Vibration-based Health Monitoring of Highway Bridge Structures Using Output Only Modal Parameter Estimation Technique

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ABSTRACT

This paper discusses the implementation of a Structural Health Monitoring system for a FRP bridge structure using vibration-based monitoring techniques. The need to monitor the long-term performance of fiber reinforced polymer (FRP) composite bridge structures prompted the installation of a vibration-based structural health monitoring system on a recently-built FRP composite highway bridge in California. Using output-only methods, ambient excitation can be used to excite the structure and the structure can remain in its operational condition during the test. Two frequency domain output-only techniques: Frequency Domain Decomposition (FDD) and Operational Deflection Shape FRF (ODS FRF) method were used in this study. Their comparative strength and weakness were discussed in the context. The modal parameters generated can then be used as input for damage detection algorithms and the change of structural performance can be monitored. The results are made available to the California Department of Transportation via a web-based interface, enabling appropriate action to be authorized prior to onsite inspection.

INTRODUCTION

Modal parameter estimation techniques have been proven to be an important part in Structural Health Monitoring (SHM) systems. Based on measured vibration response, these techniques can be used to estimate the modal parameters of the structure such as natural frequencies and mode shapes. Changes in modal parameters with time usually indicate changes in structural performance and may also reveal the location and severity of potential defects. There are two general categories of modal parameter estimation techniques: the first category is based on forced response of the structure, which means in order to perform the estimation technique successfully, the excitation, as well as the responses of the structure, have to be measured simultaneously. The second category of techniques poses no such requirement and is generally named as output-only or ambient modal parameter estimation techniques. The advantage of output-only techniques in SHM application is evident: No controlled excitation source is needed;

the structure can remain operational during the test and no interruption of service is necessary. However, in this kind of testing, responses are usually small and often contaminated by noise. Further, the loading is unknown and thus the analysis becomes more difficult.

This paper summarized part of the ongoing work conducted at University of California, San Diego in an effort to implement a SHM system on a recently-built FRP composite highway bridge. Permanent instrumentation, including accelerometers, strain gages and linear potentiometers, are installed on the bridge in order to monitor its performance. Collected data are transmitted wireless to a central data server located at UCSD. The analysis of collected data is composed of three steps: 1) Estimation of modal parameters from measured response. 2) Damage detection based on modal parameters. 3) Capacity estimation and correlation with finite element model. In this paper, focus will be placed on the first part.

For highway bridges, ambient excitation is usually the only available type of excitation due to the difficulty of installing excitation devices that can provide enough excitation input to the structure. For the current study, excitation caused by vehicle traveling across the bridge is utilized. Two output-only modal parameter estimation techniques, Frequency Domain Decomposition method and Operation Deflection Shape FRF method, are incorporated in the analysis and evaluated against each other.

THEORETICAL BACKGROUND

Frequency Domain Decomposition (FDD) Technique

First introduced by Brincker et al.(Brincker et al. 2000), Frequency Domain Decomposition (FDD) technique is an extension of classical frequency domain approach - the peak picking method. The essence of FDD technique is to perform a decomposition of the measured system power spectrum density matrix into a set of independent single degree of system (SDOF) responses. A brief review of the theoretical background of FDD technique will be provided below.

For a general multiple input-multiple output system, it can shown that the relationship between the input and output follows the following equation (Bendat and Piersol 1996):

$$\mathbf{G}_{yy} = \mathbf{H}_{\mathbf{xy}}^{'*}\mathbf{G}_{xx}\mathbf{H}_{xy} \qquad \textbf{(1)}$$

where $\mathbf{G}_{xx}$ is the $m \times m$ power spectral density matrix of the input and $\mathbf{G}_{yy}$ is the $n \times n$ power spectral density of the output. $\mathbf{H}_{xy}$ is the $m \times n$ system frequency response function (FRF) matrix. ' denote matrix transpose and * denote complex conjugate. The FRF matrix can be written in partial fraction form (Ewins 2000) :

$$\mathbf{H}_{xy} = \sum_{k=1}^{n} \frac{\mathbf{R}_k}{j\omega - \lambda_k} + \frac{\mathbf{R}_k^*}{j\omega - \lambda_k^*} \qquad \textbf{(2)}$$

where $\mathbf{R}_k$ is the residual matrix for rth mode ($\mathbf{R}_k = \phi_k \gamma_k^{'}$, ϕ_k and γ_k are the mode shape vector and modal participation vector, respectively) and λ_k is the corresponding pole. Assuming the input force spectrum is stationary white noise, i.e., its power spectrum matrix is a constant matrix **C**, then equation (1) becomes

$$\mathbf{G}_{\mathbf{yy}} = \sum_{k=1}^{n}\sum_{s=1}^{n}\left[\frac{\mathbf{R}_k}{j\omega-\lambda_k}+\frac{\mathbf{R}_k^*}{j\omega-\lambda_k^*}\right]\times\mathbf{C}\times\left[\frac{\mathbf{R}_s}{j\omega-\lambda_s}+\frac{\mathbf{R}_s^*}{j\omega-\lambda_s^*}\right] \quad \textbf{(3)}$$

After some mathematical manipulation, it can be shown that

$$\mathbf{G}_{\mathbf{yy}} = \sum_{k=1}^{n}\frac{\mathbf{A}_k}{j\omega-\lambda_k}+\frac{\mathbf{A}_k^*}{j\omega-\lambda_k^*}+\frac{\mathbf{B}_k}{-j\omega-\lambda_k}+\frac{\mathbf{B}_k^*}{-j\omega-\lambda_k^*} \quad \textbf{(4)}$$

Assume damping is light, the $\mathbf{A}_k$ term will become dominating around its pole. Also, the residual $\mathbf{A}_k$ becomes proportional to the mode shape vector

$$\mathbf{A}_k \propto d_k\phi_k\phi_k^{'} \quad \textbf{(5)}$$

At a certain frequency only a limited number of modes will contribute significantly, i.e., we can write the modal decomposition of the response matrix as

$$\mathbf{G}_{\mathbf{yy}} = \sum_{k=Sub(\omega)}\frac{d_k\phi_k\phi_k^{'}}{j\omega-\lambda_k}+\frac{d_k^*\phi_k^*\phi_k^{'*}}{j\omega-\lambda_k^*} \quad \textbf{(6)}$$

where d_k is a scaling constant.

On the other hand, the estimated output power spectral density matrix can be written as

$$\mathbf{G}_{yy}(\omega) = \begin{bmatrix} G_{y_1y_1}(\omega) & G_{y_1y_2}(\omega) & \cdots & G_{y_1y_n}(\omega) \\ G_{y_2y_1}(\omega) & G_{y_2y_2}(\omega) & & \vdots \\ \vdots & & \ddots & \\ G_{y_ny_1}(\omega) & \cdots & & G_{y_ny_n}(\omega) \end{bmatrix} \quad \textbf{(7)}$$

at each discrete frequency ω. A singular value decomposition can then be performed on the PSD matrix at each frequency

$$\mathbf{G}_{yy}(\omega) = \mathbf{U}(\omega)\mathbf{S}(\omega)\mathbf{V}(\omega) \quad \textbf{(8)}$$

Around natural frequencies of the system, if only one mode is dominating, there will only be one term in equation (6). And thus the first singular vector in $\mathbf{U}(\omega)$ is an estimate of the mode shape and the corresponding singular value corresponds to PSD of the corresponding SDOF system.

Operational Deflection Shape FRF Technique

Operational Deflection Shape (ODS) is defined as the deflection of a structure at a particular frequency. An ODS Frequency Response Function (ODS FRF) is formed by combining the Auto Power Spectrum (APS) of a roving response with the phase of the Cross Power Spectrum (XPS) between the roving response and a fixed reference response (Schwarz and Richardson 2001). The ODS FRF contains the correct magnitude of response (from the APS) and correct phase relationship to the reference response (from the XPS).

For a single degree of freedom system, an FRF is defined as the ratio of the Fourier transform of the response over the Fourier transform of the excitation,

$$H(\omega) = \frac{X(\omega)}{F(\omega)} \quad \textbf{(9)}$$

The squared magnitude of the FRF can then be written as

$$\left|H(\omega)\right|^2 = \frac{X(\omega)X^*(\omega)}{F(\omega)F^*(\omega)} \quad \textbf{(10)}$$

If the input excitation is a white noise, then the APS of the input $F(\omega)F^*(\omega)$ becomes a constant. The squared magnitude of the FRF is then equal to the APS of the response, except for a scale factor. Based on these relationships, traditional curve fitting methods such as the poly-reference polynomial method and the complex exponential method can be applied to the ODS FRF in order to get modal frequencies and mode shapes. Modal parameter estimation based on ODS FRF method is implemented in the software package ME'scopeVES (Vibrant Technology 2001).

Parameter estimation technique based on forced or ODS FRF generally involve the following steps: 1) Estimate the number of modes in the given frequency region using indicators such as modal peaks function, which are generated using the Averaged Normalized Power Spectrum Density (ANPSD) between the given frequency limits. 2) Estimate frequency and damping of the identified modes. 3) Calculate residuals for the identified modes.

AMBIENT VIBRATION MONITORING

Description of the Bridge and the Health Monitoring System

The Kings Stormwater Channel Composite Bridge is a two-span highway bridge with a total length of approximately 20.1 m and a width of approximately 13.0 m. It carries two north-bound lanes on state highway 86 in Riverside County, California. The bridge crosses a small storm water drainage where storm water from mountains drains into a lake. The superstructure is of slab-on-girder type, with two equal spans of 10.0 m, and a cap beam connecting two adjoining spans. Five precast prestressed concrete piles 343 mm in diameter support the cap beam from the river bed, as shown in Figure 1. Abutments on both ends separate the bridge from the road approach.

A long-term Structural Health Monitoring System was designed and installed on the bridge shortly after it was open to traffic. The primary purpose of the system is to monitor the performance changes of the structure, both due to environmental effect and vehicular loading, and to provide early warning of conditions that might be unsafe to the public. The system also serves the purpose for rapid condition evaluation of the structure after major events such as earthquakes and floods.

A total of 63 ICSensors Model 3140 single axis accelerometers with a dynamic range of ± 2g, a sensitivity of 1 V/g and a usable frequency response of 0-200 Hz were installed on the bridge. Accelerometers were installed in protective housings attached to the bottom of the deck. Accelerometers themselves are mounted by screws on metal mounting blocks that are glued to the bottom of the deck using high-strength epoxy. Signal cables leading to the accelerometers are protected by steel conduits that are also mounted to the bottom of the deck using epoxy. The mounting locations of accelerometers are carefully selected to form an evenly distributed 7-by-6 measurement grid, 7 in the bridge longitudinal direction and 6 in the bridge transverse direction, as shown in Figure 1. In half of the protective housings, two accelerometers were mounted to the same mounting block, one in vertical direction, and the other in horizontal direction. These are used to measure the vertical and horizontal vibration of the bridge correspondingly.

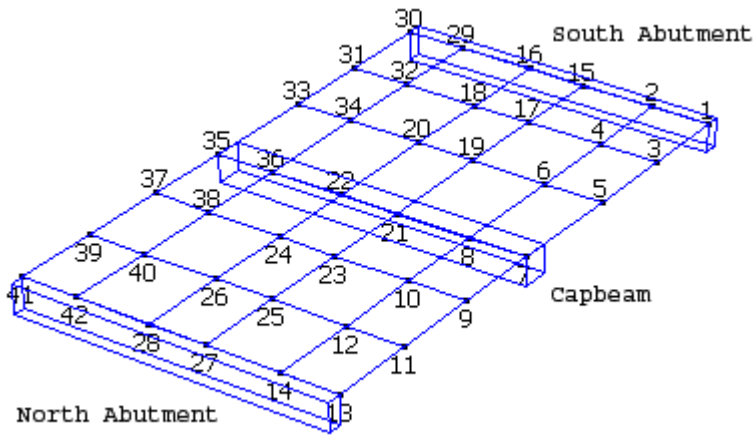


Figure 1 Accelerometer Locations

Output Only Modal Parameter Estimation

A typical acceleration time-history recorded by the Health Monitoring System was shown in Figure 2. The time-history was recorded at 200 Hz sample rate and had a total of 10000 records. This gave a total record length of 50 seconds. It is clear that the response is heavily non-stationary, which indicates the input is very likely also non-stationary.

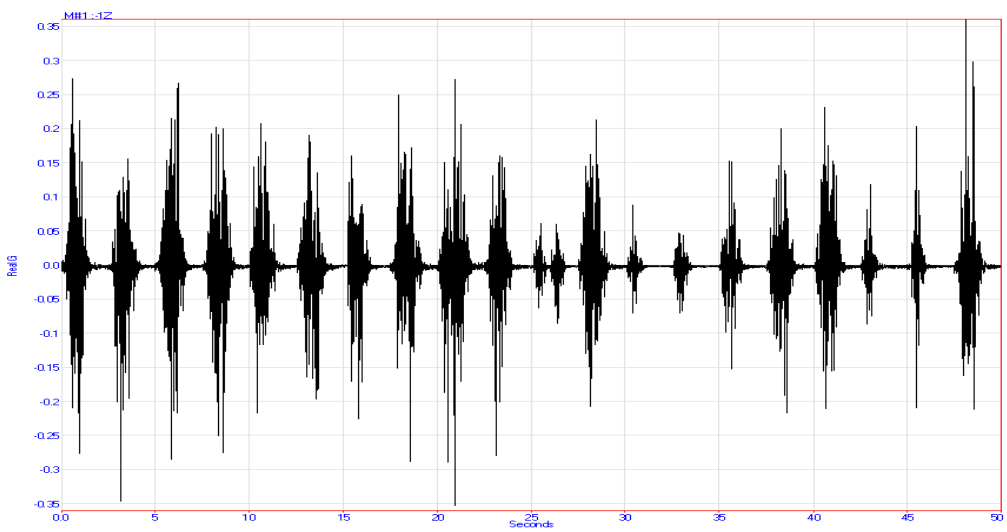


Figure 2 Typical Acceleration Time History

Figure 3 shows the singular values calculated using FDD method. The largest singular values are shown by the top line in the graph. There are two peaks easily discernable in the 8-12 Hz region on the plot of largest singular value, one at 9.96 Hz, the other at 11.52 Hz. This correlate well with the conclusion from a previous study that the structure has two modes in the 8-12 Hz region (Guan et al. 2004).

A typical ODS FRF traces was shown in Figure 4 in a Bode diagram. The magnitude plot shows two peaks at approximately 10 Hz and 11.7 Hz, respectively. The modal peaks function, shown

in Figure 5(a), however, showed three peaks in the given region. Both the first and second peaks are incorrectly identified or located. This is caused by the inherent limitations of the identification algorithm and can be compensated by using smoothed ODS FRF measurement, shown in Figure 5(b). The data did not avail itself for easy interpretation using traditional FRF curve fitting methods such as the polynomial method due to insufficient number of data points around the resonant peak region. A SDOF estimation was used instead to calculate the mode shapes and natural frequencies. Figure 6 illustrates the 1st and 2nd mode shape calculated by both FDD method and ODS FRF method.

No damping values were generated from either method. Again, this is due to the fact there were insufficient number of points around resonant peak region to support reliable damping estimate.

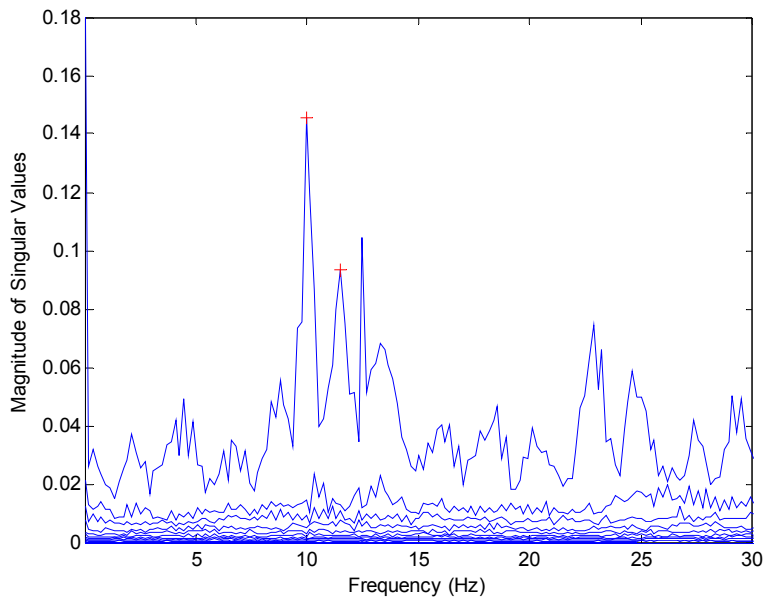


Figure 3 Singular Values – FDD Method

Table 1 Natural Frequencies from FDD and ODS FRF Methods (Unit: Hz)

	FDD	ODS FRF	ODS FRF (Smmothed)
Mode 1	9.96	10.4	9.96
Mode 2	11.52	11.6	11.5

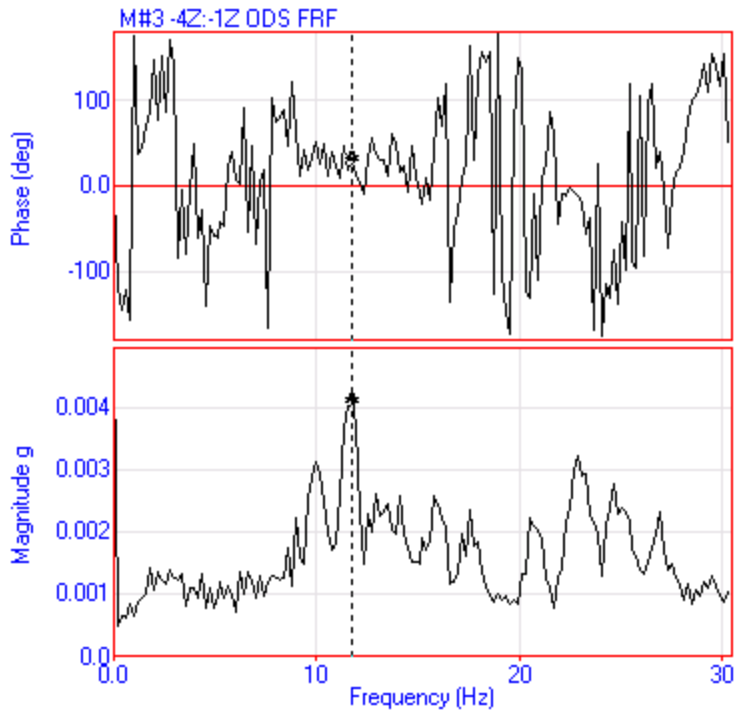
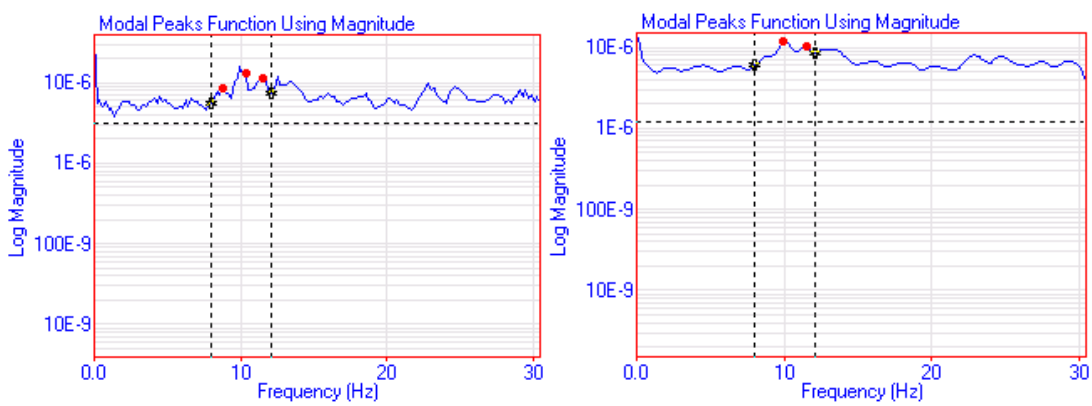


Figure 4 Typical ODS FRF Trace

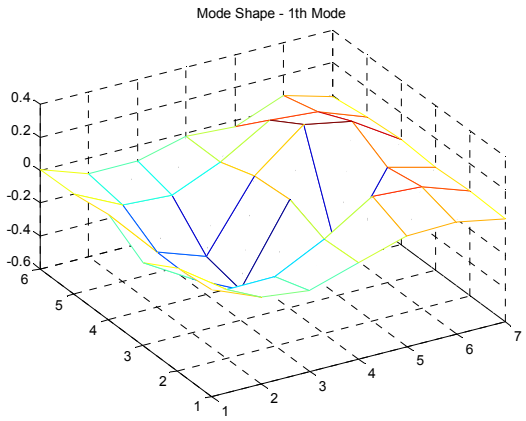


(a)Original (b)Smoothed

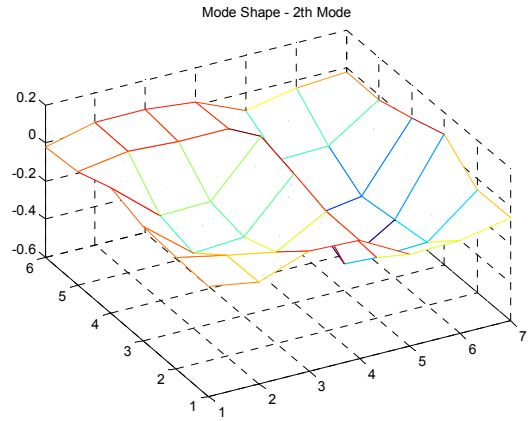
Figure 5 Modal Peaks Function

CONCLUSIONS

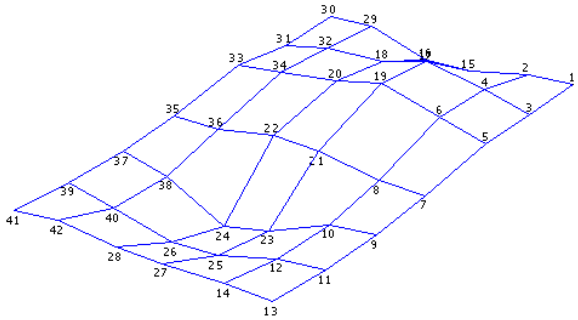
Two output-only modal parameter estimation techniques were used to retrieve modal information from heavily non-stationary ambient vibration response data sets. Both methods performed relatively well. FDD technique performed better in estimating the number of modes and natural frequencies with both parameters easily obtained. ODS FRF technique incorrectly identified number of the modes using the original data set but a smoothing operation generated acceptable results. The mode shapes from two methods show good agreement as well. Use of FDD technique in ambient vibration modal analysis to first identify the number of modes and their natural frequencies is thus recommended. After the number of modes is correctly identified, the rest of modal parameter estimation process can be carried out using ODS FRF technique.



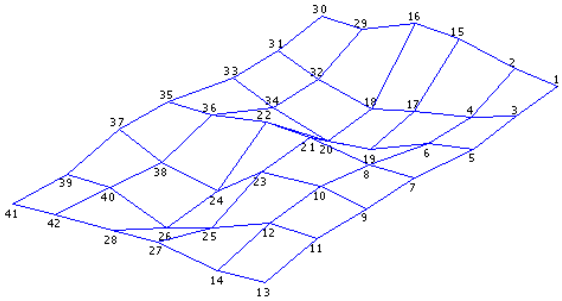
Mode 1 – FDD Method



Mode 2 – FDD Method



Mode 1 – ODS FRF Method



Mode 2 – ODS FRF Method

Figure 5 Mode Shapes – FDD Method and ODS FRF Method

REFERENCES

Bendat, J. S., and Piersol, A. G. (1996). *Random Data: Analysis and Measurement Procedures*, John Wiley & Sons.

Brincker, R., Zhang, L., and Anderson, P. "Output-Only Modal Analysis by Frequency Domain Decomposition." *International Seminar on Modal Analysis (ISMA 25)*, Katholieke Universiteit Leuven, Belgium.

Ewins, D. J. (2000). *Modal Testing: theory, practice and application*, Research Studies Press, LTD.

Guan, H., Karbhari, V. M., and Sikorsky, C. S. (2004). "Web-Based Structural Health Monitoring of a FRP Composite Bridge." *Computer-Aided Civil and Infrastructure Engineering (In Press, 2006)*.

Schwarz, B., and Richardson, M. "Modal Parameter Estimation From Ambient Response Data." *Proceedings of the 19th International Modal Analysis Conference*, Kissimmee, Florida.

Vibrant Technology, I. (2001). *ME'scopeVES Opearting Manual*, Vibrant Technology, Inc., Jamestown, CA.