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SYSTEM IDENTIFICATION OF TORSIONALLY COUPLED BUILDINGS USING EARTHQUAKE RESPONSES

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ABSTRACT

System identification plays an important role in health and condition monitoring of buildings. To identify damage in a structure, the frequencies and other modal parameters are often evaluated from dynamic measurements, and then an inference about the damage is made. The modal parameters can be extracted from the response of the structure to free and forced vibrations. The identification of frequencies and damping of a torsionally coupled system is difficult since the structural system possess closely-spaced frequencies. In this paper, three mode identification methods, Complex Exponential Algorithm, Ibrahim Time Domain Method, and Eigen Realization Algorithm are modified to use data obtained only from the recorded responses. These algorithms are evaluated for their effectiveness in estimating the modal properties of torsionally coupled buildings subjected to base excitations. A new mode shapes interpolation method to extract the mode shapes of a torsionally coupled system from modal data of only top and lowest floor has been presented. The limitations of the modified identification methods are examined for an example multi-storey torsionally coupled building.

Introduction

Determination of dynamic properties of full-scale structures is a subject of increasing importance to researchers and engineers. The design and analysis of structures to withstand seismic loads, strong winds, explosions, and other types of dynamic forces require an understanding of dynamic characteristics of the structure. Another major concern is structural health monitoring and damage detection. The occurrence of damaging earthquakes poses a problem of identifying damages in the structures. Many times the damage due to minute cracks remains undetected. Prolonging the services of such a structure without retrofitting will reduce its capacity to sustain future major events. The structural damage results in permanent changes in the structural stiffness, distribution of stiffness, and relevant material properties. These changes may be detected by monitoring the dynamic behavior of the structure.

The determination of structure dynamic characteristics, i.e., system identification, is useful for the following reasons: (1) To determine the dynamic properties of structures which are difficult or impossible to model analytically; (2) To identify damage and possible changes in the dynamic behavior of structures; (3) To detect the damage to structures without disturbing the health of the structure, and to monitor the structural safety; (4) For condition assessment of the important structures after major events like a large earthquake, damaging tsunami, explosions, etc. and (5) To update numerical models of the structure by

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adjusting the modal parameters to experimentally verified results.

There is limited published literature on the identification of system parameters of torsionally coupled buildings (Kozin and Natke 1986, Uneg et al. 2000). Many researchers have proposed parameter extraction for planar frame structures (Mau and Aruna 1994, Wang and Haldar 1994) or have identified two translational and one torsional modal parameter for building structures separately (Kadakal and Yuzugullu 1996). However, all buildings with nominally symmetric plans are asymmetric to some degree and undergo lateral as well as torsional vibrations simultaneously. As a result of coupled lateral-torsional motions, the lateral forces experienced by various resisting elements (such as frames and shear walls) differ from those experienced by the same elements if the building is truly symmetrical. Ignoring the torsional vibration may result in underestimation of the structural responses (Hejal and Chopra 1989).

Traditional system identification techniques require the full measurement of input excitation and all its corresponding responses (Kozin and Natke 1986). However, a real structure usually possesses a large number of degrees of freedom making it impossible to acquire full measurements of all degrees of freedom. Thus, system identification based on response measurements at a few degrees of freedom becomes necessary from a practical consideration. There are several different approaches proposed for extracting modal parameters from limited response measurements using general input (base excitation) and output (floor responses) methods. The Eigen Realization Algorithm (ERA) and Observer/Kalman Filter Identification (OKID) approach have been used to identify the modal parameter from time histories of the structural response (Lus et al. 1999). There have been comparative studies to highlight the difference and similarities in current modal identification algorithms, viz. Least-Squares Complex Exponential (LSCE), Poly Reference time domain (PTD), Ibrahim time domain (ITD), and Eigen-system Realization Algorithm (ERA), Rational Fraction Polynomial (RFP), Poly Reference Frequency Domain (PFD), and Complex Mode Indication Function (CMIF) methods (Allemang and Brown 1998). In many of these studies the modal parameters are extracted by modeling the building as a linear system with only one or two translational DOF per floor, and not having closely spaced frequencies. There is limited literature available on effectiveness of above methods to extract modal parameters of a system having closely spaced frequencies such as a torsionally coupled building. In this paper, time domain curve fitting techniques has been applied to extract the modal parameters of torsionally coupled building from only recorded responses.

Mode Identification Methods

The identification of frequencies and damping of a torsionally coupled system is difficult since the torsionally coupled structural system possess closely-spaced frequencies. In this investigation the time domain mode identification methods viz., Complex Exponential Algorithm (Maia 1988), Ibrahim Time Domain Method (Ibrahim and Mikulcik 1973) and Eigen Realization Algorithm (Juang and Pappa 1985) are evaluated for their effectiveness in estimating the modal properties of torsionally coupled buildings subjected to base excitations. These methods have been implemented in the Natural Excitation Technique (NExT) sense. A direct similarity has been established between the Cross Correlation and Impulse Response Functions, and also between Cross Power Spectra and Frequency Response Function of the excited structure (James 1995). Modal parameters have been extracted from Cross Correlation Functions (CCor) or Cross Power Spectral Density (CPSD) of the building treating it as an input-output system.

Complex Exponential Method

The Complex Exponential Method (CEM) parameter extraction process involves forming the polynomial equations from the CCor data and finding the roots of the polynomial to get the natural frequencies and damping ratios. The accuracy of the parameters is verified by synthesizing the CPSD from the extracted natural frequencies and residues and comparing it with the original CCor and CPSD. The CEM in original form developed to use frequency response function (FRF), which can be written in terms of receptance H_{jk} (displacement at point j due to a force at point k) for a linear, viscously damped system with N degree of freedom (DOF) can be given by the following expression (Maia 1988). In the present study cross spectral density function is used instead of FRF, as we have only responses available for parameter extraction.

$$H_{jk}(\omega)=\sum_{r=1}^{N}\left(\frac{{}_rA_{jk}}{\omega_r\,\xi_r+i\left(\omega-\omega_r\sqrt{\left(1-\xi_r^2\right)}\right)}+\frac{{}_rA_{jk}^{*}}{\omega_r\,\xi_r+i\left(\omega+\omega_r\sqrt{\left(1-\xi_r^2\right)}\right)}\right) \tag{1}$$

where, ω_r is the natural frequency, ξ_r is the damping ratio, ${}_rA_{jk}$ is the residue corresponding to each mode *r,* and the asterix (*) denotes complex conjugate quantity. The impulse response function/cross correlation function can be written as

$$h_{jk}(t)=\sum_{r=1}^{2N}{}_rA_{jk}\,e^{s_r t}=\sum_{r=1}^{2N}A_r'\,V_r \text{ and } {}_{r+N}A_{jk}={}_rA_{jk}^{*},\quad V_r=e^{s_r\cdot\Delta t} \tag{2}$$

In Eq. 2, $s_r=-\omega_r\,\xi_r+i\omega_r'$ and $\omega_r'=\omega_r\sqrt{\left(1-\xi_r^2\right)}$. The CCor data points shifted one time interval each is loaded in the Hankel matrix form (Inglesias 2000) given by

$$\underset{M\times n}{[\boldsymbol{h}]}\ \underset{n\times 1}{\{\boldsymbol{\beta}\}}=\underset{M\times 1}{\{\boldsymbol{h}'\}} \tag{3}$$

where β_i is the auto regressive coefficient. If L is the number of data points in the CCor function, then $M=L/2$, n = 1+ Order of the polynomial equation to be formed, and h_i are the CCor data point. In Eq. 3, $[\boldsymbol{h}]$ and $\{\boldsymbol{h}'\}$ are known and $\{\boldsymbol{\beta}\}$ is calculated in the least-square sense using pseudo-inverse technique. After calculating $\{\boldsymbol{\beta}\}$, it is used to calculate the roots V_r of the polynomial equation given below.

$$\beta_0+\beta_1V_r+\beta_2V_r^2+\beta_3V_r^3+\cdots+\beta_LV_r^L=0 \tag{4}$$

The natural frequencies are calculated using the relationship in Eq. 2,

$$R_r=\ln(V_r)=s_r\Delta t,\qquad f_r=\left|R_r\right|/2\pi\Delta t,\qquad \text{and}\qquad \xi_r=\sqrt{1/1+\left(\operatorname{Im}(R_r)/\operatorname{Re}(R_r)\right)^2} \tag{5}$$

where f_r and ξ_r are the frequency in Hz and the damping ratio, respectively.

Ibrahim Time Domain Method

This method uses free decay of acceleration responses to extract frequency and damping ratios (Ibrahim and Mikulcik 1973). The CCor is used to extract modal parameters since they are inverse FFTs of CPSDs that already have been averaged, reducing the noise (Maia 1988). The parameter extraction involves forming the square matrix after manipulating CCor data sets and solving the standard eigenvalue problem to get the natural frequencies and damping ratios. During free vibration the system is assumed to be described by the following equation

$$[\boldsymbol{M}]\{\ddot{\boldsymbol{x}}\}+[\boldsymbol{C}]\{\dot{\boldsymbol{x}}\}+[\boldsymbol{K}]\{\boldsymbol{x}\}=\boldsymbol{0} \tag{6}$$

where $[\boldsymbol{M}]$, $[\boldsymbol{C}]$ and $[\boldsymbol{K}]$ are the mass, damping and stiffness matrices of the structure, respectively, and

$\{\boldsymbol{x}\}$ is the displacement vector. The dots denote derivative with respect to time. The solution to this equation can be determined by standard techniques to yield the natural frequencies and damping ratios.

The responses of an *N*-degree of freedom structure at *i*-th DOF and at time-step t_j can be expressed by modal combination as:

$$x_i(t_j) = \sum_{r=1}^{2N} p_{ir} e^{s_r t_j} \tag{7}$$

where p_{ir} is the *i*-th component of the eigenvector. In the present study, the measured CCor data are arranged in a Hankel matrix form. The data sets are arranged in two matrices each having shift of one time interval, Δt, as given below, so as to obtain the system matrices in double least square sense (Ibrahim and Mikulcik 1988).

$$\left[\boldsymbol{\Phi}\right] = \left[\boldsymbol{h}_0 \quad \boldsymbol{h}_1 \quad \boldsymbol{h}_2 \quad \cdots \quad \boldsymbol{h}_{m-1}\right]^T \text{ and } \left[\hat{\boldsymbol{\Phi}}\right] = \left[\boldsymbol{h}_1 \quad \boldsymbol{h}_2 \quad \boldsymbol{h}_3 \quad \cdots \quad \boldsymbol{h}_m\right]^T \tag{8}$$

The square matrix is formed using these two data matrices in the double least square sense as follows.

$$\left[\boldsymbol{A}_S\right] = \frac{1}{2}\left[\left(\left[\hat{\boldsymbol{\Phi}}\right]\left[\hat{\boldsymbol{\Phi}}\right]^T\right)\left(\left[\boldsymbol{\Phi}\right]\left[\hat{\boldsymbol{\Phi}}\right]^T\right)^{-1} + \left(\left[\hat{\boldsymbol{\Phi}}\right]\left[\boldsymbol{\Phi}\right]^T\right)\left(\left[\boldsymbol{\Phi}\right]\left[\boldsymbol{\Phi}\right]^T\right)^{-1}\right] \tag{9}$$

After obtaining the square matrix $\left[\boldsymbol{A}_S\right]$ in Eq. 9, it is solved as a standard eigenvalue problem, which gives *m* pairs of eigenvalue and eigenvectors. The standard relationship between the eigenvalue $\beta + i\gamma_r$, and the eigenvalues of Eq. 6, are used to calculate the natural frequencies and damping ratios as

$$\beta + i\gamma = e^{s_r \Delta t} = V_r, \quad R_r = \ln(V_r) \tag{10}$$

$$f_r = \left|R_r\right| / 2\pi\Delta t, \quad \text{and} \quad \xi_r = \sqrt{1 \Big/ \left[1 + \left(\text{Im}(R_r)/\text{Re}(R_r)\right)^2\right]} \tag{11}$$

Eigen-Realization Algorithm (ERA)

The first step in ERA for modal parameter extraction is to formulate Hankel matrix **H**, from the discrete CCor data *h(t),* treating it as free response, where, *h(t)* is the cross correlation data obtained using $\ddot{\boldsymbol{x}}_{\boldsymbol{i}}(t)$ and $\ddot{\boldsymbol{x}}_{\boldsymbol{j}}(t)$ at time *t*, and $\ddot{\boldsymbol{x}}_{i}(t)$ and $\ddot{\boldsymbol{x}}_{j}(t)$ are the *i*-th and *j*-th floor acceleration response (time output signal) at time *t,* respectively (Juang and Pappa 1985). A singular value decomposition of $\mathbf{H}(0)$ is performed yielding to give

$$\mathbf{H}(0) = \mathbf{R}\boldsymbol{\Psi}\mathbf{S}^T \tag{12}$$

where $\boldsymbol{\Psi}$ is a diagonal matrix with the singular values in the diagonal, and the matrices **R** and **S** are square and unitary. The Henkel matrix can be used to obtain **A**, **B** and **C**, i.e. the system matrix, input matrix, and output matrix, respectively, of a state-space realization of the system. The natural frequencies can be obtained directly from the system matrix **A**, mode shapes are obtained by multiplying the eigenvectors of **A** with the output matrix **C**.

Torsionally Coupled Multistory Building

Many multi-story buildings have the following features: (1) All floors of the building have the same geometry in plan and same location for columns and shear walls, and (2) The ratio of the story stiffness in the *x* and *y* directions is same for all stories. With reference to the building idealization consisting of rigid floors supported on massless axially inextensible columns and walls, the special class of torsionally coupled buildings as shown in Fig. 1 is assumed to satisfy the following: (1) The principal axes of resistance for all the stories are identically oriented along the *x* and *y* axes shown, (2) The center of mass of all floors lie on one vertical axis, (3) The center of resistance of the stories lie on another vertical axis, i.e., static eccentricities e_x and e_y are the same for all stories, (4) All floors have same radius of gyration, *r*, about the vertical axis through the centre of mass, and (5) Ratios of the three stiffness quantities, i.e. translational stiffness in *x* and *y* directions, K_{xt} and K_{yt}, and torsional stiffness $K_{\theta t}$ are same for all the stories. The stiffness ratios can be expressed as

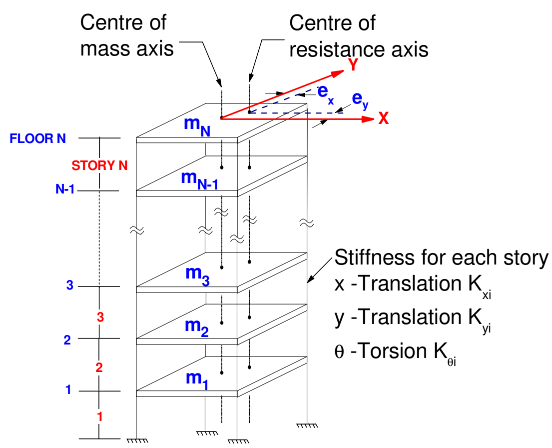

Figure 1. Torsionally coupled multi-story building.

$$\beta_y = \frac{K_{yt}}{K_{xt}} \text{ and } \beta_t = \frac{K_{\theta t}}{r^2 K_{xt}} \tag{13}$$

For the above class of torsionally coupled *N*-stories buildings, each floor has three degrees-of-freedom: *x* and *y* displacements of the centre of mass relative to the base, and rotation about the vertical axis. For floor *i*, these are denoted by u_{ix}, u_{iy} and $u_{i\theta}$, respectively. The undamped equations of motion for the building subjected to base excitations $\ddot{u}_{gx}(t)$ and $\ddot{u}_{gy}(t)$, assumed to be the same at all points of the foundation, may be expressed as

$$\begin{bmatrix} \mathbf{M} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{M} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{M} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{u}}_x \\ r\ddot{\mathbf{u}}_\theta \\ \ddot{\mathbf{u}}_y \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_x & -\frac{e_y}{r}\mathbf{K}_x & 0 \\ -\frac{e_y}{r}\mathbf{K}_x & \mathbf{K}_t & \frac{e_x}{r}\mathbf{K}_y \\ 0 & \frac{e_x}{r}\mathbf{K}_y & \mathbf{K}_y \end{bmatrix} \begin{Bmatrix} \mathbf{u}_x \\ r\mathbf{u}_\theta \\ \mathbf{u}_y \end{Bmatrix} = -\begin{Bmatrix} \mathbf{M}\,\mathbf{1}\ddot{u}_{gx} \\ \mathbf{0} \\ \mathbf{M}\,\mathbf{1}\ddot{u}_{gy} \end{Bmatrix} \tag{14}$$

In Eq. 14 the displacements vectors and mass sub-matrix are

$$\mathbf{u}_x = \{u_{1x} \quad u_{2x} \quad \cdots \quad u_{Nx}\}^T,\ r\mathrm{u}_\theta = r\{u_{1\theta} \quad u_{2\theta} \quad \cdots \quad u_{N\theta}\}^T,\ \text{and}\ \mathrm{u}_y = \{u_{1y} \quad u_{2y} \quad \cdots \quad u_{Ny}\}^T \tag{15a}$$

$$\mathbf{M} = diag\{m_1 \quad m_2 \quad \cdots \quad m_N\}^T \tag{15b}$$

in which m_i = lumped mass at floor *i.* All elements of column vector **1** are unity and the stiffness sub-matrices are given by

$$\mathbf{K}_x = \begin{bmatrix} (K_{x1}+K_{x2}) & -K_{x2} & & \mathbf{0} \\ -K_{x2} & (K_{x2}+K_{x3}) & -K_{x3} & \\ & & \ddots & \\ \mathbf{0} & & & K_{xN} \end{bmatrix} \tag{16}$$

The stiffness matrices may be expressed in terms of stiffness ratio as

$$\mathbf{K}_t = \beta_t\,\mathbf{K}_x \text{ and } \mathbf{K}_y = \beta_y\,\mathbf{K}_x \tag{17}$$

Using Eqs. 14 to 17, the building's natural frequencies and mode shapes are obtained by solving the eigenvalue problem of order 3*N*, where *N* is the number of floors in the torsionally coupled multi-story building. Because of the existence of eccentricity, the vibration modes may be closely-spaced, leading to the difficulty in identification of modal parameter.

Mode Shape Interpolation and Sensor Placement

The mode shape interpolation scheme for general torsionally coupled buildings has been proposed by (Uneg 2000), which relys on the shear mode shape ordinates at unmeasured floor levels. In the present investigation, the shear mode shape ordinates are estimated at unmeasured floor levels of an uncoupled planar system and later mode shapes of torsional building are derived based on the methodology proposed by Kan and Chopra (1997). Using the known data for the first and *N*-th floor corresponding to *i*-th mode, a set of $(N-2)\times(N-2)$ matrix equations may be obtained for the *i*-th mode (Chakraverty 2005, Yuan et al. 1998). The iterative procedure to determine the eigen-properties can be used to evaluate the first six mode shapes of a torsionally coupled building using the procedure explained below.

Mode Shape Estimation for a Torsionally Coupled Building

The mode shapes of a torsionally coupled building are estimated after extracting the mode shape of its corresponding uncoupled shear model. Hence, the first two frequencies of shear building have to be calculated from the identified natural frequencies of the torsionally coupled building (Ewins 1984, and Wenzel and Pichler 2006). The ratio of translational frequency of torsionally coupled building and its corresponding frequency of the uncoupled shear building, called Translational Frequency Ratio (**TFR**), can be expressed as

$$\mathbf{TFR} = \omega_{Tx}/\omega_x \tag{18}$$

Where, ω_{Tx} is the translation frequency of torsionally coupled building in *x*-direction and ω_x is the corresponding frequency of the shear building. Graphs of **TFR** can be developed for different values of e_x/r and e_y/r, and used to determine the natural frequencies of torsionally coupled buildings.

The frequencies in the first two modes of uncoupled shear building are required in order to extract the mode shape coefficients at the unmeasured DOFs. The frequencies and mode shapes of the system are determined using the procedure proposed by Yuan et al. (1998).

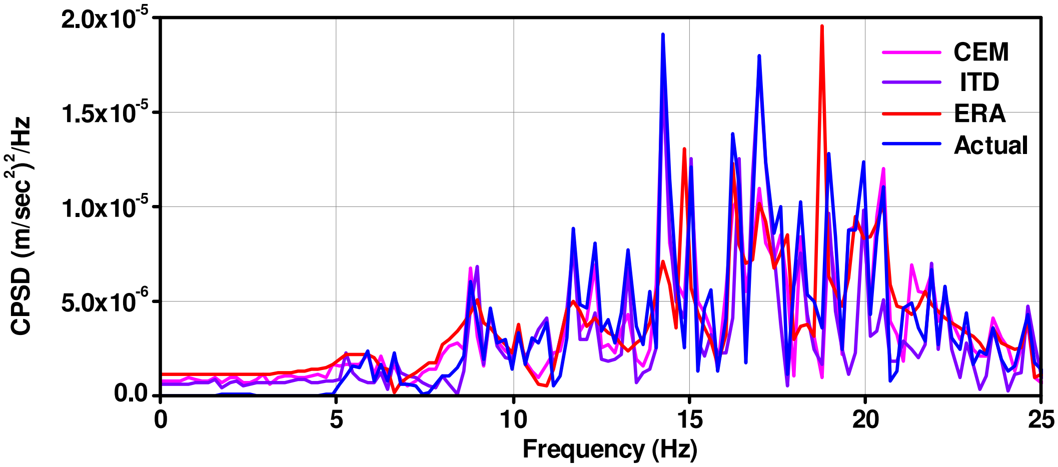

Figure 2. Synthesized response function for example building.

Numerical Verification

An eight story (N = 8) torsionally coupled building (as described in Fig. 1) has been considered to evaluate the proposed procedure for modal parameter extraction and mode shape interpolation. The lumped mass at each floor is m_i =180,000 kg, translational stiffness in x-direction of eight stories is K_x = 9.0x10^8 N/m for the first story and 8.0x10^8 N/m for the other stories; for each story β_y =1.3225 and β_t =1.6900; the eccentricities for each floor are e_x / r = 0.2 and e_y / r = 0.3, and the height of each story is h. The damping matrix of the form Caughy damping series known as Penzien-Wilson damping (Hart 1999) has been derived with a damping ratio for each natural mode of vibration of ξ = 0.05. The chosen value of eccentricity ratio represents significant eccentricity between centers of mass and resistance (for a rectangular plan, e_x / r = 0.3 represents eccentricity of 8.7 % to 12.2 % of the longer plan dimension). The structure has been subjected to El-Centro (1940) base excitation in x-direction. In order to verify the mode shape interpolation scheme, it is assumed that the shear mode shape ordinates at first floor and top floor for the first two translational modes are known. Two cases are considered: (1) Exact or with no noise (NSR=0%) in the data, and (2) Data with 20% noise (NSR=20% RMS) in recorded signal representing significant noise in the data. It may be noted that a NSR of 20% RMS value leads to a noise of about 22 dB. The modal responses are determined on all floors. The CCor of top floor with respect to first floor responses are used in the identification process of all three methods discussed earlier. The CCor are evaluated by taking the inverse FFT of Cross Power Spectral Density function using MATLAB software (Cobb 2004). The first six identified modal frequencies and damping ratios using CEM, ITD and ERA method corresponding to data with 20% noise are given in Table 1. It can be observed that the frequency is identified very accurately. The identification of damping ratio is not as good as that of frequency, but is still acceptable.

To evaluate the effectiveness of the mode identification methods, the CPSD and CCor were synthesized starting from lowest to highest model order. Fig. 2 shows the synthesized cross power spectral density function by all three methods. In each synthesis the errors between actual and synthesized response function is evaluated. As expected, with the increase of model order the error decreases, but too many calculation modes appear in the result, leading to difficulty in identifying the actual modes. It has been observed that the peaks in the response function (CPSD) include frequencies which are well spaced. Some closely spaced frequencies do not have peaks in the response function and hence are difficult to identify by just identifying the peaks of response function.

The frequency stability diagram shown in Fig. 3 has been used to identify actual modes among the calculated modes. The frequencies that appear in each response model can be identified using this figure. The frequency stability diagram is drawn to identify the stable modes and also to identify the closely spaced modes where response functions may not have proper peaks (Mohanty and Rixen 2006) It can be noted from Fig. 3(a) that the CPSD does not have noticeable peaks up to frequency range of 5 Hz. However the stability diagram clearly indicates that natural frequencies of the structure are present in this frequency range.

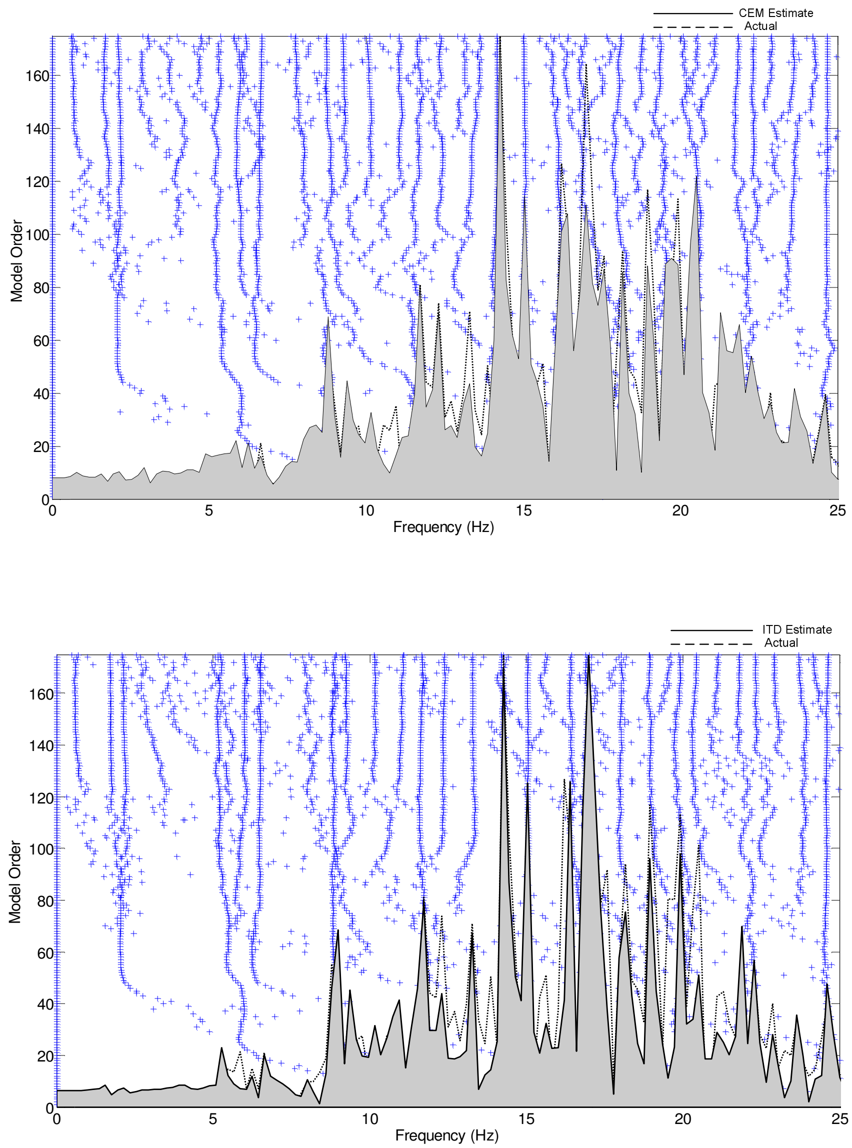

Figure 3. Frequency stability diagram, (a) CEM method, (b) ITD method.

These are shown by a vertical line formed by symbols dropping down from the top in Fig. 3 (a) and (b). It is observed that the closely spaced frequencies can be identified at higher model order. The CPSD is superimposed on frequency stability diagram to give clear idea of response of torsionally coupled building, which possesses natural frequencies very close to each other. Also the response function many not have peaks corresponding some of closely spaced modes. For example, the peak corresponding to 2.587 Hz does not appear in CPSD function plot

The CEM, ITD and ERA methods have been able to identify all frequencies using higher model order in noise-free case (Fig. 2). With 20% noise case, except for the second natural frequency, first few frequencies have been identified accurately. This shows that the CEM, ITD and ERA method are effective in identifying closely spaced frequencies and can be used for modal property identification of torsionally coupled system. The first three mode shapes calculated (Hegde and Sinha 2006) for both the cases are shown in Fig. 4. Similar accuracy is also found for other five mode shapes. It is seen that there is very good agreement between the calculated and actual mode shapes even with 20% noise in the top and first floor shear mode shape values. It is further seen that the ERA method identified all frequencies within the range of interest, and also the damping ratios are comparable to the actual one. Hence ERA can be used for parameter identification from Cross Spectral Density/Cross Correlation functions.

Table 1. Frequency and damping ratio estimates with 20% noise in the signal.

Mode	Natural Frequency (Hz)				Damping Ratio (% Critical)			
	Exact	CEM	ITD	ERA	Exact	CEM	ITD	ERA
1	1.845	1.855	1.880	1.828	5.00	6.40	6.54	7.70
2	2.207	*	*	2.210	5.00	*	*	*
3	2.740	2.587	2.575	2.636	5.00	8.73	3.68	6.12
4	5.470	5.494	5.443	5.456	5.00	4.80	4.90	5.21
5	6.542	6.600	6.620	6.610	5.00	7.88	3.52	*
6	8.122	8.914	8.971	8.976	5.00	5.87	5.40	5.12

*Not Identified

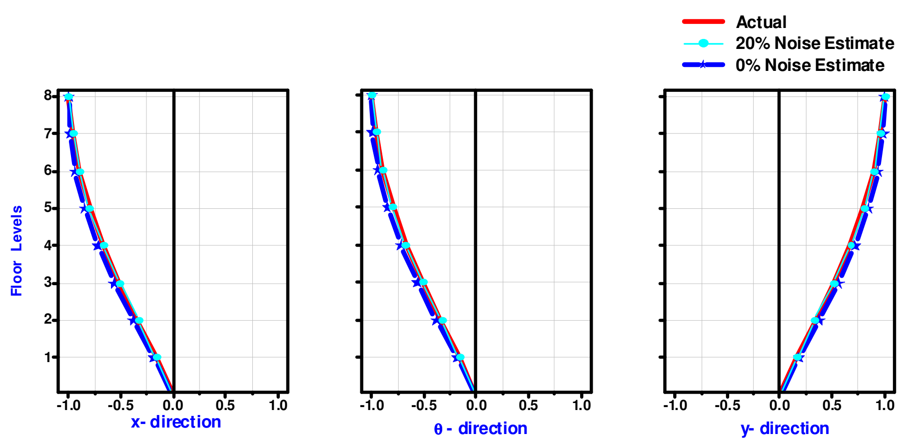

Figure 4. Estimated and actual mode shapes of example torsionally coupled building.

Conclusions

In this investigation, the cross correlation data of recorded acceleration responses of a torsionally coupled building have been used for modal parameter extraction. It has been shown that the floor vibration due to base excitations when measured at the top and the first floor are sufficient to determine the dominant modal properties for torsionally coupled buildings. Since the mode shapes ordinates are identified at only measured degrees of freedom, a mode shape interpolation technique based on uniform shear mode criteria has been extended to torsionally coupled building. The relationship between translational frequencies of torsionally coupled building and its corresponding uncoupled shear model, termed as the translational frequency ratio, has been used to extract the mode shapes. The numerical results indicate that the mode identification methods, viz. CEM, ITD and ERA, are effective in identifying closely spaced frequencies. For torsionally coupled buildings, the dominant modal parameters are accurately extracted with only two floor acceleration measurements even with high noise levels. Since the dominant frequencies, damping ratios and the mode shapes are estimated accurately, the unmeasured floor responses can be determined with low error.

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