



Title	Determination of Bridge Natural Frequencies Using a Moving Vehicle Instrumented with Accelerometers and GPS
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Abstract

An instrumented vehicle fitted with accelerometers and GPS allows recording frequencies with position. This information can be used to determine the main frequencies of a bridge as the vehicle traverses it. The accelerations, that contain the dynamic excitation result of the interaction between vehicle and bridge, can be processed using spectrum analysis. Numerical simulations are used to define the accuracy of the predicted frequency for a number of scenarios. Accuracy typically gets better as the bridge span increases, the vehicle speed decreases and the road gets smoother. Experimental data is also employed to test this measuring technique.

Keywords: frequency, vehicle, bridge, acceleration, GPS, monitoring.

1 Introduction

The frequencies at which a bridge vibrates are an important reference for the dynamic amplification that external excitations may induce in the structure. Therefore, a change in the frequency of a bridge can be sign of a change in structural behaviour due to aging, deterioration or environmental conditions. Tests in free or forced vibration are commonly used to accurately obtain bridge frequencies. These tests require instrumentation of the bridge (i.e., to measure accelerations or strains at certain points of the bridge) which is time consuming and labour expensive. This paper investigates the possibility of using a vehicle to obtain the bridge frequencies from the vehicle vibrations without the need for a bridge installation. These vehicle vibrations can be measured with accelerometers mounted onboard in addition to a GPS receiver that locates the vehicle at each point in time. The vehicle is simply driven over the bridge and the corresponding bridge frequencies are extracted from the spectrum of vehicle accelerations. This approach allows monitoring transport infrastructure periodically in an efficient way.

Preliminary studies by Yang et al [1] showed it is theoretically feasible to extract bridge frequencies from the dynamic response of a passing vehicle. They used a vehicle model consisting of a single sprung mass crossing a simple supported beam with smooth pavement, and they found that the first natural frequency of the beam could be extracted from the vertical acceleration of the moving mass. The effect of increasing the bridge damping ratio caused a drop in the peak response, but the bridge frequency could still be found. Similar results occurred when the bridge stiffness was increased. Lin and Yang [2] followed up on this research by carrying out an experimental test. A light truck (1.4 tonnes) towed a single axle cart (0.65 tonnes) across a single test span of a six span bridge (30 m each span). The light truck was used to excite the bridge while the cart, fitted with an accelerometer, scanned for bridge vibrations. Four test speeds, 13 to 52 km/h were used. An ambient vibration test was used to determine the first natural frequency of the bridge. Analysis of the field test showed that the bridge frequency could be easily identified at vehicle speeds of less than 40 km/h (11.11 m/s). At speeds beyond this value the bridge frequency was blurred by high frequency components resulting from the cart structure and road roughness. It was also found that on-going traffic resulted in significant increases in the magnitude of the cart response and it was beneficial to the test.

Previous investigations have been limited to a small sample. The purpose of this paper is to extend the analysis to other test conditions. I.e., it is possible that the frequency of long span bridges or medium to long span bridges with a smooth surface or with the simultaneous presence of heavy vehicles could be detected with higher vehicle speeds than 40 km/h. If this was the case, the test could be conducted without the need for an abnormally reduced highway speed. A 3-D FEM vehicle-bridge interaction model is employed to test the approach with theoretical simulations. Accelerations are obtained from the vehicle, then main frequencies are identified from the spectrum of accelerations and finally, they are compared to the true bridge frequency. The accuracy of the predictions is tested for various speeds, road roughness, damping levels and traffic conditions to establish the theoretical limitations of the approach. An experimental test is also carried out in a main route near Oviedo, Northern Spain, where a vehicle instrumented with accelerometers and GPS is driven over a long-span bridge to obtain its frequency.

2 Simulations

2.1 Vehicle-Bridge Interaction Model

3-D vehicle and bridge finite element models have been built using MSC/NASTRAN software [3]. The Vehicle-Bridge Interaction (VBI) is carried out using a Lagrange multiplier technique [4,5]. The accelerations at the interface of the rear tire-axle are obtained for a combination of vehicle speeds and road profiles.

Figure 1(a) illustrates the theoretical bridge model, which is a one-lane 60 m long two-span cellular bridge with edge cantilevers. The cross-section is made up of a number of thin slabs and webs which totally enclose three cells (Figure 1(b)). The modulus of elasticity is 35 kN/m². Solid diaphragms 2 m thick are located at the end and central supports. Figure 1(c) gives general dimensions of the bridge.

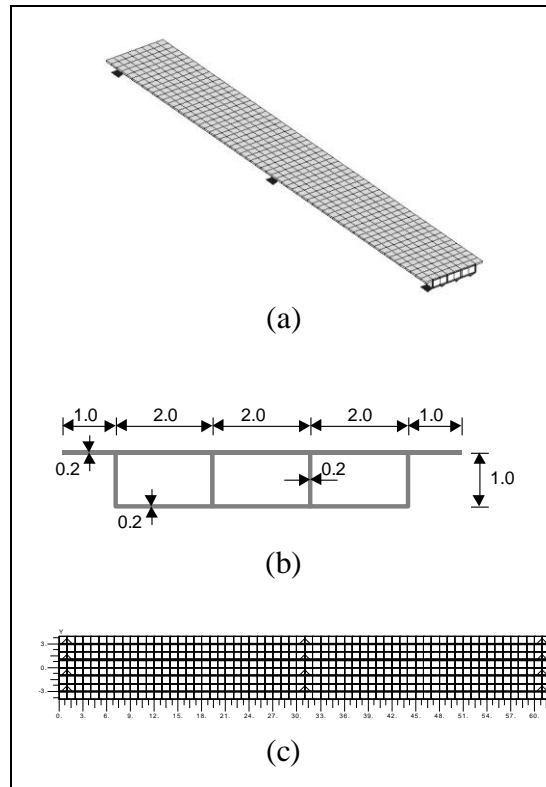


Figure 1: Finite element model of the bridge: (a) General view, (b) Cross-section, (c) Plan

The main modes of vibration of the bridge have associated frequencies of 2.95 (longitudinal), 4.60 (longitudinal), 10.98 (longitudinal), 13.14 (longitudinal), 13.66 (torsional) and 14.11 (torsional) Hz. The first four modes of vibration are illustrated in Figure 2. The bridge is assumed to have 5% structural damping. Although 1% to 2% would be a more typical value, a high value of 5% is adopted since a heavily damped bridge is a worse scenario from the point of view of frequency identification.

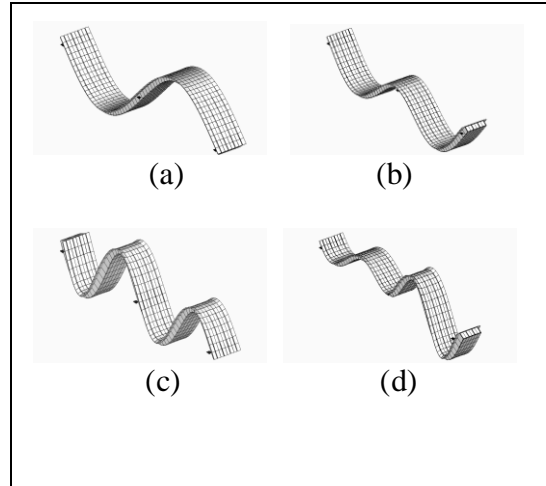


Figure 2: Main modes of vibration of the bridge: (a) 2.95 Hz, (b) 4.60 Hz, (c) 10.98 Hz, (d) 13.14 Hz

The truck model has 2 axles spaced by 5 m. The front and rear axles weigh 55.7 and 71.2 kN respectively. The distance between wheels of an axle is 2 m and the inner wheel is driven at a distance of the bridge centerline of 1 m. The mechanical parameters of the truck are based on previous experimental studies [6], and they are given in Table 1.

Table 1: Suspension and tyre properties

Spring (10^6 N*m)				Damping (10^3 Ns/m)			Axle mass (kg)		Mass moment of inertia (kgm^2)	
Tire		Suspension		Suspension	Tire					
Front axle	Rear axle	Front axle	Rear axle		5.0	Front axle	Rear axle	Front axle	Rear axle	Front axle
1.0	2.0	1.8	0.3	5.0		3.0	3.0	700	1300	600

Figure 3 illustrates the deformed and undeformed shapes of a number of modes of vibration of the truck model employed in the simulations (In the undeformed shape, vertical lines are linear spring and dampers representing a tire or a suspension system, while horizontal lines represent bar elements making up an axle or the vehicle frame).

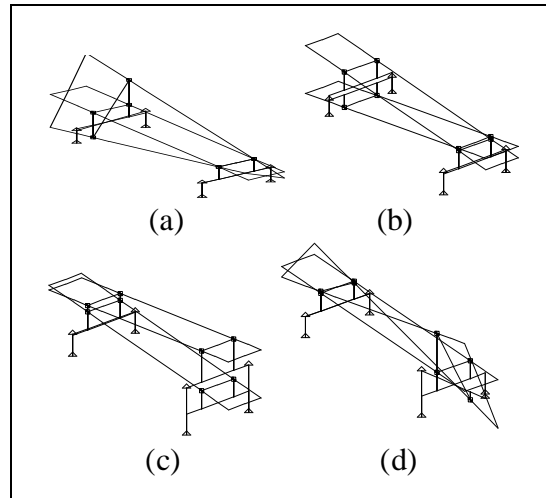


Figure 3: Modes of vibration of the truck: (a) frame twist, (b) body pitch, (c) body bounce, (d) body roll

These modes of vibration are associated to a frequency. The main frequencies of the vehicle are given in Table 2. The prior knowledge of these frequencies allows the assessment of the dynamic interaction with the supporting bridge and to differentiate vehicle and bridge frequencies. As the natural frequencies of the bridge and vehicle get closer, it becomes more difficult to separate one from the other, although a resonance effect may be noticeable.

Table 2: Main frequencies of vibration of the 2-axle truck (Hz)

Frame Twist	Body			Axle Hop		Axle Roll	
	Pitch	Bounce	Roll	Rear	Front	Rear	Front
1.05	1.40	2.35	2.54	9.48	13.49	14.59	15.65

The road profile is assumed to be a random process described by a power spectral density (PSD) function defined by ISO standards [7]. It is composed of 100 spatial frequencies between 0.01 cycles/m and 3 cycles/m.

2.2 Limitations in the Spectrum Definition

Amongst other factors, the accuracy of the bridge frequency that can be extracted from the vehicle accelerations will depend on the resolution of the spectrum which is directly related to the number of available measurements and the duration of the record. The horizontal frequency axis of the spectrum is discretized into a number of intervals of width $1/T$, where T is the total time that the vehicle takes to cross the bridge. Since this total time T is directly proportional to span length, L , and inversely proportional to vehicle speed, v , the resolution of the spectrum will improve with longer bridges and lower vehicle speeds.

The mode of vibration associated to the lowest frequency of the bridge will typically be the one having greater amplitude and a greater effect on the vehicle response. Based on experimental results, a medium-long span bridge will have an approximated first natural frequency, f_1 , of $100/L$ Hz, where L is the span length in meters [8]. Assuming $f_1 \cong 100/L$, Figure 4 illustrates the approximate first natural frequency associated to a given bridge length with a continuous line and the maximum resolution error associated to the use of a vehicle travelling at 20 m/s with two dotted lines. I.e., for a bridge length of 30 m and an hypothetical first natural frequency of 3.33 Hz, the predicted frequency could vary between 3.23 and 3.66 Hz only due to resolution. This source of inaccuracy can be reduced by using a lower speed (half the speed will double the resolution) or using several crossings of the instrumented vehicle.

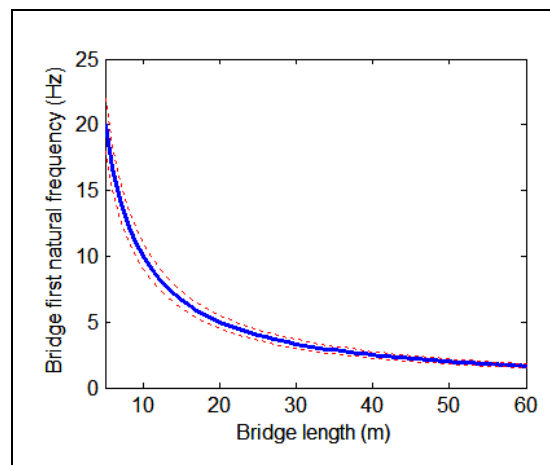


Figure 4: Theoretical maximum error in estimation of bridge frequency due to spectrum resolution for a vehicle travelling at 20 m/s

2.3 Theoretical Results

In order to test the approach, the dynamic interaction between the vehicle and bridge described in Section 2.1 is simulated in a variety of scenarios. Then, the frequencies are extracted from the vehicle accelerations and compared to the bridge frequency for a range of vehicle speeds (5, 10, 15, 20 and 25 m/s) and ‘very good’ road conditions (geometric spatial mean of $4e-06$ m³/cycle according to ISO). Figure 5 shows the vertical accelerations obtained when the vehicle is driven at 5 m/s (= 18 km/h) over the bridge.

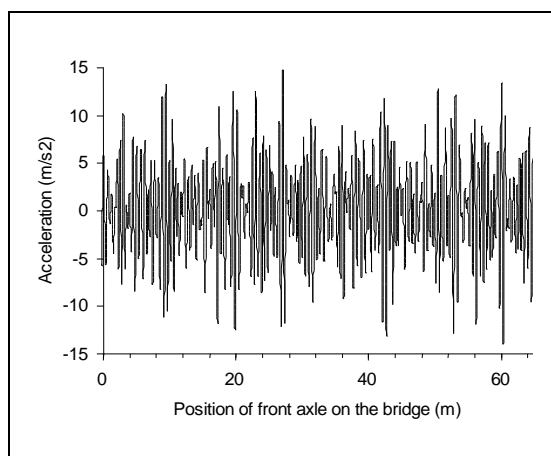


Figure 5: Acceleration measurements on a 'very good' profile

Figure 6 shows the power spectrum corresponding to the measurements of Figure 5 (bridge with 5% damping). The resolution of the spectrum is ± 0.33 Hz. Various peaks are evident in the plot. There is a high peak at 4.6 Hz in agreement with the bridge second natural frequency. The first natural frequency of the bridge (2.95 Hz) is not noticeable. The same test is carried out on a 1% damped bridge and shown in the figure. The PSD values associated to some frequency peaks are larger and they seem more distinctive when the bridge is lightly damped, but there is not difference in the frequencies being captured. For the rest of the simulations, a damping value of 5% is employed.

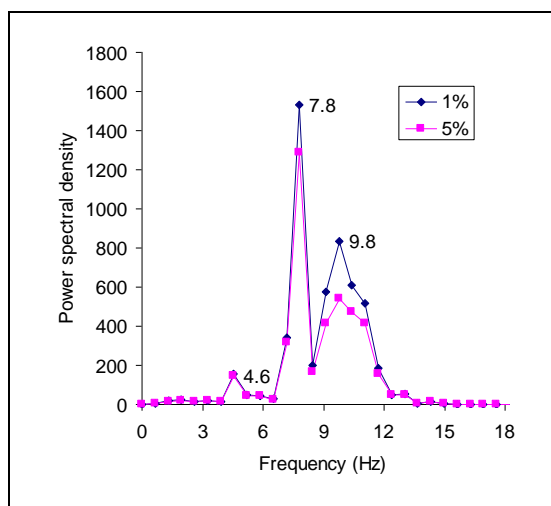


Figure 6: Frequency content of vehicle accelerations at 5 m/s on heavily and lightly damped bridges with 'very good' road profile

The possibility of 4.6 Hz to be a vehicle or road frequency is eliminated simply by checking a record of accelerations prior to the bridge. So, Figure 7 shows the

spectrum corresponding to the vehicle accelerations before entering the bridge at 5 m/s. In this case, the dominant frequencies are 1.3, 7.2, 9.1 and 11.7 Hz.

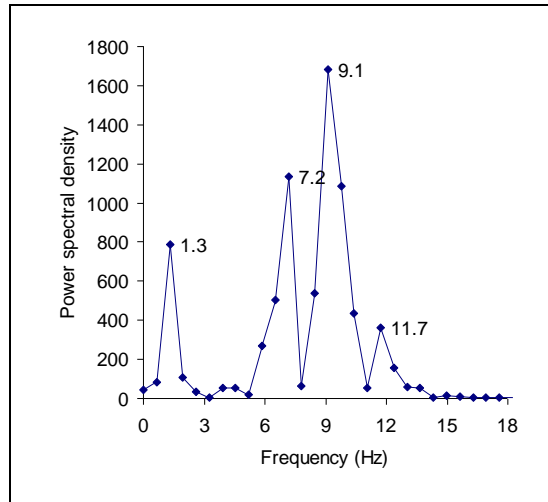


Figure 7: Frequency content of vehicle accelerations prior to the bridge

Figure 8 shows the spectrum measured at 25 m/s on a ‘very good’ road profile. Unlike the simulation in Figure 6, here it is not possible to detect the bridge frequency. This inability to catch the bridge frequency is related to the higher influence of vehicle/pavement dynamics at higher speeds and the limitations outlined in Section 2.2.

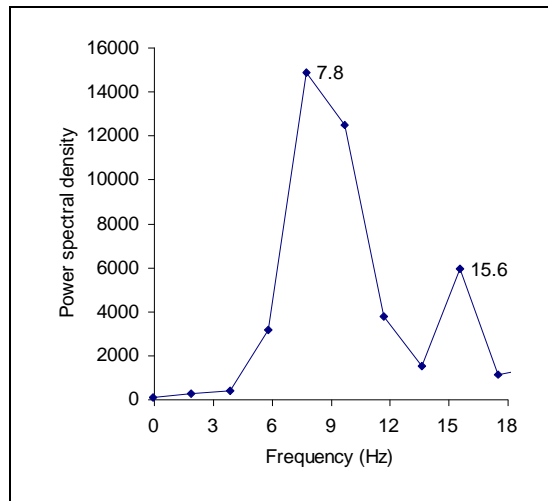


Figure 8: Frequency content of vehicle accelerations at 25 m/s on a heavily damped bridge with ‘very good’ road profile

Table 3 shows the identified frequencies within the range from 0 to 15 Hz when travelling over the ‘very good’ profile at a range of speeds. For the case under study

and speeds from 5 to 25 m/s, the 1st natural frequency of the bridge is not found. Therefore, for speeds above 5 m/s, it is not possible to detect the 2nd natural frequency of the bridge with a reasonable degree of accuracy. Even further, for speeds of 20 m/s and above, the 2nd natural frequency is not identifiable within the spectrum.

Table 3: Identified frequencies from the spectrum with a ‘very good’ profile

Vehicle speed (m/s)	Location	Identified frequencies (Hz)				
		1 st	bridge	2 nd	3 rd	4 th
5	Off the bridge	1.3	-	7.2	9.1	11.7
5	On the bridge	-	4.6	7.8	9.8	-
10	On the bridge	-	5.9	8.8	-	11.7
15	On the bridge	-	3.9	-	9.8	-
20	On the bridge	-	-	-	-	11.7
25	On the bridge	-	-	7.8	-	-

Figure 9 shows the result of running the same test at 5 m/s on three different road surfaces: a ‘very good’ road profile, a ‘good’ road profile (geometric spatial mean of 16e-06 m³/cycle according to ISO) and a ‘good-average’ road profile (geometric spatial mean of 32e-06 m³/cycle). The shape of the three profiles is the same and only the amplitude has been varied to have different levels of roughness. For all profiles, although the values of the PSD increase with road roughness, the interference of the road frequencies is not significant at the lowest frequencies and a peak at 4.6 can be clearly identified.

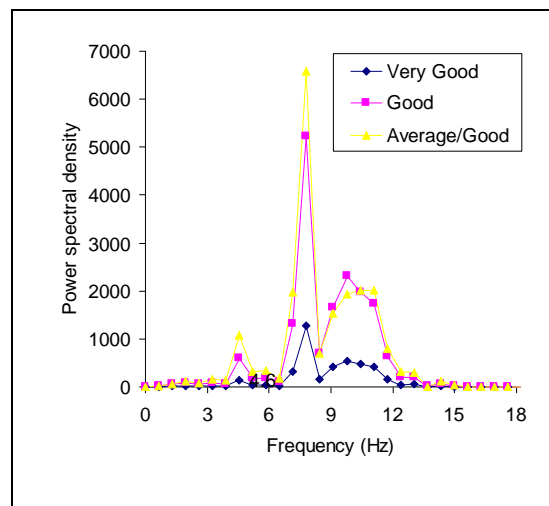


Figure 9: Frequency content of vehicle accelerations on a heavily damped bridge with three road surface conditions: ‘very good’, ‘good’ and ‘good-average’

It has been seen that for relatively small road amplitudes, it becomes very difficult to establish the bridge frequency, in particular as speed increases, i.e., the influence of the bridge deflection is far smaller than the one of the road irregularities. Hence, the range of qualified bridge scenarios for the instrumented vehicle may be extended by taking measurements in the presence of heavy traffic on the bridge. Then, the bridge deflections will be larger and the measured accelerations will contain a stronger component due to bridge vibration than if the instrumented vehicle was on the bridge by itself. Figure 10 compares the PSD resulting from taking measurements with only the 2-axle instrumented vehicle on the bridge and with the 2-axle instrumented vehicle combined with a heavy 3-axle truck (Gross vehicle weight of 269 kN) crossing the bridge in the same direction in a parallel lane (at 1 m from the bridge centreline). It has been assumed both vehicles enter the bridge at the same time and they have the same velocity of 20 m/s. Figure 10 show the bridge frequency can not be identified when the instrumented vehicle is on its own, but the simultaneous presence of another heavy vehicle on the bridge allows detecting a peak at 5.9 Hz. Nevertheless, this estimation is considerably inaccurate partially due to the poor resolution of the spectrum (± 1 Hz). This inaccuracy can be reduced increasing the number of available measurements by lowering the speed.

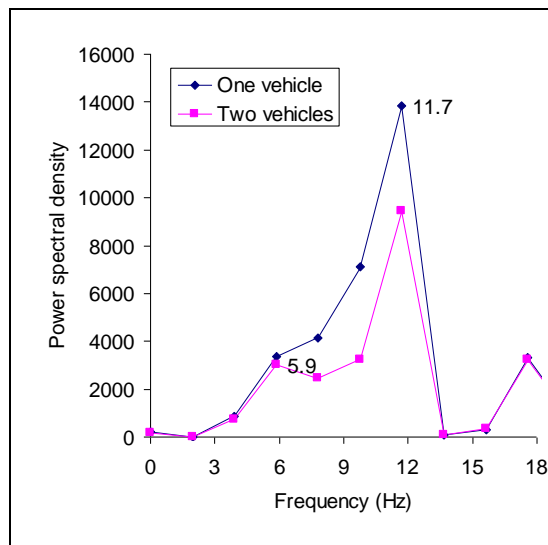


Figure 10: Frequency content of vehicle accelerations on a heavily damped bridge with two traffic conditions: ‘single-vehicle’ and ‘multiple-vehicle’ presence

3 Experimental Testing

3.1 Description of the Test

The test took place in a highway opened to the traffic recently so the pavement was in relatively good condition. The site is within the A-8 highway (Autovia del

Cantábrico), Asturias (Northern Spain), in the route that goes from the village of Ballota (43° 33' 5,8" N; 6° 19' 48,5" W) to Cadavedo (43° 32' 47,54" N; 6° 23' 10" W). There are about 6 kms and a number of bridge structures between both locations, including the bridge of Cadavedo that this experiment refers to (Figure 11). This bridge is built over the Frieras river. It has nine spans of lengths between 41 and 50 m, and a total length of 423.5 m.

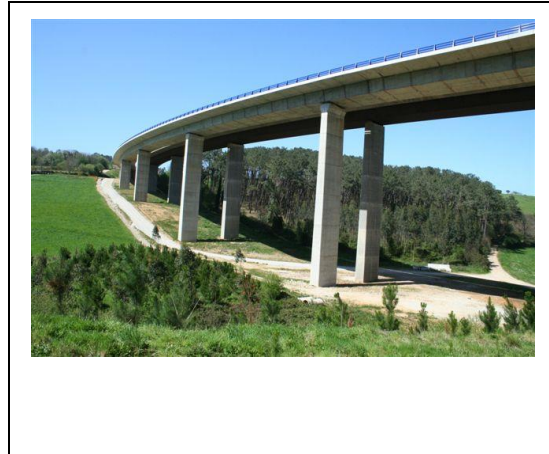


Figure 11: General view of Cadavedo bridge.

Accelerometers and GPS receiver were installed in a 2-axle light trolley (Figure 12). The trolley had a total mass of 380 kg, a total length of 3730 mm (including the front hinge), a width of 1800 mm and a platform height of 750 mm. The distance between hinge and front axle was 2280 mm, the distance between both axles was 650 mm, and the rear cantilever had a length of 800 mm. The tractor was a 4x4 vehicle with 115 CV. The tractor had an automatic speed option available that allowed maintaining constant speed during the measurements.



Figure 12: Instrumented trolley

The data acquisition equipment was placed in the tractor and wired to the accelerometers and GPS in the trolley. Three accelerometers Brüel & Kjær, models 4504-A, 4506 and 4508, were employed. Two of them (4506 y 4508) were placed near the wheels on the rear axle (Figures 13 and 14) and they measured vertical accelerations (perpendicular to the road).

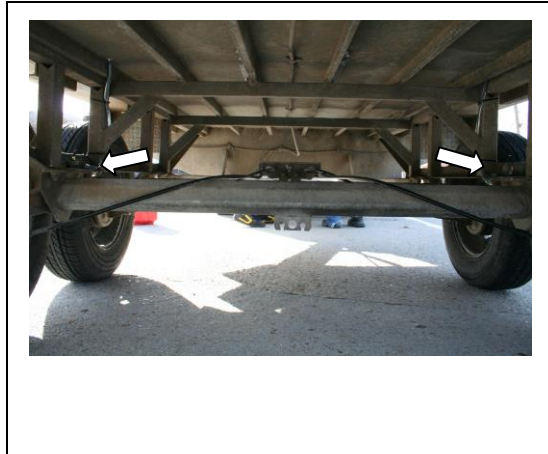


Figure 13: Location of monoaxial accelerometers

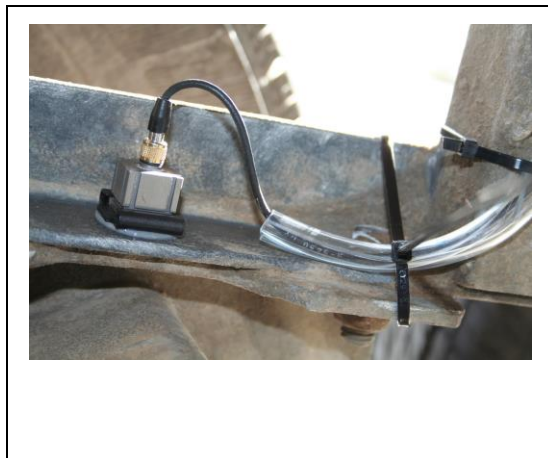


Figure 14: Installation of monoaxial accelerometer on the axle

The third accelerometer (4504-A) was placed in the middle of the trolley platform, besides the GPS antenna (Figure 15). This accelerometer recorded vertical and horizontal accelerations. The vehicle was located at each point in time using GPS dynamic measurements [9,10]. For this purpose, two Leica 1200 receivers were employed. One of the receivers was positioned statically in one fixed point on a hill closed to the route. Prior to the test, the exact location of this point was determined using a nearby GPS station as reference. The other receiver was installed in the

platform of the trolley and it moved with the vehicle. The GPS antenna was attached to a support and it stood 1500 mm over the platform (Figure 15).



Figure 15: GPS antenna and location of biaxial accelerometer

3.2 Analysis of Results

Figures 16 and 17 show the spectrum of measured accelerations on the vehicle prior and on the bridge respectively. The spectrum of Figure 16 belongs to accelerations measured away from the bridge and it allows identifying dominant vehicle frequencies of about 4.9 and 8 Hz. These two frequencies were present in the records of all 4 accelerometers. Figure 17, representative of the frequencies present as the vehicle was on the bridge (crossing it at a speed of 55 km/h), doesn't reveal any significant frequency content that could differ from Figure 16. There is a frequency of 6.6 Hz, relatively more important than in Figure 16, but this frequency is also present when the vehicle was not on the bridge. Although there is a number of frequencies below 4 Hz that could represent the bridge, the frequency content is not sufficient to be certain. This is sign that the bridge was not excited sufficiently at the time the vehicle crossed the bridge and that the road profile clearly governed over the bridge deflections on the vehicle behaviour. Hence, these preliminary results were not conclusive and it seems the test required more favourable conditions of velocity and simultaneous heavy traffic on the bridge.

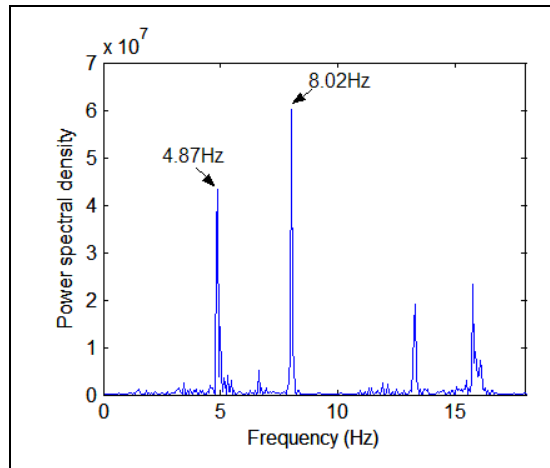


Figure 16: Spectrum of measured accelerations prior to the bridge

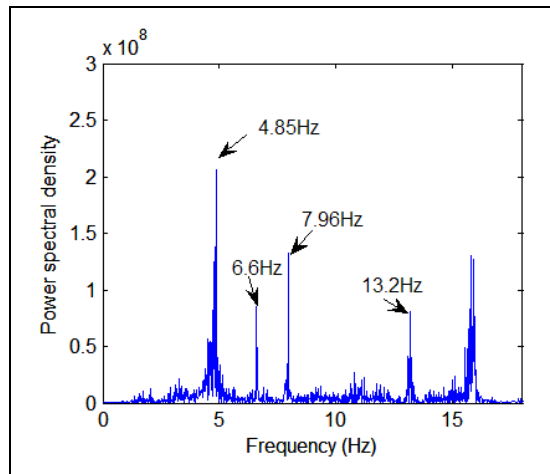


Figure 17: Spectrum of measured accelerations on the bridge

4 Conclusions

This paper has investigated the feasibility of using an instrumented vehicle to monitor the natural frequencies of a bridge. Previous studies have shown that lower speeds lead to a more accurate determination of this bridge frequency. However, theoretical studies and experiments presented in this paper have shown that this is only feasible when the degree of dynamic excitation of the bridge is high enough. So, for the theoretical bridge structural form under study, the 1st natural frequency of the bridge was unidentifiable and it has only been possible to extract the 2nd natural frequency of the bridge for very low speeds. For other speeds, the interference of the road profile frequencies corrupts the spectrum and prevents the identification of the bridge natural frequency. The inability to detect the bridge frequency at the experimental test is attributed to the relatively high vehicle speed and the lack of

heavy traffic on the bridge that would ensure the bridge deflection to be significant compared to the height of the road irregularities.

Acknowledgments

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