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Blind Source Separation Based Dynamic Parameter Identification of a Multi-Story Moment-Resisting Frame Building under Seismic Ground Motions

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Abstract

This paper addresses the application of blind source separation technique for identifying dynamic parameters of a seismic-excited multi-story building from its measured response. The structure was an instrumented moment-resisting frame office building. Its acceleration responses at different building floors were recorded during four earthquakes occurred in 2002. In this study second order blind identification - a class of blind source identification technique - was employed to obtain the structure’s dynamic parameters, i.e., natural frequency and damping factor. The results of this study were substantiated through comparison with the results of investigations carried out for dynamic parameter identification of the same building using different techniques. Results of this study were encouraging. It indicated that the methodology employed in this study could be beneficially applied for identifying dynamic parameters of the building under seismic ground motions.

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Keywords: system identification; multi-story building; blind source separation technique; seismic ground motion.

1. Introduction

Dynamic parameters of multi-story buildings identified from their responses measured under the wind, traffic, and seismic ground excitations have been gained significant attention of researchers. The structure’s dynamic parameters, viz. natural
frequencies, damping factors, and mode shapes, obtained from experimental studies are necessary, e.g., for updating numerical finite element models, studying performance of the structure, and establishing baseline of vibration based health monitoring of the structure. Measuring the forces excited the structure is frequently not possible. Consequently the dynamic parameters are plausibly obtained using the structure’s responses under these natural excitation forces. Dynamic parameter extraction utilizing these dynamic forces allows the structure undergoing testing to be in its service conditions.

Studies on dynamic parameter identification of multi-story buildings under the wind and seismic excitations were reported in Brownjohn (2003); Budipriyanto (2010); Celebi (2004); Celebi (2006); Liu et al. (2005); Saito and Yokota (1996). Responses of a 26-story building during earthquakes were monitored using seismometers mounted in 3 (three) locations along the building’s height for the dynamic parameter identification (Saito and Yokota 1996). Auto-Regressive Moving Average method was employed. The authors stated that the method could be utilized to estimate natural frequencies and damping factors of the structure from few seismic response data. In Celebi (2004); Celebi (2006); Liu et al. (2005) applicability the above mentioned method was investigated to obtain the dynamic parameters of 14-story and 20-story buildings from recorded seismic responses.

Use of finite element method to obtain appropriate model for simulating time response of the 14-story building investigated in Celebi (2004) under two earthquake loadings was demonstrated in Liu et al. (2005). Identification of dynamic parameters of the multi-story building utilizing Ibrahim Time Domain (ITD) from its seismic response was reported in Budipriyanto (2010). In the scheme presented in the paper the response needed to be selected so that ITD method could be applied to extract dynamic characteristics of the building. The results of the study showed that the dynamic parameters measured employing the scheme were good; they were similar to those obtained from studies conducted on the same building employing different methods.

Brownjohn (2003) reported results of an investigation on dynamic parameter identification of 65-story and 31-story buildings using their responses measured under wind forces. He concluded that mode shapes and natural frequencies could be obtained using limited response data. However further detailed investigations were needed for determining measured damping ratios. Michel et al. (2008) presented a procedure employing frequency domain decomposition method for evaluating a building stiffness obtained from its mode shapes when the building was under weak to moderate earthquake forces. He reported that the proposed procedure was applied successfully to simulate a 9-story building motions under earthquake ground excitations. In Rent and Zong (2004) peak picking and stochastic subspace identification methods were implemented to estimate dynamic parameter of civil engineering structures under the wind and traffic loadings. A 15- story reinforced concrete building and a tubular steel arch bridge were instrumented and their responses were recorded. They stated that these methods could identify the structures’ natural frequencies. However in most cases stochastic subspace identification method gave more reasonable results.
Blind source separation (BSS) technique using second order statistics (SOBI) was introduced in Belouchrani et al. (1997). Its applications to dynamic of civil engineering structures were reported, e.g., in Harza et al. (2010); Poncelet et al. (2007). In Poncelet et al. (2007) blind source separation method was utilized for studying the effectiveness of the method to identify dynamic parameters of a system. Numerical and experimental studies were conducted. A spring-mass system was investigated in numerical study and a blade of an engine was tested in the experimental investigation. Hazra et al. (2010) proposed a SOBI based method where correlation of the structure’s responses was computed and used in the analysis instead of response measurements. The proposed method was applied to indentify dynamic parameters of structural models, namely, a 3 DOF mass, spring, and dashpot model, a two-story aluminium frame model, and a 13-story tower finite element model. The results showed that in cases investigated in their study the proposed method had good performance.

In this paper, results of a study on dynamic parameter identification of a multi-story building using SOBI method are discussed. The building was a 14-story moment-resisting frame office building which was built in late 1980’s. It was located in an active seismic zone in Alaska, the US. In 1989 under United States Geological Survey National Strong Motion program 9(nine) accelerometers were installed in the building; 3 (three) uniaxial accelerometers were mounted on the 14th (roof) floor, 4(four) accelerometers were deployed on the 8th floor, and at the basement, there was 1(one) biaxial accelerometer installed. It enabled for measuring the building’s response in translational and horizontal directions. In 2002 four earthquakes shook the building and its acceleration responses were recorded during these ground motions. Two of these earthquakes occurred on February 6, 2002; they originated from different epicentres. Other two of these occurred on October 23, 2002 and November 3, 2002 respectively. The study presented in this paper was carried out for identifying the building’s dynamic parameters extracted from the building’s seismic responses under these earthquake ground motions. SOBI approach, which can be categorized as a blind source separation technique, was employed. Results of this study were substantiated through comparison with studies reported in Celebi (2004); Liu et al. (2005)

2. Dynamic Parameter Identification Method

Under earthquake loadings a building structure’s response may behave nonlinearly due to, for instance, the building material degradation and interaction between the structure and the site. Therefore the presence of nonlinearity in the structure’s response needs to be investigated so that an appropriate system identification technique for extracting modal parameters can be determined. Methods for identifying nonlinearity present in structure’s responses were discussed in Farar et al. (2007).When the building structure is linear dynamic parameters of the structure can be obtained using a system identification method, such as SOBI.

Coherence function can be utilized to determine whether nonlinearity is present in the structure’s response or not. This function has the values ranging from 0.0 to 1.0. When the coherence values, especially those in the vicinity of resonance frequency, are
much less than unity, it indicates that response of the structure is not linear (Farar et al. 2007). The coherence function can be obtained using,

$$\gamma_{xy}^2 = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)}$$

(1)

$S_{xy}(f)$ and $S_{xx}(f)$ denote the cross spectral density of the reference and output responses, and the auto spectral density of the input respectively.

In blind source separation (BSS) model source signal, $s(t)$, measured response, $x(t)$, and noise, $n(t)$ can be related as Belouchrani, et al. (1997; Poncelet, et al. (2007)

$$x(t) = As(t) + n(t)$$

(2)

$A$ is called the instantaneous mixing matrix or array matrix. BSS is intended to elicit the unmeasured source signal from their measured response signal. Since information regarding the mixing matrix, $A$ is not available or very little the term blind is used.

A class of BSS method -called SOBI- involves whitening of the measured response, computing the covariance matrices, and diagonalizing of covariance matrices to obtain the mixing matrix. This method was explained in details in Belouchrani (1997). Dynamic parameters of civil engineering structures can be extracted by employing Eq. 2; mode shapes can be obtained from the mixing matrix, $A$ whereas natural frequencies and damping factors are extracted from the source signal, $s(t)$.

In this study, the equation was utilized to separate the sources from seismic acceleration responses measured on building floors. Then random decrement technique was applied to obtain dynamic parameters from the source signals. The random decrement function was computed using the expressions given below (Brincker 1991),

$$RD_{xy} = \frac{\rho_{xy}}{\sigma^2_x} \rho_o$$

(3)

$$\rho_o = \frac{\int_a^b \rho_x(x)dx}{\int_a^b \rho_x(x)dx}$$

(4)

where $\rho_{xy}$ is correlation function between responses $x$ and $y$, $\rho_x(x)$ is probability density function of response, $a$ and $b$ are the lower and upper triggering levels, and $\sigma_x$ is the standard deviation of the response. When the lower and upper triggering values of 0.5$\sigma$ and $\infty$ were selected the value of $\rho_o$ for Gaussian distributed response was 1.14 $\sigma_x$. Random decrement function obtained using Eq. 4 was then fitted in the least square sense to extract natural frequencies and damping ratios.

The methodology described above was applied to identify dynamic parameters of the 14-story moment resisting frame office building from its response data which were measured during four earthquakes occurred in 2002. The investigated building dimensions were 45.5m long, 32.3m wide, and 49.7m high (measured above the ground floor). Detailed description of the building can be found in Celebi (2004). Under United States Geological Survey National Strong Motion program the building acceleration
responses were measured during four earthquakes via 9(nine) channels of acceleration sensors installed on the building floors. Since the building’s bending modes were investigated in this study the dynamic parameters were identified from four acceleration responses mounted on the 14th (roof), 8th, and basement of the building. However the parameter identification of other modes of the building could be conducted using the methodology described in this paper.

3. Results and Discussion

Coherence functions of the building seismic acceleration responses measured on the basement, the 8th floor, and the 14th were computed using Eq. 1 for the four earthquakes. Figures 1(a) and 1(b) show the coherence functions computed using response of the 8th and the 14th building’s floors under earthquakes occurred on February 6, 2002 at 17:18:46 pm and at 17:19:29 pm respectively. The functions computed using the floor responses under the October 23, and November 3, 2002 are shown in Figures 1(c) and 1(d). In this study dynamic parameters of the building’s first bending mode were investigated. Previous studies showed that the building natural frequency for this mode ranged from 0.4 to 0.6 Hz. As seen in Figs 1(a) and 1(b) in the frequency range of interest, the coherence function values computed using response under the February 6, 2002 earthquakes were nearly 0.92 whereas these values obtained using responses the October 23, and November 3, 2002 earthquakes were very close to unity. Hence it could be justified that the building dynamic response behaved linearly when it was excited by these earthquake excitations. This step is necessary to be carried out so that a dynamic parameter identification technique could be appropriately applied.

Blind Source Separation technique was applied to seismic acceleration responses of the building when it was excited under these four ground motions. The source signals of the building responses recorded on the basement, 8th floor and the 14th floor are presented in Figures 2(a), 2(b), 2(c), and 2(d). The methodology described earlier was implemented to obtain dynamic parameters of the building investigated in this study. The random decrement functions were obtained from these source signals of the building responses by applying Eq. (3) for four earthquake ground motions. The functions were fitted in least square sense to estimate natural frequencies and damping factors of the building under these four earthquake forces investigated in this study. For illustration purposes the functions computed using the 8th and 14th building floor responses measured during the October 23 and November 3, 2002 earthquakes are shown in Figures 3(a) and 3(b). As seen in these figures the curve fit technique employed in this study could simulate random decrement functions computed from the measured signals under these ground excitations. The functions obtained from signals measured from other floors of the building and those measured under the February 6, 2002 earthquakes are not presented in this paper for the sake of brevity. However dynamic parameters identified from the building responses under these earthquakes are reported in this paper.

The natural frequencies and damping factors extracted via the random decrement functions for these four earthquake ground motions are presented in Table 1. Results of
studies on the building’s dynamic parameters reported in Celebi (2004); Liu et al. (2005) are also presented in the table. In Liu et al. (2005) the building was only studied under the October 23, and November 3, 2002 earthquakes. Therefore the dynamic parameter values under the February 6, 2002 earthquakes could not be presented in this paper. Natural frequencies and damping factors presented in Table 1 were averaged values obtained using methodology described earlier in this paper.

As seen in the table the building’s dynamic parameters, i.e., natural frequencies and damping factors extracted from these ground motions using methodology employed in this study were similar to the values reported from studies carried out on the same building using different dynamic parameter identification methods.

![Coherence magnitudes](image1.png)

(a) February 6, 2002 at 17:18:46 pm  
(b) the February 6, 2002 at 17:19:29 pm  
(c) October 23, 2002  
(d) November 3, 2002

Figure 1. Coherence magnitudes of the building responses recorded on the 8th and 14th floors under the (a) February 6, 2002 at 17:18:46 pm, (b) at 17:19:29 pm, (c) October 23, and (d) November 3, 2002 earthquakes.
Figure 2. Source signals obtained using the building responses recorded on the 8th floor under the (a) February 6, 2002 at 17:18:46 pm, (b) at 17:19:29 pm, (c) October 23, and (d) November 3, 2002 earthquakes.

Figure 3. Measured and fitted random decrement functions obtained using the building responses recorded on the 8th and 14th floors under the (a) October 23, and (b) November 3, 2002 earthquakes.
Natural frequencies of the building under the February 6, 2002 earthquakes were slightly higher than those under the October 23, and November 3, 2002 earthquake excitation forces. It might be due to the effect of the building and soil interaction since the epicentre of the February 6, 2002 earthquakes were closer than other two earthquakes investigated in this study. In addition results of this study were consistent with results reported in the previous studies. Hence it demonstrated the efficacy of the methodology presented in this study for identifying modal parameters of the building.

4. Concluding Remarks

Dynamic parameters of a 14-story moment-resisting frame building were extracted from its responses measured under four earthquake ground motions. In the study presented in this paper, prior to carrying out dynamic parameter identification coherence functions of the building’s responses were computed to investigate whether the building behaved linearly under these earthquake loadings. A blind identification based method—called Second Order Blind Identification—is applied successfully for identifying natural frequencies and damping factors of the building. Results of the study were compared with results of studies on the same building using different identification methods. The results were promising. It was demonstrated that the methodology utilized in this investigation was capable of identifying dynamic parameters of the building under seismic ground motions.

References


