Chapter 10
Modal Identification of Rooftop Mechanical Equipment with Different Attachment Designs on a Full-Scale Ten-Story Shake Table-Tested Building

Xianzhao Zhang, Jiachen Zhang, Shokrullah Sorosh, and Tara C. Hutchinson

Abstract Modal properties are critical for estimating the seismic acceleration and displacement demands of nonstructural components, whose satisfactory performance during earthquakes can help ensure the continued functionality of buildings. While vibration-based system identification techniques have advanced significantly for large structural systems, their application to real-world nonstructural components subjected to increasing earthquake-induced load scenarios remains limited due to a lack of recorded data. To address this gap, five lightweight mechanical equipment units, comprising three slender and two squat aspect ratios, were installed on the rooftop of a full-scale, ten-story cold-formed steel building, and subsequently tested on the UC San Diego six-degree-of-freedom outdoor shake table. The equipment's base attachments were strategically designed to evaluate the impact of different boundary conditions, such as direct (fixed) attachment or the use of vibration isolation interfaces. The variation in base attachment leads to different dynamic properties reflective of realistic installation variability. Fundamental periods and damping ratios of each unit were extracted from white noise test data using three output-only system identification algorithms, with the aim of correlating local damage to changes in global modal features.

Keywords Experimental modal analysis · Modal parameters · Nonstructural components · System identification · Shake table test

Introduction

The six-degree-of-freedom (6-DOF) Large High-Performance Outdoor Shake Table (LHPOST6) at the UC San Diego offers a unique opportunity to extract dynamic behavior-critical modal parameters of civil structures through experimental and operational modal analysis techniques. The first landmark system identification study of an as-built structure tested on the UC San Diego shake table was conducted by Moaveni et al. [1], who evaluated the modal parameters of a seven-story reinforced concrete structural wall building slice using input-output and output-only system identification methods, and correlated the identified natural frequencies with different damage states. Subsequently, Astroza et al. [2, 3] carried out modal identification of a five-story reinforced concrete building furnished with a variety of nonstructural components and systems, while it was both fixed and base-isolated at its attachment to the shake table. The high-damping rubber isolation system was found to elongate the predominant period and increase damping of the building-nonstructural system. The first comprehensive system identification study of a metal structure tested on the UC San Diego shake table was conducted by Wang and Hutchinson [4]. This study embarked to understand the evolution of modal characteristics of a six-story cold-formed steel (CFS) building under a multi-hazard loading scenario, namely involving both earthquake and live-fire tests. Mugabo et al. [5] explored changes in natural frequencies and damping ratios of a two-story mass timber building as shaking intensity increased and further examined the effects of repair and retrofit measures during the experimental program.

Significant progress has been made in system identification of structures tested on 1-DOF shake tables. However, these studies face limitations as the imposition of excitation along a single DOF limits the characterization. Uncertainty analyses

Xianzhao Zhang · Jiachen Zhang · Shokrullah Sorosh · Tara C. Hutchinson
Department of Structural Engineering, University of California San Diego, La Jolla, CA 92093, USA
e-mail: xiz217@ucsd.edu; j-charlie-zhang@ucsd.edu; ssorosh@ucsd.edu; tara@ucsd.edu

Kristin B. Zimmerman, PhD (eds.), *Model Validation and Uncertainty Quantification, 2026, Vol. 3*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.1007/97887-438-1442-9_10

of system identification results [6] revealed that excitation amplitude had the greatest influence on the variability of the identified modal parameters, particularly the first-mode natural frequency. Consequently, for the structural axis that did not experience sufficient excitation, the identified modal parameters may be less accurate.

Moreover, although various system identification methods have been applied to building structures with different construction materials, heights, hazard scenarios, and damage states, few studies have focused on estimating the modal parameters of nonstructural components. Amongst the most relevant to the present study, the work of Astroza et al. [7], using base excitation (pulse, white noise, and earthquake) and pull back tests investigated a rooftop-mounted cooling tower supported by four isolation mounts. Pull back tests were conducted while the tower was both empty and fully water-filled. The presence of the isolation mounts led to a vertical direction dominant mode with a fundamental period of 0.21 sec.

Description of the Rooftop Equipment

As shown in Figure 1(a), five lightweight air-conditioning condenser units, representing two different models, were installed on roof curbs atop a full-scale ten-story CFS building [8], tested at LHPOST6. Figures 1(b, c) illustrate the geometric features of the slender and squat units, respectively. The slender unit measured 1,000 mm × 368 mm in plan and 1,365 mm in height, with a resulting maximum aspect ratio (AR) of 3.7, while the squat unit measured 902 mm × 902 mm in plan and 972 mm in height, with a resulting AR of 1.1. The slender unit was supported by two manufacturer-prefabricated steel tracks with four feet attached to its bottom face, whereas the squat units had no such installation aids. The weights of the slender and squat units were estimated at 1,434 N and 1,339 N, respectively, assuming a full refrigerant charge.

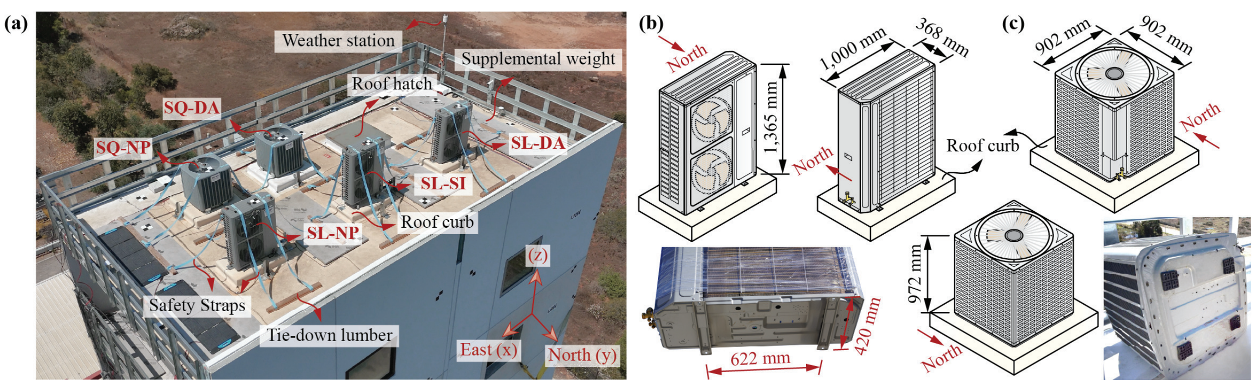

Fig. 1 Overview of rooftop mechanical equipment: (a) aerial view of the equipment layout, view from the northeast corner, (b) slender unit geometry, and (c) squat unit geometry

Two types of commonly used vibration and acoustic mitigation hardware, neoprene pads and spring isolators, were installed at the interface between the slender units and a roof curb. As a benchmark configuration, one slender unit was directly screw-mounted at its four manufacturer-provided feet to CFS studs of the roof curb. To modify its base boundary conditions, two alternative attachment strategies were implemented. In the first case, four neoprene pads, each placed beneath a shim plate, were installed under the equipment feet. In the second case, each equipment foot was supported by a spring isolator. For the squat units, both were installed using four steel angle support clips. One of the squat units was additionally supported by four neoprene pads placed beneath the equipment. Each clip was fastened to the equipment housing with three self-drilling screws, and to the CFS studs of the roof curb with two self-drilling screws. For brevity, SL-DA denotes the slender unit with direct attachment, SL-NP the slender unit with neoprene pads, SL-SI the slender unit with spring isolators, SQ-DA the squat unit with direct attachment, and SQ-NP the squat unit with neoprene pads. Further details about the rooftop mechanical equipment and their attachment designs are provided in [9].

Instrumentation Plan and Dynamic Tests

A total of 36 analog sensors were used to monitor the rooftop mechanical equipment, including 16 accelerometers and 20 linear potentiometers. The accelerometers were micro-electro-mechanical systems-based, with a full-scale range of ±10 g, a frequency bandwidth of 350 Hz, and a dynamic range of 76 dB. These sensors were connected to a distributed multi-node data acquisition system, operating at a sampling rate of 256 Hz. The layout of accelerometers for the equipment is shown in Figure 2. For the slender unit, two uniaxial accelerometers oriented in the y-direction were mounted at the northwest and southeast corners of the top surface, approximately 76 mm from the edges. In addition, one uniaxial accelerometer in the x-direction and another in the z-direction were installed at the center of the top face. For the squat unit, one uniaxial accelerometer in each of the x- and y-directions was installed at the center of the top surface, while no z-direction accelerometers were deployed. The recorded acceleration time series was baseline-corrected and filtered using a fourth-order bandpass Butterworth filter with cutoff frequencies of 0.2 Hz and 35 Hz, to remove low- and high-frequency signal noise while retaining the frequency range containing the primary vibration modes that contributed significantly to the equipment response.

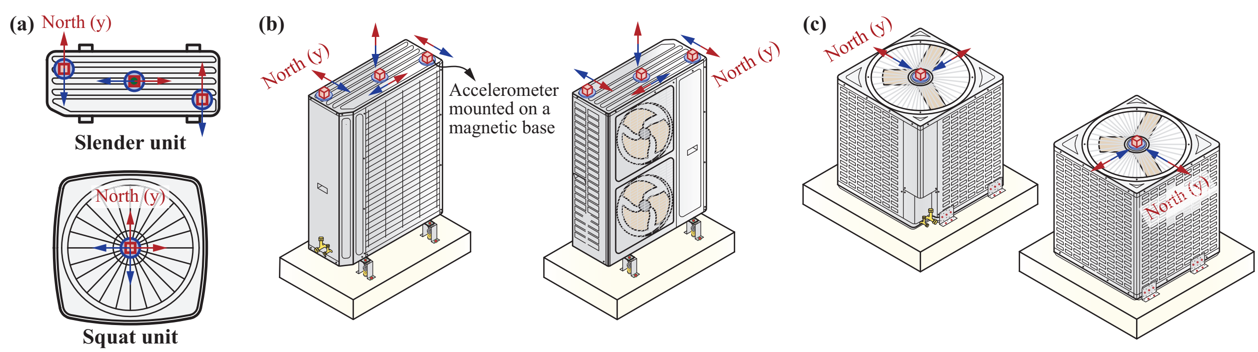

Fig. 2 Accelerometer instrumentation: (a) top view of slender and squat units, and representative layout of accelerometers for (b) SL-SI and (c) SQ-NP

A sequence of low-amplitude vibration tests, including white noise (WN) tests and ambient vibration (AV) tests, were performed before, during, and after multi-directional earthquake tests. The earthquake test suite included 15 service-level earthquakes (SLEs), one design-level earthquake (DE), and two risk-targeted maximum considered earthquakes (MCE$_R$s) [10]. Translational (unidirectional) WN tests with a target 3%–4% g root-mean-square (RMS) acceleration, and vertical WN tests with a target 10% RMS acceleration, were imposed sequentially at the base of the building. Each WN test consisted of multiple 16-second windows within a frequency band of 0.125–25 Hz. Except for WN tests 1–3 and 8–10, which had durations of 160 seconds, the remaining WN tests had a duration of 64 seconds. In total, 37 WN tests were conducted, including 17 in the x-direction, 17 in the y-direction, and three in the z-direction, along with 13 AV tests. The timeline of the low-amplitude vibration test protocol is summarized in Figure 3. The focus of this paper is on system

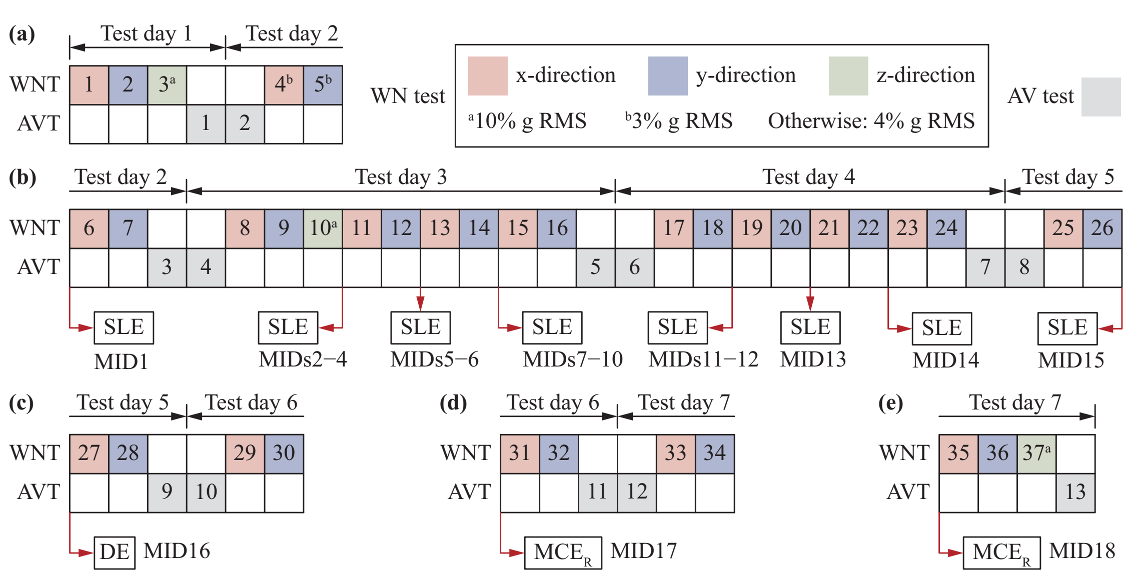

Fig. 3 Timeline of the low-amplitude vibration test protocol: (a) pre-earthquake testing, (b) during SLE phases, (c) post-DE and pre-first MCE$_R$, (d) post-first and pre-second MCE$_R$, and (e) post-second MCE$_R$. MID = motion identification (see [10])

identification using data obtained from WN tests because the equipment experienced sufficient and relatively consistent excitation.

Modal Parameters Identified from WN Tests

Three state-of-the-art output-only system identification methods were applied to the WN test data. These methods include the Enhanced Frequency Domain Decomposition (EFDD) [11], the Natural Excitation Technique combined with the Eigensystem Realization Algorithm (NExT-ERA) [12, 13], and the Covariance-Driven Stochastic Subspace Identification method (SSI-COV) [14]. All three methods assume a linear time-invariant model of the equipment, with energy dissipation represented by linear viscous damping. Accordingly, the identified natural periods and damping ratios correspond to the modal parameters of an equivalent linear viscoelastic system.

Figure 4 shows the identified fundamental periods, T_a from the WN test data for three slender units, SL-DA, SL-NP, and SL-SI, in both the x- and y-directions, along with normalized values expressed relative to the initial T_a. At the beginning of the test sequence, the fundamental periods T_a, in the x-direction were 0.16 sec, 0.18 sec, and 0.77 sec for SL-DA, SL-NP, and SL-SI, respectively, while in the y-direction they were 0.24 sec, 0.25 sec, and 0.73 sec. These values reflect the average across the three system identification methods. An elongation of T_a was observed as the excitation intensity increased from

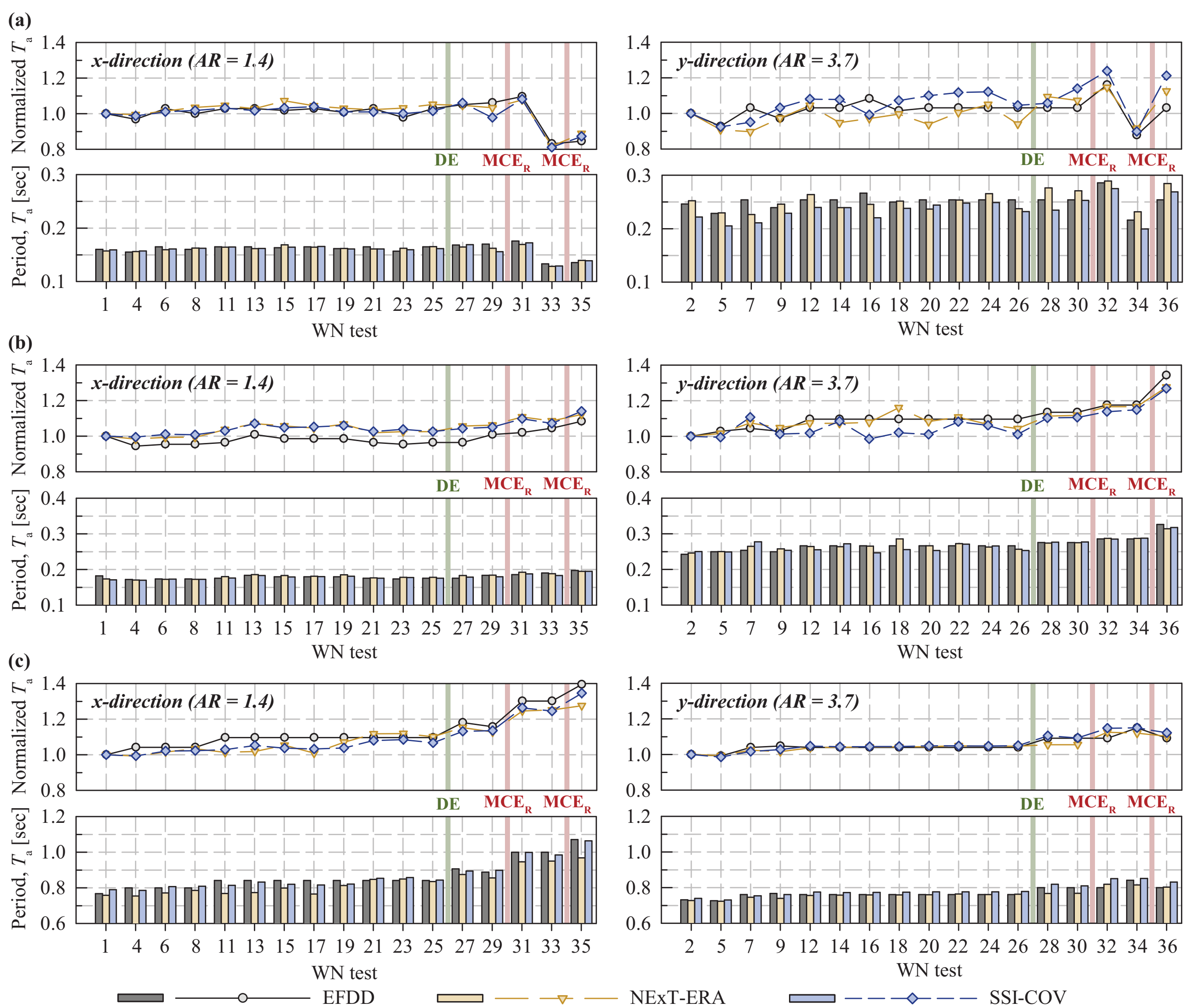

Fig. 4 Variation of natural periods of slender units from WN test data: (a) SL-DA, (b) SL-NP, and (c) SL-SI

the DE to the MCE$_R$ test phase. For SL-DA, T_a increased by 8.6% in the x-direction and 18.2% in the y-direction after the first MCE$_R$ test phase, relative to the initial T_a at the start of testing. The elongation of T_a is attributed to anchorage failure at one attachment point [15]. After retrofitting the failed anchorage, a noticeable reduction in T_a was observed prior to the second MCE$_R$ test phase.

For SL-NP, no visible damage was identified during the post-test inspection. However, T_a increased by 11.6% and 29.7% in the x- and y-directions, respectively, by the end of the testing program. This elongation may be attributed to subtle damage mechanisms not easily detected visually, such as micro-slippage or wear of screw threads, localized bearing damage between screws and CFS studs, or minor crushing of the cementitious panel around the fasteners. For SL-SI, the average increases in T_a were 33.9% in the x-direction and 10.6% in the y-direction after the second MCE$_R$ test phase. This elongation is associated with localized deformation of the spring isolator anchorages and permanent bending of the supporting track [15]. Similarly, the variation of T_a from the WN test data for the two squat units, SQ-DA and SQ-NP is shown in Figure 5. A subtle increase of 7.9% in the y-direction T_a was observed for SQ-NP. However, post-test inspection revealed no visible damage to either squat unit. As shown in Figure 6, T_a associated damping ratios, ζ_a exhibited much larger variations across the different system identification methods and test sequences. For example, for SL-SI during the SLE test phase, which can be considered a damage-free condition, the coefficient of variation of the damping ζ_a was 28.3% in the x-direction and 14.5% in the y-direction. This level of variability suggests that relying solely on identified damping ζ_a may not be sufficient to characterize physical damage.

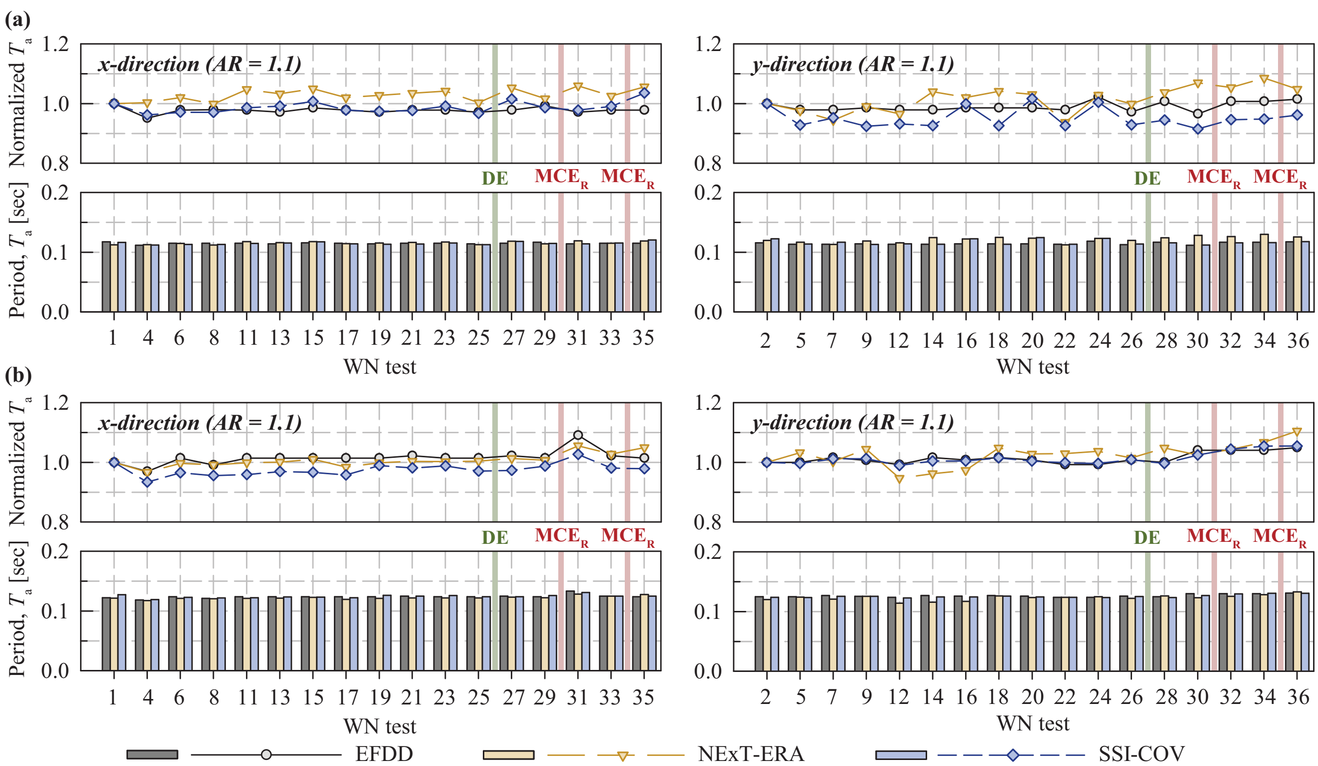

Fig. 5 Variation of natural periods of squat units from WN test data: (a) SQ-DA and (b) SQ-NP

Figures 4–6 aim to show the changes in identified modal parameters of the slender and squat units using different system identification methods at various test phases. When floor response spectra are employed to analyze uncoupled nonstructural components, knowledge of T_a and ζ_a is important and necessary. From the variations of T_a shown in Figures 4–5 it can be inferred that the modal parameters of the equipment in its intact condition can be established from system identification prior to the DE test phase. In other words, the initial undamaged state of the equipment can be characterized using the first 12 x-direction WN tests and the first 12 y-direction WN tests.

Figure 7 summarizes the mean values of T_a and ζ_a obtained from three system identification methods using WN test data prior to the design level test. For the slender unit, the use of neoprene pads for acoustic and vibration mitigation will increase T_a by 12.5% and 8.3% in the x- and y-directions, respectively, while ζ_a increased by 25.7% and 24.2%. When spring isolators were used, which can be considered a more effective vibration mitigation strategy, T_a increased dramatically by 406.3% and 216.7% in the x- and y-directions, respectively. Such a large elongation poses a potential risk of resonance with

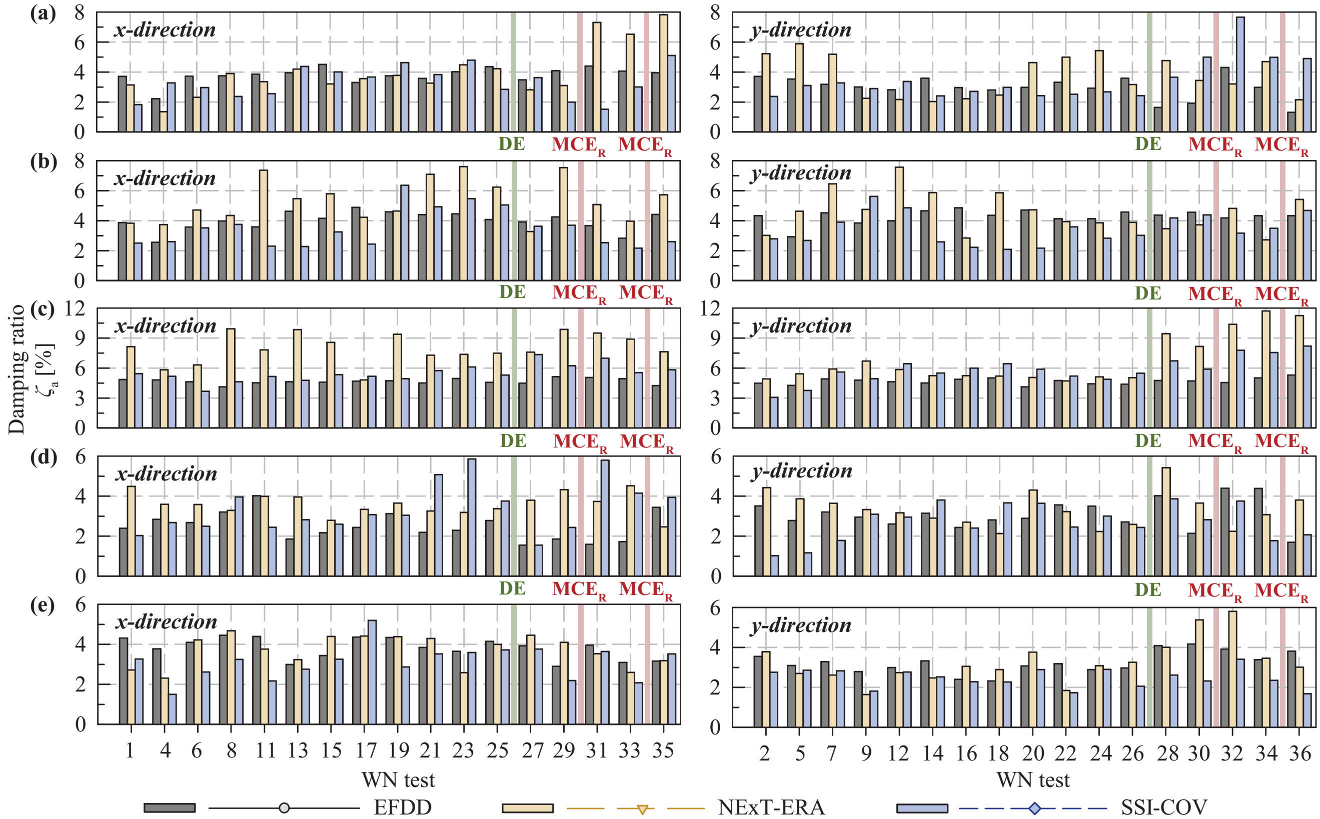

Fig. 6 Variation of damping ratios of slender and squat units from WN tests data: (a) SL-DA, (b) SL-NP, (c) SL-SI, (d) SQ-DA, and (e) SQ-NP

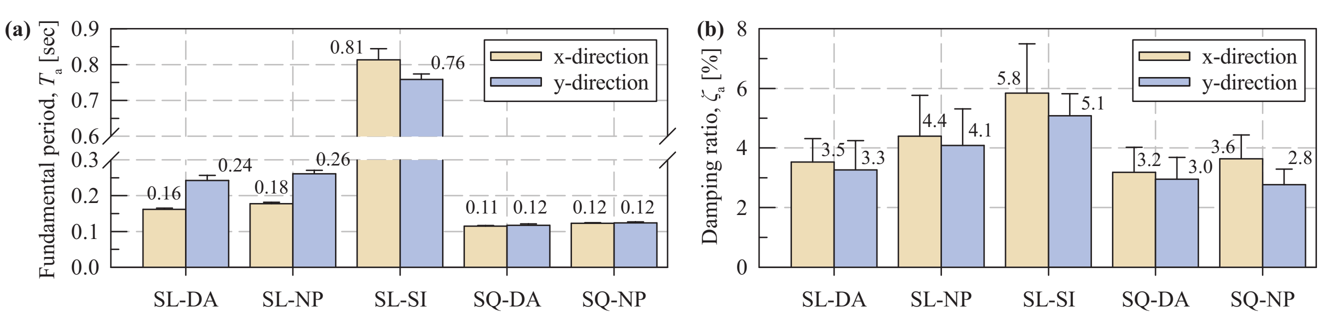

Fig. 7 (a) Natural periods and (b) damping ratios identified using WN test before design level test

the supporting structure, even though it also beneficially increased ζ_a by 65.7% and 54.5%. For the squat unit, T_a in both the x- and y-directions remained small (on the order of about 0.1 sec), and the use of neoprene pads appeared to have negligible influence.

Conclusions

This paper examines the dynamic characteristics of lightweight rooftop mechanical equipment with different attachment strategies, installed on a full-scale ten-story CFS building. The building was tested at the UC San Diego outdoor shake table under sequentially increasing multi-directional earthquake scenarios. Modal parameters were identified from WN tests using three output-only system identification methods. Results highlight the important role that the equipment unit's attachment design plays in dynamic characteristics, influencing both natural periods and damping ratios.

For the slender units, the directly attached configuration (SL-DA) experienced elongation of period, T_a, due to anchorage failure, which was recovered after retrofit. The neoprene-pad-supported unit (SL-NP) showed moderate period elongation without visible physical damage, suggesting the presence of possible subtle degradation mechanisms. The spring-isolator-supported unit (SL-SI) exhibited period elongation linked to anchorage and support rack deformation. Squat units (SQ-DA and SQ-NP) had the shortest periods ($\sim$0.12 sec) and only minor elongation by the end of testing. Damping ratios, ζ_a, displayed significant variability across methods and test phases in the WN tests, though all units attained damping values $> \sim 3\%$. While vibration and acoustic mitigation hardware increased damping, it also introduced dramatic elongation of periods, raising the potential risk of resonance with the supporting structure.

Acknowledgments This project was executed with support of the National Science Foundation under Grants CMMI-1663569 and CMMI-1663348, together with numerous other federal, state, and industry partners. Specific to the rooftop mechanical equipment discussed herein, additional support was provided by Mason West, Inc., Mason Industries, Inc., and Wells Plumbing and Heating Supplies, Inc. A complete list of sponsors and partners is available at: cfs10.ucsd.edu/sponsors-partners. The authors gratefully acknowledge all undergraduate and graduate students and visiting scholars (cfs10.ucsd.edu/people), as well as the LHPOST6 facility staff (esec.ucsd.edu/about/personnel), for their contributions to the project. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsoring organizations.

References

1. Moaveni, B., He, X., Conte, J.P., Restrepo, J.I., and Panagiotou, M. "System identification study of a 7-story full-scale building slice tested on the UCSD-NEES shake table". *Journal of Structural Engineering*, 137.6: 705−717 (2011) https://doi.org/10.1061/(ASCE)ST.1943-541X.0000300
2. Astroza, R., Ebrahimian, H., Conte, J.P., Restrepo, J.I., and Hutchinson, T.C. "System identification of a full-scale five-story reinforced concrete building tested on the NEES-UCSD shake table". *Structural Control and Health Monitoring*, 23.3: 535−559 (2016) https://doi.org/10.1002/stc.1778
3. Astroza, R., Conte, J.P., Restrepo, J.I., Ebrahimian, H. and Hutchinson, T. "Seismic response analysis and modal identification of a full-scale five-story base-isolated building tested on the NEES@ UCSD shake table". *Engineering Structures*, 238: 112087 (2021) https://doi.org/10.1016/j.engstruct.2021.112087
4. Wang, X. and Hutchinson, T.C. "Evolution of modal characteristics of a mid-rise cold-formed steel building during construction and earthquake testing". *Earthquake Engineering & Structural Dynamics*, 49.14: 1539−1558 (2020) https://doi.org/10.1002/eqe.3316
5. Mugabo, I., Barbosa, A.R., Sinha, A., Higgins, C., Riggio, M., Pei, S., van de Lindt, J.W. and Berman, J.W. "System identification of UCSD-NHERI shake-table test of two-story structure with cross-laminated timber rocking walls". *Journal of Structural Engineering*, 147.4: 04021018 (2021) https://doi.org/10.1061/(ASCE)ST.1943-541X.0002938
6. Moaveni, B., Barbosa, A.R., Conte, J.P. and Hemez, F.M. "Uncertainty analysis of system identification results obtained for a seven-story building slice tested on the UCSD-NEES shake table". *Structural Control and Health Monitoring*, 21.4: 466−483 (2014) https://doi.org/10.1002/stc.1577
7. Astroza, R., Pantoli, E., Selva, F., Restrepo, J.I., Hutchinson, T.C., and Conte, J.P. "Experimental evaluation of the seismic response of a rooftop-mounted cooling tower". *Earthquake Spectra*, 31.3: 1567−1589 (2015) https://doi.org/10.1193/071513EQS205M
8. Hutchinson, T.C., Eladly, M., Ji, R., Rivera, D., Rukundo, F.C., Singh, A., Sorosh, S., Zhang, J., Zhang, X., Padgett, L., Jones, H., Karns, J. and Schafer, B.W. "Advancing use of cold-formed steel framing systems for mid-rise residential construction in seismic zones via full-scale shake table testing". In *Proceedings of the 8th Residential Building Design & Construction Conference*, State College, Pennsylvania (2026)
9. Zhang, X., Zhang J., and Hutchinson, T.C. "Shake table testing of rooftop mechanical equipment with different attachment strategies on a full-scale ten-story building". In *Sixth International Workshop on the Seismic Performance of Non-Structural Elements*, Yokohama, Japan (2026)
10. Zhang J., Sorosh S., Ji R., Lotfizadeh K.H., Schafer B.W., Hutchinson T.C. "Full-scale 10-story cold-formed steel building shake table test: Protocol development and shake table performance". In *Proceedings of the 13th National Conference on Earthquake Engineering*, Earthquake Engineering Research Institute, Portland, Oregon (2026)
11. Brincker, R., Zhang, L., and Andersen, P. "Modal identification of output-only systems using frequency domain decomposition". *Smart Materials and Structures*, 10.3: 441−445 (2001) https://doi.org/10.1088/0964-1726/10/3/303
12. Juang, J.N. and Pappa, R.S. "An eigensystem realization algorithm for modal parameter identification and model reduction". *Journal of Guidance, Control, and Dynamics*, 8.5: 620−627 (1985) https://doi.org/10.2514/3.20031
13. Carne, T.G., and James III, G.H. "The inception of OMA in the development of modal testing technology for wind turbines". *Mechanical Systems and Signal Processing*, 24.5: 1213−1226 (2010) https://doi.org/10.1016/j.ymssp.2010.03.006
14. Magalhães, F., Cunha, A., and Caetano, E. "Online automatic identification of the modal parameters of a long span arch bridge". *Mechanical Systems and Signal Processing*, 23.2: 316−329 (2009) https://doi.org/10.1016/j.ymssp.2008.05.003
15. Zhang, X., Zhang J., and Hutchinson, T.C. "Physical damage to rooftop mechanical equipment considering variations in attachment designs". In *Proceedings of the 13th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Portland, Oregon (2026)