SYSTEM IDENTIFICATION OF A TYPICAL PRE-CODE HIGHWAY BRIDGE IN OPERATION USING HEAVY VEHICLE EXCITATIONS

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Abstract

System identification of a pre-code reinforced concrete highway bridge is performed to obtain the fundamental natural period and damping ratio. A bridge constructed during 1970s across a major highway of Nepal, the East-West Highway (EWH), is considered as a case study bridge. The bridge is a major crossing over one of the largest rivers of Nepal, Narayani river at the border of Chitwan and Nawalparasi districts. The bridge is 420 m long, has 14 spans, and two traffic lanes. Vibration measurements was conducted on the bridge for one hour during a peak traffic flow condition. The traffic flow included more than 40 tons lorries and other vehicles. Three triaxial accelerometers were placed on the bridge. The recorded vibration measurements are used to estimate natural frequencies and damping ratios of the bridge using different methods such as peak picking from smoothed power spectra, auto-regressive moving average model (ARMA), and N4SID algorithm. The different methods are found to yield similar results. Uncertainty in estimation is estimated by dividing the measurements into different windows and carrying out system identification in each window. It was found that the fundamental and second mode frequencies can be estimated relatively reliably, while there are larger uncertainties in the higher mode frequencies. Uncertainties in the damping ratios are rather large, with standard deviation almost as large as the expected value. The results show that the test method described here can be used for quick dynamic characterization of bridges, and possibly useful in calibrating and updating finite element models. An example application where the estimated system model expressed as an ARMA system is used to estimate response of the bridge to a known excitation, in the form of an earthquake ground motion is also presented. One of the limitations of the presented method is that the excitation does not excite all modes of the structures that participate in seismic response. This explains the uncertainties in estimated parameters of some of the modes. It is also found that signal processing for these kinds of measurements is challenging due to multiple transients induced by recurring traffic, and it is difficult to apply an automation algorithm. Careful manual processing to remove transients as much as possible, although tedious, was found to yield reasonable results.

Keywords: system identification; ambient vibration measurement; RC bridge; pre-code construction.

1. Introduction

Condition assessment and rehabilitation of bridges have grave importance to assure the continuity of operation of highway bridges. If inoperable, highway bridges may cost millions. As highway bridges are the major backbones of road transport, their safety is of great concern. As bridges are obvious to observe multiple hazards during their service lives, long-term resilience and loss assessment approaches are gradually surfacing and being implemented (see e.g. [1]). As there is obvious need of structural parameters to model the bridges in finite element programs, tests are usually required. To obtain the parameters, ambient vibration tests are widely used nowadays due to their portability, easy handling, low space consumption, and easy operation. We performed ambient vibration measurement in a strategic bridge (Narayani bridge) of East-West Highway in Nepal. Narayani bridge (27.6995N, 84.4189E) is an RCC-T beam bridge located at Chitwan and Nawalparasi districts in central Nepal. The bridge has 420 m length and 14 spans. The roadway width of bridge is 11 m and the foundation is provided with reinforced concrete. As the East-West Highway (EWH) was completed during 1970s-80s, the bridge has been deteriorated. Furthermore, there are no any details regarding seismic design and detailing of this bridge. Despite regular maintenance, no any other rehabilitation and strengthening are done so far. As the bridge is aging, identification of dynamic characteristics would be important to incorporate further rehabilitation planning. Aiming to identify the dynamic characteristics of aging Narayani bridge, which was constructed before seismic codes were enforced in Nepal, we conducted ambient vibration measurements using three accelerometers during heavy vehicle passing hours.

Many researchers have considered dynamic identification of structures and infrastructures (see e.g. [2], [3], [4], [5], [6], [7], among others). As reported by [8], dynamic identification of structures and infrastructures can be effectively carried out using ambient vibration records, we took 60 minutes long ambient vibration measurements. Three accelerometers were deployed at three locations of the bridge. Details of orientation and methods are reported in the following section.

2. System identification

Modal identification was performed by using traffic-induced vibration measurement. Three digital accelerometers were installed in three of the spans of the bridge. and vibrations were measured at 100Hz for 30 minutes. The accelerometers are ETNA-2 manufactured by Kinemetrics Inc. The tested bridge is as shown in Fig. 1. Each of the accelerometers recorded time through a GPS connection. The measured vibrations at the three piers were synchronized before being further processed. Three accelerometers were placed in the first three piers from the right bank of the river and all three accelerometers were placed orienting the X-direction towards north as shown in Fig. 1.

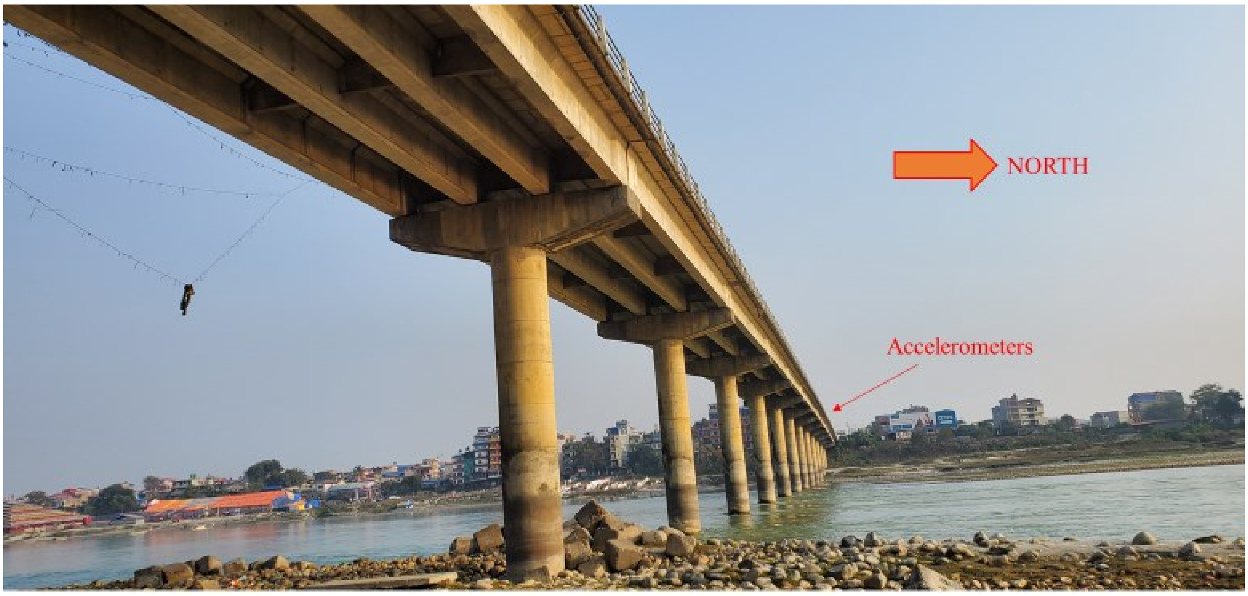

Fig. 1- Narayani bridge

Only the two horizontal components of vibration were used in system identification. The recorded signals were detrended before further processing. Each signal was divided into 10 segments. Each of these segments were checked for unusual spikes and offsets. Such spikes and offsets were removed by windowing the segments by visual inspection. The windowed signals were low pass filtered using a fourth order Butterworth filter with a corner frequency of 20 Hz. The filtered signals were then tapered with a Tukey Window. System Identification was then carried out using two methods described as follows.

2.1. Non-parametric methods

This method was based on the power spectral densities (PSD) of the recorded signals. PSD of the signals were computed by using the Welch's averaged periodogram considering 10 windows of equal length and 50% overlap between the windows. The recorded signals are considered as response and the excitation is assumed to be a white noise. Denoting the PSD of response and excitation as $S_{yy}(f)$ and $S_{uu}(f)$, respectively, with f denoting frequency, an estimate of the squared amplitude of the frequency response function of the structure is given by:

$$|H(f)|^2 = \frac{S_{yy}(f)}{S_{uu}(f)} \tag{1}$$

When the excitation assumed to be a white noise, the squared amplitude of the complex frequency response function is proportional to the PSD of the response. The peaks of this function can be interpreted as the modal frequencies of the structure.

The complex frequency response functions estimated in this way are normalized by their value at 0 frequency. The normalized functions at the three accelerometers are shown in Fig. 2, the top and the bottom row corresponding to X and Y directions respectively. For all the sensor locations, complex frequency response functions show clear peaks at about 1 Hz and 4.5 Hz in the X direction, indicating the first two modes of vibration in this direction. In the Y direction, the dominant peak is around 4.5Hz, but there is a peak at 1 Hz also. This is an indication that the vibrations in the two directions are not independent.

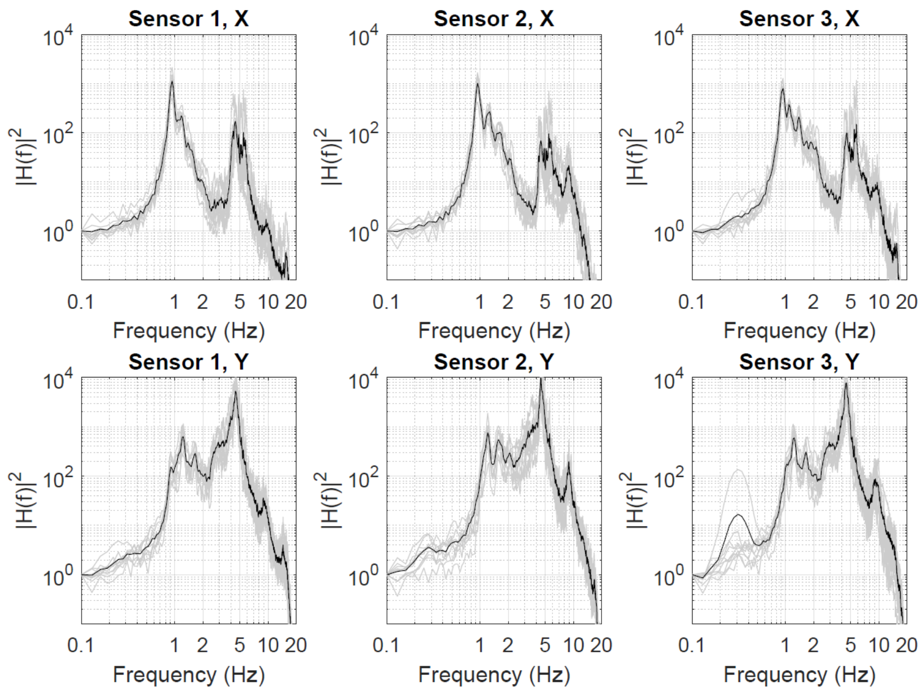

Fig. 2- Normalized amplitudes of complex frequency response function of the bridge estimated from Welch's average power spectral density function of traffic induced vibration. The gray lines correspond to 10 segments of the measurements and the black lines are their averages.

2.2 Operational Modal Analysis (OMA) method

2.2.1 Next-ERA method

The OMA method used here in the Natural Excitation Technique [9] combined with the Eigensystem Realization Algorithm [10], denoted as (NExT-ERA). This method has been found to be suitable to estimate modal parameters of structures with measured vibration response and unknown excitation [11]. This method has been used for system identification of bridges in the past (see, for example, [5]). In the first phase of this method, the NeXt phase, cross correlation functions of measured response at various locations of the structure with that at some pre-selected location(s) are estimated either in the time or the frequency domain. The measurement at the pre-selected location(s) are called as reference channels. The cross-correlation function satisfies a second order homogeneous differential equation of similar form as the free vibration response of a structure. Using the frequency domain method, the cross-correlation function can be estimated as the inverse Fourier transform of the cross-spectral density function. In this study, the cross-spectral density functions are estimated by using the Welch's average periodogram method. The recorded measurement is divided into 10 segments and identification is carried out separately in each of these segments. In each segment, Welch's method is used with 9 windows and a 50% overlap between them. The measurement at accelerometer 1 (or sensor 1) is used as the reference in calculating cross-spectral densities. Vibrations in X and Y directions are treated separately. After the cross-correlations functions are available, the ERA algorithm is used to identify the modal properties of the structure. More details of the ERA algorithm and practical guidelines for implementing can be found in [12]. Using this algorithm, one can estimate the impulse response function of the structure, which can be converted to complex frequency response function by taking its Fourier Transform. The normalized amplitudes of the complex frequency response functions are shown in Fig. 3. Similar to the non-parametric method, the vibration frequencies in the X direction are estimated to be around 1 Hz and 4.5 Hz and those along Y direction are dominant around 4.5 Hz, as can be inferred from visual inspection of Fig. 3. It is interesting to note that the variation in the frequency response function across different windows is the smallest in the reference channel. This method also allows to estimate modal frequencies and damping ratios. The extracted values for the first mode in X and Y directions are shows in Table 1.

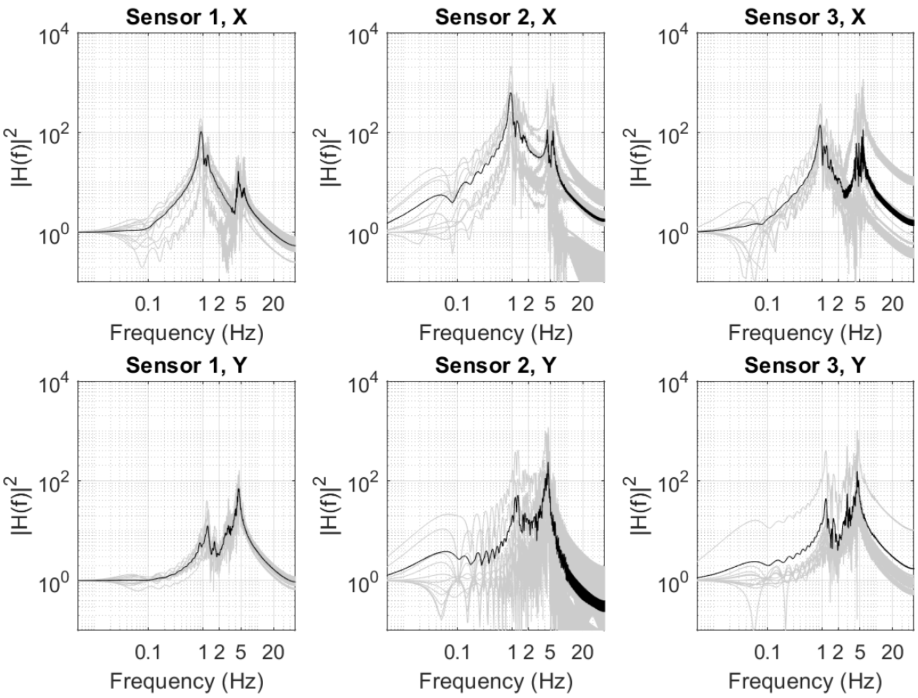

Fig. 3- Normalized amplitudes of complex frequency response function of the bridge estimated from the NExT-ERA algorithm. The gray lines correspond to 10 segments of the measurements and the black lines are their averages

Table 1. Modal frequencies and damping ratios of the bridge identified by the Next-ERA method

Window	Frequency (Hz)		Damping ratio (%)	
	X	Y	X	Y
1	0.95	4.59	6.00	0.03
2	0.92	3.48	4.49	4.28
3	0.94	4.29	5.57	0.57
4	0.96	3.37	6.12	8.01
5	0.96	4.45	4.15	0.09
6	0.97	4.44	4.34	0.12
7	0.93	4.26	3.79	0.89
8	0.95	2.64	6.34	8.33
9	0.97	3.78	8.07	9.71
10	0.94	4.37	6.96	0.56

Mean	0.95	3.97	5.58	3.26
Std	0.02	0.63	1.38	3.96

3. Concluding remarks

We present system identification of an aging bridge located along the EWH in Nepal. Due to continuous degradation, concerns were raised regarding the serviceability limits of the bridge. Being a pre-code bridge, seismic components per the guidelines were not known to be assured in the bridge. To this end, system identification of the aging bridge is conducted using three accelerometers during peak vehicle movement hours. The heavy excitations were captured and processed to perform system identification using non-parametric and OMA approaches. The non-parametric method resulted the frequency at about 1 Hz and 4.5 Hz in the X direction which indicate the first two modes of vibration along the same direction. Similar results were also obtained for the Y direction. The results obtained from OMA highlight that the frequencies of the bridge in X and Y directions are respectively 0.95 Hz and 3.97 Hz. Furthermore, damping of 5.58 and 3.26 are obtained for X and Y directions respectively. Standard deviations for the estimated frequencies are relatively smaller than that for estimated damping factors. The system identification results could be beneficial in modal updating and creating finite element models of aging bridges with significant deterioration. Our analysis shows that non-parametric and OMA provide a strong basis for system identification of structures under heavy excitations by heavy trucks passing through intermittently.

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