Experimental Investigation of the Detection of Bridge Dynamic Parameters using a Moving Vehicle

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ABSTRACT

This paper investigates the feasibility of using an instrumented vehicle to detect bridge dynamic parameters, such as natural frequency and structural damping, in a scaled laboratory experiment. In the experiment, a scaled vehicle model crosses a steel girder which has been adopted as the bridge model. The bridge model also includes a scaled road surface profile. The effects of varying vehicle model mass and speed are investigated. The damping of the girder is also varied. The bridge frequency and changes in damping are detected in the vehicle acceleration response in the presence of a rough road surface profile.

INTRODUCTION

Highway structures such as bridges are subject to continuous degradation primarily due to ageing and environmental factors. Most developed economies now require the implementation of Bridge Management Systems for the monitoring of this transport infrastructure in order to provide adequate maintenance and guarantee the required levels of transport service and safety. Thus, increasingly in recent years, bridges are being instrumented and monitored on an ongoing basis. However, the process is expensive, requiring the installation of sensors and data acquisition electronics on the bridge. Given the very large number of bridges that are not instrumented, some alternative method is needed to detect any change in behaviour in the structure which might be an indicator of some form of damage. This paper investigates the use of instrumented vehicle with accelerometers on its axles to monitor bridge dynamic behaviour.

The feasibility of detecting bridge dynamic parameters from the dynamic response of a vehicle passing over a bridge has been verified theoretically (Yang *et al*, 2004; Oshima *et al*, 2008, McGetrick *et al*, 2009) and experimentally in field tests (Lin and Yang, 2005). Experimental investigations have also been carried out which indicate the feasibility of the approach as part of a drive-by inspection system for bridge monitoring (Kim and Kawatani, 2009; Toshinami *et al,* 2010).

Recent evidence (Curadelli *et al*, 2008; Modena *et al*, 1999) suggests that the presence of cracks can result in a change in the dynamic response of a bridge to passing traffic. Specifically, it has been found that the damping coefficient is quite sensitive to this kind of damage. Therefore, this paper aims to add to the approaches of Kim and Kawatani and Toshinami *et al* by focusing on the detection of not only bridge frequency but the damping of the bridge also. An experimental investigation is carried out using a scaled bridge and vehicle laboratory model. These are discussed in more detail in the following section. The two-axle vehicle model is fitted with accelerometers on its axles. The investigation involves the analysis of the frequency spectra of vehicle accelerations obtained from the dynamic response of the vehicle model as it crosses the scaled bridge. The frequencies of vibration are identified in the vehicle acceleration spectra and compared to the frequencies obtained from bridge free vibration tests. Bridge damping is varied to investigate the effect. The vehicle mass and vehicle speed are also varied. Results indicate the most favorable conditions for the approach.

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EXPERIMENTAL SETUP

The experimental setup consists of a scaled steel girder bridge model (Fig. 1(a)) and a scaled two axle sprung mass vehicle model (Fig. 1(b)). The vehicle travels along a track on the girder which has a scaled rough road surface profile. The speed of the vehicle is maintained constant by an electronic controller. Two vehicle speeds are used in the experiment; S1=0.93m/s and S2=1.63m/s. The vehicle model can be adjusted to obtain different mass and dynamic properties. In this experiment, two vehicle models are used (V1 and V2 respectively) and their properties are given in Table 1. The vehicle model is fitted with 2 accelerometers; at the centre of the front and rear axles respectively. It is also equipped with a data acquisition system. The scanning frequency used in all experiments is 100 Hz.
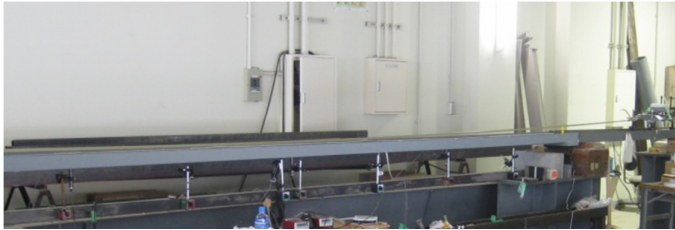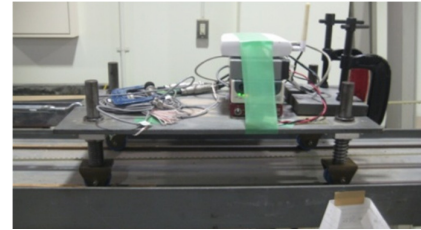

| Fig. 1 (a) Experimental Girder | Fig. 1(b) Experimental Vehicle |

The bridge model is a simply supported 5.6 metre long steel girder. It has a Modulus of Elasticity, E, of 2×10^{11} N/m^2 and mass per unit length, μ, of 53.66 kg/m. The girder is fitted with accelerometers and displacement transducers at quarter span, mid span and three-quarter span. The girder's dynamic properties obtained from free vibration tests are given in Table 2. Only the natural frequency corresponding to the first bending mode of the girder is presented here as this frequency will be the focus of this paper. Three damping scenarios are tabulated. The Intact scenario represents the girder with no adjustments. The other two scenarios represent the girder with its damping varied. The damping of the girder is varied in this experiment by applying old displacement transducers at particular points on the girder in addition to a 17.8kg mass added at midspan. The layout of these transducers is illustrated in Fig. 2. The old transducers are used as they provide frictional resistance to bridge displacements at the chosen locations. The additional mass is used to adjust the frequency of the girder as frequently damage which causes changes in damping may cause some changes in frequency. The two damping scenarios including the mass are chosen as they provide a suitable range of values for the girder damping constant.

Table 1 Vehicle Properties

Vehicle Model	Frequency (Hz)	Mass (g)
V1	2.93	21345
V2 Axle 1	2.86	25885
V2 Axle 2	2.93	

Table 2 Girder Properties (See Fig. 2)

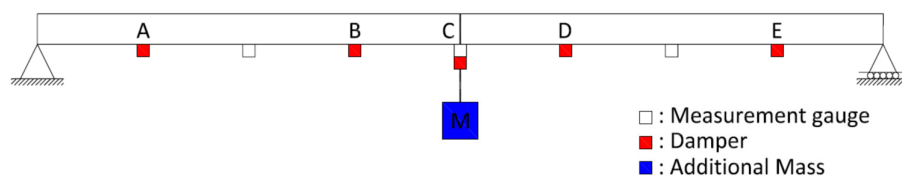| Scenario	Additional Mass (kg)	Frequency (Hz)	Damping Constant
Intact	0	2.7	0.014
Damper @C	17.8	2.5	0.021
Dampers @ABCDE	17.8	2.5	0.043

Fig. 2 Locations of Dampers and Additional Mass

EXPERIMENTAL RESULTS

DETECTION OF FREQUENCY FROM VEHICLE RESPONSE
This section discusses the results obtained for the 'Intact' scenario i.e. no dampers or additional mass are applied to the girder. Therefore, changes in damping are not considered yet. To determine if girder frequency is detected by the vehicle, the frequency spectra of vehicle accelerations are analysed and compared to the frequency spectra of girder accelerations. Figure 3 shows the frequency spectra obtained from accelerations of the girder (Fig. 3(a)) and vehicle (Fig. 3(b)) during the crossing of vehicle model V1 over the girder at a speed of 0.93m/s. The frequency peak at 2.41 Hz visible in Fig 3(a) corresponds to the first natural frequency of the girder and it also occurs in the vehicle spectra. Therefore it can be confirmed that for this vehicle model and speed it is possible to detect the bridge frequency from the vehicle response in this experiment. However, it should be noted that the peak corresponding to the bridge in the vehicle spectra is not always the most dominant peak – for axle 1 of the vehicle in Fig. 3 (b) the dominant peak is at 3.95 Hz.

It is found that lower speed gives better spectral resolution but less dominant bridge peaks in the vehicle spectra. While S2 may be too fast to obtain high enough resolution in the vehicle spectra, a clear bridge frequency peak can still be identified for this speed at 3.13 Hz in Fig. 4(b). Also, vehicle acceleration spectra magnitude increases with increasing speed. Axle 1 tends to give the maximum response due to its lighter axle weight and this can be observed in Fig. 3(b) and Fig. 4(b). Similar results are obtained for vehicle V2.
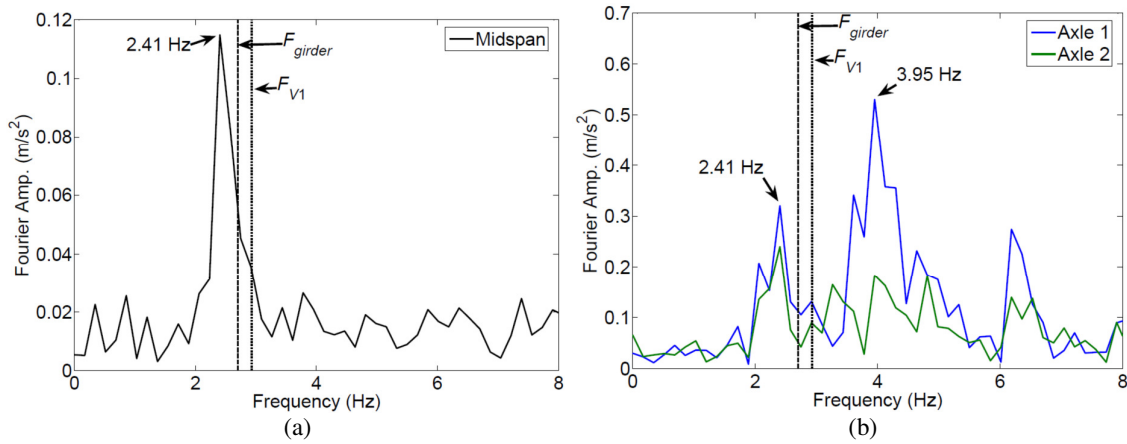

Fig. 3 Fourier spectra of acceleration response of (a) Girder midspan and (b) V1 axles for speed S1 (0.93m/s)
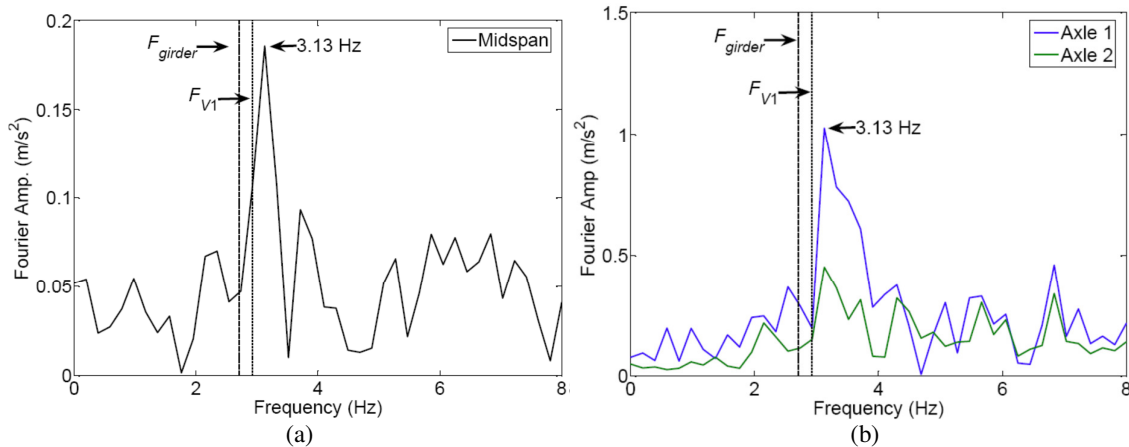

Fig. 4 Fourier spectra of acceleration response of (a) Girder midspan and (b) V1 axles for vehicle S2 (1.63m/s)

DETECTION OF CHANGES IN DAMPING FROM VEHICLE RESPONSE
This section discusses results obtained for the scenarios 'Damper @C' and 'Dampers @ABCDE'. Detecting the bridge frequency peak is more difficult in vehicle spectra as the increased girder damping reduces the magnitude of the spectra relative to the level of noise in the signal. To account for this, the accelerations are passed through a low pass filter with a cutoff frequency of 8 Hz and the Power Spectral Density of accelerations is analysed in place of Fourier amplitude. As a result, the frequency peaks are clearer and easier to identify in the spectra for the purpose of analysing damping scenarios. Fig. 5 compares the mean acceleration spectra of the

girder and vehicle obtained in all scenarios for 5 crossings of vehicle V1 at speed S1. The bridge frequency peak at 2.44 Hz occurs in both Fig. 5(a) and (b). It can be seen that as the damping increases i.e. from 'Intact' to 'C' to 'ABCDE', the peak magnitude at the bridge frequency in the vehicle spectra decreases. This trend also occurs at the peak in vehicle spectra at 3.91 Hz. This suggests it is possible to detect changes in bridge damping.
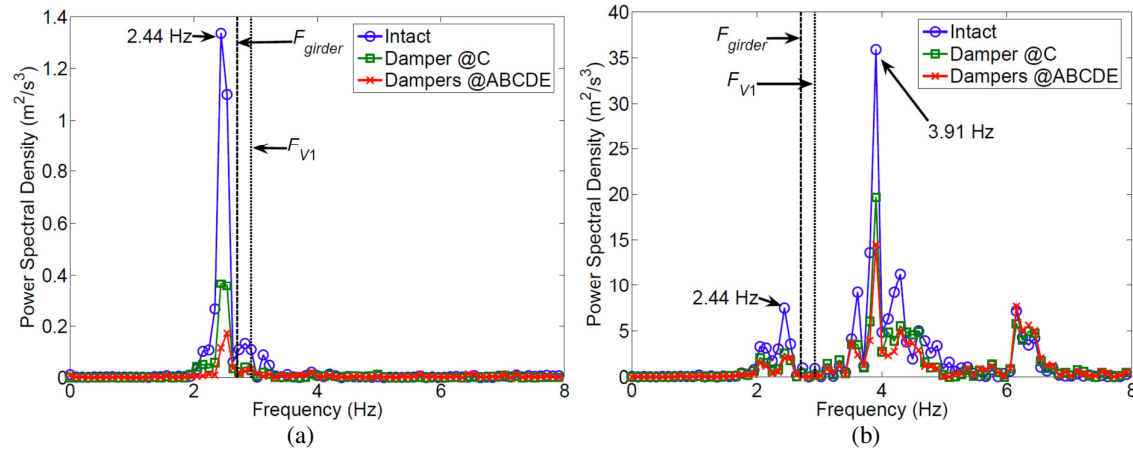

Fig. 5 Spectra of mean acceleration responses of (a) Girder midspan and (b) Axle 1 of V1 for speed S1 (0.93m/s)

CONCLUSIONS

This paper has investigated the feasibility of using an instrumented vehicle to detect the natural frequency and changes in structural damping of a bridge in a scaled laboratory experiment. For all scenarios investigated, the bridge frequency was identified in the vehicle spectra. It is clear that selection of vehicle speed is an important factor in the detection of the bridge frequency. The higher speed, S2 = 1.63m/s, provides larger magnitude peaks in the spectra but the spectral resolution is not as high as for speed S1. For vehicle 1 and speed 1, changes in damping are detected in the vehicle spectra. These results indicate that it is possible to detect the bridge frequency and changes in damping from the acceleration measurements of a moving vehicle. To confirm the feasibility of the system, further investigation of vehicle configuration, speed and girder damping scenarios is necessary.

ACKNOWLEDGEMENT

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