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System Identification of a Base-Isolated Bridge Using Ambient Vibration Data

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ABSTRACT: Sciarapotamo Bridge located in Reggio Calabria Province, Italy has been recently retrofitted by replacing the deteriorated concrete bridge deck with composite concrete-steel deck, and isolating the deck with eight high damping rubber (HDR) and four multi-directional sliding bearings. Full-scale ambient vibration dynamic commissioning tests were performed on the bridge in June 2012 just before the bridge has become fully operational. The dynamic response of the bridge was recorded using an array of 4 uni-axial and 4 tri-axial force-balanced accelerometers placed along the entire length of the bridge. Different output-only system identification methods are used to identify the modal parameters of the bridge including: (1) Multiple Reference Natural Excitation Technique in conjunction with Eigensystem Realization Algorithm (MNExT-ERA), (2) Enhanced Frequency Domain Decomposition (EFDD). In this study, modal parameter estimation results obtained using different system identification methods are compared. Especially estimated damping coefficients are of great value showing the total damping in the system in as-built conditions. The experimentally obtained modal parameters for the bridge set the undamaged benchmark state of the bridge for future potential damage assessment studies.

1 INTRODUCTION

Civil engineering structures are exposed to different external effects that change their dynamic characteristics. Damage can be defined as changes affecting the structural performance of a system. The fact that damage can alter stiffness, mass, and/or energy dissipation capacity of a structure, which in turn results in detectable changes in its vibration signature, is the underlying principle of vibration-based structural health monitoring (SHM) (Doebling et al., 1998). SHM involves monitoring a structure continuously or intermittently and extracting damage sensitive properties for assessing its current state. Estimating dynamic parameters (i.e., modal parameters) by using global vibration response has attracted increasing attention in recent years in civil engineering research community, and has become an important tool for civil engineering structures for damage assessment and prognosis, model calibration, assessing retrofitting strategy and performance before and after retrofitting work (Farrar et al., 2007; Nayeri et al., 2007). Experimental modal analysis is used as a technology to extract modal parameters of vibrating structures using low level vibration data. Modal parameters to be extracted are natural frequencies, mode shapes, damping ratios, and modal participation factors (Peeters et al., 2001).

It is possible to classify system identification methods used in structural health monitoring in two categories, input-output methods and only-output methods. Exciting civil engineering structures with known functions is a challenging task due to their size and impracticality of measuring accurately the input/excitation motion. Therefore, output-only system identification also known as operational modal analysis (OMA), which does not require measurement of input excitation, is the most appropriate way for civil engineering structures (Peeters et al., 2001). OMA methods use broad-band vibration response due to micro-tremors, traffic, wind, and due to daily use.

In the literature numerous surveys exist on the recent developments of structural health monitoring techniques applied to civil engineering structures based on changes in their vibration characteristics. Interested readers can be directed to works by Doebling et al. 1998, Sohn et al. 2003 (Peeters et al., 2001; Sohn et al., 2003). He et al. (2006) compares the performance of three different system identification method using ambient and free vibration response data of a suspension bridge.

The purpose of this study is to identify modal parameters of Sciarapotamo Bridge located in Reggio Calabria Province, Italy which is recently retrofitted with composite concrete-steel deck, and isolating the deck with eight high damping rubber (HDR) and four multi-directional sliding bearings. Modal parameters are identified by using MNExT-ERA, and EFDD. Estimation results are compared. Estimated damping coefficients are of great value showing the total damping in the system in as-built conditions at low ambient vibration levels. The experimentally obtained modal parameters for the bridge set the undamaged benchmark state of the bridge for future potential damage assessment studies.

2 DESCRIPTION OF THE BRıDGE AND THE ıSOLATION SYSTEM

Three-span Sciarapotamo Bridge is located along the road Mastrologo-San Fili in the Province of Reggio Calabria (Italy). The bridge was a reinforced concrete structure built in the late 1950s. The original structure consisted of three continuous spans with total length of 28.8 m supported by two heavy full unreinforced concrete pier shown in Figure 1. The deck was realized with four reinforced concrete beams each with a section of 50x60 cm, topped with a weakly reinforced concrete slab of 40 cm thickness.

Figure 1. State of the bridge before retrofitting, general view and close-up views of the bridge deck.

Due to the increase of traffic density on the road, it was required to increase the width of the bridge from 5.5 m to 7.5 m to comply with the new road regulations. The reinforced concrete beams of the bridge were highly deteriorated, and at some locations steel rebars were exposed therefore were corroded (see Figure 1).

The bridge also had to be verified based on the new Italian building code (Norme Tecniche per le Costruzioni, NTC 2008), and due to the low quality of the concrete and high deterioration it was decided to replace the old deck with a composite concrete-steel deck, and isolating the deck with eight high damping rubber (HDR), and four multi-directional sliding bearings to reduce the lateral force acting on the existing piles and abutments. General views of the bridge after the retrofitting are shown in Figure 2.

Figure 2. General views of the bridge after retrofitting (composite steel deck and HDR isolators and sliders).

The high damping rubber bearings (HDR) have a diameter of 250 mm, and a total height of 218 mm, the bearings were designed to accommodate a peak-to-peak horizontal displacement of 270 mm (+/- 135mm) under a maximum vertical static load of 500 kN, and 200 kN under earthquake action. The experimentally determined effective stiffness of the isolator is equal to 0.451 N/m with a damping coefficient of 15%.

3 SYSTEM IDENTIFICATION METHODS USED

3.1 Multiple Reference Natural Excitation Technique with Eigensystem Realization Algorithm (MNExT-ERA)

First developed by James et al. 1992, the underlying principle of NExT method is that cross-correlation function calculated between two response measurements from a structure excited by broad-band excitation has the same analytical form as the free vibration or impulse response of the structure. Therefore modal parameters can be estimated using cross-correlation functions (James et al., 1993). The effectiveness of the method in estimating modal parameters has been demonstrated in different applications. Multiple reference channels can be used to avoid missing modes in the identification process due to the proximity of the reference channel to a modal node which is the main idea behind MNExT approach (Moaveni et al., 2011). Estimation of the cross-correlation functions are done by using Welch-Bartlett method (Manolakis et al., 2000). Welch-Bartlett method estimates auto- or cross-correlation power spectral density functions in frequency domain, and reduces estimation variance by incorporating different window functions, and overlapping the windowed data to increase the number of power spectral densities to be averaged. Once the auto- and/or cross-power spectral density functions are estimated, correlation functions in time-domain are obtained by discrete inverse Fourier transform. These functions can either be used directly or be used in the next stage with ERA method to estimate modal parameters.

There are numerous techniques used for identifying modal parameters from free vibration/impulse response data (Doebling et al., 1998; Sohn et al., 2003). In this study ERA method is used to extract modal parameters and model reduction of linear systems. The method is first proposed by Juang and Pappa 1985 to identify modal parameters of multi-degree-of freedom system using free vibration response. In ERA method, Hankel matrix is formed using free vibration response of the system. By applying singular value decomposition (SVD) to the Hankel matrix, the rank (i.e., model order) can be determined in the case of noise free measurement. Since real life measurements are always noisy, the model order can be determined by sorting the singular values in descending order, and performing partitioning of the SVD decomposition accordingly (Moaveni, 2007; He et al., 2005). Smaller singular values correspond to computational (nonphysical) modes whereas larger singular values correspond to the real physical modes (Caicedo et al., 2004). Once the model order is determined, based on the realization algorithm, the estimates of discrete-time state space matrices can be constructed. From the reduced order state space realization and sampling interval natural frequencies, damping ratios, and mode shapes can be obtained. In this study, MNExT-ERA method is programmed in Matlab® programming environment.

3.2 Enhanced Frequency Domain Decomposition (EFDD)

The Frequency Domain Decomposition method is an extension of classical pick picking (PP) technique and is based on the classical frequency domain approach also known as basic frequency domain technique. The classical technique has shortcomings such as identifying closely-spaced modes and furthermore frequency estimates are limited by the frequency resolution of power spectral density estimates and damping estimations are highly uncertain (Brincker et al., 2001). In EFDD method, output power spectral density (PSD) matrix is estimated at discrete frequencies, then the spectral matrix is decomposed using SVD. Natural frequencies and damping ratios are estimated using PSD functions of single-degree-of-freedom systems by transforming them back to time domain using inverse discrete Fourier transform. Auto-correlation function for a SDOF system in time domain can be used for estimating frequency and damping values by using zero-crossing times and logarithmic decrement. EFDD method is programmed in Matlab® programming environment.

4 EXPERIMENTAL WORK

Experimental program performed on the retrofitted bridge is composed of ambient and forced vibration tests. In addition to these tests, several man jumping and running tests were performed on the bridge in order to excite vertical modes. Forced vibration tests were conducted using an eccentric mass shaker and the results from these tests are used to estimate damping ratio in as-built condition as well as frequency response functions of the bridge along two horizontal axes. In this paper, only the results obtained from ambient vibration tests are presented.

In order to estimate the modal parameters of the bridge in as-built conditions using ambient vibration data, 4 uni-axial and 4 tri-axial accelerometers (total of 16 channels) were deployed on the bridge. Accelerometers used on the bridge have amplitude range of ± 3g, frequency bandwidth of 0-1000 Hz, and signal to noise ratio of 300-500 ng (RMS)/$\sqrt{Hz}$. Data acquisition system used for the tests is a 16 channel portable system with 24-bit resolution and wireless data streaming capability. Figure 3 shows the plan of the first sensor layout (a), and a picture showing the actual test setup (b). Sensor locations are indicated in the figure as circles and station numbers are also shown. During the test another sensor configuration (2^{nd} configuration) is used to capture the lateral motion (y-direction) of the bridge. The second configuration is the same as the one shown in Figure 3 except that sensors at stations 2 and 8 are along the x-axis, 3 and 5 are along the y-axis.

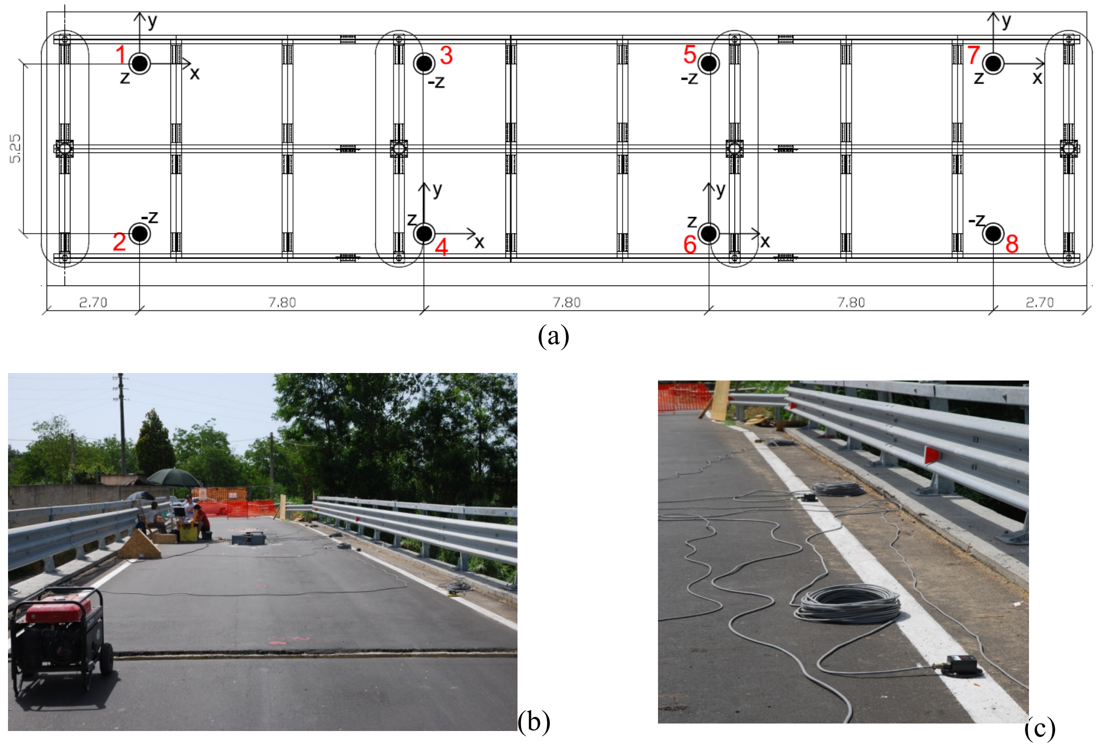

Figure 3. First sensor layout configuration (a), test setup on the bridge (b) and (c).

Sensors are placed on the bridge equidistantly from each other of about 7.8 meters along x, and 5.25 meters along y directions. Total of 8 ambient vibration tests were performed on the bridge. Each test was 8 minutes long.

5 MODAL IDENTIFICATION RESULTS

Ambient vibration tests were sampled at a rate of 200 Hz which results in a Nyquist frequency of 100 Hz. It is assumed that 100 Hz is higher than the anticipated frequency of interest of the bridge. Two different output-only system identification methods mentioned earlier are applied and results are presented below.

5.1 Estimated Modal Parameters by MNExT-ERA Method

In MNExT-ERA method, the reference signals are chosen as the vertical responses at stations 3 and 4 for sensor configuration-1. Raw recorded acceleration data is first band-pass filtered with a high-order FIR filter between 0.25 Hz-80 Hz. Response cross-correlation functions are estimated by inverse Fourier transform of the corresponding cross-spectral density (CSD) function. CSD functions are estimated by using Welch-Bartlett method in which ambient vibration recordings are subdivided into 6 windows with 50% overlap in order to reduce estimation variances. In ERA, Hankel matrix of size $(8\times 500)\times 500$ (8 vertical channels from configuration-1) is constructed by using 500 points from the estimated cross-correlation functions. The stabilization diagram is used to decide for the order of the reduced dynamic system which in turn is used to extract the modal parameters. The results are shown in Figure 4.

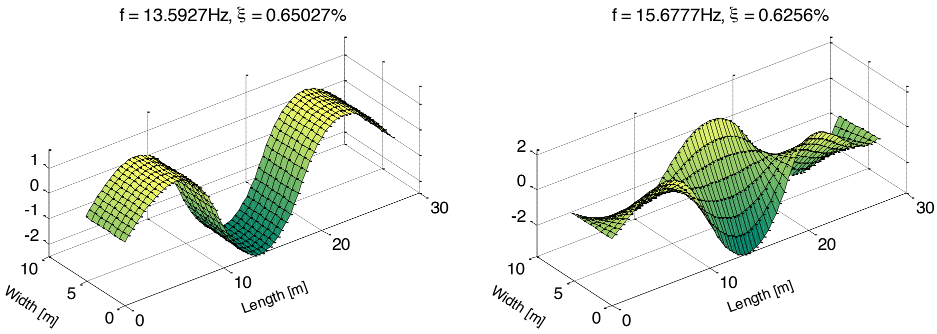

Figure 4. Estimated vertical mode shapes, natural frequencies, and damping ratios of the isolated bridge using MNExT-ERA method.

These estimated modes are the modes of the steel deck, and are the first vertical and first torsional modes with natural frequencies of 13.59 Hz and 15.68 Hz, respectively, and with damping ratios of 0.65% and 0.63%, respectively.

A similar identification work is carried out for estimating the lateral modes using configuration-2. Estimation results are presented in Figure 5.

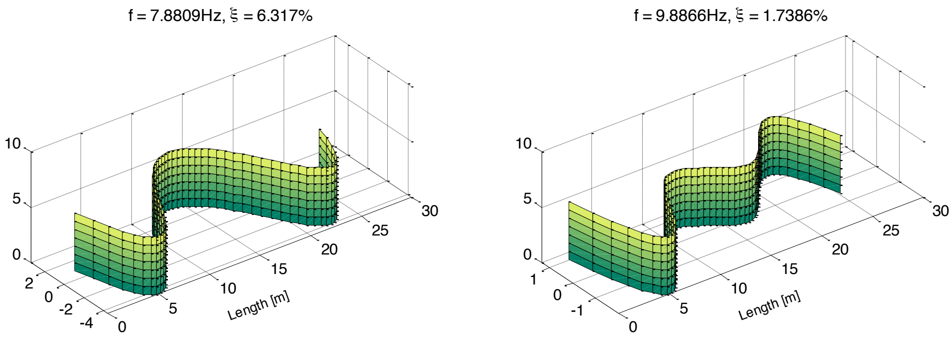

Figure 5. Estimated lateral mode shapes, natural frequencies, and damping ratios of the isolated bridge using MNExT-ERA method.

The estimated lateral modes are the modes of the steel deck, and are the first and the second lateral modes with natural frequencies of 7.88 Hz, and 9.89 Hz, respectively, and with damping ratios of 6.32%, and 1.74%, respectively. It should be noted again that these damping ratios are estimated under low level ambient vibration conditions.

5.2 Estimated Modal Parameters by EFDD Method

In EFDD method, raw recorded acceleration data is first band-pass filtered with a high-order FIR filter between 0.25 Hz-80 Hz. Cross spectral density (CSD) matrix is formed by using CSD estimations between each sensor recordings in frequency domain by Welch-Bartlett method with the same parameters used before. Once the CSD matrix is formed, SVD is performed on this matrix, and singular vectors with higher modal assurance criteria (MAC) are chosen as physical mode shapes. Corresponding singular values belong to the single degree of freedom (SDOF) auto-spectral density functions. By inverse Fourier transform of SDOF back into the time domain, natural frequencies and damping ratios are estimated by zero crossing times and logarithmic decrement. Logarithmic decrement method for damping ratio estimation works in this case because SDOF systems have single vibration frequency. The results are shown in Figure 6.

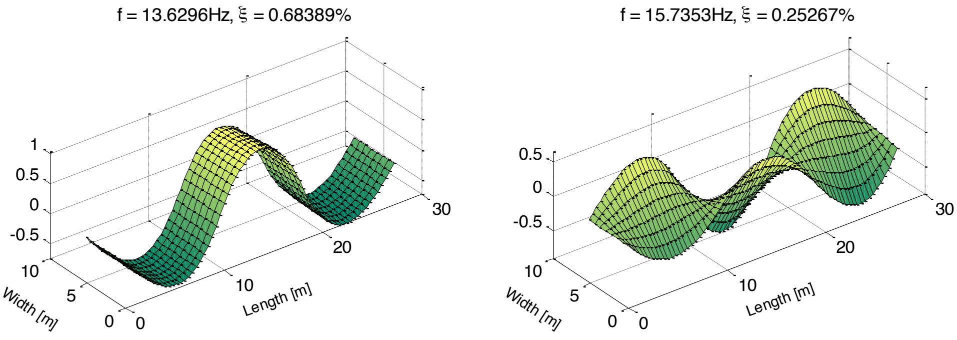

Figure 6. Estimated vertical mode shapes, natural frequencies, and damping ratios of the isolated bridge using EFDD method.

Natural frequencies of the estimated first vertical, and first torsional mode shapes are 13.62 Hz, and 15.74 Hz, respectively. Similarly estimated damping ratios for the same modes are 0.68%, and 0.25%, respectively.

A similar identification work is carried out for estimating the lateral modes using configuration-2. Estimation results are presented in Figure 7.

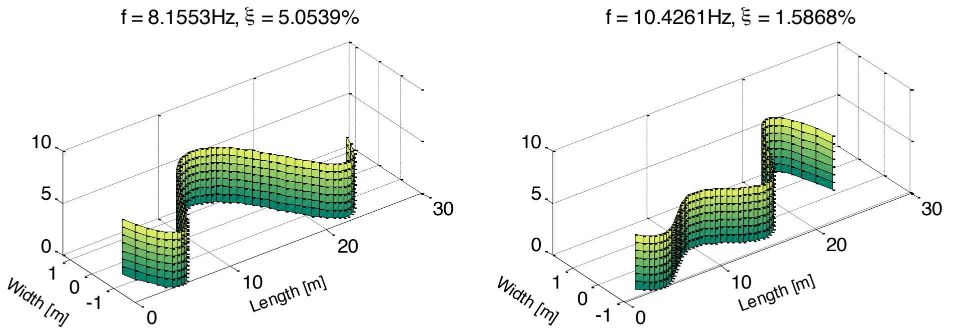

Figure 7. Estimated lateral mode shapes, natural frequencies, and damping ratios of the isolated bridge using EFDD method.

Natural frequencies of the estimated first and second lateral mode shapes are 8.16 Hz and 10.43 Hz, respectively. Similarly estimated damping ratios for the same modes are 5.05% and 1.59%, respectively.

6 CONCLUSIONS

The purpose of this study is to identify modal parameters of the recently retrofitted Sciarapotamo Bridge located in Reggio Calabria Province, Italy. The bridge is retrofitted with composite concrete-steel deck, and isolating the deck with eight high damping rubber (HDR) and four multi-directional sliding bearings. Modal parameters of the bridge are identified by using two different only-output system identification methods, namely MNExT-ERA, and EFDD. The estimation results are summarized in Table 1.

Table 1. Comparison of estimated modal parameters using two different output-only system identification methods.

Mode Shape	NExT-ERA		EFDD		MAC
	Frequency [Hz]	Damping Ratio [%]	Frequency [Hz]	Damping Ratio [%]	
1st Vertical	13.59	0.65	13.62	0.68	0.99
1st Torsional	15.68	0.63	15.74	0.25	0.84
1st Lateral	7.88	6.31	8.16	5.05	0.99
2nd Lateral	9.89	1.74	10.43	1.59	0.73

Both NExT-ERA and EFDD are able to identify the first two vertical and lateral mode shapes of the bridge deck, both methods estimate the natural vibration frequencies associated with these modes in close agreement. Based on the finite element analysis of the bridge, the anticipated isolated frequency along two lateral directions is around 0.5 Hz. Both methods fail to identify the isolated natural frequency under ambient vibration conditions. It is possible to identify the isolated frequency by broad-band forced vibration tests which can be performed by linear shakers capable of exerting broad-band excitations. MAC values calculated between the mode shapes estimated by NExT-ERA and EFDD methods are close to unity showing that mode shapes estimated by these methods are in good agreement.

Regarding the damping ratios, both methods are able to identify similar values for the damping ratios associated with vertical mode shapes, there is a slight discrepancy between NExT-ERA and EFDD for the first torsional mode where EFDD identifies less damping. For the lateral modes, both methods are able to identify similar damping ratios, and these values are considerably higher than the damping ratios associated with vertical modes. This shows that even under low vibration levels, high damping rubber isolators increase the level of lateral damping in the system. During a larger dynamic event this value is expected to be much higher. This is an added beneficial effect of retrofitting structural systems such as the bridge presented in this paper with isolators. The experimentally obtained modal parameters of the bridge set the undamaged benchmark state of the bridge for future condition assessment studies.

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