration is analysed. In Fig. 3(left) it is evident that the maximum amplification of the free vibration response signals occurs for a load traversing the first span in the time it takes the bridge to undergo 0.5 times its vibration cycle. It is also shown that the lowest amplification of the signal occurs when the load traverses the first span in the time it takes the bridge to undergo a full cycle. The other ratios give intermediate results and the results are the same for both displacement and acceleration. This is sensible (and expected) as it indicates that when the load is completely in phase with the bridge motion (i.e. pushing down on span 1 as it naturally deflects downwards due to periodic motion, then moving to span 2 as this naturally deflects downwards) we achieve maximum amplification. When the load acts to resist the bridge's own oscillatory motion, we achieve the lowest amplification.

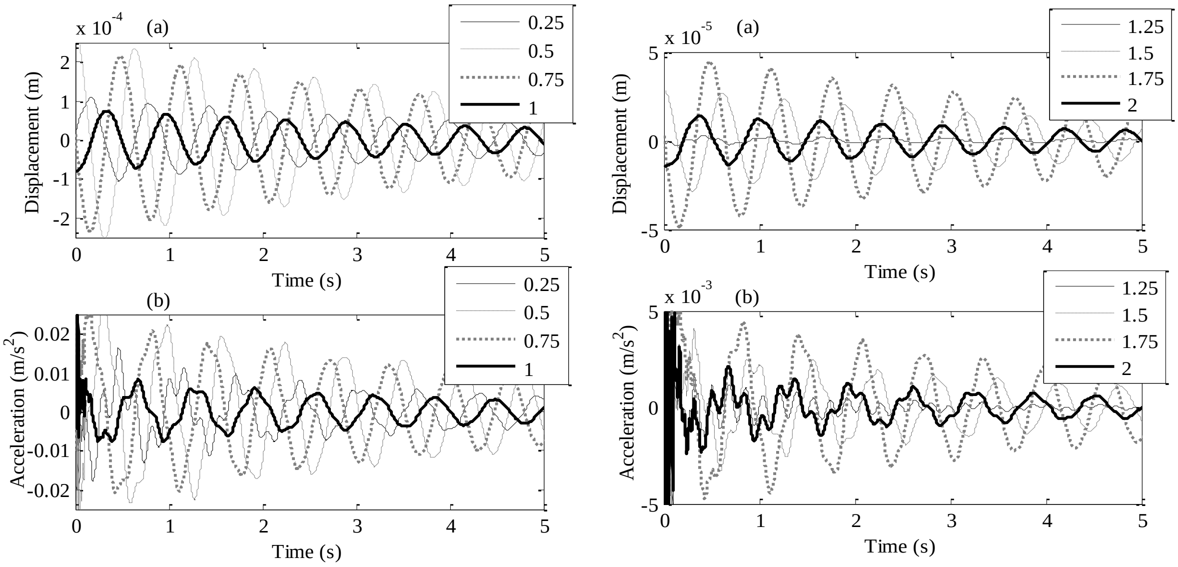

Fig. 3. Lateral pier top signals for load traversing span 1 in specified ratio.
left – ratios < 1, right – ratios > 1

Fig. 3(right) shows the results for the load traversing span 1 in a time that is multiples of the bridge's natural period. The amplitude results in this case are almost an order of magnitude less pronounced (to be expected as there is an element of the load acting against the bridge movement for every case). The results for Fig. 3(right) indicate a different outcome than those in Fig. 3(left). The maximum signal amplification occurs when the load reaches the end of span 1 in a time that is 1.75 times the bridge's period as opposed to 1.5 times which might have been expected from the first set of results. Also the lowest amplification occurs for the load traversing span 1 in 1.25 times the bridge period as opposed to 2 times, as might have been expected. The amplitude of the free vibration is a function of the bridge displacement, velocity and acceleration at the point when the load leaves the bridge and this can have a significant effect on the amplitude of the signal in free vibration. The results are less intuitive than when the load traverses in a specified ratio less than 1 of the bridge period as in this case it is easy to see when the load will act to impede the bridge motion. For ratios greater than 1, there is a trade-off effect in place as at some stage during the loading, the load will always be 'working against' the bridge motion to some degree. These results highlight the complicated interaction process at play in this problem and moreover show that using vehicle-induced vibration signals for bridge damage detection could potentially lead to issues with time-domain based SHM techniques.

4 Conclusion

Vibration-based Structural Health Monitoring is a growing research area. In this paper we describe the application of the approach to investigate reliable methods to detect damage arising in bridge structures using dynamic response measurements. For scour detection using vibration-based methods, the lateral response of a bridge sub-structural element has been shown to be most sensitive to scour. Obtaining dynamic signals from a bridge is mostly undertaken by monitoring its response to ambient traffic loading. Therefore, it is of interest to study potential effects that could arise from the interaction between the rate of loading a two-span integral bridge and the measured response. In this paper, vehicle velocity effects were investigated in terms of how they can amplify or diminish the dynamic response of a bridge. The results show that the response magnitude in free vibration can vary significantly depending on how the load interacts with the bridge in terms of its own oscillatory motion. The results in many cases may not be intuitive and this study aims to highlight potential disparities that can arise. This phenomenon could become an issue for time-domain related SHM techniques, as a diminished signal magnitude could become absorbed into the noise band of a standard sensor for example. Signal clarity can be a serious issue for many of these methodologies.

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