Ambient and forced vibration testing of an eleven-span motorway off-ramp bridge

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ABSTRACT: Dynamic testing of full-scale bridges is indispensable for acquiring the real dynamic characteristic of structures due to the presence of real boundary conditions, actual loading and response mechanisms and absence of scaling. This paper presents in-situ ambient and forced dynamic tests on an eleven-span motorway off-ramp bridge and experimental modal analysis. In the ambient vibration tests (AVT), nearby traffic, wind, and possibly micro-tremors were used as excitation sources. In the force vibration tests (FVT), large eccentric mass shakers were utilized in a frequency sweep mode to excite the bridge in the frequency range up to 10 Hz. Two complementary system identification methods were implemented to extract the modal properties of the bridge: the frequency domain decomposition (FDD) and the data-driven stochastic subspace identification (SSI) method. It was found the two methods yield consistent natural frequency results, while SSI give better estimates of mode shapes. By comparing the identified modal parameter results between AVT and FVT, it is observed that the first two lateral bending modes could not be identified from AVT, likely due to inadequate energy of the excitation at the corresponding frequencies, whereas the first two vertical bending modes could be identified even under weak excitation conditions. The identified natural frequencies and mode shapes agree satisfactorily between the corresponding modes, but the mode shapes from FVT are much smoother due to the stronger excitation level and better signal-to-noise ratio. Furthermore, a lateral mode as high as above 9 Hz could be clearly identified without traffic on the bridge in AVT on this continuous concrete bridges, which is rare. The comparisons between AVT and FVT and the different identification techniques provide useful reference information for field dynamic testing of similar bridges.

KEY WORDS: Full-scale bridge; Ambient vibration testing; Forced vibration testing; Eccentric mass shaker; Frequency domain decomposition; Stochastic subspace identification; Modal parameters, Experimental modal analysis, Operational modal analysis.

1 INTROUDUTCTION

Modal parameters of bridge structures, i.e. natural frequencies, damping ratios and mode shapes, are essential for vibration-based structural health monitoring, calibration and validation of analytical models, and safety evaluations against different severe loading conditions, such earthquakes and strong wind. In-situ dynamic testing, either ambient vibration tests (AVT) or forced vibration tests (FVT), is the most reliable method to obtain the true modal properties of bridge structures in their actual environment. The two testing methods have different characteristics. Excitations for AVT are widely distributed on structures, are small, uncontrollable and may contain several sources, such as traffic, wind, micro-tremors, etc. On the contrary, the excitation force of FVT is usually concentrated at one point of the structure, is relative large and the researcher can control it. AVT permits the measurement of structural responses under natural excitation sources and can avoid shutting down vehicular traffic during the tests, while FVT (such as using shakers) can provide a clean excitation input but requires significant resources, such as transporting heavy equipment, mounting the shaker on the bridge, supplying high power and so on. Applying the appropriate testing methods to a particular bridge to obtain good testing results is an important aspect of the dynamic testing art. Some researchers investigated the feasibility aspects of AVT and FVT. Green [1] concluded that shakers produced the best results for short to medium span bridges (spans<100 m), while AVT were most appropriate for medium to long span bridges (spans＞70m). Farrar et al. [2] pointed out that although there does not appear to be consensus that one particular method is better than the other, for large bridges AVT seems the only practical alternative of exciting the structure. They also pointed out that AVT was also used for smaller bridges when other constraints prevent the bridge from being taken out of service during FVT. In terms of the effectiveness, Farrar et al. [3] observed that natural frequencies extracted from impact hammer test data were more statistically reliable that those obtained using ambient excitation. On the other hand, Peters et al. [4] reported that ambient excitation was found to yield comparable results to those obtained using either a band-limited shaker input or drop weight impact. From a review of previous studies, no clear consensus has been reached about the feasibility and effectiveness of AVT and FVT due to many factors involved, such as bridge structure type, testing environments, testing equipment, bridge span length and many other. Another aspect of in-situ testing is that sensors are exposed to noisy outdoor testing environment, which present a challenge to accurately identify the modal parameters based on the vibration testing data contaminated by noise, especially when the responses are small. Though many modal identification techniques using output-only information have been developed, their effectiveness of dealing with noisy data needs further investigation.

This paper investigates further the feasibility and effectiveness of AVT and FVT for obtaining dynamic characteristics of full scale bridge structures. Both kinds of testing were conducted on the 11-span Nelson St off-ramp bridge. The structure as well as the detailed AVT and FVT programs are described first. Based on the collected data from AVT and FVT, two output-only modal parameter identification techniques, the frequency domain decomposition (FDD) and the data-driven stochastic subspace identification (SSI), were executed. The identified frequencies, damping ratios and mode shapes of the bridge from AVT and FVT, and identified using FDD and SSI were compared. Thus, the ability and reliability of the AVT under weak excitation levels to identify the modal parameters of the relative short-span continuous concrete bridge were addressed and found satisfactory.

2 BRIDGE DESCRIPTION

The Nelson St off-ramp bridge is a part of the motorway network in the CBD of Auckland, New Zealand. The bridge is currently closed to traffic and this creates excellent opportunities for an extensive, undisturbed testing program. Figure 1 shows an aerial view of the bridge, which is a curved, post-tensioned, continuous concrete structure with a hollow box section girder. The bridge was built in 1976 using a moveable scaffolding system and comprises a total of 137 precast box-girder segments. It has a total length of 272 m, width of 7.5m (for two lanes of traffic) and consists of 11 spans, with the longest span of 40 m. An elevation sketch and span length information are given in Figure 2 and Table 1, respectively.

Figure 1. Aerial view of the Nelson St off-ramp bridge.

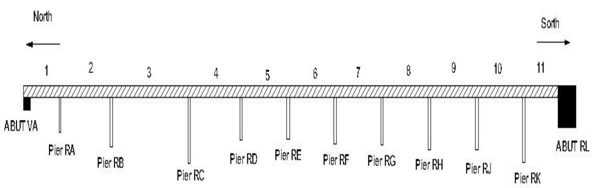


Figure 2. Elevation view of the Nelson St off-ramp bridge.

Table 1. Bridge span lengths.

Span	1	2	3	4	5	6	7	8	9	10	11
Length (m)	18	26	40	26	24	24	24	24	24	24	18

3 AMBIENT AND FORCED VIBRATION TESTS

The bridge under testing is currently closed to vehicles. In AVT, the excitation sources mainly came from vehicles traveling on the motorway sections adjacent and underneath the bridge, wind, and possible micro tremors. In the FVT, a controlled input force was imposed onto the bridge by exciters and provided a level of excitation much higher compared to the ambient forces.

3.1 *Instrumentation*

For AVT, conducted on March 4th, 2013, a dense measurement location plan on the bridge deck was used for a good resolution of mode shapes. Wireless 3-axial, stand-alone MEMS accelerometers [5] model X6-1A (Figure 3a) and X6-2 (Figure 3b), were utilized to capture the response. Time stamped data in three perpendicular directions were recorded at a user selectable rate of 160 Hz on micro SD memory cards available in each of the accelerometers,. and the data was subsequently uploaded to a computer via a USB connection. Model X6-1A is powered by a D-cell battery and model X6-2 is powered by an internal lithium-polymer battery chargeable via an USB port. The accelerometers were installed along both bridge curbs (Figure 4). The distance between two measurement stations ranged from 2m to 4m. As a result, a total of 188 locations were measured. Four test setups were used to cover the whole length of the bridge. In each setup, 4 reference accelerometer stations and 46 roving measurement stations were used. The ambient vibration response of the bridge was simultaneously recorded for 40 minutes at all the roving accelerometers and base stations for one setup. Once the data was collected, the roving stations were moved to the locations of the next setup, while the base stations remained in their original locations. This sequence was repeated four times to obtain measurements at all stations on the bridge deck and progressing from the North end of the bridge to the South end.

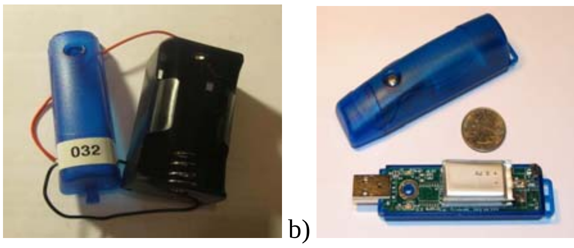
a)  b)

Figure 3. Wireless accelerometers: a) X6-1A, and b) X6-2.

Figure 4. Accelerometers arranged along the bridge curbs.

For FVT, two ANCO MK-140-10-50 eccentric mass exciters were employed [6]. The shaker system consists of a dual-arm rotating adjustable eccentric mass, drive motor, timing belt speed reducer, Danfoss VLT-5011 variable frequency drive control system and interconnecting three-phase cables. The total mass of the system is approximately 600 kg. The eccentric mass shaker has maximum unidirectional frequency and force capacities of 30 Hz and 98 kN. On May 7th, 2013, the two shakers, with a 3.6 kg rotating mass attached to each flywheel, were anchored on the bridge deck (Figure 5) to perform a frequency sweeping testing program in both the vertical and lateral direction up to 10 Hz. Based on a preliminary finite element analysis, the longest span between pier RB and pier RC (Figure 2) was selected to mount the shakers. The horizontal shaker was located at the mid-span along the midline of the bridge deck and the vertical shaker at 1/3 of the span length towards the West traffic lane so as to also excite possible torsional modes. During the sweeping, the frequency increment was set as 0.1 Hz, and each frequency increment was held around 15 seconds with a 5 second ramp up time from the previous excitation frequency. This excitation protocol allowed the bridge to achieve steady state response at each excitation frequency increment. The accelerometers were the same as those used in the AVT but 80 Hz was selected as the sampling frequency. During vertical direction tests, 60 wireless accelerometers were arranged along both curbs of the bridge deck. Representative measuring location of each bridge span, such as the 1/2 and 1/4 span-length points were chosen as the measuring locations. As a result, 30 measuring locations on each bridge curb side were scheduled to cover the whole bridge length. During lateral direction tests, all wireless accelerometers were arrayed along the midline of the bridge deck with around 4 m spacing to obtain better mode shape resolution. A typical measurement stations arrangement of the span between pier RB and pier RC is shown in Figure 6. The sensor arrangement of other spans was similar.

Figure 5. Eccentric mass shakers mounted on the bridge.

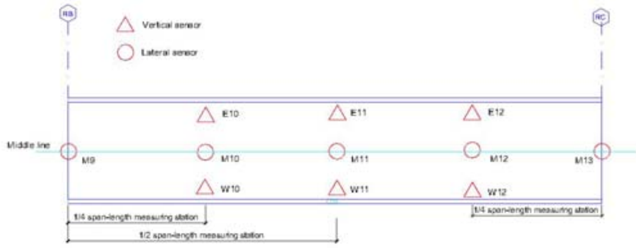


Figure 6. FVT typical accelerometer layout.

4 MODAL PARAMETER IDENTIFICATION

Figure 7a shows a typical record of 20 minutes of vertical and lateral acceleration response at mid-span point located between Pier RB and Pier RC during AVT. The peak value of the vertical and lateral response acceleration is 0.02 m/s^2 and 0.013 m/s^2, respectively, and the lateral peak value is thus approximately half of the vertical one. Figure 7b displays the recorded acceleration response of the same measuring station in the vertical and lateral direction, respectively, when performing a vertical frequency sweep. It can be observed that in this case the peak acceleration response is far greater than in AVT, especially in the vertical direction.

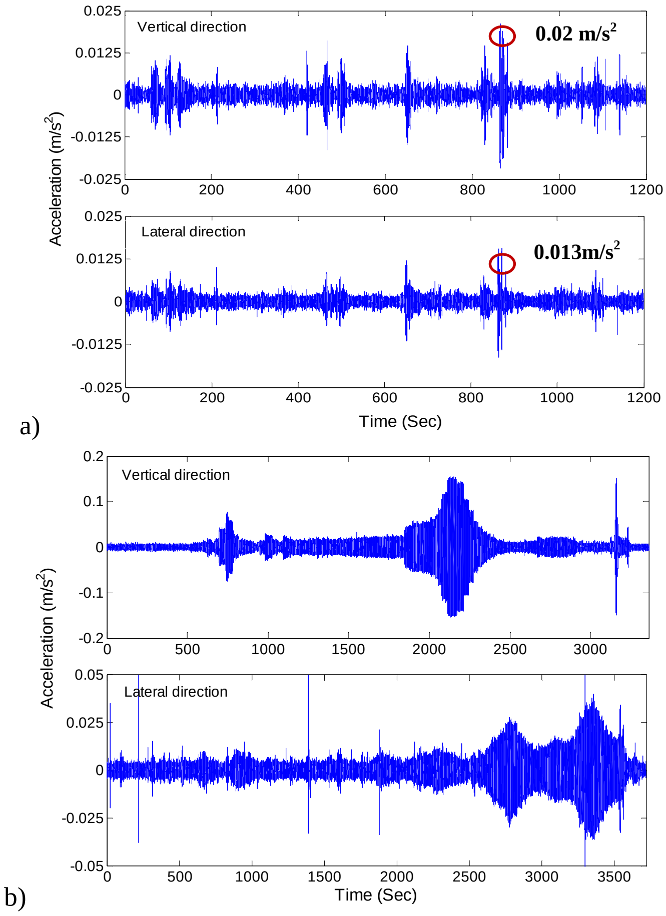


Figure 7. Typical acceleration response in the middle of the longest span: a) AVT, and b) FVT.

After in situ dynamic testing, the collected accelerometer data from each measuring station was used for modal parameter identification. All data were processed by using a MATLAB based GUI modal property identification toolbox developed at the University of Auckland [7] to extract the natural frequencies, damping ratios and mode shapes. Several signal pre-processing operations were adopted to clean the noisy data: de-trending the measured acceleration records to remove any linear DC offset; visual inspection of the acceleration records by plotting their time histories to identify any malfunctioning of sensors (if an accelerometer contained repetitive errors such as bias or large spikes, the recorded data was disregarded from further processing and analysis); and filtering with a 5-pole digital Butterworth band pass filter with the cut-off frequencies at 0.1 and 10 Hz to reduce the low and high frequency components embedded in the data that would adversely affect further data processing. Two data post-processing methods FDD [8] and SSI [9] were executed to identify the structural dynamic characteristics. The FDD technique mainly consisted of estimation of the spectral matrix with a frequency resolution of 0.078 Hz, Singular Value Decomposition (SVD) of the spectral matrix at each frequency, and the inspection of the curves representing the singular values to identify the resonant frequencies and estimation of the corresponding mode shapes using the information contained in the singular vectors. SSI was implemented with a Hankel matrix of size 40 and system order between 2 and 100 to produce stability diagrams. The identified stable poles around the singular values generated from the SVD were compared. If two consecutive poles within ±0.25 Hz of the singular value had a change in frequencies within 1%, change in damping within 50% (a looser criterion for damping due to its relative large variability), and the modal assurance criterion value greater than 0.90, both poles were kept and averaged. If the poles did not meet these criteria, the first pole was discarded and the second pole was compared to the subsequent one. This series of comparisons was continued until all the stable poles in the frequency range of interest had been identified and averaged. The resulting mode shape, natural frequency and damping ratio were the combination of several stable poles and therefore provided a robust method of system identification. Correlation studies of the structure identification results from the two separate methods verified that the identified bridge parameters are reliable.

5 IDENTIFICATION RESULTS

5.1 Comparison between FDD and SSI

Table 2 and 3 show the identified natural frequencies and damping ratios from field testing data based on FDD and SSI for AVT and FVT, respectively. The labels V and L stand for vertical bending and lateral bending mode, respectively. (Note not all modes were identified from AVT.) Because AVT was divided into four setups, the mean value was calculated from each setup to represent the identified natural frequencies and damping ratios of the bridge. The frequency difference column shows the largest identified natural frequency departure between FDD and SSI is only 1.6% for 1st vertical bending mode. This demonstrates that the frequency domain based FDD and time domain SSI yield the mutually consistent natural frequency results. The largest frequency difference between AVT and FVT is 3.7%. It again is small and furthermore the AVT and FVT result are not expect to agree completely because of a possible frequency-response amplitude relationship. Overall, these results give a high level of confidence that the identified natural frequencies are the true ones of the bridge structure. Damping ratios of between 0.4% and 2.6% were identified using SSI alone. These damping ratios are broadly in the range expected for concrete bridges. Differences between AVT and FVT damping results are clearly visible but are not larger than commonly encountered in experimental modal analysis.

Table 2. Natural frequencies and damping ratios from AVT.

Mode	Natural frequency (Hz)		Frequency difference (%)	Damping ratio (SSI) (%)
	FDD	SSI		
1V	3.17	3.22	1.6	1.8
2V	3.83	3.82	0.3	1.4
3L	3.72	3.77	1.4	1.2
4L	4.50	4.46	0.9	1.3
5L	5.46	5.47	0.2	2.1
6L	6.64	6.63	0.2	1.2
7L	7.56	7.50	0.8	2.4
8L	9.37	9.38	0.1	2.5

Table 3. Natural frequencies and damping ratios from FVT.

Mode	Natural frequency (Hz)		Frequency difference (%)	Damping ratio (SSI) (%)
	FDD	SSI		
1V	3.16	3.18	0.6	1.1
2V	3.87	3.91	1.0	1.5
3V	4.18	4.19	0.2	0.5
4V	4.77	4.79	0.4	1.5
5V	5.66	5.66	0	2.1
6V	7.15	7.15	0	1.6
7V	7.93	7.92	0.1	1.8
1L	1.88	1.86	1.1	0.4
2L	2.54	2.56	0.8	0.5
3L	3.63	3.65	0.6	1.0
4L	4.53	4.54	0.2	1.1
5L	5.55	5.57	0.4	1.5
6L	6.64	6.61	0.5	1.9
7L	7.54	7.61	0.9	2.6
8L	9.38	9.32	0.6	1.3

Figures 8a-f display the lateral AVT mode shapes along the East curbside identified from FDD (red line) and SSI (black line). Overall, a good agreement can be observed between the two methods, which means that the identified results have a relatively high reliability. However, the identified mode shape curves from SSI are typically much smoother than those from FDD. Especially for the 3L mode (Figure 8a), SSI gave much better identified results, without the discontinuity seen in the

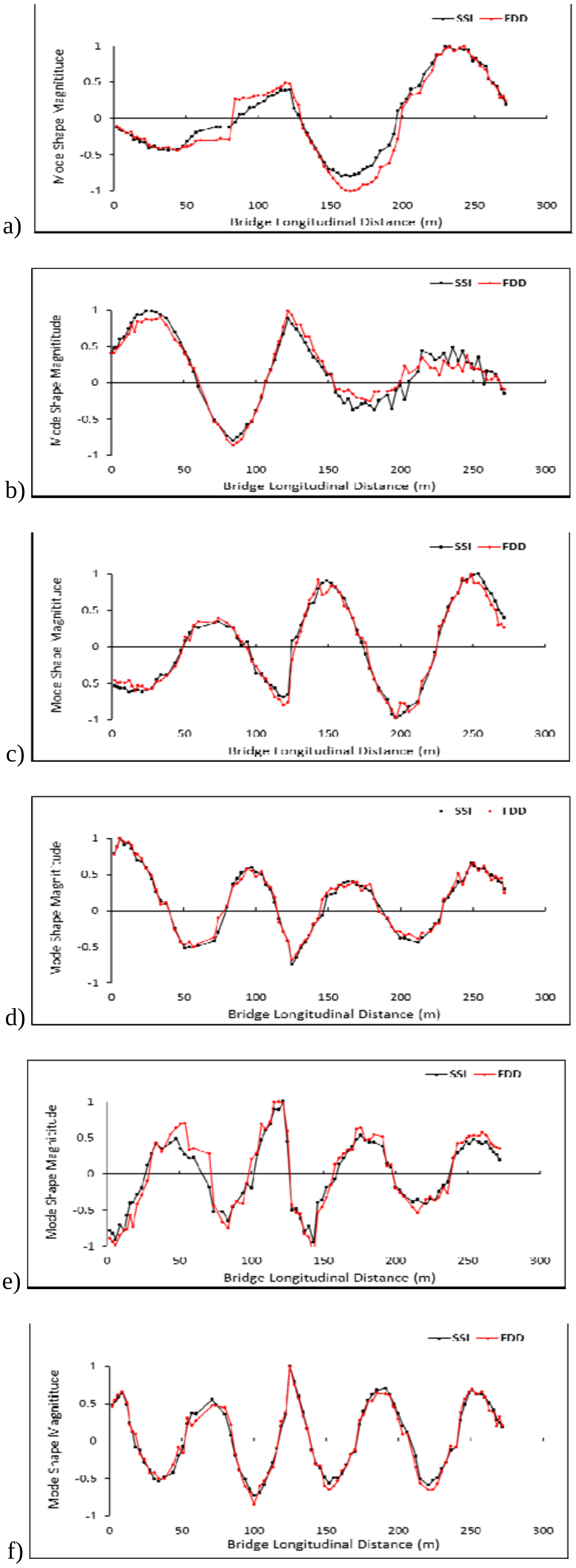


Figure 8. AVT mode shape comparison between FDD and SSI: a) 3L, b) 4L, c) 5L, d) 6L, e) 7L, and f) 8L.

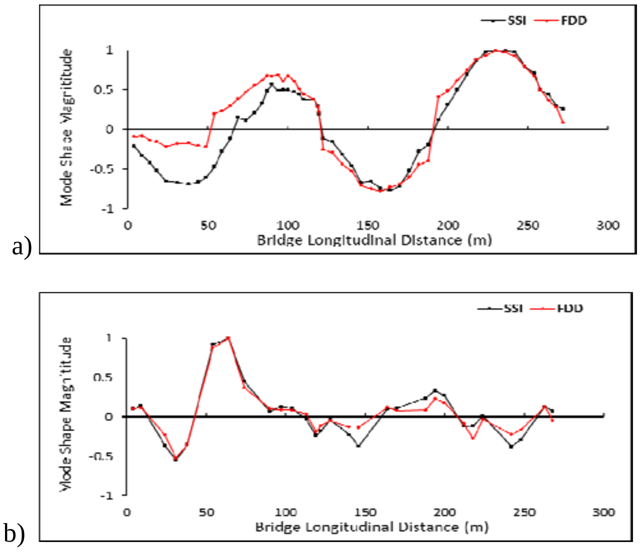


Figure 9. FVT mode shape comparison between FDD and SSI: a) 3L, and b) 5V.

FDD results. It can be concluded that SSI is more robust for dealing with in-situ dynamic testing data contaminated by noise. On the other hand, for FVT both algorithms behaved well and gave consistent mode shape identification results, since the FVT data had a much higher signal-to-noise ratio compared to the AVT data due to the greater excitation force level. Only the 3L and 5L modes from FVT are shown in Figure 9a and b, as these exhibit larger discrepancies. Although some relatively large difference at certain measuring points or longer lengths are noticeable, the whole mode shape curves agree reasonably well.

5.2 *Mode shape comparison between West and East bridge curbside*

Figure 10a-c depicts the identified AVT mode shapes along the East and West curbside using SSI. It can be observed that the East side mode shapes (black color) are smoother that those of the West side (red color). It is hypothesized that this could be because traffic on the neighboring highway caused more electromagnetic disturbance to the sensors on the West side.

5.3 *Comparison between AVT and FVT*

Since AVT and FVT are two alternative techniques to explore the dynamic properties of full-scale structures, it is interesting to compare their results. Observing their results in Table 2 and 3, it can be found the first two lateral bending modes could not be identified from AVT. This was probably because the frequency content of external excitation sources below 3 Hz in the lateral direction is too weak to excite these modes. Alwash et al. [10] also reported that in their testing the resonant response at the fundamental natural frequency could not be distinguished from background vibrations while higher mode responses could be identified when ambient vibrations due to wind and flowing water were recorded without traffic on the bridge. However, modes 1V and 2V could be identified from AVT despite the weak excitation energy. The identified natural frequencies of the corresponding modes from AVT and FVT agree well. Figures 11a-f display the mode shapes comparison between AVT and FVT based on SSI. Overall, a good agreement of mode shapes can be observed and this gives confidence that the identified lateral modes are the true mode shapes of the bridge. However, the curves of mode shapes from FVT are much smoother because large eccentric shaker can produce a clean harmonic input and stronger excitation force maximizing the signal-to-noise ratio.

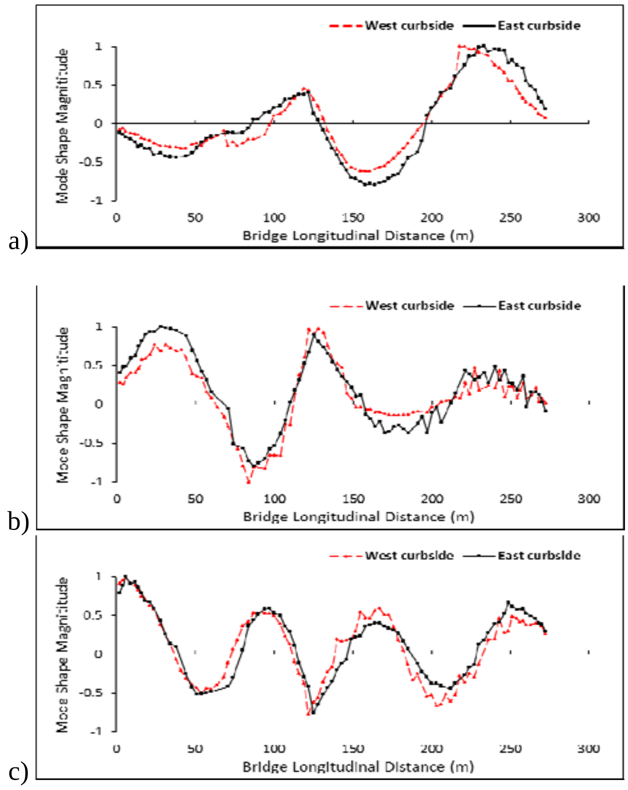
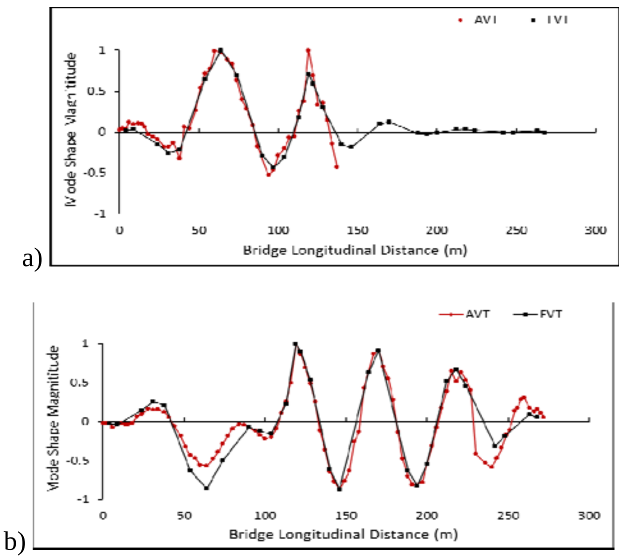


Figure 10. AVT mode shape comparison between West and East curbside: a) 3L, b) 4L, and c) 6L.



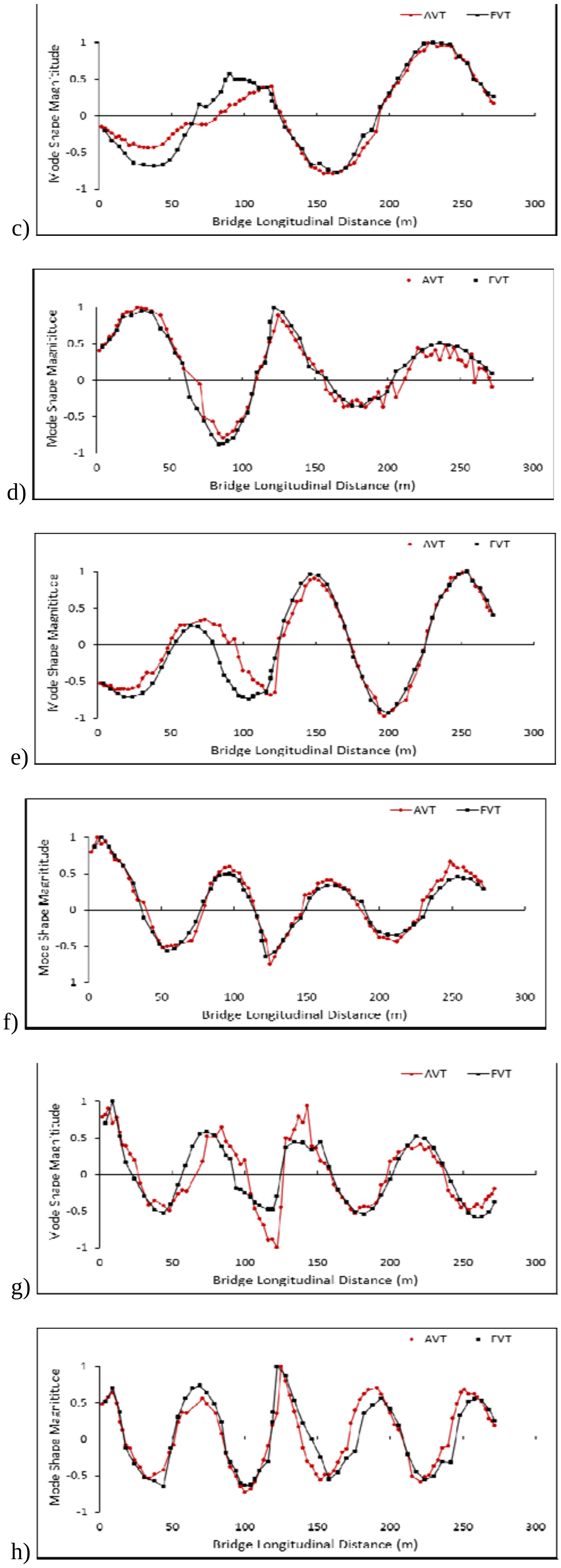


Figure 11. AVT and FVT mode shape comparison: a) 1V, b) 2V, c) 3L, d) 4L, e) 5L, f) 6L, g) 7L, and h) 8L.

Furthermore, it should be noted that it is still rarely reported in the literature to be able to identify with confidence lateral natural modes as high as above 9 Hz without traffic on the bridge when conducting AVT on a continuous concrete bridge. The identification of such a mode was possible most likely because of the external excitation frequency content.

5.4 3D plots of typical identified mode shapes

Based on the identification results from SSI, Figures 12-14 display typical identified full 3D mode shapes from AVT and FVT.

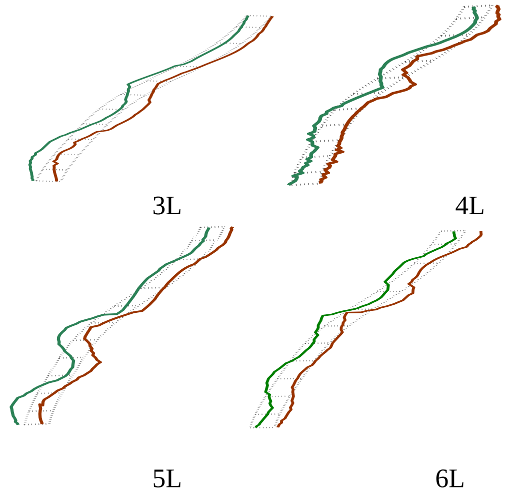


Figure 12. 3D lateral bending mode shapes from AVT.

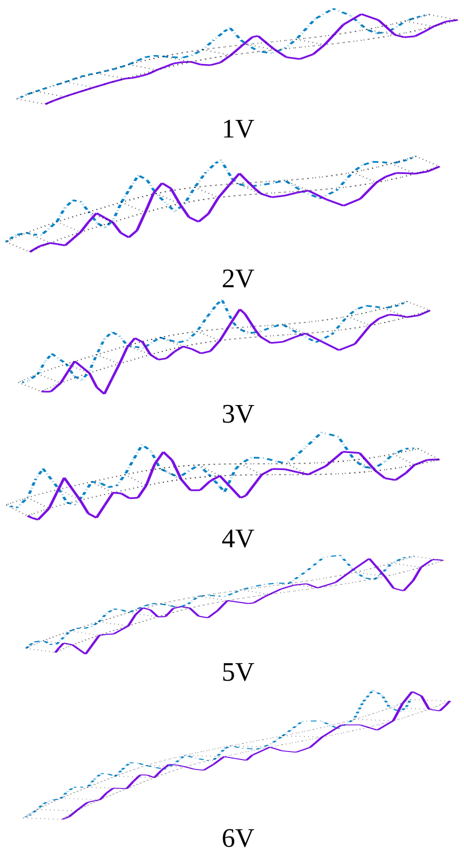


Figure 13. 3D vertical mode shapes from FVT.

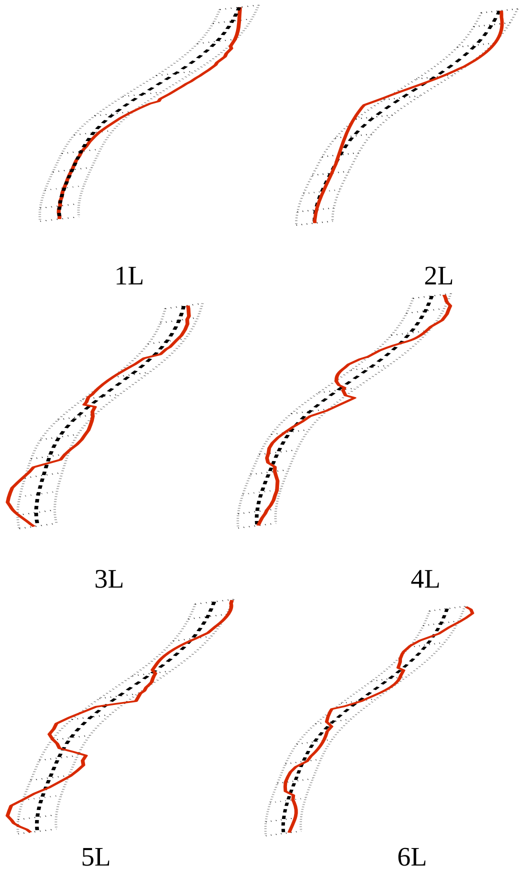


Figure 14. 3D lateral mode shapes from FVT.

6 CONCLUSIONS

Both AVT and FVT have been carried out on an 11-span continuous concrete structure, Nelson St off-ramp bridge. Through the experimental modal identification using the FDD and SSI methods, the most important dynamic characteristics of the bridge, i.e. natural frequencies, damping ratios and mode shapes, were determined from the field testing data. The following observations and comments can be made:

1) FDD and SSI are able to yield mutually consistent natural frequency estimations from both weak ambient excitation force levels and relatively large forced vibration levels.
2) The frequency domain method FDD is relatively more vulnerable to the measurement noise than the time domain SSI method with respect to the estimation of mode shapes.
3) The sensor noise level may have a great impact on the mode shape identification results. A relatively high noise level may distort the identified mode shape results as seen in the comparison between the mode shape estimates close to and far away from traffic.
4) The excitation force level also plays an important role in the mode shape identification quality. FVT was able to produce better mode shape estimations due to the clean harmonic input and stronger excitation force.
5) For relatively short-span, continuous concrete bridges, AVT can be used to acquire satisfactory information on multiple lateral bending modes even without vehicles crossing the bridge. In addition, it is also possible to obtain the lowest vertical bending mode shapes.

6) The identified natural frequencies and mode shapes between AVT and FVT are in agreement.

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