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SIMULATING THE DYNAMIC RESPONSE OF DIVINE BRIDGES

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ABSTRACT

This paper presents dynamic models of three bridges tested as part of the recently completed Dynamic Infrastructure Vehicle Interaction Experiment (DIVINE). Two of the bridges are from tests conducted in Switzerland and the fourth is from Australian tests. The Swiss bridges have first natural frequencies of 3.0 Hz (Deibüel) and 4.4 Hz (Föss) with main span lengths 41 m and 31 m, respectively. The Cameron's Creek bridge in Australia is much shorter (9 m) with a first natural frequency of 11.3 Hz. The Deibüel bridge has a first natural frequency corresponding to the bounce mode of heavy vehicles with leaf-sprung suspensions while the Föss bridge has a natural frequency slightly greater than the bounce modes of heavy vehicles. The natural frequency of the much shorter Cameron's Creek bridge corresponds to the wheel-hop modes of heavy vehicles.

The bridges are modelled by simple beam models to obtain mode shapes. A comparison between the theoretical mode shapes and those obtained from tests on the bridges is made. These mode shapes are then combined into a convolution method developed by the first author to predict the dynamic response of the bridge to dynamic wheel loads. By using the Fast Fourier Transform algorithm, the convolution integral, and hence the dynamic response of the bridge, is evaluated in the frequency domain.

The dynamic displacement responses of the bridges are calculated. The dynamic loads of the vehicle are estimated by a sinusoidal load added to the static wheel load. The predicted and measured test results are compared to discuss the validity and possible refinement of the bridge and vehicle simulations. The potential for extending the study to include more complicated vehicle models and varying bridge surface profiles is discussed.

INTRODUCTION

Over the last ten years, considerable research has been conducted into the "road-friendliness" of vehicles. In particular, much attention has been paid to the damaging effects of different vehicle suspensions. Many studies have concluded that air suspensions cause less damage to roads than do steel suspensions. These results have even led regulators to encourage air suspensions instead of steel suspensions. Although many studies have examined the effects of different vehicle suspensions on roads, very few investigators have studied the effects of air-sprung vehicles on the dynamic response of bridges.

To rectify the dearth of information on the effects of vehicle suspension design in bridge dynamics, project 6 in the Dynamic Infrastructure Vehicle Interaction Experiment (DIVINE) was devoted to the effects of vehicles on bridges. Although the DIVINE project produced very valuable experimental data, more research is required to fully understand the impact of different vehicle suspensions on the dynamics of bridges. This paper is a continuation of the work conducted in the DIVINE project, and focuses on modelling the bridges tested in the DIVINE project. Once the models are developed and validated against the DIVINE experiments, extensive analytical parametric studies will be conducted to understand fully the effects of vehicle suspension design on different types of bridges.

BACKGROUND

The first researchers to approach this topic were Green (1990) and Green et al. (1995). They conducted a theoretical parametric study using three different bridges by comparing the dynamic response caused by a steel suspended vehicle to that caused by an air suspended vehicle. They found that the air suspended vehicle caused lower dynamic responses in the bridges than the steel suspended vehicle. Further theoretical work in this area has demonstrated that air suspended vehicles are generally more “bridge-friendly” than steel suspended vehicles (Green 1996, Varadarajan 1996). These general results should be taken with some caution, however, because air suspended vehicles can cause substantially larger dynamic responses on certain types of bridges than are caused by similar steel suspended vehicles.

Gyenes et al. (1992) conducted some of the first experiments in this field. They measured dynamic vehicle loads on bridges and found that air suspended vehicles applied lower dynamic loads to bridges than did other types of vehicles.

The DIVINE program was a major attempt to examine the effects of vehicle suspensions on the dynamics of highway bridges (Cantieni and Heywood 1997). The research was conducted in Switzerland and Australia and focused on short to medium span bridges. The Swiss bridges have first natural frequencies of 1.6 Hz (Sort), and 3.0 Hz (Deibüel), 4.4 Hz (Föss) with main span lengths 70 m, 41 m, and 31 m, respectively. The Deibüel bridge has a first natural frequency corresponding to the bounce mode of heavy vehicles with leaf-sprung suspensions while the Sort bridge has a natural frequency corresponding to the bounce mode of air-sprung vehicles. Tests were conducted on each bridge with both an air suspended vehicle and a steel suspended vehicle. They found that the steel suspended vehicle caused larger dynamic responses on the Deibüel and Föss bridges, but that the air suspended vehicle caused larger dynamic responses on the Sort bridge.

In Australia, the work was mainly concerned with short span bridges where the natural frequencies matched the wheel-hop modes of the vehicles. Four bridges were tested and air suspended vehicles were found to cause extremely large dynamic responses of some bridges when the surface profile excited the vehicle in the wheel-hop mode.

DESCRIPTION OF BRIDGES

Three of the bridges tested as part of the DIVINE project were modelled. The first bridge is the Deibüel bridge in Switzerland which is a three-span, continuous, prestressed concrete box girder bridge. The main span is 41 m long and the first natural frequency is 3.0 Hz with a damping ratio of 0.8%. The other two spans are 32 m and 37 m long. Table 1 shows the measured natural frequencies for the first 4 flexural modes.

The Föss bridge is very similar to the Deibüel bridge, but the spans are slightly shorter. The main span is 31 m and the side spans are both 24 m. This bridge has a first natural frequency of 4.4 Hz with a damping ratio of 1.6%. Other dynamic properties for this bridge are shown in Table 1.

The third Swiss bridge is the Sort bridge which is considerably longer than the other two. The Sort bridge is also a prestressed concrete box girder, but consists of 5 spans rather than 3. The span lengths are 36 m, 58 m, 70 m, 58 m, and 36 m. With longer spans, the first natural frequency is considerably lower at 1.6 Hz with a damping ratio of 1.0%. Table 1 contains natural frequencies for the first few flexural modes.

The fourth bridge is the Cameron's Creek bridge in Australia. This bridge is much shorter with spans of only 9 metres. The bridge is constructed with four spans of prestressed concrete planks. The first natural frequency is 11.3 Hz with a damping ratio of 1.5%.

Table 1. Natural frequencies and damping ratios

Bridge	Mode	Measured Frequency (Hz)	Predicted Frequency (Hz)
Deibüel	1	3.0	
	2	4.2	
	3	5.4	
	4	10.0	
Föss	1	4.4	4.4
	2	6.4	7.0
	3		8.5
Sort	1	1.6	
	2	2.5	
	3	3.0	
Cameron's Creek	1	11.3	11.3
	2		45.1
	3		101.7

MODELLING OF BRIDGES

The bridges were modelled as simple beams. For the Swiss bridges, the beams were continuous over the specified number of spans. The Cameron's Creek bridge was modelled as a series of four, simply-supported beams. To adequately model the bridge, estimates of the mass per unit length and flexural stiffness were required. The mass per unit length was obtained from drawings of the bridge by estimating the cross-sectional area. The flexural stiffness was calculated to give the correct first natural frequency of the bridge. Table 2 contains the estimated properties of each bridge.

Table 2. Bridge properties

Bridge	Mass per unit length (kg/m)	Flexural rigidity, EI ($\times 10^9$ N·m^2)
Deibüel	16000	95.5

Föss	24600	107.3
Sort	17000	137.5
Cameron's Creek	10900	3.95

Using the bridge properties given in Table 2, the natural frequencies of the bridges were calculated as tabulated in Table 1. The predicted natural frequencies compare reasonably well with the measurements.

In addition to natural frequencies, mode shapes were also calculated. In the case of the Deibüel bridge, a cubic spline was fit to measured mode shape data (Cantieni 1992). The estimated mode shapes for the first four modes are shown in **Fig. 1**. For the Föss and Cameron's Creek bridges, the mode shapes were found using simple beam theory (**Figures 2 and 3**). Mode shape predictions for the Sort bridge have not been completed at the time of writing. The predicted mode shapes compare well with the mode shape measurements presented in the DIVINE report (Cantieni and Heywood 1997).

MODELLING OF BRIDGE RESPONSES

The dynamic bridge responses were calculated using a convolution algorithm based on mode shapes (Green 1994). The mode shapes from the previous section were input into the convolution program and combined with the wheel loads. The convolution integral was solved by transforming to the frequency domain using the Fast Fourier Transform (FFT) algorithm. Once the solution was found in the frequency domain, the inverse FFT was used to recover the time domain solution. This method of calculating the dynamic bridge response is significantly more efficient than equivalent time domain methods of evaluating the convolution integral.

Dynamic loads

The dynamic vehicle loads were predicted using two different methods. For the Deibüel bridge, the bridge response program was combined with a vehicle simulation package developed by Cole and Cebon (1992). This vehicle package incorporates non-linear suspension elements and has been extensively validated against measurements on vehicles. Two different vehicle models were used. The first model was a four axle, articulated vehicle with leaf-spring suspensions (**Fig. 4**). The second model was similar to the first, but the leaf-springs on the drive and trailer axles were replaced by air-springs. Although these vehicle models are different from the vehicles used in the DIVINE tests, they do allow for a comparison of the effects of leaf-sprung and air-sprung vehicles.

For the Föss and Cameron's Creek bridges, the dynamic loads were simply taken as a sinusoidal dynamic component added to the static wheel loads of the vehicles used in the DIVINE project. This dynamic component had an amplitude of 10% of the static wheel loads. For the Föss bridge, the frequency of the dynamic component was taken equal to the bounce mode frequency of each vehicle. For the Cameron's Creek bridge, the frequency of the dynamic component of the load was taken as 11.3 Hz to simulate matching of the wheel-hop mode of the vehicle to the first natural frequency of the bridge.

Dynamic bridge responses

Figure 5 shows the dynamic response of the Deibüel bridge to the leaf-sprung vehicle and the air-sprung vehicle at a speed of 15 m/s (54 km/h). The dynamic response caused by the leaf-sprung vehicle is significantly larger than that caused by the air-sprung vehicle. These predicted responses are qualitatively similar to those measured during the DIVINE project (Cantieni and Heywood 1997) at a speed of 51 km/h even though the vehicle models are different from the vehicles used in DIVINE. Further results with more appropriate vehicle models are required to properly validate the bridge response calculation.

Figure 6 shows the displacement response of the Föss bridge at a speed of 4.1 m/s (15 km/h). This response is very similar to that measured during the DIVINE tests. The maximum measured response due to the steel suspended vehicle was 1.5 mm which compares very well with a predicted maximum response of 1.3 mm. The predicted results also show slightly larger dynamic responses when the frequency of the wheel loads is equal to the bounce frequency of the leaf-sprung vehicle (i.e., case (b)) . This trend was also confirmed by the DIVINE tests.

The response of the Cameron's Creek bridge to moving dynamic loads travelling at a speed of 16.7 m/s (60 km/h) is shown in **Figure 7**. This predicted response is very similar to measurements made in the field where matching between the vehicle wheel-hop frequency and the first natural frequency of the bridge occurred. The maximum dynamic response predicted by the simulation was 1.8 mm. For comparison, air suspended vehicles caused maximum dynamic responses in the range of 1.8 mm to 2.7 mm in the DIVINE tests.

FURTHER WORK

The research presented in this paper will be extended to incorporate more realistic models of the vehicles actually used in the DIVINE project. Once the bridge and vehicle models are fully developed, they will be more rigourously validated against the experimental results. The models can then be used in a systematic study of the important parameters influencing the effects of vehicle suspensions on the dynamics of highway bridges.

CONCLUSION

Three bridges tested as part of the Dynamic Infrastructure Vehicle Interaction Experiment (DIVINE) were modelled, and the mode shapes and natural frequencies of the bridges were predicted. The predicted mode shapes compared well with those obtained from tests. Additionally, the dynamic responses of the bridges to dynamic wheel loads were calculated. The calculated responses were in reasonable agreement with the experimental results obtained in DIVINE. More rigourous validation of the bridge and vehicle models is still required.

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REFERENCES

Cantieni, R. 1992. Dynamic Behaviour of Highway Bridges under the Passage of Heavy Vehicles. EMPA Report No. 220, Section Concrete Structures, EMPA, Dubendorf, Switzerland.

Cantieni, R., and Heywood, R.J. 1997. Final Report on OECD DIVINE Project Element 6, Bridge Research, June.

Cole, D.J., and Cebon, D. 1992. Validation of articulated vehicle simulation. *Vehicle System Dynamics*, vol. 21, pp. 197-223.

Green, M.F. 1990. The Dynamic Response of Short-Span Highway Bridges to Heavy Vehicle Loads. Ph.D. thesis, University of Cambridge, England.

Green, M.F. 1996. Assessment of bridge-friendliness of heavy vehicle suspensions. *International Journal of Vehicle Design*, Special Issue on Vehicle/Road and Vehicle/Bridge Interaction.

Green, M.F., Cebon, D., and Cole, D.J. 1995. Effects of vehicle suspension design on the dynamics of highway bridges. *ASCE Journal of Structural Engineering*, Vol. 121, No. 2, pp. 272-282.

Gyenes, L., Mitchell, C.G.B., and Phillips, S.D. 1992. Dynamic pavement loads and tests of road-friendliness for heavy vehicle suspensions. *Heavy Vehicles and Roads: Technology, Safety, and Policy, Proceedings of the 3rd International Symposium on Heavy Vehicle Weights and Dimensions*, Cambridge, England, 28 June - 2 July, Thomas Telford, London, pp. 243-351.

Varadarajan, G. 1996. An Assessment of 'Bridge-Friendliness' of Heavy Vehicles with Different Suspensions. M.Sc. thesis, Queen's University, Kingston, Canada.

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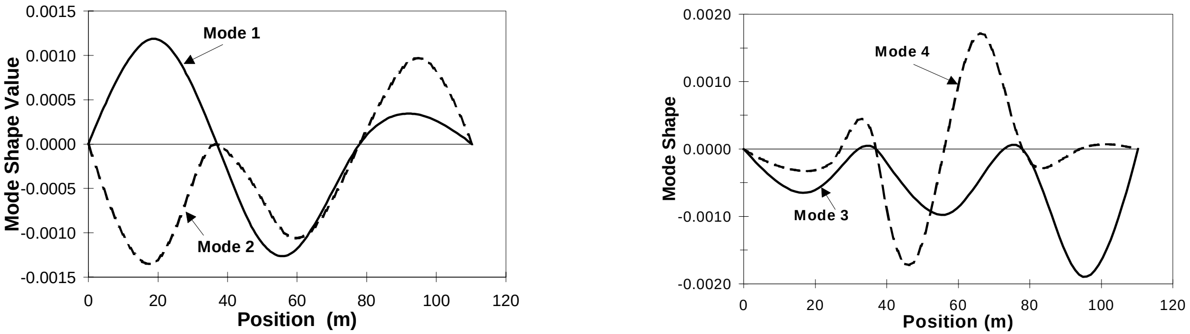

Figure 1. Mode shapes for the Deibüel bridge

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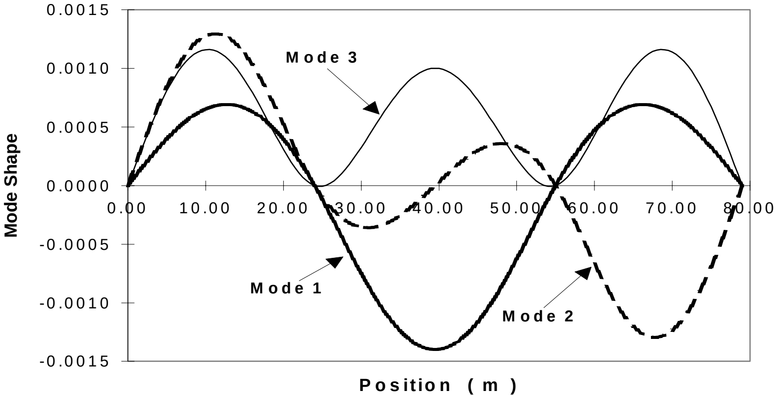

Figure 2. Mode shapes for the Föss bridge

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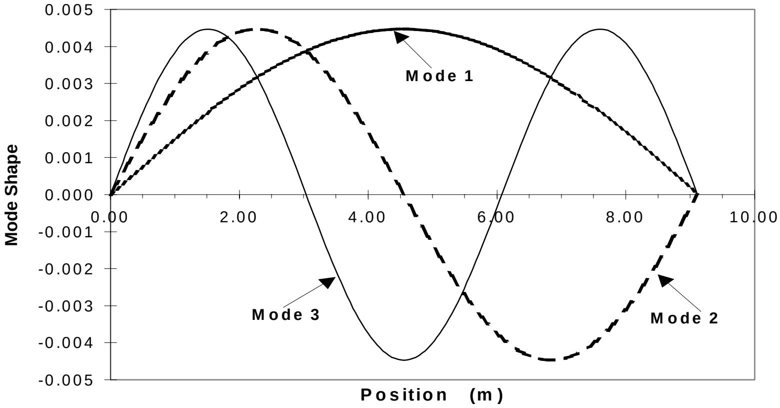

Figure 3. Mode shapes for the Cameron's Creek bridge

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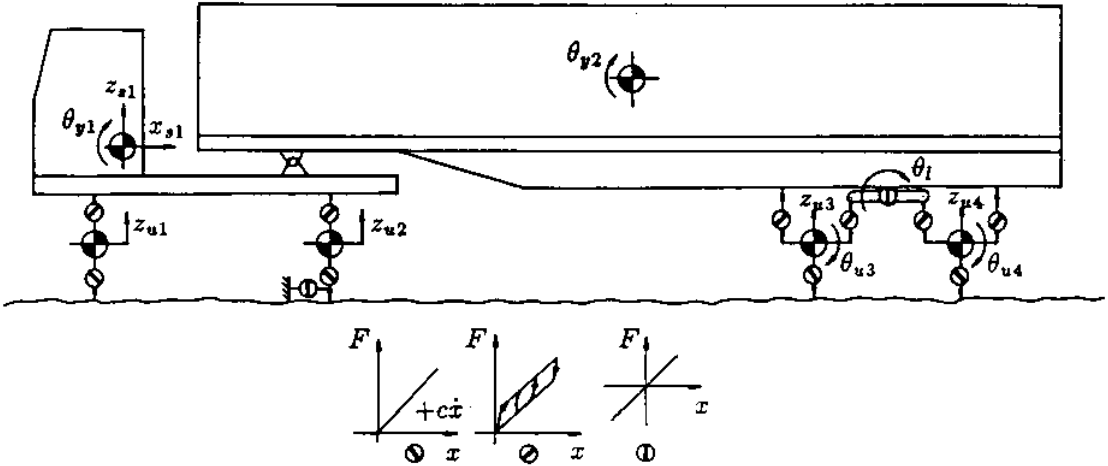

Figure 4. Two-dimensional tractor and trailer vehicle model with leaf-spring suspensions (Cole and Cebon 1992)

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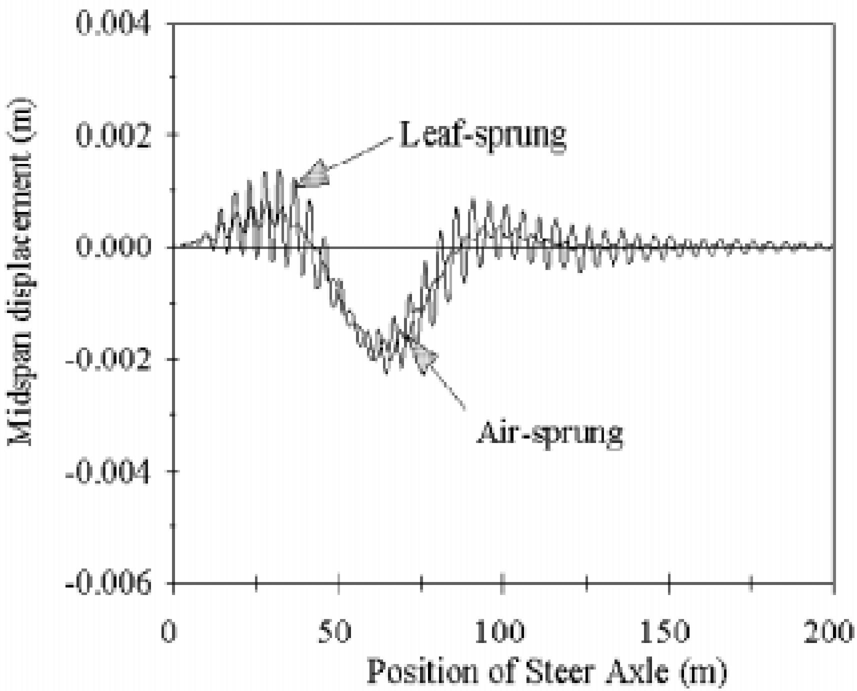

Figure 5. Displacement response of Deibüel bridge at a speed of 15 m/s

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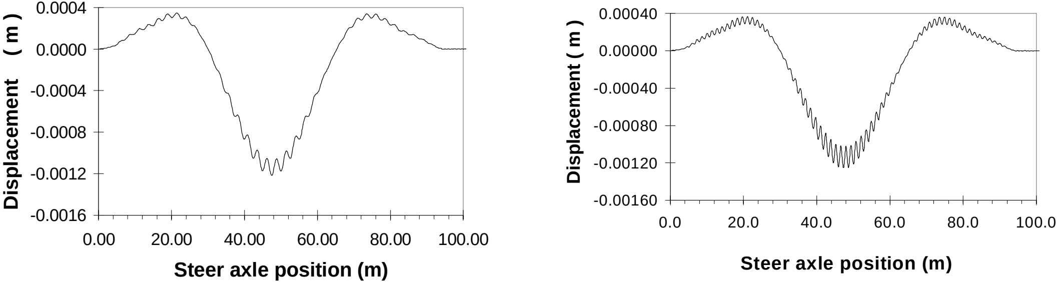

(a) Sinusoidal frequency = 1.6 Hz

(b) Sinusoidal frequency = 3.0 Hz

Figure 6. Displacement response of the Föss bridge at a speed of 4 m/s

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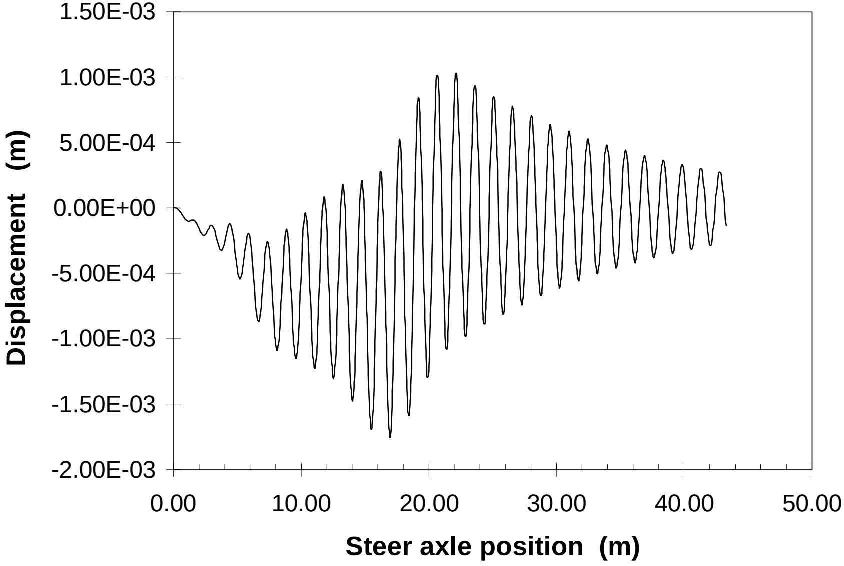

Figure 7. Deflection response of the Cameron's Creek bridge at a speed of 16.7 m/s.

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