16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING
THESSALONIKI 18 - 21 JUNE 2018

STRUCTURAL HEALTH MONITORING; COMPARISON OF SYSTEM ID TECHNIQUES FOR A 3-STORY FRAMED BUILDING

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ABSTRACT

Recent structural health monitoring has focused on using an ultra-low forced vibration technique (UL-FVT) for system identification. In the UL-FVT, a small, portable linear shaker is used to apply an almost trivial harmonic force (typ. 30 lb/133 N) to the building structure. At resonance, the harmonic force produces a measurable structural dynamic response which can be used to determine the natural frequencies, mode shapes and damping ratios. At present, the upper limit of building size successfully tested using UL-FVT is a 5-story, 180,000 ft^2 (18,000 m^2) reinforced concrete library building. Extending UL-FVT to larger structures would require a larger, likely non-portable, shaker. As an alternative, it was decided to investigate application of the stochastic subspace identification (SSI) technique. This technique lends itself to determine the desired dynamic properties, based on ambient vibration measurements, where the vibration is caused by random ambient loading. This paper compares dynamic properties determined by UL-FVT and SSI. Initially, a comparison is made for a 3-story laboratory model. Then, comparison is made for a real building, a 3-story concentrically braced steel-frame structure. The laboratory model was subjected to white noise simulating ambient vibration and to harmonic loading. Nine accelerometers (3 degrees of freedom per floor) were used. The braced frame structure was investigated for ambient vibration and forced vibration. Concurrent accelerometer measurements were made with 3 accelerometers at each floor.

Keywords: System Identification; Forced Vibration; Stochastic Subspace Identification

1. INTRODUCTION

Assessing the dynamic properties of a structure, such as natural frequencies, mode shapes and damping, is an integral component of structural health monitoring. The authors developed and implemented a new concept in forced vibration testing (FVT) for low-rise building structures using ultra-low force amplitudes. The goal of FVT is to experimentally determine a building's natural mode shapes, periods, and damping. This Ultra-Low Forced Vibration Test (UL-FVT) procedure is a drastic departure from FVT methods typically employed by other researchers. In a typical FVT, the accelerations produced by the experimental setup can be large enough to inflict damage on the building. Conversely, in the UL-FVT method, a small portable harmonic shaker is placed on the upper floors of the building. The resulting floor accelerations are recorded throughout the structure using highly sensitive accelerometers and sophisticated data acquisition software. The UL-FVT research allowed exploration of many aspects in relation to system identification, most recently damage detection in framed structures (Rosenblatt et al. 2017), complex building modeling, the effect of non-structural components, and wood diaphragm flexibility (Zavala et al. 2017).

At present, the upper limit of building size successfully tested using UL-FVT is a 5-story, 180,000 ft^2 (18,000 m^2) reinforced concrete library building. Extending UL-FVT to larger structures will require a

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larger, likely non-portable, shaker. As an alternative to UL-FVT, the application of the stochastic subspace identification (SSI) technique (Van Overschee and Moor 1996, Katayama 2005) is investigated in this paper. This technique lends itself to determine the desired dynamic properties, based on ambient vibration measurements, where the vibration is caused by random ambient loading. This paper compares dynamic properties determined by UL-FVT and SSI for a 3-story laboratory model and for a 3-story concentrically braced steel-frame building. The laboratory model was subjected to white noise simulating ambient vibration and to harmonic loading. The braced frame structure was investigated for forced vibration and ambient vibration. Concurrent accelerometer measurements were made with 3 accelerometers at each floor.

System identification methods such as Stochastic Subspace Identification (SSI) or Frequency Domain Decomposition (FDD) methods have existed for several decades (Brinker et al. 2000). Research has examined the accuracy of such methods on structural testing within controlled laboratory environments and on data collected with multiple samples over a prolonged period of time (Ubertini et al. 2016). Interest in these methodologies and their applications is increasing with the growing interest in structural health monitoring systems for damage detection in buildings. Output only methods introduce a simplification in data collection and allows for structural health monitoring for cases that do not lend themselves to forced vibration testing to determine modal response. While these methods may prove accurate under certain controlled stochastic conditions (Sadhu et al. 2017), the absence of input may cause greater error from noise in the output data. Understanding the accuracy and limitations of output-only system identification methods and algorithms in practical use on shake table models and building structures is essential knowledge to have in order to determine when and how to effectively implement them both in the lab and in the field (Xing 2011).

Output-only system identification methods were investigated using the 'System Identification Toolbox' (SIT) for modal analysis (Beskhyroun 2011). Several output-only techniques were applied: Peak Picking (PP), Frequency Domain Decomposition (FDD) and Stochastic Subspace Identification (SSI). PP and FDD were included for comparison purposes and do not provide damping estimates.

Figure 1. 3-story shake table model

2. LABORATORY STRUCTURE

2.1 Structural details and instrumentation

The laboratory shake table experiment was conducted on the 3-story structure shown in Figure 1. It has a 3.5 ft (1.2 m) by 3 ft (0.9 m) footprint and is 7.4 ft (2.25 m) tall. Floor and roof elevations are 24.75 in (629 mm), 56.75 in (1441 mm) and 88.75 in (2254 mm). The lateral system consists of 4 corner columns and 4 perimeter beams at each floor level made of 1.5 in x 2 in x 1/8 in (38 mm x 51 mm x 3.2 mm) rectangular aluminium tubing. Floor weights are 263 lb (119 kg) each. The geometry of the structure results in a fundamental period of vibration of approximately 0.3 sec which simulates a realistic period of vibration for a 3-story building. Three accelerometers were located at each floor level to pick up two translational and one rotational degrees of freedom. The structure was placed on a uniaxial shake table and the shake table accelerations (structure base) were also recorded. Only the three floor accelerations aligned with the input motion were reported on in this paper.

2.2 System Identification

Initially, the structure was subjected to FVT with steady state harmonic loading. Results from FVT are considered the 'reference' dynamic characteristics in this paper. Figure 2 shows the frequency response curves for excitation frequencies near the first mode response for each floor. Table 1 shows the resonant frequencies and damping ratios for the three translational modes. The damping ratios were determined with the Half-power band-width method (Chopra 2012). Figure 3 shows the mode shapes.

The shake table model was also subjected to random vibration testing. A random acceleration signal with 2 Hz to 30 Hz uniform frequency content was used as input motion. Data was recorded over several 60 second windows and then analyzed with the SSI method. Natural frequencies and damping ratios are given in Table 1. Mode shapes for SSI are shown in Figure 3 (PP and FDD shown for reference).

It is clear from Table 1 and Figure 3 that SSI provides reliable estimates of the natural frequencies and mode shapes. It is also seen that the damping ratios matched well for the 2nd and 3rd modes. The SSI method provided an unrealistically high damping ratio for the 1st mode. These results gave the authors confidence in implementation of SSI in the System Identification Toolbox for use for larger and more complex structures. It is noted that the results do not confirm the ability of the SSI method to identify torsional modes.

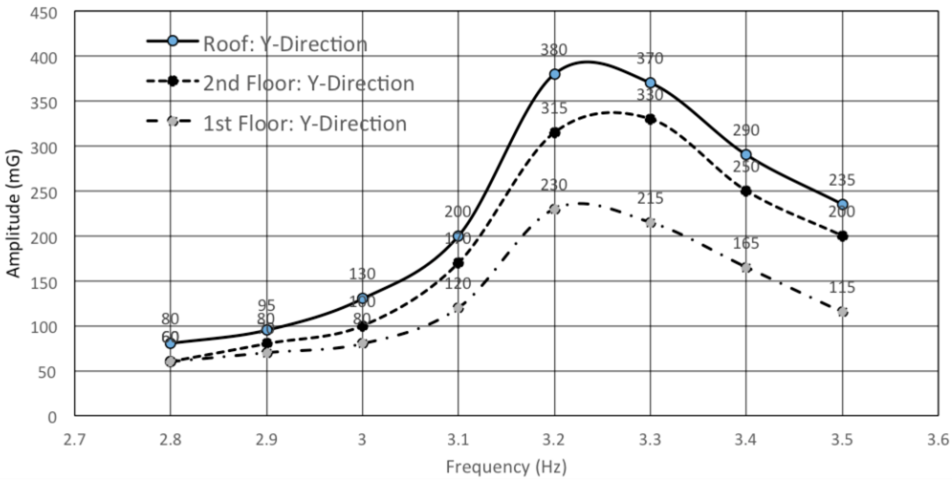


Figure 2. 3-story shake table model, 1st mode frequency response

Table 1. 3-story shake table model, natural frequencies and damping ratios

	FVT		SSI	
Mode	Frequency (Hz)	Damping ratio	Frequency (Hz)	Damping ratio
1	3.25	2.8%	3.29	11.3%
2	12.4	3.0%	12.68	3.4%
3	24.4	2.3%	24.38	2.1%

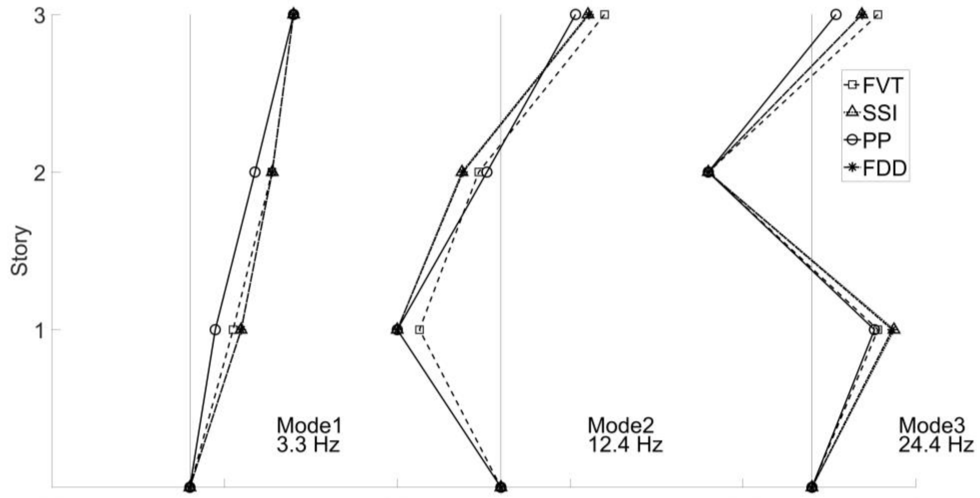


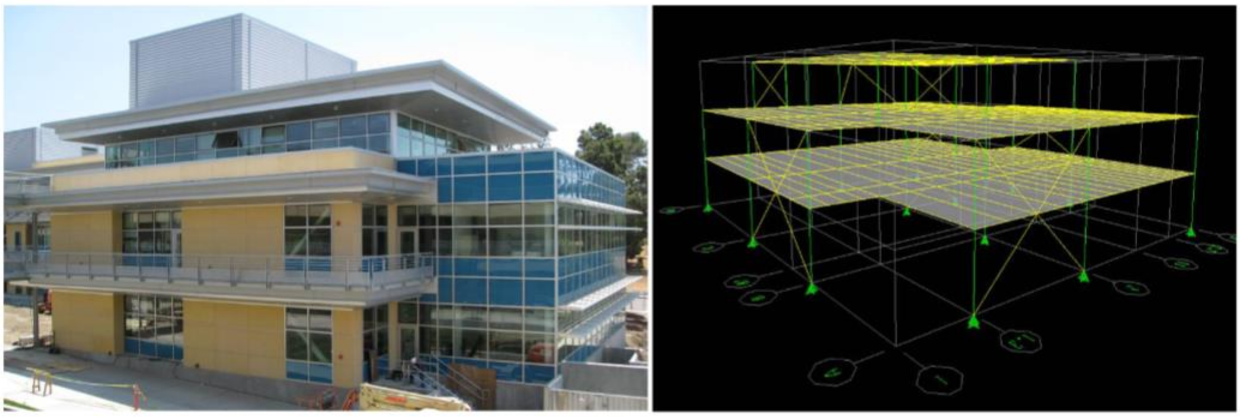
Figure 3. 3-story shake table model, mode shapes

3. 3-STORY BUILDING

3.1 Structural details and instrumentation

Figure 4 shows the three-story steel braced frame building subjected to forced vibration and ambient vibration testing. Its floor plan is irregular with an extent of approximately 85 ft. (26 m) in both the North-South and East-West directions. The roof is relatively light in comparison to the 2nd and 3rd floors because of its smaller area and being composed of lighter materials and finishes. The lateral system is visible in Figure 4(b) with bracing on all four sides. All floors are considered rigid diaphragms.

Three accelerometers were placed at each floor to pick up two translational and one rotational degrees of freedom assuming rigid floor diaphragm behavior. Two accelerometers were placed near the center of mass, one in the in N-S direction (y) and one in the E-W direction (x). The third accelerometer was offset 20 ft (6.1 m) and oriented in the y-direction (y_e), see Figure 5.



(a) photograph (b) structural model

Figure 4. 3-story steel braced frame building

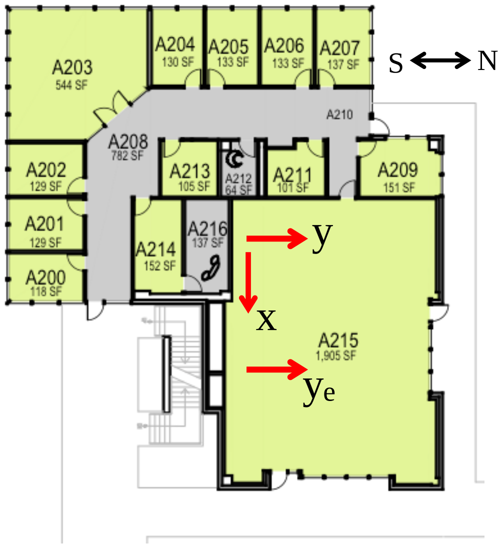


Figure 5. 3-story building, plan, accelerometer layout (typ.)

3.2 System Identification - UL-FVT

First, the building was subjected to UL-FVT testing with a 30-lb (133 N) force output mass shaker. Six modes shapes were identified from the frequency response curves shown in Figure 6. This required placing the shaker at strategic locations and orientations to maximize the response of the mode of interest and while minimizing the influence of adjacent modes. Once the resonant frequencies were established, the mode shapes were found from the peak acceleration responses and phase angles at resonance with tight filtering around the frequency of interest. Table 2 shows the natural frequencies and mode shape characteristics. Figure 7 shows axiometric and plan views of all UL-FVT mode shapes. Strong coupling between translation and rotation clearly reveals the irregularity of the structure.

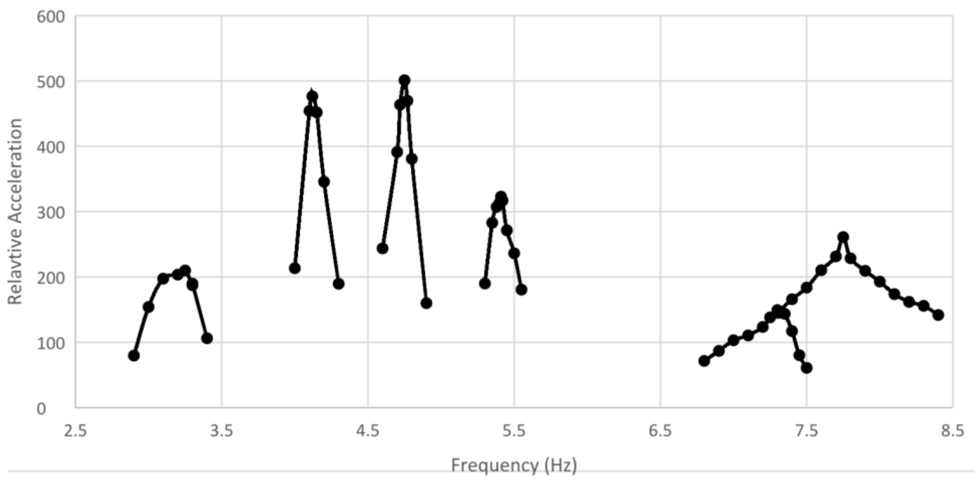


Figure 6. Frequency Response Curves from UL-FVT testing

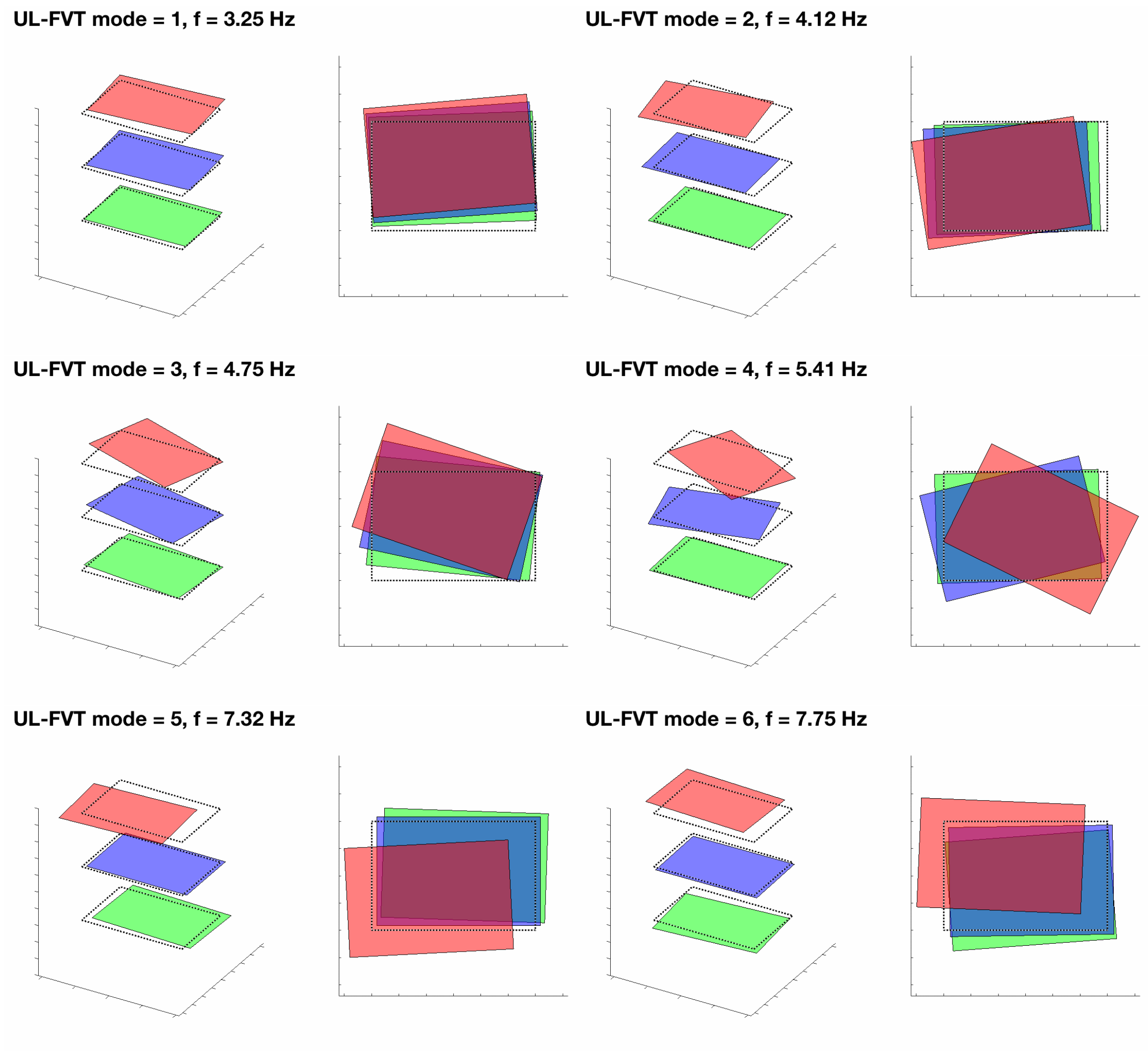


Figure 7. 3-story building, UL-FVT mode shapes

Table 2. 3-story building, UL-FVT results

Mode	Frequency (Hz)	Damping ratio (%)	Characteristic
1	3.25	5.4	Translation N-S
2	4.12	1.8	Translation E-W
3	4.75	1.6	Torsion 1
4	5.41	1.9	Torsion 2
5	7.32	2.7	Translation SW-NE
6	7.75	3.9	Translation NW-SE

3.3 System Identification - sine sweep

The building was subjected to a sinusoidal sweep ranging from 3 Hz to 8 Hz over a 10 minute interval using two parallel 30 lb mass shakers at the first floor. The shakers was positioned at the first floor in the center and oriented in both N-S (y) and E-W (x) directions. Two datasets were recorded in each shaking direction. SSI, PP and FDD calculations were carried out for the two orthogonal directions using N-S shaking results for y-direction modes shapes and E-W shaking results for x-direction mode shapes. Accelerations were recorded at a rate of 2000 Hz, decimated by a factor of 14 to a rate of 142.9 Hz and filtered through a 16th order Butterworth 2 Hz-10 Hz band-pass filter. SSI analysis was conducted, despite the non-random force input, based on a maximum system order of 30. Table 3 and Table 4 show identified frequencies for the three first modes in the x-direction and first 6 modes in the y-direction based on the first sweep dataset in each direction (results for 2nd sweep near identical). Numbers in parenthesis indicate the correlation with the 6 UL-FVT modes given in Table 2. Stable poles were identified with two methods SSI and SSI2 (Beskhyroun 2011).

As expected UL-FVT translational modes 1 and 2 were clearly identified by all methods in the y- and x-directions, respectively. UL-FVT modes 3 and 4 are torsion dominated modes and would likely only be picked up in the y-direction. UL-FVT mode 3 was only identified by the SSI2 method. UL-FVT mode 4 was identified by methods PP, FFD and SSI, but not SSI2.

As indicated above, sine sweeping was done at the first floor from a central location. Torsional modes 3 and 4 would likely have expressed clearer had the shakers been placed eccentrically in an additional sweep. Additionally, clearer identification could have been obtained with the shakers operating at the roof where the torsional modal responses generally achieve highest amplitude. UL-FVT translational mode 5 was captured by SSI in both x and y directions (but not by SSI2). UL-FVT translational mode 6 was captured by all methods in the y direction, but not by SSI2 only in the x direction.

Table 3. Sine sweep, x-direction modes from x-direction excitation (Hz)

Method	Mode 1		Mode 2		Mode 3	
PP	4.05	(2)	5.79	(-)	7.18	(5)
FDD	4.12	(2)	5.89	(-)	7.15	(5)
SSI	3.91	(2)	7.19	(5)	11.86	(-)
SSI2	4.18	(2)	6.36	(-)	7.62	(6)

Table 4. Sine sweep, y-direction modes from y-direction excitation (Hz)

Method	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
PP	3.21 (1)	4.12 (2)	5.30 (4)	6.49 (-)	7.67 (6)	11.58 (-)
FDD	3.21 (1)	4.12 (2)	5.27 (4)	6.52 (-)	7.67 (6)	11.54 (-)
SSI	2.91 (1)	5.11 (4)	7.20 (5)	7.85 (6)	11.37 (-)	- (-)
SSI2	3.25 (1)	4.63 (3)	6.10 (-)	7.66 (6)	8.26 (-)	- (-)

Figure 8 shows mode shape plots for the x (translation) and y (translation and rotation) components of the modes shapes for UL-FVT, PP, FDD, SSI and SSI2. Using the UL-FVT (FVT) modes as reference, it is seen that the shapes of the translational modes were captured reasonably well with SSI and SSI2: mode 1 (y), mode 2 (x), mode 5 (x) and mode 6 (y). The exception is SSI2 for mode 5 that deviated significantly from the UL-FVT mode shape. The rotational component of the mode shapes (difference between y_e and y) was expected to be minor for the translationally dominated modes 1, 2, 5 and 6. Figure 8 shows for mode 1 that all rotational mode shape estimates, except for SSI, trended with the UL-FVT mode shape. The rotational component for the torsion dominated mode 4 was captured reasonably well with most of the rotation concentrated at the roof. The shape of the rotational component for mode 6 was captured reasonably well with all methods.

3.4 System Identification - ambient vibration

Ambient response was recorded. The following discussion is based on 10 min recordings acquired and processed similarly to the sine sweep data. The ambient vibration accelerations reached a maximum 100 micro-g which were relatively small in comparison to the sine sweep accelerations that reached a maximum of 500 micro-g. Tables 5 and 6 show the natural frequencies (Hz) identified and ordered by frequency. In Table 5, it is seen that UL-FVT mode 2 and 5 frequencies were identified correctly by all methods in the x-direction. Likewise, Table 6 shows that UL-FVT mode 1 and 6 frequencies were identified correctly in the y-direction. It was not possible to identify the torsional modes 3 and 4 from the ambient data and processing techniques applied. Figure 9 shows translational response of mode shapes 1, 2, 5 and 6. Mode 1 was captures well by SS1, however, SSI2 did not produce meaningful estimates of this mode. Modes 2, 5 and 6 were captured reasonably well by SSI and SSI2. Torsional (rotation) responses for modes 1 and 6 were not captured accurately (not shown). Overall, it was found that translational mode frequencies and mode shape forms were captured reasonably well by SSI and SSI2. However, capture of torsional modes and torsional components of translational modes was not possible.

Table 5. Ambient vibration, x-direction modes (Hz)

Method	Mode 1		Mode 2		Mode 3	
PP	4.21	(2)	5.98	(-)	7.32	(5)
FDD	4.18	(2)	5.92	(-)	7.35	(5)
SSI	4.20	(2)	5.40	(-)	7.49	(5)
SSI2	4.14	(2)	-	(-)	7.46	(5)

Table 6. Ambient vibration, y-direction modes (Hz)

Method	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
PP	3.23 (1)	6.53 (-)	7.81 (6)	- (-)	11.60 (-)	14.22 (-)
FDD	3.23 (1)	6.53 (-)	7.87 (6)	- (-)	11.57 (-)	- (-)
SSI	3.39 (1)	6.69 (-)	8.02 (6)	- (-)	11.02 (-)	- (-)
SSI2	3.33 (1)	6.41 (-)	7.92 (6)	9.58 (-)	- (-)	- (-)

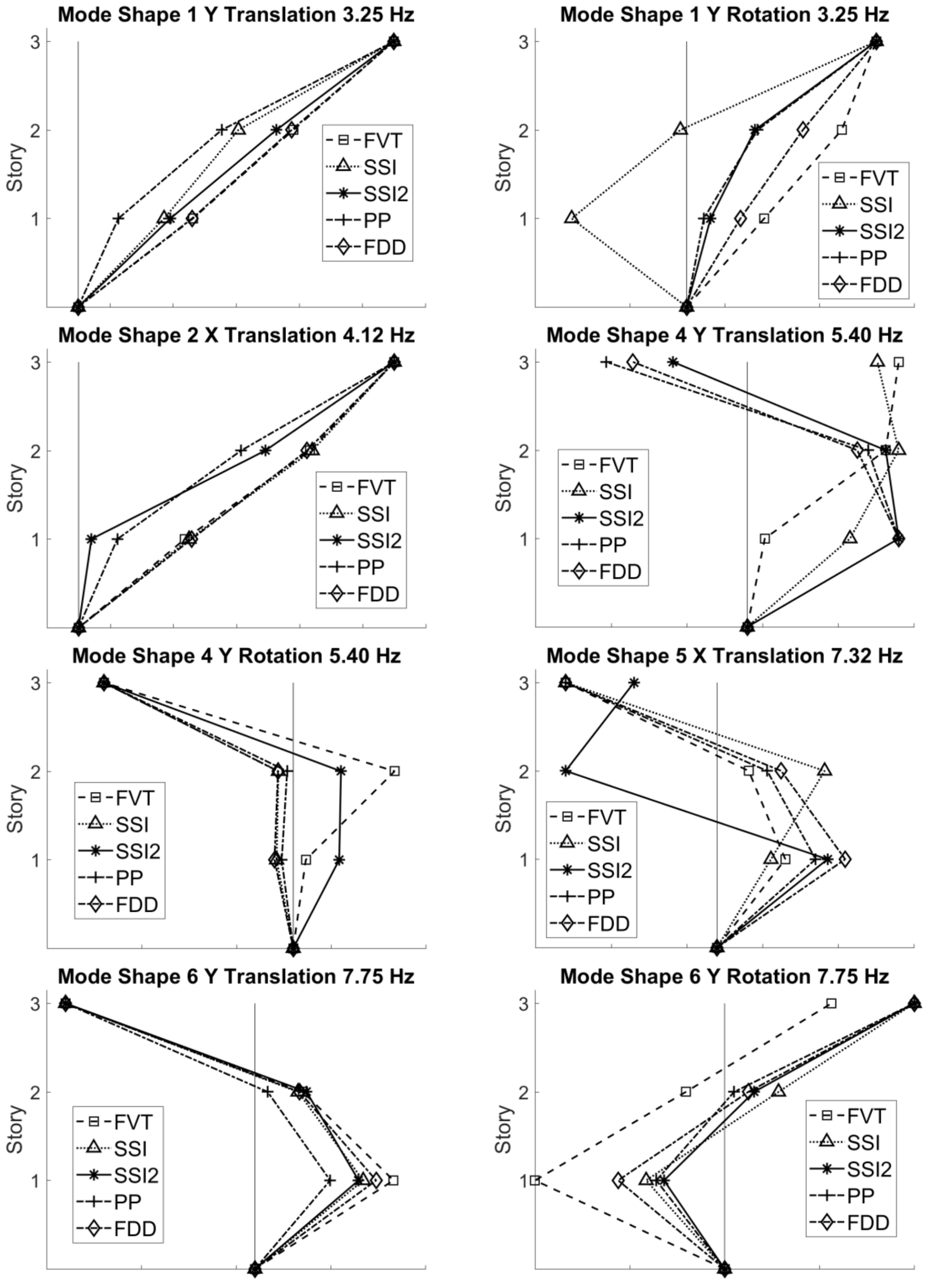


Figure 8. 3-story building, sine sweep, mode shape comparison

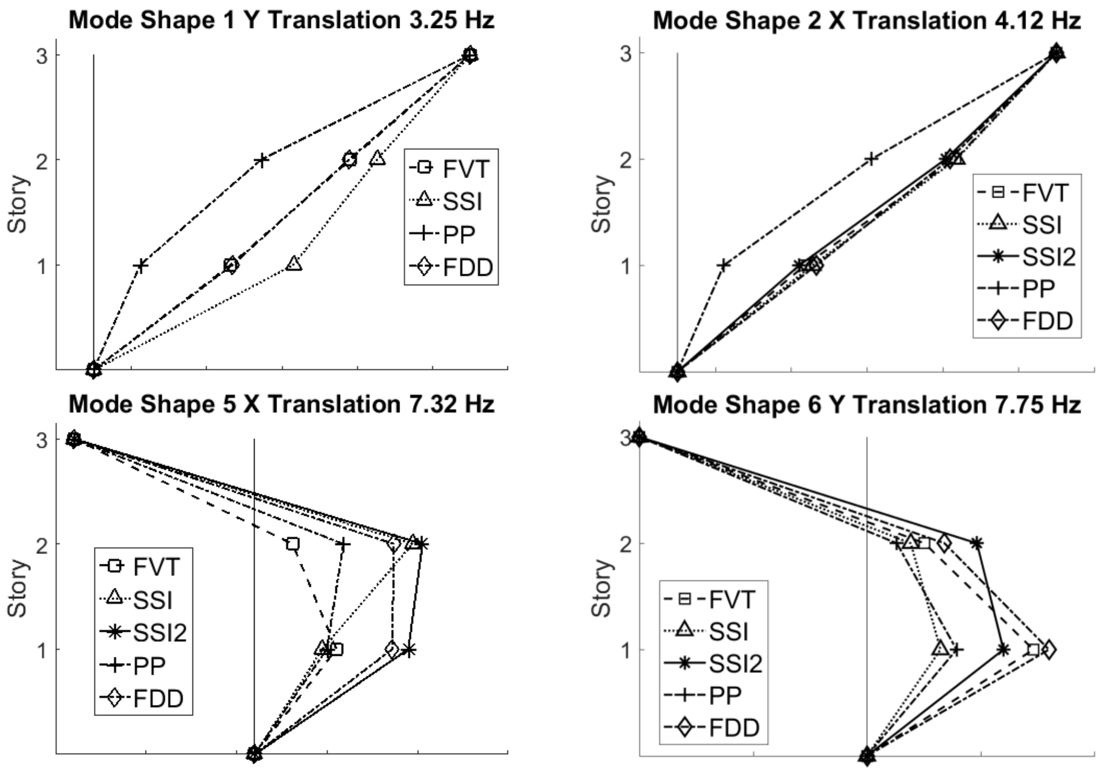


Figure 9. 3-story building, ambient vibration, mode shape comparison

4. CONCLUSIONS

Recent structural health monitoring research has focused on using an ultra-low forced vibration technique (UL-FVT) for system identification. Extending UL-FVT to large structures requires heavy shaking equipment with limited mobility. The main focus of this paper was to investigate the stochastic subspace identification (SSI) technique (output only), as an alternative to the robust UL-FVT technique.

Initially, a 3-story laboratory model was subjected to both harmonic loading and white noise. Using the UL-FVT results as reference, analysis showed that the SSI method provided an accurate estimate of the natural frequencies and modes shapes. Modal damping was accurately estimated for modes 2 and 3, but flawed for mode 1. Further refinement of the model loading, acceleration measurements and SSI analysis is expected to improve the damping estimates. The conclusion from the 3-story shake table model experiment is that the SSI method is accurate for relatively simple and regular structures subjected to well-defined loading and encouraged the authors to apply the SSI method to a real building. The laboratory experiment was carried out on a regular structure (no translational/torsional coupling) and thus did not expose whether the SSI method can capture torsional response.

Subsequently, a 3-story concentrically braced steel-frame structure was tested. The irregular was investigated for harmonic loading, sine sweep forced vibration and ambient vibration. Using the UL-FVT results as reference data, it was found that the SSI method applied to the sine sweep data readily could identify the principal translational UL-FVT mode shapes (1, 2, 5 and 6). The second torsional mode, mode 4, was identified by SSI (and other methods) as a part of the y-direction response. Mode 3, the first torsional mode, was not as prominent, however it was identified by the SSI method (but not by other methods). Spurious frequencies were persistent in the analysis, notably 5.9 Hz, 6.5 Hz and 11.5 Hz. It is believed that these frequencies were generated by MEP systems on the roof.

Analysis of the ambient vibration signals revealed that the SSI method could identify the principal translational UL-FVT mode shapes (1, 2, 5 and 6), and that the mode shapes were similar to those from the sine sweep analysis. The torsional modes, modes 3 and 4, evaded capture.

The authors were encouraged that the SSI methods found the majority of the mode shapes and frequencies but were at the same time troubled by the inaccuracies, and the missing and spurious modes. A serious drawback was the SSI method's inability to detect torsionally dominated modes from ambient vibration data. Such modes could be of crucial importance for assessment of building response and integrity. The UL-FVT method readily provides robust 3D mode shapes from a 3-dimensional data stream. In contrast, the SSI method only provides one-dimensional mode shapes for orthogonal directions that are difficult to piece together to a 3-dimesional representation in an automated fashion. In that light, it is important to advance a methodology to stitch the SSI 1D mode shapes together to form complete 3D mode shapes.

Future research topics include: Improve the system identification for ambient vibration by recording multiple long data sets, preferably at night-time when the MEP systems are off, and establish statistically more robust results. Investigate the 3-story building sine sweep data using an SSI input-output model for reference to the output only models. Enhance the UL-FVT results for the 3 story building using the mode shapes presented herein as a springboard for fine-tuning modes 1-6 and obtaining the remaining 3 modes. Extend the 3-story laboratory structure experiment by introduction of model asymmetry and determination all 9 mode shapes (including torsionally dominated modes) with UL-FVT and SSI.

5. ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Dr. Sherif Beskhyroun, for allowing the authors to use the 'System Identification Toolbox' for modal parameter identification he developed at the University of Auckland, New Zealand.

6. REFERENCES

Beskhyroun, S. (2011). Graphical Interface Toolbox for Modal Analysis, *Proceedings of the Ninth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Society*, 14-16 April, 2011, Auckland, New Zealand.

Brincker R., Zhang L., and Andersen P. (2000). Modal Identification from Ambient Responses using Frequency Domain Decomposition, *Proceedings of the 18th International Modal Analysis Conference (IMAC)*, USA.

Chopra, A. K. (2012). Dynamics of Structures: Theory and Applications to Earthquake Engineering. *Prentice Hall*.

Farrar C R, James G H. (1997.) System Identification from Ambient Vibration Measurements on a Bridge, *Journal of Sound and Vibration*, 205(1): 1−18.

Katayama T. (2005). Subspace Methods for System Identification, *Springer*.

Rosenblatt, W., Laursen, P.T., McDaniel, C, Archer, G. (2017). Structural damage detection through forced vibration testing, *Proceedings of the 16th World Conference on Earthquake Engineering*, Santiago Chile, January 9-13, 2017, Paper No. 302.

Sadhu, A., Narasimhan, S., Antoni, J. (2017). A review of output-only structural mode identification literature employing blind source separation methods. *Mechanical Systems and Signal Processing*. 94. 415-431. 10.1016/j.ymssp.2017.03.001.

Ubertini, F., Comanducci, G., & Cavalagli, N. (2016). Vibration-based structural health monitoring of a historic bell-tower using output-only measurements and multivariate statistical analysis. *Structural Health Monitoring, 15*(4), 438-457. doi:http://dx.doi.org.ezproxy.lib.calpoly.edu/10.1177/1475921716643948.

Van Overschee P. and Moor B. D. (1996). Subspace Identification for Linear Systems, *Kluwer Academic Publishers*.

Xing, Shutao (2011). Structural Identification and Damage Identification using Output-Only Vibration Measurements, *Utah State University*, https://digitalcommons.usu.edu/etd/1067.

Zavala, A., Tipping, S., McDaniel, C., Laursen, P., Archer, G. (2017). Influence of Nonstructural Components and Systems (NCS) on the Dynamic Behavior of Buildings, *Structural Engineering Association of California Convention*, San Diego, CA, September 13-15, 2017.