Vertical System Identification of a 52-Story High-Rise Building Using Seismic Accelerations

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ABSTRACT

In this study, various system identification approaches are utilized to estimate the dominant, vertical-component modes of a 52-story, steel, moment-and-braced frame building in downtown Los Angeles resulting from vertical seismic accelerations. Tall buildings exhibit complex three-dimensional responses during an earthquake due to the varying material and geometric properties along the building's height. For high-rise buildings, the dynamic response during shaking events is often sensitive to multiple vibration modes, and multiple-mode structural behavior under horizontal ground motion has been extensively studied. However, the vertical component of ground motion can also excite higher modes and vertical-polarity propagating seismic waves. Their effects are seldom studied due to the scarcity of data. Still, they are important because they can provide information on the axial loads on columns or stresses at floor slab connections. The 52-story high-rise, with its dense triaxial sensor array distributed vertically along the height of the building, provides a suitable basis for examining vertical responses. System identification is performed using state-space methods with low-amplitude earthquake data. Given the high spatial density of the building recordings, we show how we can detect modal characteristics and identify the type of deformation that can occur when considering the vertical component of seismic responses.

INTRODUCTION

An office building in downtown Los Angeles was instrumented with an embedded 60-station (180 channels) accelerometer network. The 52-story high-rise office building has 60 triaxial sensors, one per floor that starts at the lowest basement level and extends to nearly every floor along the building's height. The accelerometer sensors along the floors of the building are a component of the Community Seismic Network (CSN), which currently consists of approximately 1000 stations densely spaced around the Los Angeles, California area. The CSN sensor array consists of relatively inexpensive

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triaxial MEMS accelerometers, which record vibration data continuously to the cloud [1, 2, 3]. These sensors have been deployed at several locations at ground level, as well as upper floors of mid- and high-rise buildings [4, 5, 6].

It is known that structures experience earthquake shaking in both the horizontal and vertical direction during an earthquake. Most structural analysis involves horizontal ground motions and little attention has been given to the vertical response of structures caused by the vertical component of ground motion. Large vertical amplitudes are not as common as the large horizontal amplitudes seen in strong-motion earthquakes, nonetheless, relatively large vertical amplitudes can be seen even for smaller magnitude earthquakes. The embedded sensor network from CSN provides a unique platform that allows for the use of small-magnitude earthquake vibrations, particularly focusing on the vertical component in this paper, for system identification of structural modal properties.

Since system identification uses data to identify modal properties such as natural frequencies, damping, and mode shapes of a system, it has been adapted for structural engineering applications to estimate structural parameters, such as stiffness and damping, which have been used to perform model updating for structures such as bridges, roads, and buildings [7, 8, 9]. System identification models have also been developed for structural health monitoring of structures to identify damage [10, 11]. With the increased complexity of multivariable structural systems, it has become particularly appealing to use state-space model representations of systems for system identification. Of the many existing subspace system identification algorithms, subspace state-space system identification (N4SID) is utilized in this paper. N4SID is numerically reliable in the estimation of state-space matrices using measured input and output data.

The objective of this study is to use subspace state-space system identification to investigate the structural response of a high-rise building to ground motions with large vertical amplitudes. Given the high spatial density of the building recordings, we show how we can detect modal characteristics and identify the type of deformation that can occur in this tall building.

52-STORY BUILDING AND ITS MONITORING SYSTEM

52-Story High-Rise Building

Constructed in 1988, the 52-story, 717-foot-height office building is one of the few high-rise buildings in downtown Los Angeles exceeding 700-ft [12]. The building comprises of a dual lateral force-resisting system that consists of an interior steel braced frame core with outrigger beams at various levels to tie the core to the perimeter structural column framework [4]. The beams act as moment-resisting beams to reduce the lateral deflection and base moment. In addition, there are five basement levels. Figure 1 shows a typical floor plan and the orientation of the seismic framing system. The floor and roof diaphragms consist of cast-in-place concrete slabs over metal deck. Additional building details are available in [4].

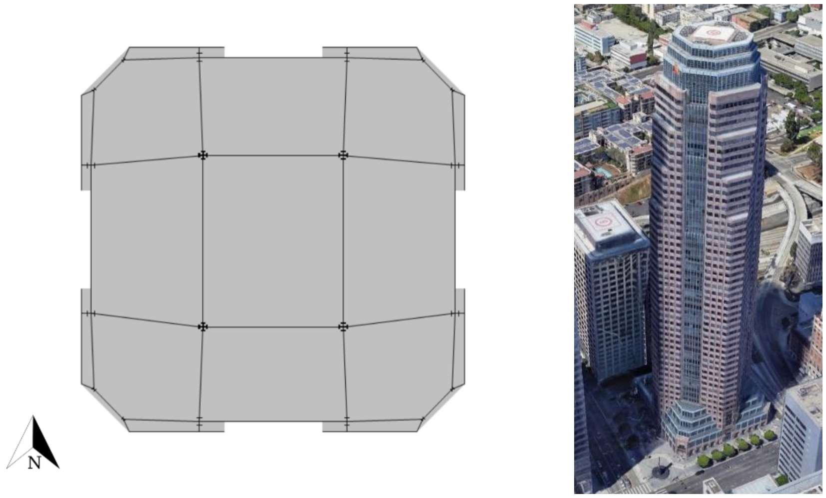

Figure 1. (A) Typical floor plan (floor 27) and (B) 3D image of the 52-story high-rise building in downtown Los Angeles (image from Google Earth)

Earthquake Data

The CSN sensor network is continuously recording acceleration data and has recorded several earthquakes, including the M4.2 earthquake in Pacoima, California that took place on July 30, 2020, at 4:29 p.m. local time. As reported by USGS Earthquake Hazards Program (2021), the epicenter was located approximately 20 miles from the 52-story high rise building [13]. CSN raw data collected for this earthquake show a maximum absolute acceleration of 1%g recorded at level two. Figure 2 shows the acceleration time series for the Pacoima earthquake along the building height after detrending to remove any signal bias and arbitrarily normalizing each acceleration time series by the same constant in order to show comparable relative amplitudes.

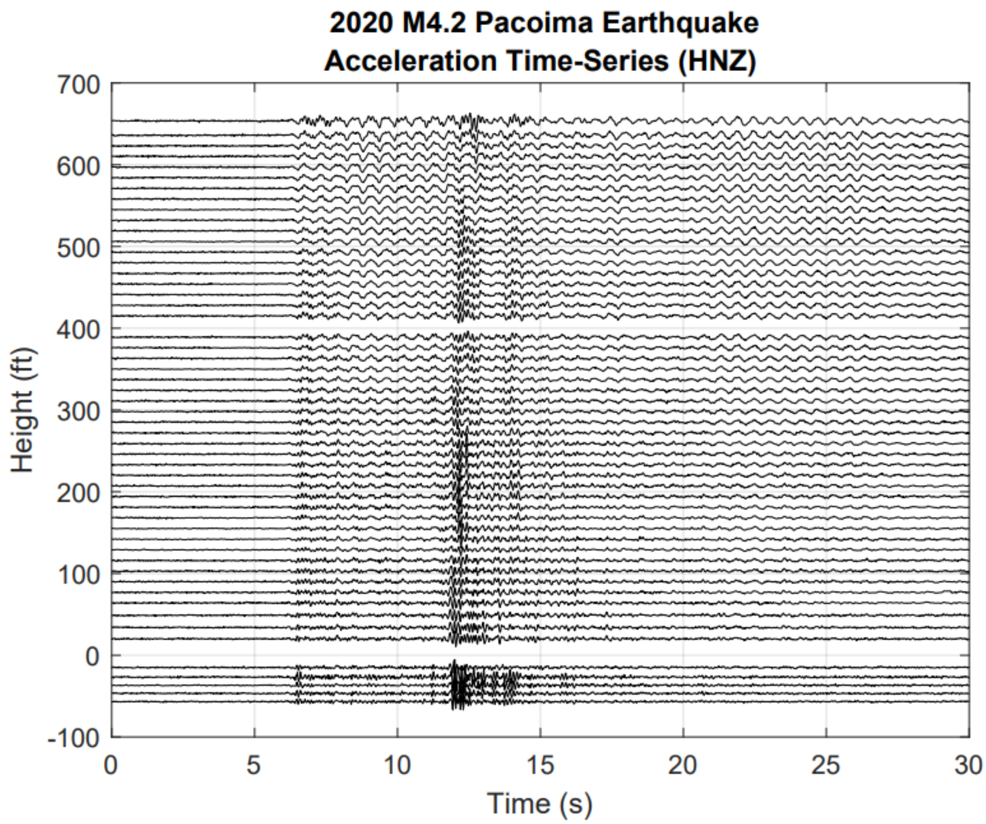

Figure 2. Story accelerations from the vertical component of CSN sensors in a 52-story building in downtown Los Angeles. Acceleration amplitudes are normalized by the same arbitrary constant to show amplitudes as a function of height (in feet).

SYSTEM IDENTIFICATION AND MODAL PROPERTIES

Subspace State-Space System Identification

System identification is a methodology that aims to approximate dynamic models of systems based on observed input and output data. Subspace methods of system identification build upon realization theory and focus on estimating the state vectors by making projections of certain subspaces generated from input-output data and solving the least squares problem for state-space realizations. It is known that a linear time-invariant (LTI) system can be represented by a set of first-order differential equations. Assuming the dynamical system's model structure is a discrete-time LTI system, the state-space formulation is given by

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

where A is the state matrix, B is the input matrix, C is the output matrix, and D is the throughput matrix. Using (1), the matrix input-output equations can be written as

$$\begin{bmatrix} y(t) \\ y(t+1) \\ \vdots \\ y(t+k-1) \end{bmatrix} = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{k-1} \end{bmatrix} x(t) + \begin{bmatrix} D & CB & \dots & \\ CB & D & & \\ \vdots & \ddots & \ddots & \\ CA^{k-2}B & \dots & CB & D \end{bmatrix} \begin{bmatrix} u(t) \\ u(t+1) \\ \vdots \\ u(t+k-1) \end{bmatrix} \tag{2}$$

Constructing block Hankel matrices for the input data $u(t)$ and output data $y(t)$ allows for the use of linear algebra techniques to solve the differential equations of (2) [14]. In particular, the subspace state-space system identification (N4SID) algorithm developed by Van Overschee and DeMoor shows that through oblique projection, the state vector is a basis of the past and future input and output matrices [15]. Therefore, using block Hankel and shifted block Hankel matrices for representation of past and future input and output, the state vector $x(t)$ can be computed using singular value decomposition (SVD) of past and future subspace configuration. After computing the state vector $x(t)$, matrices A, B, C, and D are solved by using the least-squares technique. More details on the mathematical formulation of N4SID algorithm can be found in [14, 15].

Modal Properties of 52-Story High-Rise Building

The state-space model obtained from N4SID is effective in describing the dynamic behavior of the structure. With the system matrices, modal parameters such as natural frequencies (f), damping ratios (ζ), and mode shapes (ϕ) can be obtained. Using the complex eigenvalues (λ) and eigenvectors (ν) of the system matrix A, and assuming small and classical damping, the modal properties of the undamped system can be approximated as in (5) [16, 17].

$$f_n = |\lambda_n|/2\pi, \qquad \zeta_n = Re(\lambda_n)/2\pi f_n \qquad \phi_n = |C\nu_n| \cdot sgn(Re(C\nu_n)) \tag{5}$$

where n is the n-th mode, $Re(\cdot)$ is the real part, and $sgn(\cdot)$ is the algebraic sign.

The N4SID algorithm has been implemented in the System Identification Toolbox of MATLAB (2023) and is used for results of modal identification of the 52-story building. To simplify analysis, it is assumed the building is a LTI system. For data pertaining to the Pacoima earthquake, the excitation signal used as the known input vector is set to be the acceleration measurement closest to the ground level on the second floor. Fourier spectra were obtained by computing the Fast Fourier transform (FFT) of the 120 second acceleration time-series containing the seismic signal. Figure 3 shows the smoothed Fourier spectra of the three-component acceleration records after removing individual means from the recording. The spectra show the excitation of lower frequencies particularly in the vertical (HNZ) direction during this earthquake.

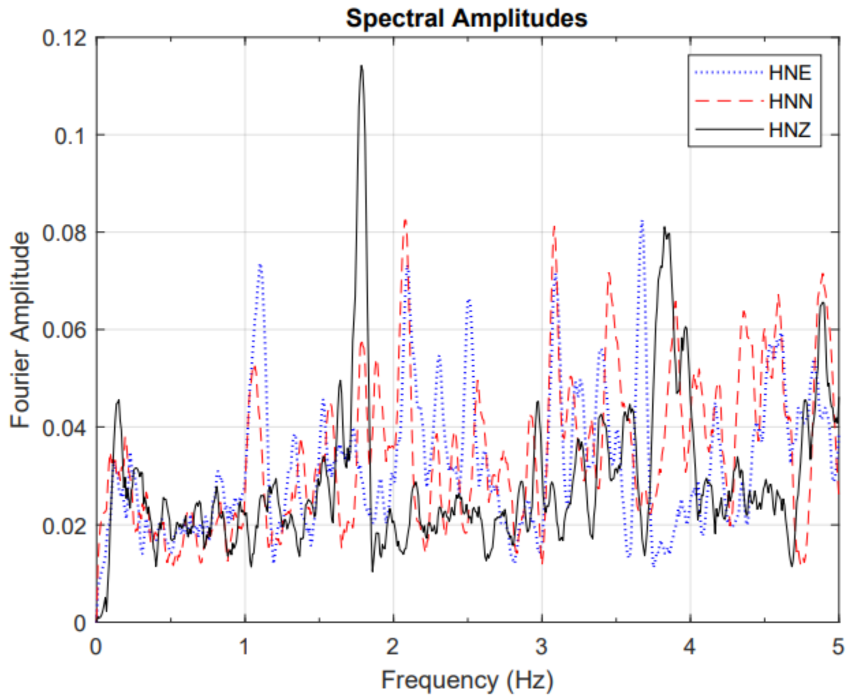

Figure 3. Smoothed Fourier spectra of the three components, horizontal directions HNE and HNN and vertical direction HNZ, of floor two for the 2020 Pacoima earthquake.

For response or output vectors, the remaining upper floor acceleration measurements are used. Basement level measurements are not used since the focus is on structural behavior above ground level. For implementation of the N4SID algorithm, the order of states to consider must be determined, which can be a challenging problem the more degrees of freedom you have. Only focusing on the vertical degrees of freedom (DOF), for floors two to fifty-two, the 52-story building is considered a 50-DOF system for our purposes. At minimum, model order greater than the number of degrees of freedom is needed. Due to inherent measurement noise, higher model order is typically needed to extract as many stable modal parameters as possible. To distinguish stable modes from modes that are not consistent with increasing model order, stability criteria are set to focus on changes in estimated frequencies, damping ratios and modal assurance criterion (MAC) with increasing model order. Stability plots are created using tolerances:

$$\Delta f < 1\%, \qquad \Delta\zeta < 50\%, \qquad MAC > 99\% \tag{6}$$

Figure 4 displays the stability plot for model identification using data from the Pacoima earthquake with red circles for stable modes determined by tolerance criteria from (6).

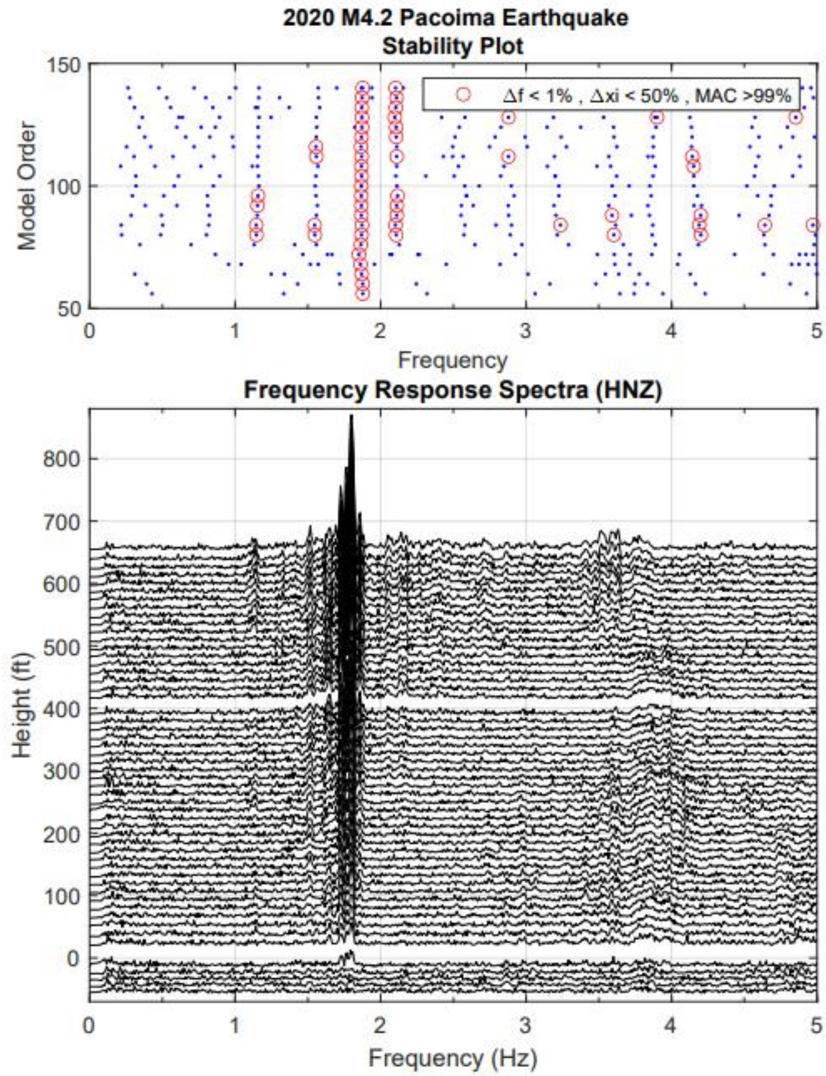

Figure 4. Stability plot for system identification results from recorded responses to the Pacoima earthquake with FFT overlay of floor 2. The y-axis represents the selected model order.

There is a clear dominant coherent pattern of stable natural frequency at around 1.86 Hz. It is important to note that the identified mode shape vectors that can be determined from the SID results are only identifiable at measured DOF. Figure 5 shows the resulting mode shape, arbitrarily scaled, associated with the first fundamental natural frequencies detected of 1.86 Hz. This is a simple 2-D elevation view to capture the basic overall vertical deformation behavior of the floor levels. The type of deformation seen is either extending vertically by a positive amount or compressing vertically by a negative amount. This type of mode can be considered a compressional vertical mode. For other modes detected like the one at about 2.1 Hz, the behavior is not all positively/negatively extending and compressing at each floor level. This can be due to contamination from a horizontal mode or a combination of horizontal and flexural motion. A fifth translational mode in the North-South direction at around this frequency was observed for the 52-story building in [4].

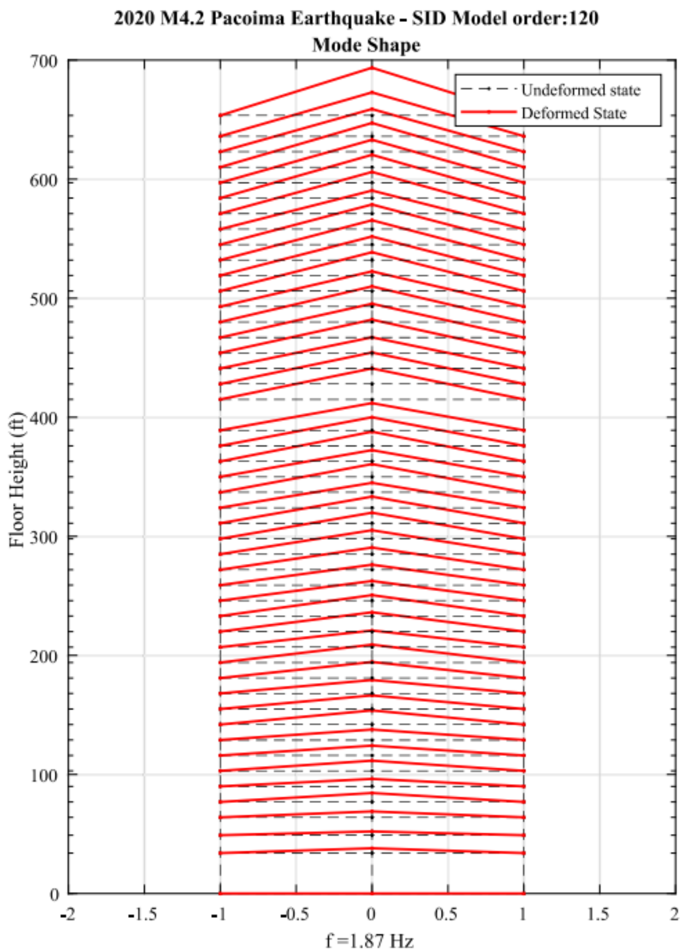

Figure 5. Mode shape results from system identification results for natural frequency of 1.86 Hz.

CONCLUSION

Subspace state-space system identification (N4SID) is tested for its effectiveness in capturing dominant modes excited using the vertical component earthquake data for a 52-story high-rise building in downtown Los Angeles. This mode consists of compressional and extensional motions in the vertical direction, caused by overall axial extension of columns. Axial loads have significant effects on the ductility of columns. For lateral systems such as reinforced concrete columns that typically do well under confinement, the extension of columns can cause reduction in ductility and overall performance of columns. In addition, differences in vertical stiffness of inner core and outrigger beams on joints caused by the extension and compression of columns can cause increased stress among beam-column or slab-column critical points which can be damage-inducing for some types of earthquake scenarios.

Further studies using data from other earthquake events that exhibit large vertical amplitudes are needed to fully capture other dominant modes that can arise for the high-rise building due to the vertical components of ground motion. Future work will concentrate on using SID results and finite element modeling of the tall building to understand the type of deformations and stress transfers that can occur for higher modes in the vertical direction.

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