論文 / 著書情報
Article / Book Information

論題(和文)	屋外鉄骨避難階段の振動特性 その4 微動測定に基づくモード形状評価
Title(English)	Dynamic Characteristics of an External Steel Emergency Staircase Part 4: Evaluation of Mode Shapes Based on Ambient Vibration Measurements
著者(和文)	SORIANO Razelle, 佐藤大樹, 陳引力, 鎌野隆貴, 李ミンフェイ
Authors(English)	Razelle Dennise Agoba Soriano, Daiki Sato, Yinli Chen, Ryuki Kamano, Minfuei Ri
出典 / Citation	日本建築学会関東支部研究報告集, I, , pp. 393-396
Citation(English)	, I, , pp. 393-396
発行日 / Pub. date	2026, 3
権利情報	一般社団法人 日本建築学会

2045

2025年度日本建築学会
関東支部研究報告集 I
2026 年 3 月

屋外鉄骨避難階段の振動特性
その 4　微動測定に基づくモード形状評価

構造－振動

正会員 ○ SORIANO, Razelle [＊1]　　正会員　佐藤大樹 [＊2]
〃　　陳引力 [＊3]　　〃　　鎌野隆貴 [＊4]
〃　　李ミンフェイ [＊4]

Outdoor steel staircase　FDD
System Identification　Singular Value Spectra

1. Introduction

Steel staircases often serve as emergency exits in buildings. These structures are typically slender and are frequently attached to pre-existing buildings constructed from different materials. Their dynamic behavior is influenced not only by environmental loads but also by human-induced forces, particularly during emergency evacuations when occupants move at higher-than-normal speeds. Consequently, these staircases can experience significant vibrations, making the assessment of their dynamic properties essential for structural design, occupant comfort, and long-term maintenance [1–2]. Despite their importance, relatively few studies have focused on the dynamic behavior of outdoor steel staircases, and investigations on parameter selection for modal identification remain particularly limited.

Ambient vibration testing provides a non-intrusive method for evaluating the dynamic response of such structures [3]. Frequency Domain Decomposition (FDD) is commonly used to extract modal properties, including mode shapes, from these measurements [4]. The reliability of FDD results depends on data processing parameters, such as preprocessing methods, ensemble duration, and number of ensembles, which can strongly affect the stability of singular value (SV) spectra [5]. For full-scale structures, the true modal characteristics are generally unknown, making it important to identify parameter selection strategies that produce robust and repeatable results.

In this study, ambient vibration measurements of an outdoor steel staircase were analyzed to determine processing strategies that yield stable SV spectra for FDD. The resulting mode shapes provide insight into the dynamic behavior of the staircase and the spatial distribution of structural deformations under ambient excitations.

2. Ambient Vibration Testing

Due to practical limitations in the number of sensors, the ambient vibration test was conducted using two measurement configurations, with sensors relocated between stair and landing positions as summarized in Table 1 and illustrated in Figure 1. Detailed sensor information is provided in Part 3 and is not repeated here. Setup 1 is the primary configuration used to establish strategies for obtaining stable SV spectra, while Setup 2 is used for limited verification of the accuracy of the selected parameters.

Table 1. Sensors used for each ambient vibration test setup

	SETUP 1	SETUP 2
Sampling freq.	500 Hz	500 Hz
Duration	1220 s	1665 s
Sensors used	4L1, 4S1, 4S2, 3S1, 3L2, 3S2, 2S1, 2L2, 2S2, 2S3, 2S4	4L1, 4L2, 3L1, 3S1, 3L2, 2L1, 2S1, 2L2, 2S2, 2L3, 2L4

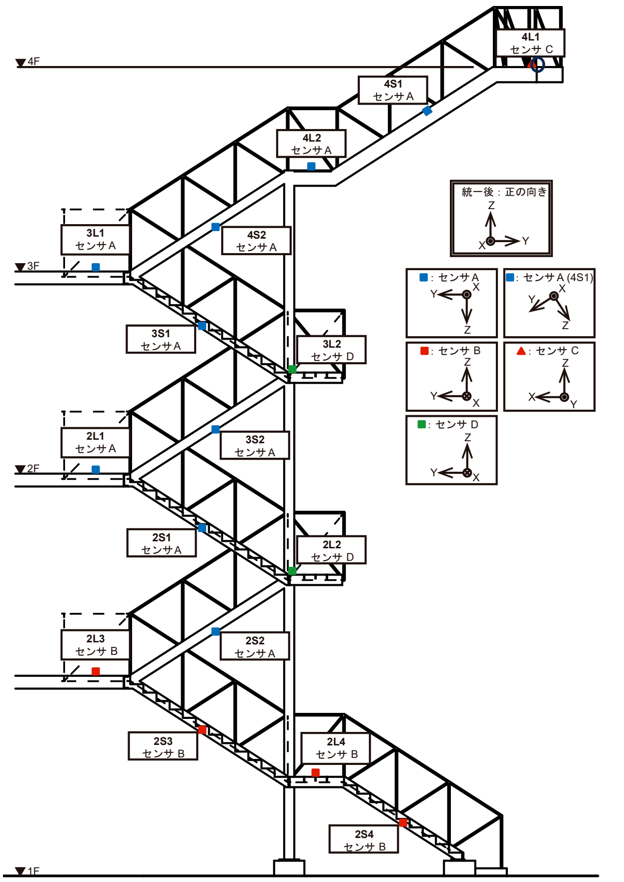


Figure 1. Ambient vibration sensor placements.

Dynamic Characteristics of an External Steel Emergency Staircase
Part 4: Evaluation of Mode Shapes Based on Ambient Vibration Measurements

SORIANO Razelle Dennise A.　SATO Daiki
CHEN Yinli　KAMANO Ryuki
LI Minhui

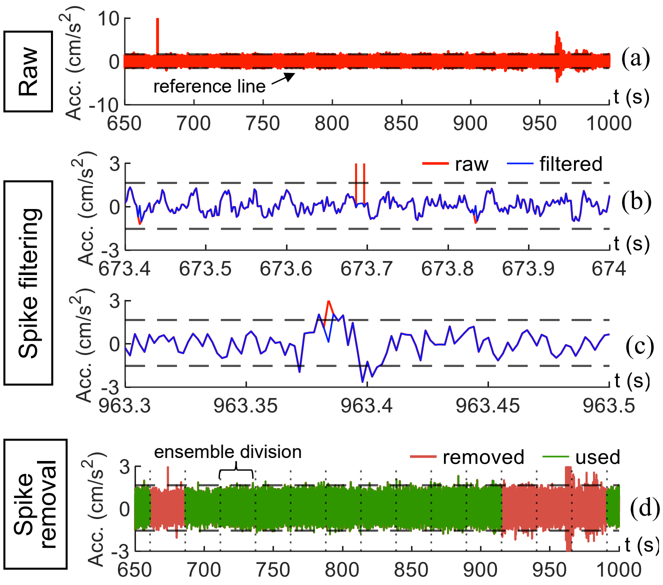


Figure 2. Comparison of raw, spike-filtered, and spike-removed acceleration time histories (Sensor 2L2, Setup 1).

3. Pre-processing of Acceleration Records

Inspection of the raw acceleration time histories revealed the presence of transient impulsive spikes, as illustrated in Figure 2(a). These spikes are not associated with the structural response and are presumed to originate from sensor disturbance, temporary loss of contact, or external incidental impacts during the measurement.

Since FDD assumes that the input excitation can be approximated as broadband, stochastic excitation, the presence of such impulsive, non-Gaussian components can distort power spectral density estimates and SV spectra. To ensure the validity of the modal identification results, preprocessing procedures were applied to mitigate the influence of these spikes prior to FDD analysis.

3.1. Spike filtering of acceleration records

To suppress isolated impulsive disturbances while preserving the ambient vibration characteristics, a Hampel filter was applied to the acceleration time histories. The Hampel filter identifies outliers based on the local median and median absolute deviation (MAD) within a moving window and replaces detected outliers with the corresponding local median value [6].

For a signal x_i, the local median m_i and MAD s_i are defined as

$$m_i = \text{median}\,\{x_{i-k}, \dots, x_{i+k}\}, \tag{1}$$

$$s_i = 1.4286\ \times \text{median}\,\{|x_j - m_i|\} \tag{2}$$

where $k = (w-1)/2$ and w is the window length. A data point is classified as an outlier if

$$|x_i - m_i| > \alpha s_i \tag{3}$$

with α denoting a threshold parameter. In this study, window size of $w = 30$ samples and a threshold of $\alpha = 3$ were adopted. This approach is particularly suitable when the available measurement duration is limited, as it allows the entire time history to be retained while suppressing isolated outliers. A Hampel filter effectively attenuates transient spikes while preserving the statistical and spectral characteristics of the ambient vibration response.

Figures 2(b-c) show the filtered acceleration time histories. The dashed lines represent reference thresholds based on median ± $5s_i$ and are used to highlight impulsive outliers. As seen in Figure 2, the Hampel filter is effective in suppressing isolated, high-amplitude spikes (Figure 2(b)). However, it also shows that when impulsive disturbances occur in close temporal proximity, some spikes exceeding the reference threshold remain, indicating a reduced filtering effectiveness for clustered outliers (Figure 2(c)).

3.2. Spike removal from acceleration records

To evaluate the extent to which spike filtering alone is sufficient for reliable identification of vibration characteristics, an alternative preprocessing approach was considered in which spike-contaminated data were completely excluded from the analysis. The acceleration records were segmented into ensembles, and any ensemble containing significant spikes was removed prior to spectral estimation (Figure 2(d)). This spike removal approach eliminates the influence of impulsive disturbances without modifying the signal itself and can therefore be regarded as a reference case representing cleaner ambient vibration data.

The influence of spike filtering and spike removal on SV estimation is examined in the following section through a systematic study of ensemble duration and number.

4. Stability of Singular Value Spectra in FDD

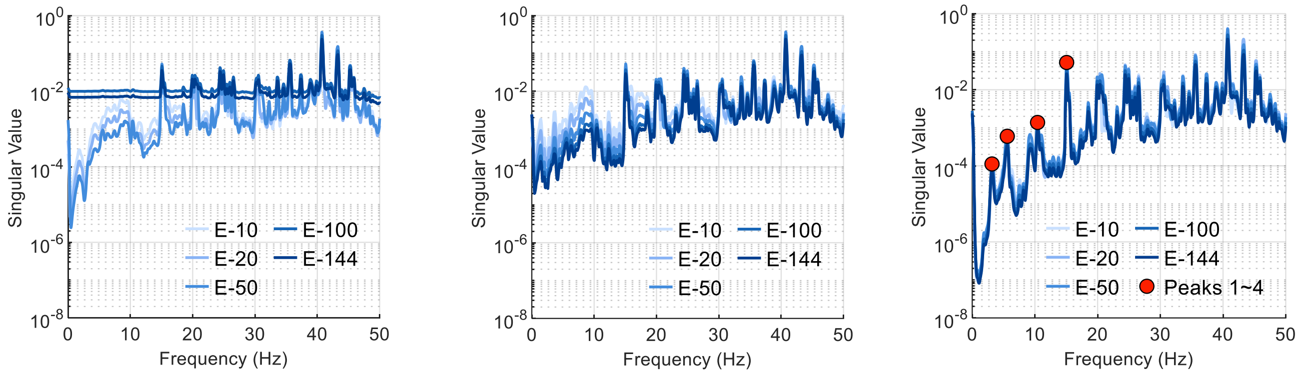
For reliable modal identification using FDD, a clear and stable SV spectrum is required. As SV estimation is sensitive to preprocessing and ensemble parameters, their influence is systematically examined to ensure robust modal peak identification.

4.1. Effect of pre-processing on estimated SV

Figure 3 compares the SV spectra obtained from the raw, Hampel-filtered, and spike-removed acceleration records for different ensemble numbers (denoted as E-10, E-20, etc.). When spikes are not removed, increasing the number of ensemble averages leads to distorted SV estimates, particularly in the low and high frequency range. Application of the Hampel filter mitigates this distortion; however, residual low-frequency noise and variations in modal peak amplitudes remain evident across different ensemble numbers. In contrast, complete removal of spike-contaminated segments results in clearer low-frequency SV spectra, with minimal dependence on the number of ensemble averages. These observations indicate that while filtering is beneficial when preservation of data length is required, complete spike removal provides more stable and accurate SV estimates. Accordingly, subsequent analyses in this study are based on SV spectra obtained from spike-removed data.

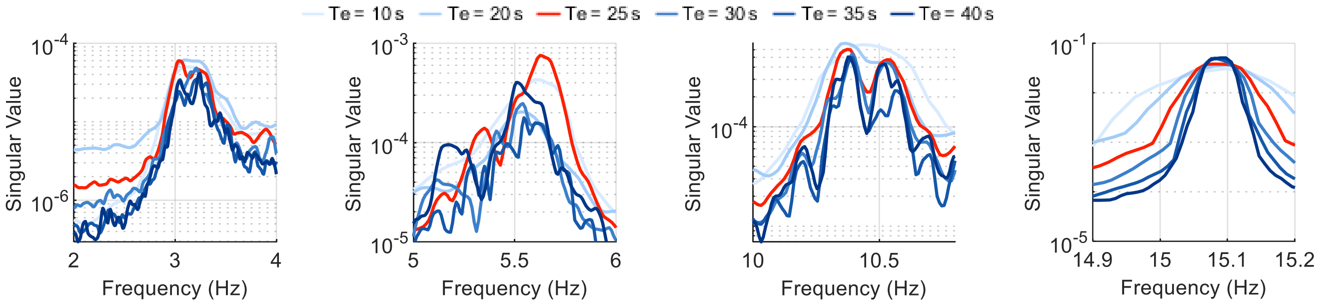
4.2. Selection of ensemble duration

The duration of each ensemble must be long enough to resolve the lowest frequency of interest, which in this study is approximately 3.265 Hz (Peak 1), corresponding to the first clearly observable peak in Figure 3c. Each segment must contain at least 20 to 30 cycles of the lowest peak frequency, which translates to a duration of $Te \geq 20{\sim}30/f_{min} \approx 6$ s,



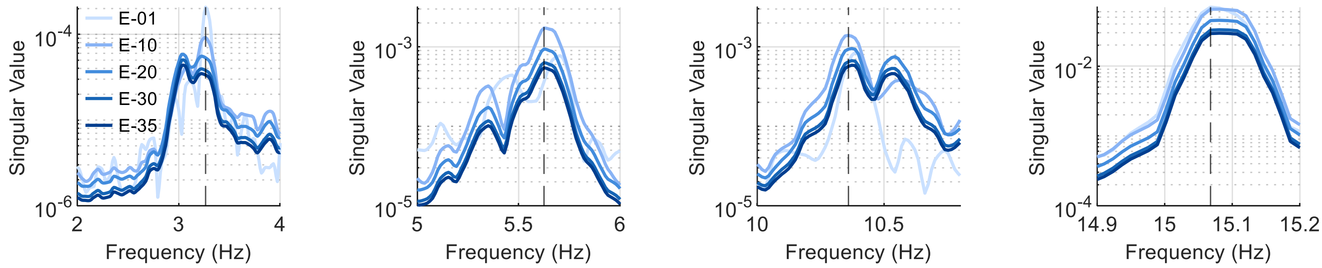
(a) Raw (b) Filtered (c) Spike removal

Figure 3. SV plots of stair microtremor data obtained using different processing methods (Setup 1, Z-axis).



(a) Peak 1 ($f = 3.265$ Hz) (b) Peak 2 ($f = 5.625$ Hz) (c) Peak 3 ($f = 10.360$ Hz) (d) Peak 4 ($f = 15.068$ Hz)

Figure 4. SV plots of stair microtremor data from different ensemble duration, T_e (Setup 1, Z-axis, Spike removal).



(a) Peak 1 ($f = 3.265$ Hz) (b) Peak 2 ($f = 5.625$ Hz) (c) Peak 3 ($f = 10.360$ Hz) (d) Peak 4 ($f = 15.068$ Hz)

Figure 5. SV plots of stair microtremor data using different ensemble number (Setup 1, Z-axis, Spike removal, $T_e = 25$s).

for $f_{min} = 3.265$ Hz. To examine the effect of ensemble duration on singular value (SV) estimation, we tested durations of $Te = 10$, 20, 25, 30, 35, 40 s. SV spectra were obtained for each duration in the Z-direction (Figure 4) using $N_{ens}^{max} - 10$ ensembles, where N_{ens}^{max} is the maximum number of ensembles available for that duration. This approach maintains a comparable number of ensembles across different durations.

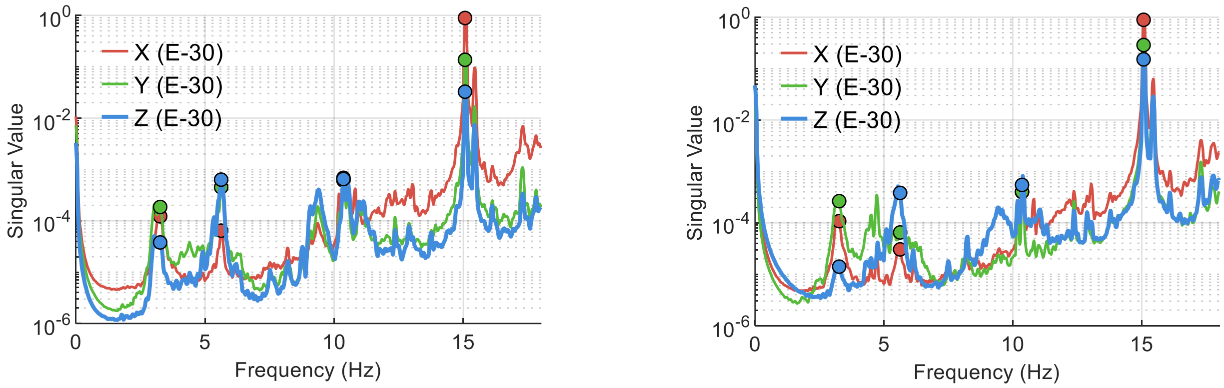
The results show that $Te = 25$ s provides the shortest ensemble duration for which modal peaks are clearly defined, sharp, and stable. Shorter durations result in poorly resolved peaks, making it difficult to identify modal frequencies accurately. Conversely, longer durations reduce the number of available ensembles for averaging, which can increase spectral noise and lead to the appearance of multiple closely spaced peaks. Based on this analysis, $Te = 25$ s was selected for subsequent FDD computations.

4.3. Selection of ensemble number for mode peak picking

After determining the duration of each ensemble, the next step is to select the number of ensembles to use for modal peak picking. As shown in Figure 5, ensemble averaging with 10 or more ensembles produces consistent frequency values, indicating stable frequency components in the SV spectra. While damping ratio estimation would also require consideration of SV amplitude stability, this study focuses solely on obtaining clear SV spectra for modal peak identification. Based on this analysis, 30 ensembles were used, providing stable and well-resolved modal peaks for subsequent FDD analysis.

5. Estimation of Mode Shapes by Peak Picking

With the ensemble duration and number of ensembles established, the final singular value (SV) spectra can now be used for modal peak picking to extract the corresponding mode shapes. Figure 6 shows the final SV spectra obtained



(a) Setup 1 (b) Setup 2

Figure 6. SV plot comparison between the two setups and considered peaks for peak picking.

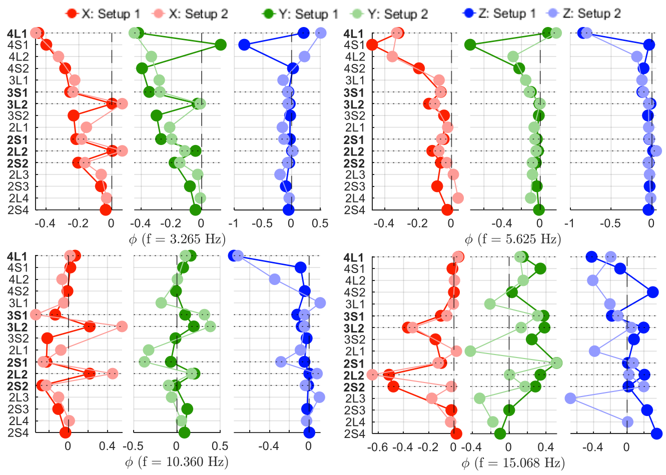


Figure 7. Estimated mode shapes for each peak.

using the selected parameters for Setups 1 and 2. For most peaks, the identified frequencies are consistent, with only minor differences in amplitude. An exception is the second peak in the Y-direction, which is slightly shifted to a lower frequency in Setup 2 compared to Setup 1. Nevertheless, for consistency in mode shape comparison, the peak frequencies identified in Setup 1 are also applied to Setup 2. As a result, the second Y-direction peak in Setup 2 appears with a lower amplitude than in Setup 1.

Figure 7 compares the mode shapes obtained from Setups 1 and 2 for all directions. Because the sensor sets and their placements differ between the two setups (see Table 1 and Figure 1), some measurement locations are available in one setup but not in the other. The Y-axis in Figure 7 lists the sensor names, with bold labels indicating sensors common to both setups (4L1, 3S1, 3L2, 2S1, 2L2, and 2S2). The signs of the estimated mode shapes were aligned using these common sensor locations. Since the FDD analysis was conducted independently for each setup, slight differences in scale are expected; nevertheless, the overall mode shape characteristics can be compared. The mode shapes corresponding to the first two peaks (f = 3.265 Hz and 5.625 Hz) show good agreement, particularly at the common sensor locations. For higher-frequency peaks, while most points remain generally consistent, some locations exhibit slight discrepancies, which may be attributed to reduced signal quality at higher frequencies and the independent FDD analyses performed for each setup.

6. Conclusion

This study investigated procedures to obtain clear and stable SV spectra for mode shape estimation of a four-story external steel emergency staircase using ambient vibration records. The main conclusions are:

- Outlier spike filtering effectively removes distortion while retaining low-frequency noise; if sufficient data are available, complete spike removal is preferred.
- Ensemble duration should be long enough to clearly define modal peaks but not so long that averaging fewer ensembles increases noise; the shortest duration giving stable peaks is recommended.
- The number of ensembles should ensure stable frequency SV spectra estimates; amplitude stability must also be considered for damping estimation.
- Mode shapes are generally consistent across the two setups, with minor discrepancies observed in higher-frequency modes, likely due to reduced signal quality.

References

1) Manolis, G. D., Makarios, T. K., Terzi, V., & Karetsou, I. (2015). Mode shape identification of an existing three-story flexible steel stairway as a continuous dynamic system. Theoretical and Applied Mechanics, 42(3), 151-166.
2) Belver, A. V., Zivanovic, S., Dang, H., Istrate, M., & Iban, A. L. (2012, March). Modal testing and FE model updating of a lively staircase structure. In Topics in Modal Analysis I, Volume 5: Proceedings of the 30th IMAC, A Conference on Structural Dynamics, 2012 (pp. 547-557). New York, NY: Springer New York.
3) Wenzel, H., & Pichler, D. (2005). Ambient vibration monitoring. John Wiley & Sons.
4) Brincker, R., Zhang, L., & Andersen, P. (2001). Modal identification of output-only systems using frequency domaindecomposition. Smart materials and structures, 10(3), 441.
5) Sato, D., Soriano, R. D. A., Shegay, A., Miyamoto, K., She, J., & Kasai, K. (2025). Estimation of wind force time-history using limited floor acceleration responses by modal analysis. Journal of Fluids and Structures, 132, 104203.
6) Pearson, R. K. (2002). Outliers in process modeling and identification. IEEE Transactions on control systems technology, 10(1), 55-63.

*1 東京科学大学 研究員・博士（学術）
*2 東京科学大学 総合研究院 准教授・博士（工学）
*3 東京科学大学 総合研究院 助教・博士（学術）
*4 東京科学大学 大学院生

Researcher, Institute of Science Tokyo, Ph.D. *1
Associate Prof., Institute of Science Tokyo, Dr. Eng. *2
Assistant Prof., Institute of Science Tokyo, Ph.D. *3
Graduate Student, Institute of Science Tokyo *4