MODAL IDENTIFICATION OF BILL EMERSON BRIDGE

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ABSTRACT :
The Bill Emerson Memorial Bridge is well known as it has been used worldwide as the Benchmark model for the structural control problem of cable-stayed bridges under seismic excitation. In addition, this bridge has also been used for structural health monitoring studies. 83 sensors were installed on the bridge and surrounding soil to monitor the action of the bridge after construction. This paper presents the modal identification of the bridge based on experimental data. The Eigensystem Realization Algorithm (ERA) in conjunction with the Natural Excitation Technique (NexT) is employed to analyze the ambient vibration records from sixteen of the eighty-three channels of acceleration from the bridge. To validate the modal identification results, estimated modal parameters are compared to those from the finite element model of the bridge and the identification results from other researchers.

KEYWORDS:
NExT, ERA, modal identification, Bill Emerson Memorial Bridge, cable-stayed bridges

1. INTRODUCTION

Large flexible structures such as cable-stayed bridges play an important role in modern life by serving as the main connectors of transportation networks. One of the main challenges of system identification of cable-stayed bridges is how correctly understand and assess their dynamic response external excitations such as traffic, wind and earthquakes. Investigation of any dynamic response of cable-stayed bridges is dependent on the knowledge of the structure's dynamic characteristics, such as modal frequencies, mode shapes and modal damping values. The techniques required to determine these parameters are well known as modal identification methods.

Modal identification methods can be categorized as deterministic and stochastic system identifications depending on the use of input information. The deterministic system identification employs the input-output relation to estimate the system typically in the state-space representation. However, input excitation is not available under many conditions, which restricts the application of input based identification techniques. A more practical approach to determine dynamic characteristics of structures is through ambient vibration measurements. The ambient response of a structure under unknown input excitations (i.e. under working conditions) can be measured by means of highly sensitive velocity or acceleration sensors. The rapid development of sensors and computer technology enables us to carry out dynamic measurement of ambient structural vibrations and the evaluation of these signals quickly. The dynamic characteristics extracted from vibration signals are not only used to check numerical models at a point in time, but have the potential to be used to keep track of the load-bearing capacity of the bridge over time.

In this paper the Eigensystem Realization Algorithm (ERA) (Juang and Pappa 1985) in conjunction with Natural Excitation Technique (NExT) (James et al. 1992; James et al. 1993), one of the most popular stochastic system identification approach, is employed for the modal identification of the Bill Emerson Bridge. The Emerson Bridge is a well known cable-stayed bridge as it has served as the Benchmark on structural control of cable-stayed bridges under seismic excitation (Dyke et al. 2003) as well as structural health monitoring (Caicedo 2003). A total of 83 sensors were installed on the bridge and surrounding soil, providing acceleration responses. To validate the modal identification results, estimated modal parameters are compared to those from the finite element model of the bridge and the identification results from other researchers. Seven vertical vibration modes below 1 Hz are identified and validated.

2. Bill Emerson Bridge Description

2.1 Introduction to Bill Emerson Bridge

The Bill Emerson Memorial Bridge (shown as Figure 1) is a cable stayed bridge crossing the Mississippi River in Cape Girardeau, Missouri, USA and was opened to public in 2003. The bridge has a total length of 1205.8 m (3956 ft). The main span of the cable-stayed section is 350.6 m (1150 ft) and the side spans are 142.7 m (468 ft). The main bridge has two towers and 128 cables made of high-strength, low-relaxation steel. Twelve additional piers are used to support the Illinois side.

The structure has been permanently instrumented with acceleration sensors distributed along the structure and surrounding soil. A total of 66 accelerometers have been installed in the bridge. Out of them 23 are vertical sensors, 11 are horizontal sensors and 22 are oriented in the transverse direction. The 16 vertical sensors located at the two sides of the bent are as shown in Figure1, and the detailed sensor information can be found in Çelebi (2006).

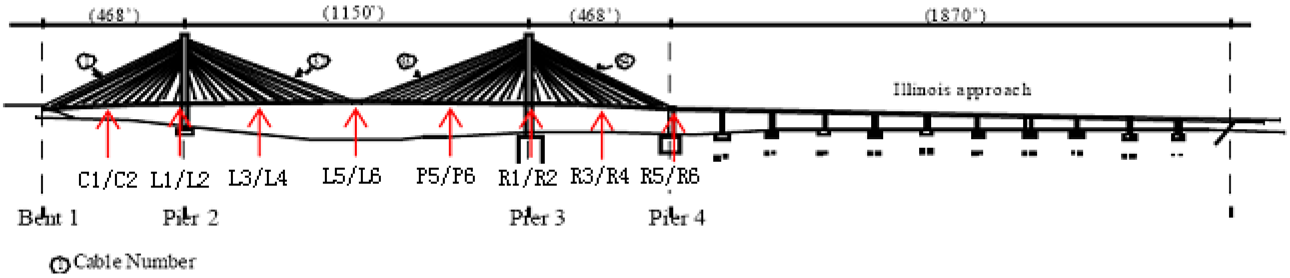


Figure 1 Drawing of the Bill Emerson Bridge(Arrows denote the sensors)

2.2 Analytical Finite Element Model of the Bridge

A finite element model (FEM) of the Emerson Bridge was constructed in Matlab. The model is shown in Figure 2 and has a total of 579 nodes, 420 rigid links, 162 beam elements, 134 nodal masses and 128 cable elements. The towers are modeled using 50 nodes, 43 beam elements and 74 rigid links. Constraints are applied to restrict the deck from moving laterally at piers 2, 3 and 4. Boundary conditions restrict the motion at bent 1 to allow longitudinal displacement (X) and rotations about the Y and Z axes. The cables are modeled with truss elements. In the FEM the nominal tension is assigned to each cable. Cable-stayed bridges exhibit nonlinear behavior due to variations of the catenary shape of the inclined cables, cable tensions that induce compression forces in the deck and towers, and large displacements. The catenary shape and its variation with the axial force in the cable are modeled using an equivalent elastic modulus (Ernst 1965). The detailed model information can be found in

Caicedo (2003). The analytical dominant vibration frequencies of the deck and the corresponding mode shapes will be shown later.

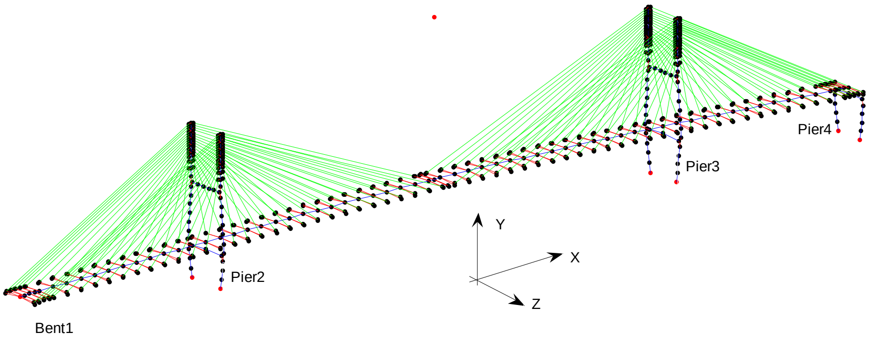


Figure 2 Finite Element Model of Bill Emerson Bridge

3. NExT/ERA

As mentioned previously, the modal identification method used in this study is the combination of NExT and ERA. The NExT is based on the fact that the correlation function satisfies the equation of motion for free vibration. Thus, the correlation functions of responses under the unknown input can be used as the input of ERA to estimate the modal parameters. This is performed by creating a Hankel matrix of the free response data, performing a singular value decomposition of the Hankel matrix to obtain the highest ranking characteristic values of the system and building a state space system whereby modal parameters of a structure can be identified.

The equation of motion for a structure with *n* degrees of freedom can be expressed as:

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=F(t) \tag{3.1}$$

where ***M***, ***C*** and ***K*** are the *n* by *n* mass, damping and stiffness matrices, respectively; *F* is the *n* by 1 forcing vector, **x** is the vector of displacement. Assuming that the excitation is not correlated with the outputs (Caicedo 2006),

$$M\ddot{R}_{\ddot{x}\ddot{x}_i}(\tau)+C\dot{R}_{\ddot{x}\ddot{x}_i}(\tau)+KR_{\ddot{x}\ddot{x}_i}(\tau)=0 \tag{3.2}$$

where $R_{\ddot{x}\ddot{x}_i}(\tau)$ is the vector of cross correlations between the vector of accelerations $\ddot{x}$ and the reference acceleration $\ddot{x}_i$. Eq. (3.2) shows that the cross correlation function is a solution of the homogeneous differential equation of motion and therefore will have the same properties as a free response signal of the structure.

The ERA is then used to realize the system using the cross-correlation vectors previously obtained. A time-invariant system can be described by the discrete state space equations

$$\begin{aligned} x(k+1) &= Ax(k)+Bu(k) \\ y(k) &= Cx(k)+Du(k) \end{aligned} \tag{3.3}$$

where the matrices **A**, **B**, **C** and **D** are the system matrices, **y** is the vector of outputs and x is the state vector at the *k*-th step. From Juang and Pappa (1986), the matrix **A** can be calculated using Eq. (3.4).

$$A=\sum^{-1/2}R^T H(1)S\sum^{-1/2} \tag{3.4}$$

where **Σ** is a diagonal matrix of singular values, R and S are orthonormal matrices obtained from a singular value decomposition of the Hankel matrix such that $H(0)=R\sum S^T$. The Hankel matrix $H(j)$ is formed from the cross correlation records as

$$H(j)=\begin{bmatrix} R_{\ddot{x}\ddot{x}_j}(j) & R_{\ddot{x}\ddot{x}_j}(j+1) & \cdots & R_{\ddot{x}\ddot{x}_j}(p+j) \\ R_{\ddot{x}\ddot{x}_j}(j+1) & R_{\ddot{x}\ddot{x}_j}(j+2) & & R_{\ddot{x}\ddot{x}_j}(p+j+1) \\ \vdots & & \ddots & \\ R_{\ddot{x}\ddot{x}_j}(j+q) & R_{\ddot{x}\ddot{x}_j}(j+q+1) & & R_{\ddot{x}\ddot{x}_j}(p+j+q) \end{bmatrix} \tag{3.5}$$

where p and q are the number of columns and rows of the Hankel matrix respectively. Similarly, it can be shown that the matrix **C** corresponds to the first m columns of the observability matrix calculated as

$$O_q = R\sum{}^{1/2} = \begin{bmatrix} C & CA & \cdots & CA^{q-1} \end{bmatrix}^T \tag{3.6}$$

where m is the number of outputs of the system. The natural frequencies and damping ratios of the structure can be calculated from the eigenvalues of **A**, and the output shapes can be calculated as $\Phi_{id} = C\Phi$, where Φ is the vector of eigenvectors of **A** and Φ_{id} is the matrix of identified mode shapes. The matrix Φ_{id} will have as many rows as sensors are in the structure and as many columns as modes are identified. The coordinate of the mode shape is identified at the location of the sensor.

4. Performance of the NExT/ERA to Bill Emerson Bridge

The NExT/ERA previously described is applied to identify the dynamic characteristics of the Bill Emerson Bridge. In previous studies, Song et al. (2006) applied ARMAV method to detect the natural frequencies and mode shapes of the Emerson Bridge using sixteen channels of acceleration data on the two sides of deck; and Caicedo et al. employed the NExT/ERA to conduct modal identification of the Bridge by using six hours of twenty five channels of acceleration data from the sensors located in the deck and towers. The indentification results of the two works match each other not very well to some degree. In this paper, several refinements were made to the NExT/ERA processes of the Bill Emerson Bridge by using sixteen channels of acceleration data at the two sides of the deck in order to further investigate the modal properties of the Emerson Bridge. To apply the NExT/ERA, the following four issues are considered.

Frequency range:
Based on the power spectra of the measured acceleration, the frequency range used in the subsequent system identification is selected up to 1 Hz. Because the sampling frequency of the original acceleration is 200 Hz, a low pass filter with a cutoff frequency of 1 Hz is applied, and then the filtered accelerations are resampled to obtain better resolution of the cross spectra in the frequency domain.

Reference channel:
Channel R3 is selected as the reference channel, considering that the reference should not be located at the node of a mode.

True mode:
In most cases, the identified system contains noise modes as well as true modes. To distinguish the true modes from the noise modes, the damping factor and modal assurance criterion (MAC) are considered. Because the cable-stayed bridges are generally lightly damped, an identified mode with a damping factor greater than 5% is considered as a noise mode. In addition, the cutoff value for the MAC is selected as 0.9 so that any identified mode with a MAC less than 0.9 is discarded.

5. MODAL IDENTIFICATION OF THE EMERSON BRIDGE

5.1 Estimated Dynamic Properties from PSD Analysis

Since most of the interesting dynamic responses of the bridge were associated with motions of the deck, then the vertical ambient vibration signals of the deck were collected. Figure 3 shows part of the recorded acceleration signals along the deck in the vertical direction.

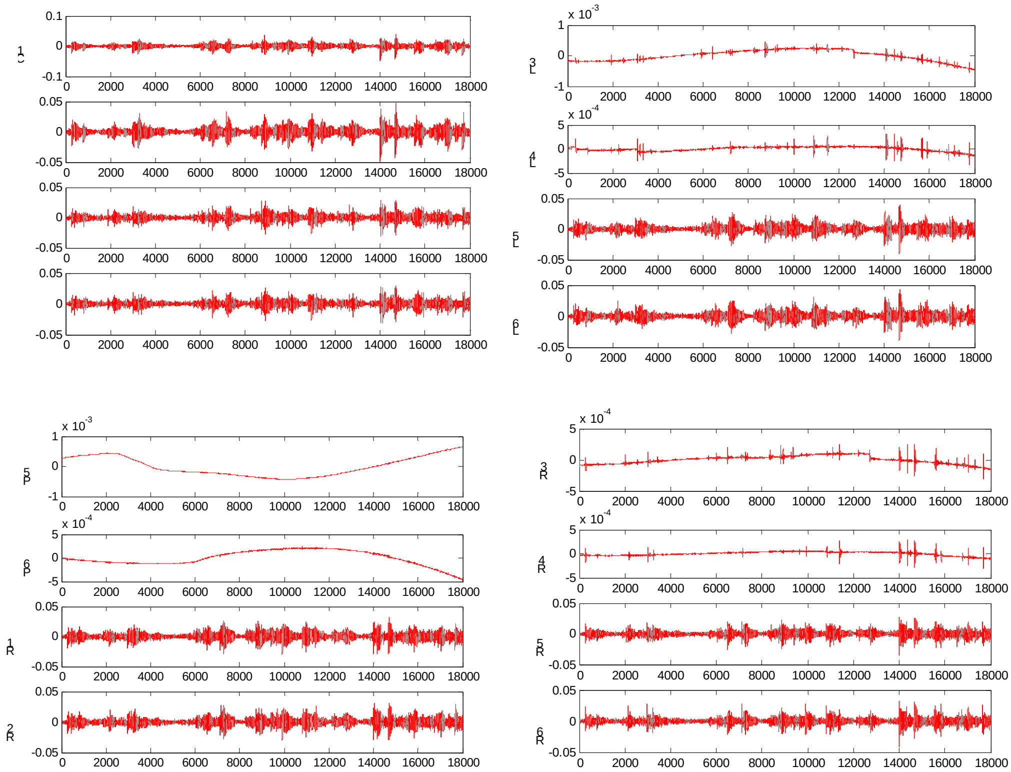


Figure 3 recorded acceleration data at the selected channels

From Figure 3, the signals collected at channels L3 and L4, P5 and P6, R5 and R6 are much smaller than the other channels because these channel locations are close to the tower and at both ends of the bridge (close to the abutments). Therefore the signals at 10 channels other than the 6 channels above were adopted in this study. For each individual position, Fourier spectra were calculated. Figure 4 shows the average power spectral density amplitude of the vertical deck vibration below 1.0Hz over all 10 Channels. It is observed that for frequencies below 1.0Hz, there are several peaks in Fourier amplitude identified which are in consistent with the analytical results (as shown in Table 1).

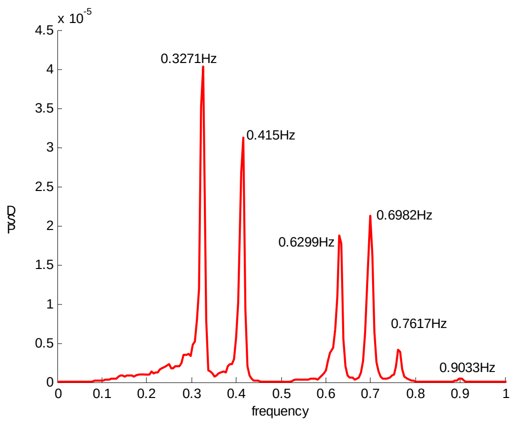


Figure 4 the average PSD over all the channels

5.2 Estimated Dynamic Properties of Bridge From NExT/ERA Method

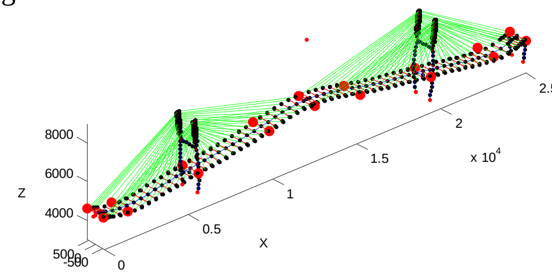
The system modal frequencies, damping ratios and mode shapes are identified using the NEXT/ERA technique. The results are shown in Table 1 and Figure 5. To demonstrate the accuracy of the identification, comparation was conducted among the results in this paper, the results of FEM model and the existed identification results obtained by other scholars previously.

The accuracy of modal frequencies is the most important criteria for estimating efficacy of the identification. The identified frequencies by NExT/ERA, PSD and FEM and the identified frequencies in Wei Song 2006 and Caicedo 2006 are listed in Table 1. Identification of modal frequencies below 1 Hz is the objectives of this work. By comparing Figure 4 and Table 1, it can be concluded that the identified modes are in good accordance with the peaks of PSD function except for the 3^{rd} mode, which was failed to detect in PSD analysis but was detected using NExT/ERA method.. From Table 1, it can be concluded that the first seven modes show good agreement with the results of Wei Song 2006, the results provide a convincing demonstration of the effectiveness of the NExT/ERA approach. The 4^{th}, 5^{th}, 6^{th} and 7^{th} mode of the FEM model is a mode which combines torsional and lateral motions, and is not identified in this preliminary analysis using the channels recording vertical motion only. The counterpart of the 4^{th}, 5^{th}, 6^{th} and 7^{th} mode of NExT/ERA is the 5^{th}, 6^{th}, 8^{th} and 10^{th} mode of FEM, which is further demonstrated by the comparison of mode shapes in next section.

Table 1 Modal frequencies comparision

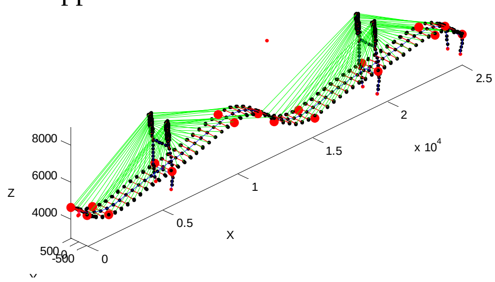
Modal Freq.	NExT/ERA	Wei Song 2006	Caicedo 2006	PSD	FEM
1	0.3137	0.3264	0.324	0.327	0.2786
2	0.4119	0.4152	0.413	0.415	0.3730
3	0.5733	0.5737	0.635	/	0.4873
4	0.6340	0.6329	0.706	0.629	0.5927(5^{th} mode)
5	0.7010	0.7009	/	0.698	0.6600(6^{th} mode)
6	0.7661	/	/	0.762	0.7293(8^{th} mode)
7	0.9005	/	/	0.903	0.8775(10^{th} mode)

Furthermore, the first seven vertical mode shapes obtained from NExT/ERA are compared with those from the FEM. The numerically obtained mode shapes are shown in Figure 5 and the identified modes are superimposed on these diagrams with MAC value indicated. Note that there is excellent agreement between the identified and numerical mode shapes, and all the MAC values are greater than 0.9. Please also be aware that the 4^{th}, 5^{th}, 6^{th}, 7^{th} modes of NExT/ERA are compared with the 5^{th}, 6^{th}, 8^{th}, 10^{th} modes of FEM, respectively. The results provide a convincing demonstration of the effectiveness of the NExT/ERA approach.



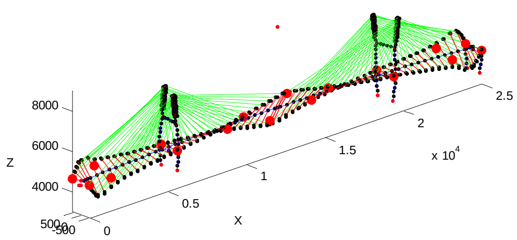
Identified modeshape 1 vs. FEM modeshape 1

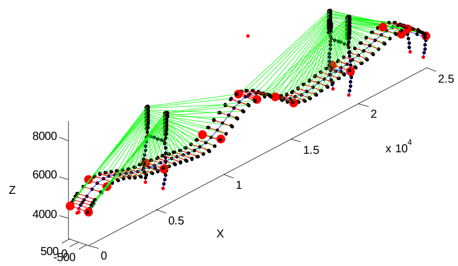
MAC=98.6867



Identified modeshape 2 vs. FEM modeshape 2

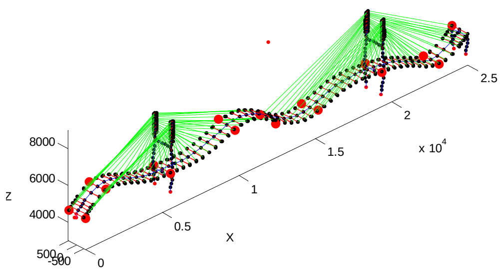
MAC=99.2060

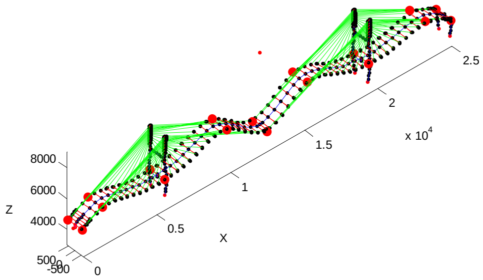




Identified modeshape 3 vs. FEM modeshape 3 | Identified modeshape 4 vs. FEM modeshape 5

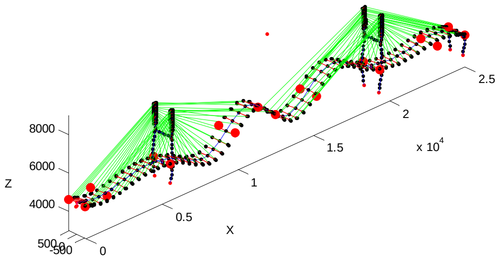
MAC=93.6105 | MAC=99.3361





Identified modeshape 5 vs. FEM modeshape 6 | Identified modeshape 6 vs. FEM modeshape 8

MAC=99.0717 | MAC=99.7334



Identified modeshape 7 vs. FEM modeshape 10

MAC=90.4806

Figure 5Comparation between the identified modal shapes and FEM modal shapes

6. CONCLUSION

NExT/ERA technique was used in this paper to conduct the modal identification of the Bill Emerson Bridge. Sixteen, 30-minute vertical acceleration records are employed for identification. Seven frequencies and mode shapes are identified and validated through a comparison with the modal parameters obtained from PSD analysis, FEM calculation, the work of Song (2006) and Caicedo (2006). The approach was proved to be effective in modal identification of long-span bridges. Further study will be carried out based on more data channels and concentrated on identification of coupled and closely-spaced vibrational modes.

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