A comparison of operational modal parameter identification methods for a multi-span concrete motorway bridge

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ABSTRACT: Operational modal analysis deals with the estimation of modal parameters using vibration data obtained from unknown or ambient excitation sources in operational rather than laboratory conditions. The paper compares three operational modal parameter identification approaches for identifying modal parameters of a multi-span concrete motorway bridge when subjected to either ambient or broad-band linear chirp excitation. The algorithms examined include the frequency-domains methods, peak picking and frequency domain decomposition, as well as the time-domains method stochastic subspace identification (SSI). The results show that natural frequencies can be identified from either the frequency domain methods or the time domain methods with high accuracy. On the other hand, the damping identification results given by SSI have large scatter. In terms of mode shapes, SSI technique is more robust for dealing with noisy testing data from real-world bridges since it produces smoother vibration mode shape curves.

1 INTRODUCTION

Acquiring the experimental global dynamic properties of civil engineering structures from the collected vibration responses is a necessary step in several types of analysis including, for instance, model updating (Jaishi and Ren 2005), structural health monitoring (Cross et al. 2013), non-destructive damage assessment (Farrar et al. 2001), and vibration mitigation and control (Caetano et al. 2008). Conventional experimental modal analysis methods utilise well established input-output modal identification techniques to accurately identify the main dynamic characteristics of structures. However, this is not generally feasible in civil engineering applications due to safety concerns and the massive size of these structures. On the other hand, operational modal analysis (OMA) aims at utilising only response measurements of the structures in operational condition to identify modal characteristics, and has drawn great attention in civil engineering community with applications for off-shore platforms, buildings, towers, bridges, etc. OMA has many advantages, such as: OMA is cheap and fast to conduct; no elaborate excitation equipment is needed; OMA belongs to the type of multi-input/multi-output method, which makes the closely spaced or even repeated modes identifiable. A number of operational modal parameter identification approaches have been developed and documented in the scientific literature (Maia and Silva 2001; Peeters and De Roeck 2001). Given the current abundance of identification schemes, comparative studies maintain significant interest. Although certain efforts to produce qualitative and quantitative comparisons among different methods, mostly based on numerical simulation data (Yi and Yun 2004), pseudo-experimental data from benchmark structures (Lew et al. 1993), or from data of real-scale bridges (Magalhães et al. 2007), can be mentioned, comparison studies are rarely redundant, providing different insights into various applications and conditions. For instance, the ability of different identification techniques to capture the vibrational signal characteristics in a real noisy measuring environment is still not clear, especially when using different types of excitation sources. Furthermore, the quality of mode shape estimation is generally ignored and not well studied in detail in the previous work due to time restricted testing schedules with a limited spatial resolution of measuring grid on complex large civil structures. Consequently, more efforts need to be made for examining the real performance of different modal parameter identification techniques, especially when facing one of the major challenges from unavoidable measurement noises which sensors are exposed to.

The present paper aims to investigate some of the key points considered by comparative studies in evaluating the performance of different output-only techniques, which includes the estimation accuracy and robustness, algorithmic efficiency, and computational costs. To this end, a large size, 11-span, post-tensioned concrete motorway bridge located in Auckland, New Zealand is selected as the testing structure. The bridge structure characteristics as well as a series of field dynamic testing programs, which comprises measurements from environmental sources, and broad-band linear chirp excitation induced by electro-dynamic shakers, are described. This is followed by a description of a range of system identification approaches that has been utilized as well as listing of the identification results. Finally, a set of conclusions rounds up the paper.

2 THE BRIDGE STRUCURE AND TESTING PROGRAMME

The bridge tested in this research is the Nelson Street off-ramp bridge built in the mid-1970s, and locates on the southern fringe of the Central Business District of Auckland, New Zealand, at a confluence of three major motorways. Figure 1 displays a bird's-eye view of the bridge and the elevation sketch. The bridge has a total length of the 272 m and comprises 11 post-tensioned concrete spans. The main span is 40 m long and the remaining spans vary in length between 18 and 26 m, with the majority of them 24 m long. Ten solid octagonal piers of height between 4.27 and 14.43 m and the maximum width and thickness of 2.85 m and 1.42 m, respectively, provide intermediate supports (refer to Fig. 1b) for pier numbers.

In the first stage-the ambient vibration testing (AVT), the environmental excitation sources, which mainly come from vehicles traveling on the motorway sections adjacent and underneath the bridge, wind, and possible micro tremors, are utilised. A scheme with highly dense measuring stations on the bridge deck was formulated. The distance between two measurement stations over the bridge ranged from 2 m to 4 m. As a result, a total of 188 locations on the bridge deck were measured, and four separate recordings (setups) were required to cover these planned positions along the bridge spans. The sampling rate on site was 160 Hz and the ambient vibration response of the bridge was simultaneously recorded for 20 minutes (refer to Fig. 2a). 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.

At the second stage-the electro-dynamic shaker testing (EDST), two APS Dynamics Model 400 ELECTRO-SEIS® long stroke shakers with APS 0412 Reaction Mass Assembly (Ma et al. 2007) were deployed to excite the bridge. The shaker locations are shown in Figure 1b. The two shakers were synchronised and were able to provide sine excitation force with the peak of 890 N in the range of frequencies from 1 Hz to 12 Hz. The shakers operating in the vertical direction are shown in Figure 2b. Slow linear chirp excitation sweepings are implemented up to 10 Hz within a relative long time window around 60 mins. This excitation protocol allows the structure to vibrate adequately as much as possible at every small frequency increment point within a very narrow frequency sweeping band, which was expected to be capable of exciting the relevant modes in the frequency range of interest. Unlike the AVT, one setup over the bridge deck was scheduled to increase the efficiency of EDST. The sampling rate on site was 80 Hz to reduce the amount of data.

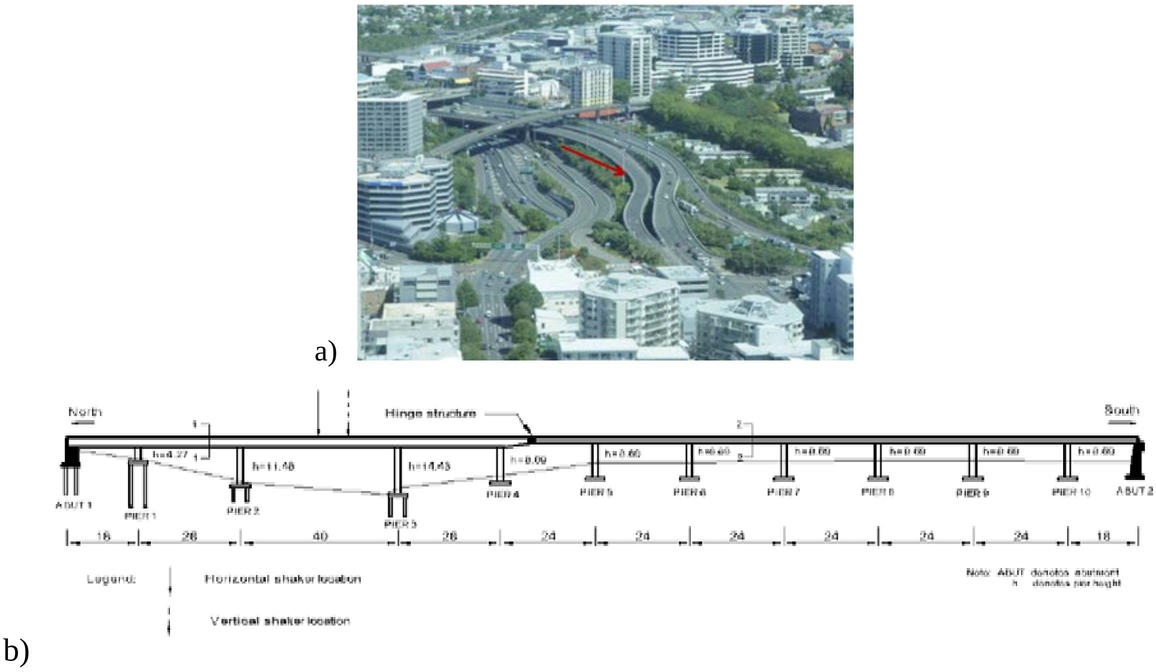


Figure 1. The Nelson St off-ramp bridge: a) Bird's-eye view, and b) Schematic elevation drawing.

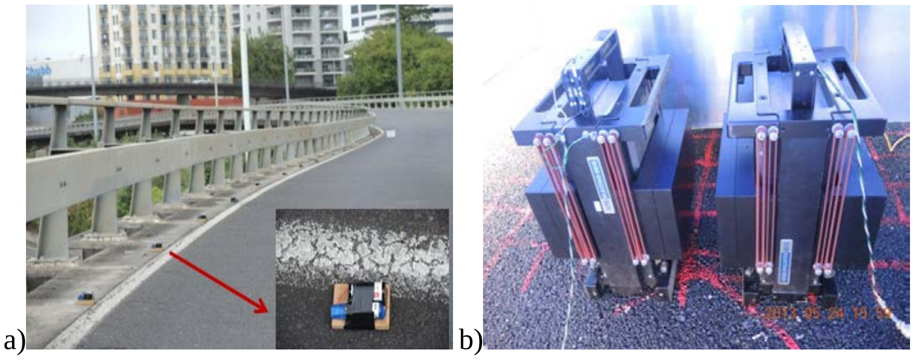


Figure 2. In situ vibration testing: a) Tri-axial MEMS accelerometers recording response in AVT, and b) APS Dynamics shakers exciting the bridge in the vertical configurations.

3 OPERATIONAL MODAL ANALYSIS

In the present work, the frequency domain methods which include the peak picking method (PP) and frequency domain decomposition (FDD), and the time domain method stochastic subspace identification (SSI) are applied for operational modal analysis. The PP identifies natural frequencies by locating maxima in the auto power spectral density function, whereas mode-shape components are then determined by the values of the transfer functions computed for each response measurement point with respect to the reference station at the natural frequencies. In the FDD procedure, the cross power spectral matrix of the output responses is orthogonally decomposed using singular value decomposition (SVD) at all discrete frequencies to obtain the singular value (SV) and singular vector. Modal frequencies can be located by the peaks of the first SV curve of the spectral matrix, which contributes the dominant energy of the structural system. The corresponding mode shapes are estimated using the information contained in the singular vectors of the SVD. In the application of the PP and FDD methods to the investigated bridge structure, the auto-and cross-spectra were calculated based on Welch's method using 38.5 s long segments (1024-point), which resulted in a frequency resolution of 0.026 Hz. Hanning windows with 50% overlap were used in order to reduce the effects of spectral leakage (Maia and Silva 2001).

The SSI algorithms extract a state-space model in the discrete form by using measured data directly. Such models are a good representation of linear-time-invariant structural systems. Once the mathematical description of the state space model is found, the modal parameters can be readily extracted from the corresponding model matrices. Generally, a series of modal parameters are identified from a set of models with different orders, which are then represented in a stabilisation diagram to aid in discriminating spurious modes from the physical modes of vibration. The stabilisation diagram shows frequencies on the horizontal axis and model orders on the vertical axis. The poles corresponding to a certain model order are compared with the poles of a two-order-lower model. Physical modes are identified at the same frequency with increasing model orders forming a vertical line of stable poles. In the present application case, SSI was implemented with a Hankel matrix of size 50 and system orders 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 ±0.1 Hz of the singular value had a change in frequencies within 1%, change in damping within 20% (a looser criterion for damping due to its relative large variability), and the modal assurance criterion value (MAC) (Allemang and Brown 1982) 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. These series of comparisons were continued until all the stable poles in the frequency range of interest had been identified and averaged. To conveniently deal with the large volume of collected acceleration data from the testing, a MATLAB based system identification toolbox was developed at the University of Auckland (Beskhyroun 2011).

4 COMPRASION OF MODAL IDENTIFICATION RESULTS

For AVT, testing in four setups was conducted to cover 188 positions along the bridge spans, and therefore an independent identification was performed with each setup dataset. As a result, every setup yielded independent information about natural frequencies, modal damping coefficients and a part of the mode shapes. The final estimates of the natural frequencies and damping ratios were estimated by averaging the values provided by different setups and the mode shape segments were glued by means of the common reference sensors. Because only one setup over the bridge was implemented in EDST, the obtained modal parameters provide a global estimation.

Table 1 and Table 2 list the identified natural frequencies and damping ratios, where vertical and lateral modes are indicated respectively by symbols V and L and the mode number. The frequency differences among different identification techniques are generally small and have small standard deviations. It is demonstrated that both frequency domain methods PP, FDD and time domain method SSI are able to yield mutually consistent natural frequency estimations from either AVT or EDST, and the testing results of natural frequencies are of high reliability. However, computationally PP is much faster and preferably used on site to quickly judge the overall dynamic characteristics of structures. The damping ratio is identified with SSI and a significant scatter of the modal damping ratio for AVT can be observed via the standard deviation ranging from 0.2% to 0.5%. It is clear that the estimate of this parameter is associated with high uncertainty, possibly due to a combination of factors such as the nonstationarity of the excitation process, effect of different identification algorithms, presence of noise, etc.

Mode shape provides both global as well as more local information for understanding the dynamic behavior of structures compared with natural frequency, and thus it is the indispensable identification component in vibration testing. The corresponding mode shape consistency from different identification algorithms was evaluated with MAC. The mode shapes with a MAC value equal to 1 represent a perfect correlation (i.e. linear dependence), whereas modes which are completely orthogonal (i.e. linearly independent) have a 0 MAC value. MAC are shown in Figure 3 to visually compare the results. It is clearly seen that the correlation between FDD and SSI has the highest MAC values (most of them are above 0.9), which means FDD and SSI yield more mutually similar mode shape estimates than those from PP. Contrary to this, the MAC values of PP/SSI and PP/FDD are rather low in some cases, such for mode V2 shown in Figure 3a, and modes V1, V3, V4, V5, V6 shown in Figure 3b. This observation implies that PP is not able to give good mode shape estimates for some certain modes from dynamic measurements, despite the fact that the tested bridge structure in this study possesses well-separated modes. FDD and SSI are more powerful in accurately extracting the mode shapes, since they employ robust numerical techniques, such as singular value decomposition (separating noisy data from disturbance caused by un-modelled dynamics and measurement noise) and least squares fitting. Observing the MAC between FDD and SSI in Figure 3b, modes V4 and V5 have relatively low MAC values. This indicates that the credibility of these modes identified from vibration tests tend to be weak. The possible explanation for this is that there is not enough external input modal force provided by EDST to strongly excite these modes.

The following comparative analysis is conducted to study the detailed performance of FDD and SSI in terms of mode shapes. For AVT, MAC values based on FDD and SSI for modes L3, L4, L5, L6, L7, L8 are very high (over 0.95) as shown in Figure 3a, which indicate very high correlation of the identified modes. Similarly, for EDST, the MAC values for modes L1 to L8 are also very high (over 0.88). However, it is noted that MAC is a correlation parameter in a global sense. The high density sensor grid on the bridge deck in this research can display more detailed local comparison between the mode shapes identified from different identification techniques. To that end, full views for the identified mode shapes are displayed in Figure 4 for comparing the smoothness of vibration mode shape curve visually. It is noted that for both AVT and EDST, the identified mode shape curves from SSI are typically smoother than those from FDD. Especially for mode L3 mode from AVT, SSI gave much better identified results, without the discontinuity seen in the FDD results. It is demonstrated that SSI is more robust for dealing with in-situ dynamic testing data from weak excitation source measurements. The reason can be that the mode shapes identified by SSI are based on the combination of several stable poles from the approximate system state-space models with different dimensions and therefore provided smoother identification outcomes. However, because the SSI technique normally requires significantly high computational load, which is rather time consuming, it is more appropriate to carry out SSI for detailed analysis to obtain quality mode shapes offsite. The simple nonparametric FDD method, which is less computationally demanding compared to the SSI method, could be beneficial for gaining a first insight into the identification problem so as to guide the setting of the analysis parameters in SSI algorithms.

Table 1. Mean and standard deviations (in parentheses) of natural frequencies and damping ratios identified from AVT.

	AVT			
Mode	**Natural frequency (Hz)**			**Damping ratio (%)**
	PP	**FDD**	**SSI**	**SSI**
V1	3.22(0.02)	3.17(0.01)	3.19(0.01)	1.7(0.4)
V2	3.83(0.01)	3.83(0.01)	3.82(0.01)	0.7(0.2)
L3	3.71(0.05)	3.72(0.03)	3.65(0.06)	2.1(0.5)
L4	4.50(0.04)	4.49(0.03)	4.49(0.02)	2.2(0.3)
L5	5.47(0.02)	5.59(0.04)	5.58(0.04)	2.0(0.4)
L6	6.60(0.03)	6.72(0.04)	6.63(0.04)	2.3(0.4)
L7	7.58(0.05)	7.61(0.04)	7.68(0.03)	2.7(0.3)
L8	9.30(0.05)	9.31(0.05)	9.38(0.03)	1.7(0.3)

Table 2. Identified natural frequencies and damping ratios from EDST.

	EDST			
Mode	Natural frequency (Hz) f_{SSI} (Hz)			Damping ratio (%)
	PP	FDD	SSI	SSI
V1	3.17	3.17	3.17	0.9
V2	3.87	3.87	3.87	1.0
V3	4.18	4.18	4.18	0.7
V4	4.78	4.77	4.73	6.5[a]
V5	5.63	5.63	5.65	3.8[a]
V6	7.15	7.15	7.16	1.0
L1	1.88	1.88	1.85	0.9
L2	2.58	2.58	2.57	1.1
L3	3.63	3.71	3.62	1.1
L4	4.47	4.53	4.50	1.4
L5	5.50	5.50	5.50	1.6
L6	6.72	6.64	6.70	1.4
L7	7.62	7.66	7.67	1.3
L8	9.41	9.38	9.42	0.8

[a] Not reliable estimate; the MAC between FDD and SSI is relatively low.

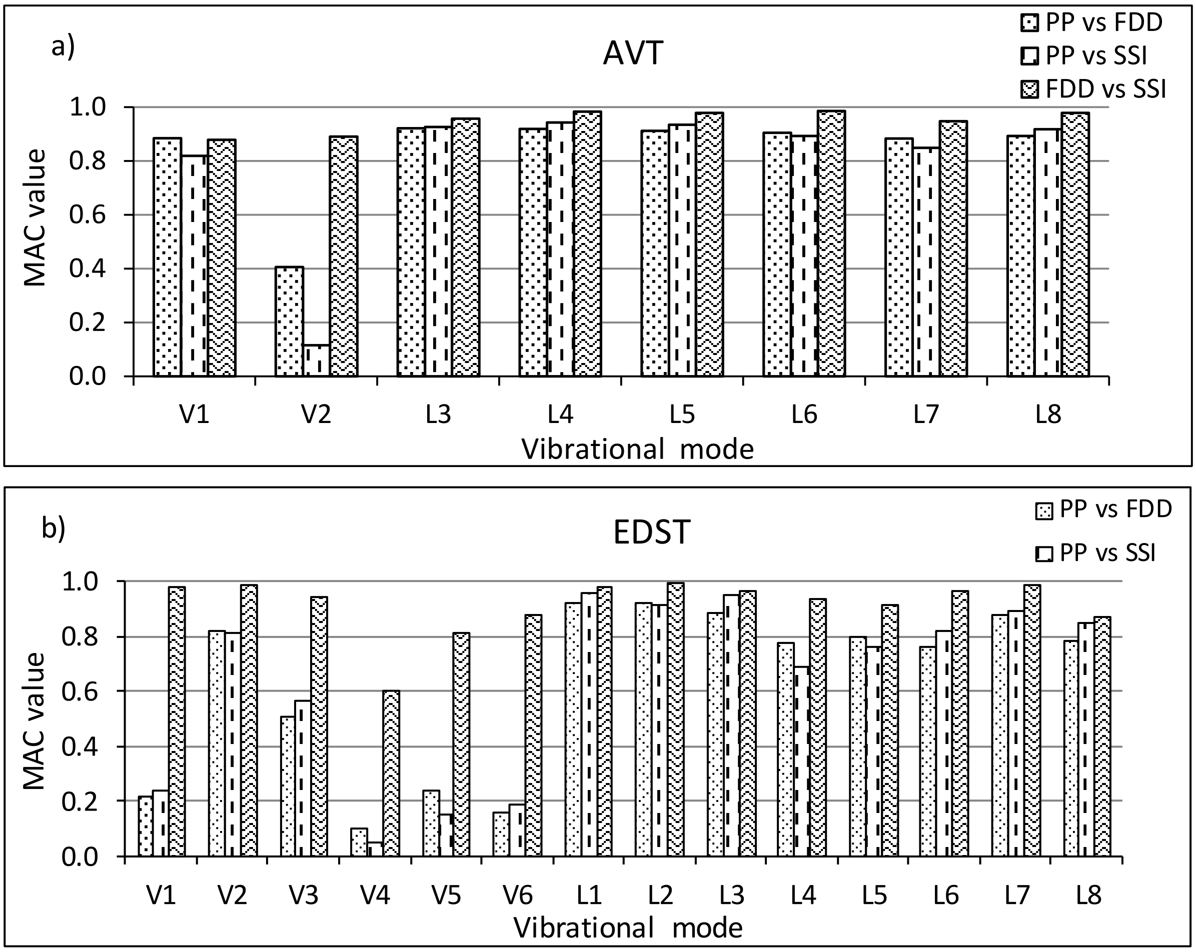
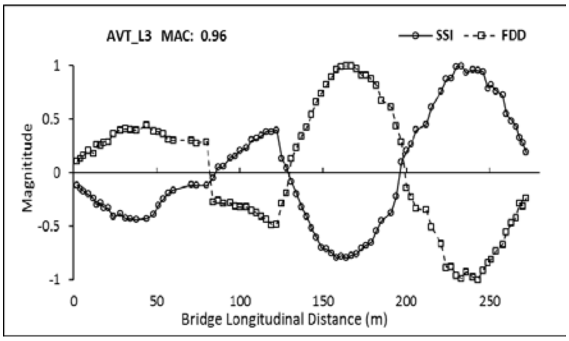
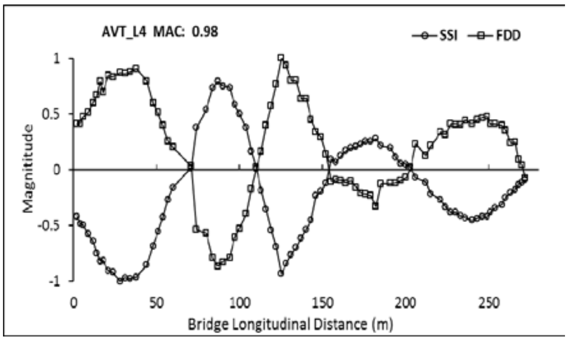
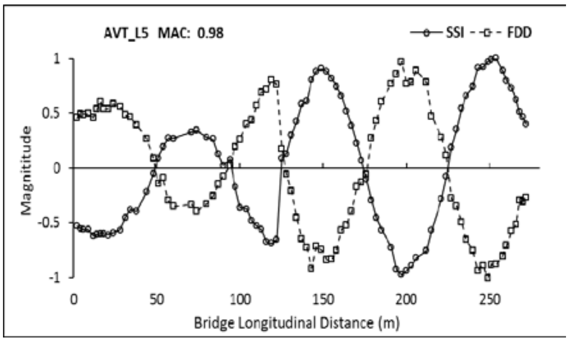
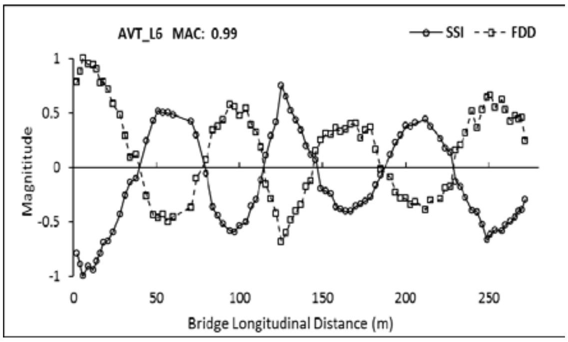


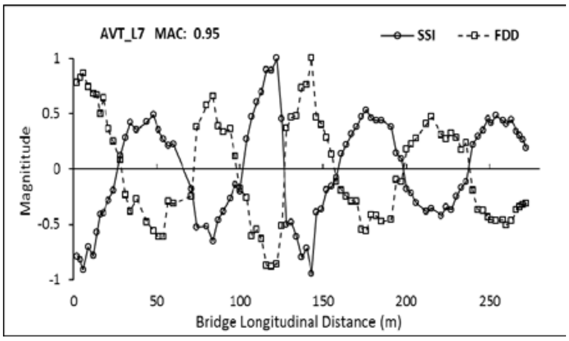
Figure 3. MACs among PP, FDD and SSI: a) AVT, and b) EDST.


AVT_L3 MAC: 0.96
SSI
FDD
Magnititude
1
0.5
0
-0.5
-1
0
50
100
150
200
250
Bridge Longitudinal Distance (m)


AVT_L4 MAC: 0.98
SSI
FDD
Magnititude
1
0.5
0
-0.5
-1
0
50
100
150
200
250
Bridge Longitudinal Distance (m)


AVT_L5 MAC: 0.98
SSI
FDD
Magnititude
1
0.5
0
-0.5
-1
0
50
100
150
200
250
Bridge Longitudinal Distance (m)


AVT_L6 MAC: 0.99
SSI
FDD
Magnititude
1
0.5
0
-0.5
-1
0
50
100
150
200
250
Bridge Longitudinal Distance (m)


AVT_L7 MAC: 0.95
SSI
FDD
Magnititude
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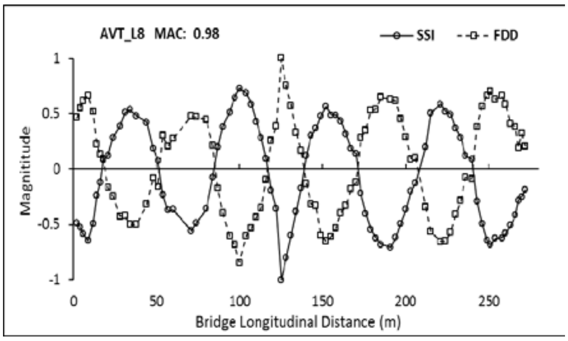
0.5
0
-0.5
-1
0
50
100
150
200
250
Bridge Longitudinal Distance (m)


AVT_L8 MAC: 0.98
SSI
FDD
Magnititude
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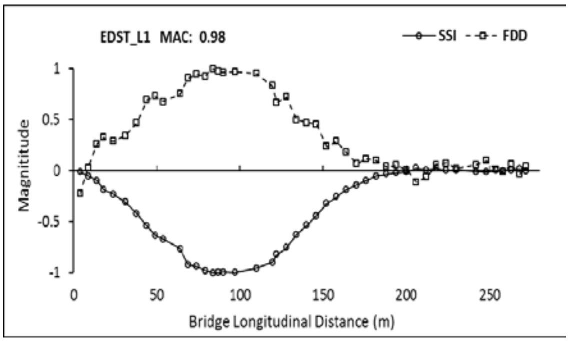
0.5
0
-0.5
-1
0
50
100
150
200
250
Bridge Longitudinal Distance (m)


EDST_L1 MAC: 0.98
SSI
FDD
Magnititude
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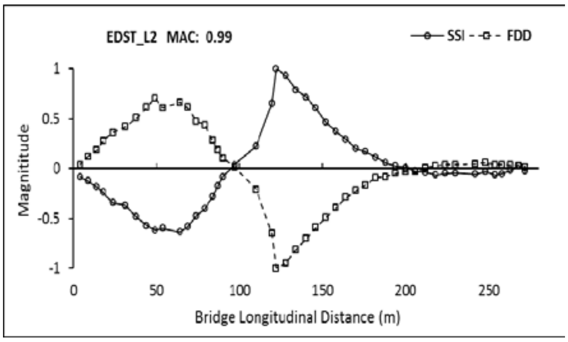
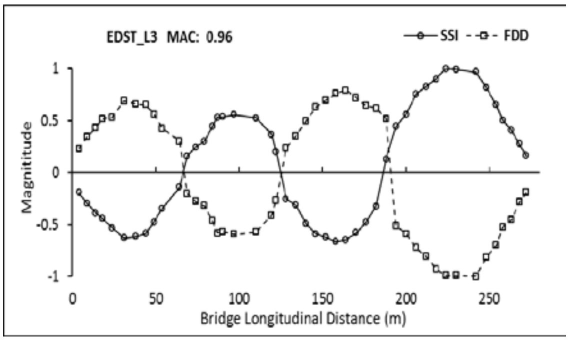
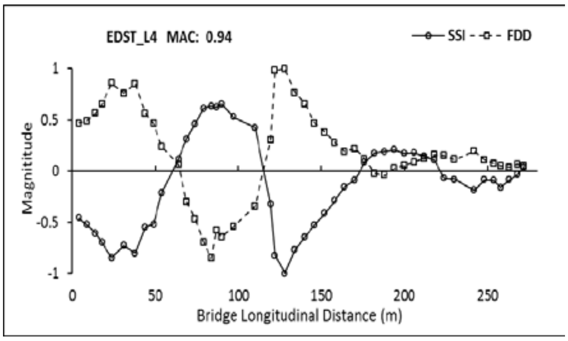
0.5
0
-0.5
-1
0
50
100
150
200
250
Bridge Longitudinal Distance (m)


EDST_L2 MAC: 0.99
SSI
FDD
Magnititude
1
0.5
0
-0.5
-1
0
50
100
150
200
250
Bridge Longitudinal Distance (m)


EDST_L3 MAC: 0.96
SSI
FDD
Magnititude
1
0.5
0
-0.5
-1
0
50
100
150
200
250
Bridge Longitudinal Distance (m)


EDST_L4 MAC: 0.94
SSI
FDD
Magnititude
1
0.5
0
-0.5
-1
0
50
100
150
200
250
Bridge Longitudinal Distance (m)

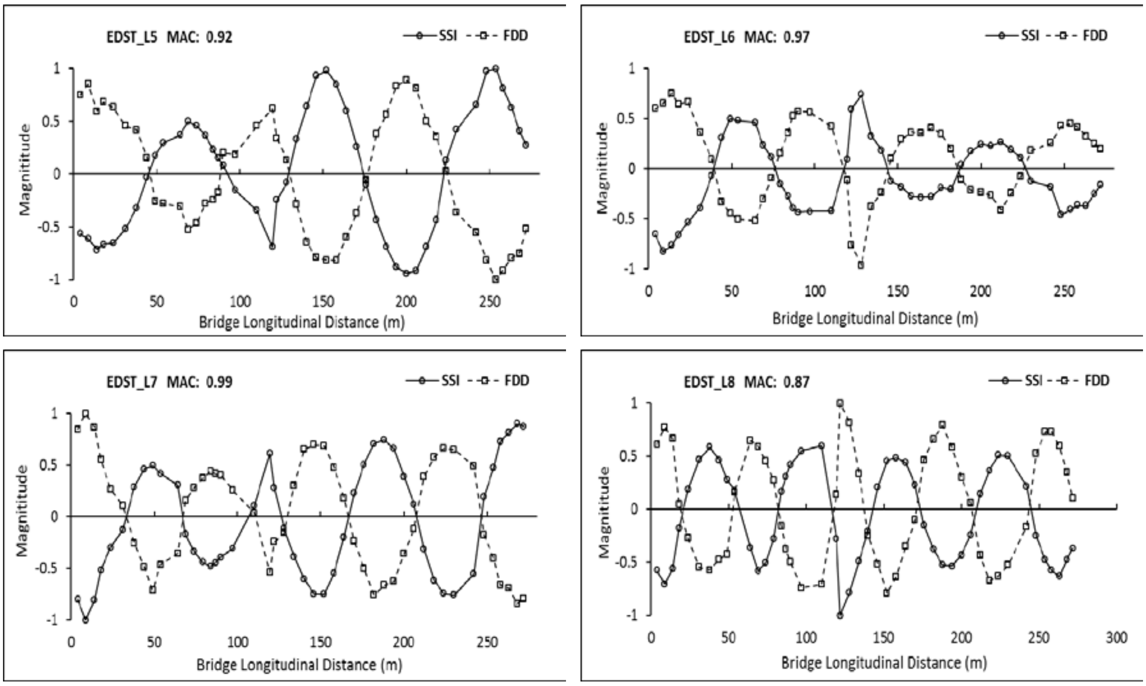


Figure 4. Comparison of full mode shape from AVT and EDST.

5 CONCLUSIONS

The experimental response of a multi-span concrete motorway bridge to either environmental sources or broad-band linear chirp excitation has been used to analyse and compare the performance of three different output-only procedures for modal identification (PP, FDD and SSI). The results show that reliable natural frequency values could be extracted from either the frequency domain methods or the time domain methods and small differences amongst the different modal parameter identification technique exists. The damping ratios identified by SSI in AVT bear relative large uncertainties, since they exhibit a large scatter among each independent setup identification result due to the possibly varying testing environment such as non-stationarity of the excitation process. SSI has better ability to deal with the noisy testing data for mode shape estimation especially in the case of AVT which exert relatively weak vibrational forcing level on the structure. However, SSI consumes much more computational resources as well as needs relatively long calculation time to obtain results.

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