



Modal Response Measurement and Analysis of Xiamen Fortune Center Structural Array

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Abstract. The modal parameters, including frequency and vibration mode, obtained through measuring and analyzing the vibrations of high-rise buildings under different sources of vibration, hold significant importance in understanding the overall deformation mode and seismic performance of the structures. Using measured seismic, air gun, and noise data, this paper analyzed the displacement and natural frequency of various levels within the building structure, including basement level 5, level 4, level 14, level 24, level 30, and level 42. The analysis was conducted based on the structural array, which consisted of a wideband seismic recorder installed on the Xiamen Fortune Center. The first four periods, damping ratio, and vibration mode of the structure were determined by utilizing the cross-power spectral density of different vibration sources. The findings demonstrate that the air gun source can detect the high-order modes of the structure, while the noise source can identify the low-order modes. Combining the two sources produces results comparable to those obtained from seismic signal analysis. The results indicate that the air gun source, when combined with noise and utilized in conjunction with the structure array, can successfully identify the first four modes of the structure. This modal analysis method introduces a novel non-destructive source detection approach.

Keywords: High-rise building, Modal identification, Vibration mode.

1 Introduction

Due to the ongoing economic and societal growth, an increasing number of high-rise buildings are being constructed. However, the stiffness and damping ratio of the structures often decrease over time, making them more sensitive to excitations such as wind-induced vibration, earthquakes, and external environments. Meanwhile, high-rise building structures in coastal cities are especially prone to accumulating damage from typhoons or earthquakes, resulting in a weakened resistance to natural disasters. Therefore, it is particularly important to employ scientific methods to assess structural health.

On-site measurement represents the most direct and reliable approach to studying the dynamic characteristics of structural vibrations. The sources of vibrations analyzed

for conventional building structures' dynamic characteristics include wind-induced vibration, earthquake, blasting, and noise. For instance, Wang [1] conducted a study on damping, wind field observation, and wind-induced responses in high-rise buildings. Fang [2-5] used typhoons to perform measurements and modal analyses on the Shenzhen Diwang Building. Shan [6] analyzed the natural vibration characteristics of the Shanghai Jinmao Tower under environmental excitations. Li et al. [7] investigated the wind-induced dynamic characteristics of a high-rise building in Xiamen. Yang [8] examined the propagation characteristics of blasting seismic waves, the dynamic response, and the safety criteria of building structures subjected to such waves.

The studies above primarily focused on wind-induced vibration in high-rise building structures influenced by typhoons. Both typhoons and earthquakes can lead to the accumulation of damage in building components and structures. Blasting is restricted due to environmental considerations. Hence, it is crucial to develop a new non-destructive method for inspecting building structures, allowing for extracting dynamic characteristic parameters without causing harm to the components. This study utilized a structural array installed in the Xiamen Fortune Center. We collected velocity-time response data for six floors of the structure under various vibration sources, including air gun sources, natural earthquakes, and noise signals. Additionally, we simulated and calculated displacement in different orientations for these six floors. Cross-power spectral density was employed to analyze the first four periods, damping ratio, and vibration modes of the structure under different vibration sources. The measured results were then compared and analyzed alongside finite element analysis outcomes, aiming to develop a non-destructive technology for detecting the health of building structures.

2 Overview of Fortune Center and Introduction of Structural Array

2.1 Overview of Fortune Center

Xiamen Fortune Center is situated on the eastern side of Lujiang Road in the southwest of Xiamen City. The primary building is a 43-story commercial office building, reaching a height of 192 m. The building consists of five underground floors, extending 21.2 m below ground level. The first floor above ground serves as a lobby and commercial space, with a 9.0 m height. The 2nd to 13th, 15th to 23rd, and 25th to 43rd floors are designated as standard office floors, with a height of 4.2 m. The 14th and 24th floors are designated as refuge and equipment floors, with a height of 4.8 m. The primary building features a drum-like plan shape, incorporating a structural system composed of a circular steel tube concrete column-frame-steel support system. The frame columns consist of circular steel tube concrete columns with rectangular steel tube supports placed between them. Additionally, each floor includes zigzag and single oblique steel tube supports. The main building exhibits a plan shape similar to that of a drum, featuring a height-to-width ratio of 5:7 and the absence of a podium structure

[10]. Figure 1 illustrates the structural elevations, whereas Figure 2 displays the floor plans of the standard floor at the Fortune Center.



Fig. 1. Elevation plan of Xiamen Fortune Center

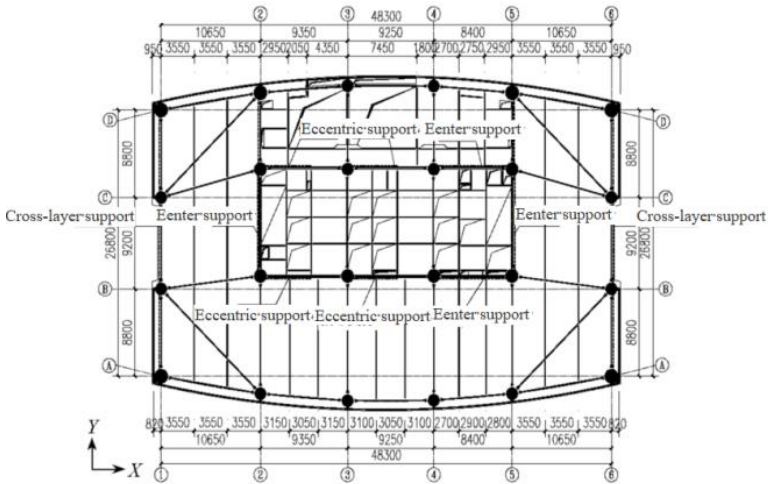


Fig. 2. The plan of the standard floor

2.2 Introduction of Structural Array

In order to enhance the study of dynamic characteristics in high-rise buildings and ensure precise measurement of parameters such as the first four periods, damping ratio, and vibration mode of the building structure, the Xiamen Fortune Center utilizes a structural array comprising seven wideband integrated seismographs. The seismographs specifically Guralp CMG-40TD portable digital velocity meters with a frequency range of 100Hz to 40s were employed to collect structural vibration modal

response data under various vibration sources. The observation was carried out on six floors of the building: basement level 5, level 4, the abrupt-change rigidity layer on level 14 and level 24, level 30, and top-level 42 (Figure 3). Each measurement point was strategically positioned within the reinforced electrical room of each floor, with two horizontal components and one vertical component at each point. As the building's surroundings had an influence on the measurements, the free field measurement point was situated approximately 450 meters away from the structure, within the premises of the Siming District Environmental Protection Bureau.

Each measurement point within the structural observation array consists of two parts, i.e., a seismograph and a 4G mobile data transmission device (Figure 4). The seismograph's built-in data collector converted the gathered displacement information into digital signals, storing them within the seismograph's internal memory. Subsequently, these signals were transmitted to a remote data stream server via a dedicated network protocol facilitated by the 4G transmission device. Additionally, to ensure precise timing for each measurement point in the structural array, the 4G mobile data transmission device was connected to an NTP high-precision network time server, guaranteeing accurate time synchronization for each seismograph.

In June 2019, the Xiamen Fortune Center structural array conducted synchronous observations during the high-capacity air-gun source detection experiment conducted by the Fujian Provincial Seismological Bureau. During this period, the structural array also captured data from two natural earthquakes that occurred along the east coast of Taiwan Island. This paper primarily analyzes and studies the data received by the Fortune Center structural array.

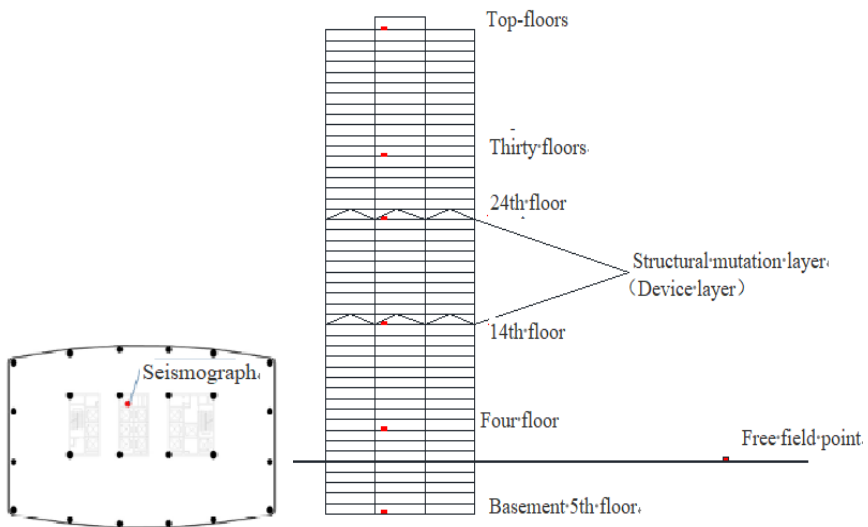


Fig. 3. Schematic diagram of table arrangement of structure

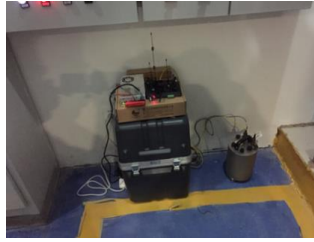


Fig. 4. The layout plan of observation instruments

3 Analysis of Structural Array Measurement Records

Figures 5, 6,7 and 8 depict the signals captured by the structural array in response to the M5.8 earthquake and M3.8 earthquake on the east coast of Taiwan, as well as air gun signals generated in the vicinity of Xiamen Island, respectively. Each column of signals corresponds to the floors from basement level 5 to top level 42, arranged from bottom to top. The structural array effectively records both seismic and air gun signals. Analyzing the natural seismic signals recorded by the structural array, it was observed that the peak displacement of different floors within the structure varied. The natural seismic signals exhibited relatively high main frequencies, and the displacement response of the structure increased gradually with the elevation of each floor. In contrast, the displacement response to the air gun source did not exhibit this consistent variation pattern.

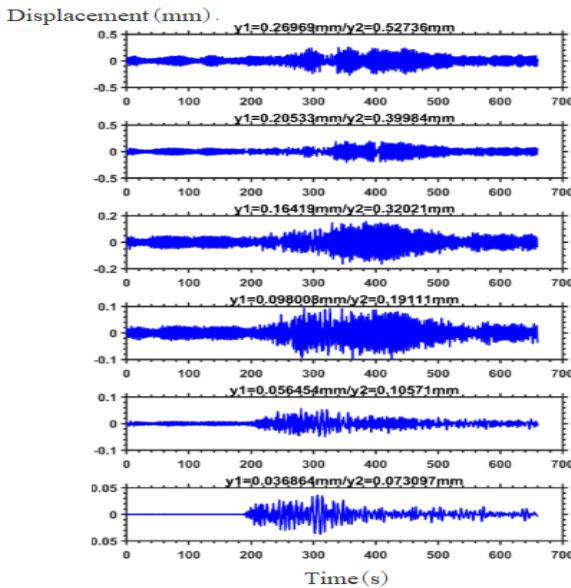


Fig. 5. The Y direction (short direction) signal of the M5.8 seismic array

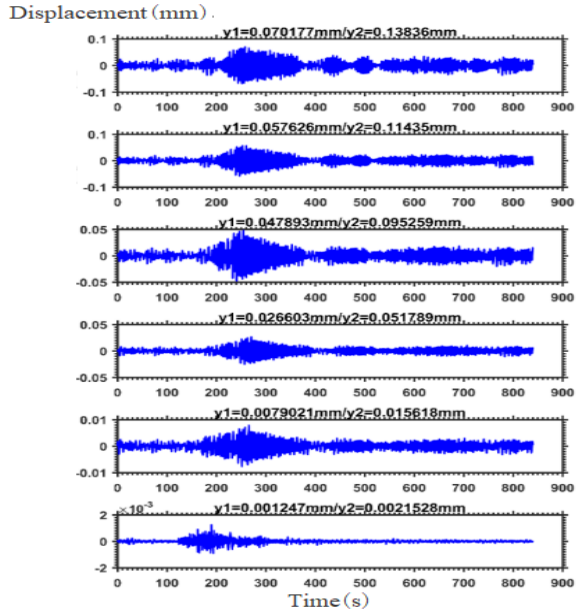


Fig. 6. The Y direction (short direction) signal of the M3.8 seismic array

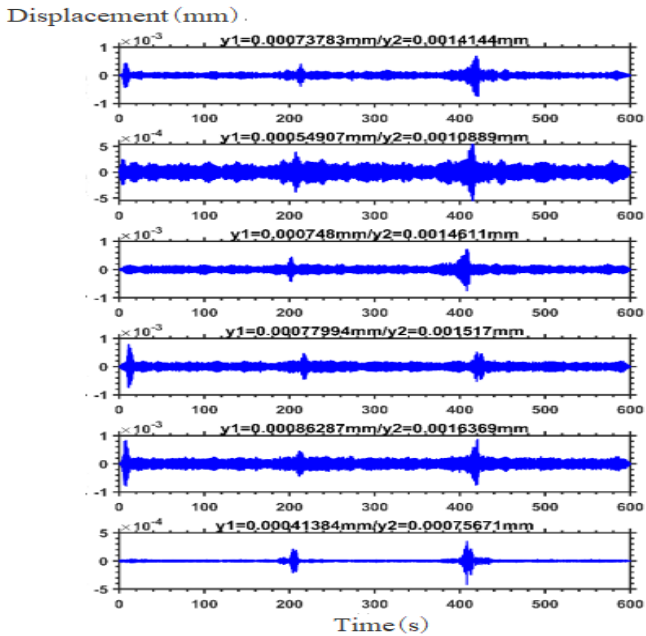


Fig. 7. The Y direction (short direction) signal of the air gun source array

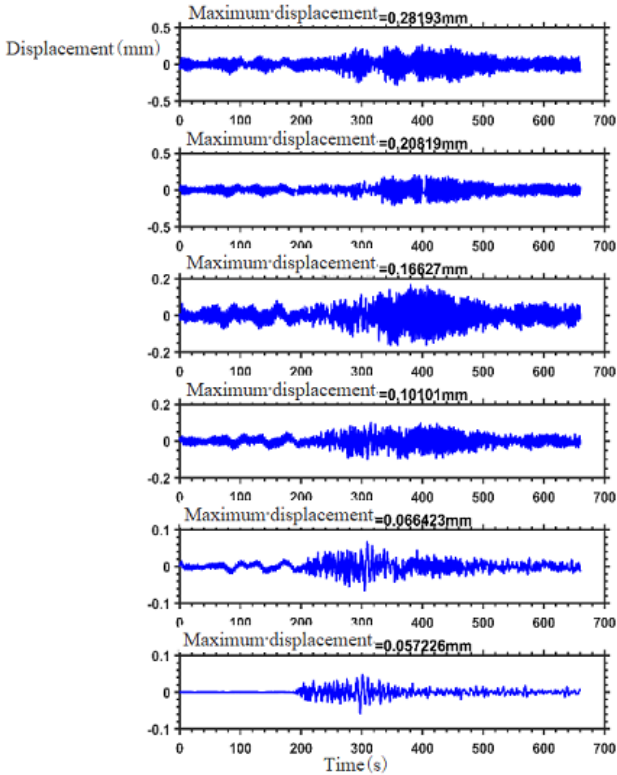


Fig. 8. Noise signal

The seismic events and air gun signals recorded by the structural array on the east coast of Taiwan and around Xiamen Island are displayed in Figures 5, 6, 7, and 8. Each column represents the respective levels, including the basement level, the 4th level, the 14th level, the 24th level, the 30th level, and the 42nd level, arranged from bottom to top. The structural array effectively captures both seismic and air gun signals, enabling analysis of the peak displacement values across different floors based on the recorded natural seismic signals. Natural earthquakes exhibit relatively high main frequencies, and the displacement response of the structure to these earthquakes gradually increases as the floor level rises. However, the displacement response of the air gun source does not demonstrate such consistent patterns of change.

4 Modal Response Identification

4.1 Principle of Modal Identification

Based on the engineering vibration inversion theory by Li Guoqiang[11], linear modal parameters such as vibration mode and modal frequency are determined to measure the

dynamic characteristics of the Xiamen Fortune Center structure. However, given the structure's location in a bustling urban area, the presence of measurement noise and excitation spectrum is inevitable, and the modal frequency may not necessarily align with the peak of the structure's response self-power spectrum[12]. To address this, the principles proposed by Li Guoqiang were applied to identify the structural modal frequency based on the spectral characteristics of the structure response as follows.

(1) The peak self-power spectrum of each measurement point in the structure's response is situated at the same frequency.

(2) The coherence function between measurement points at the modal frequency exhibits relatively high values.

(3) The measurement points demonstrate either the same or opposite phase at the modal frequency.

4.2 Modal Identification Results

By utilizing the aforementioned methods and principles, a customized program was developed on the MATLAB platform to identify the first four periods, damping ratios, and vibration modes of the structure. Cross-power spectral density results for seismic events, air gun sources, and noise sources were analyzed and presented in Figures 9 to 12, respectively. Table 1 displays the identified first four periods of the structure. Figure 13 showcases the first four vibration modes identified through the analysis of the M5.8 earthquake, while Table 2 exhibits the corresponding first four damping ratios calculated using the half-power method.

Table 1. The first four cycles (In: s)

Working condition	Y (Short axis)			
	First order	Second order	Third order	Fourth order
M5.8	4.038	1.056	0.535	0.333
M3.8	4.029	1.076	0.564	0.324
Air gun	--	0.998	0.508	0.304
Noise	4.001	1.002	--	--

Table 2. The first four order damping ratio (In: %)

Working condition	Y (Short axis)			
	First order	Second order	Third order	Fourth order
M5.8	4.247	1.135	0.728	0.534
M3.8	4.244	1.132	0.714	0.509
Air gun	--	1.254	0.856	0.589
Noise	4.178	1.189	--	--

As depicted in Table 2, the damping ratios of the Xiamen Fortune Center structure in the Y-direction for the first mode are approximately 4.2%, noticeably higher than that of the second to fourth modes. This observation suggests that the primary vibration of the high-rise building structure is predominantly governed by the first mode.

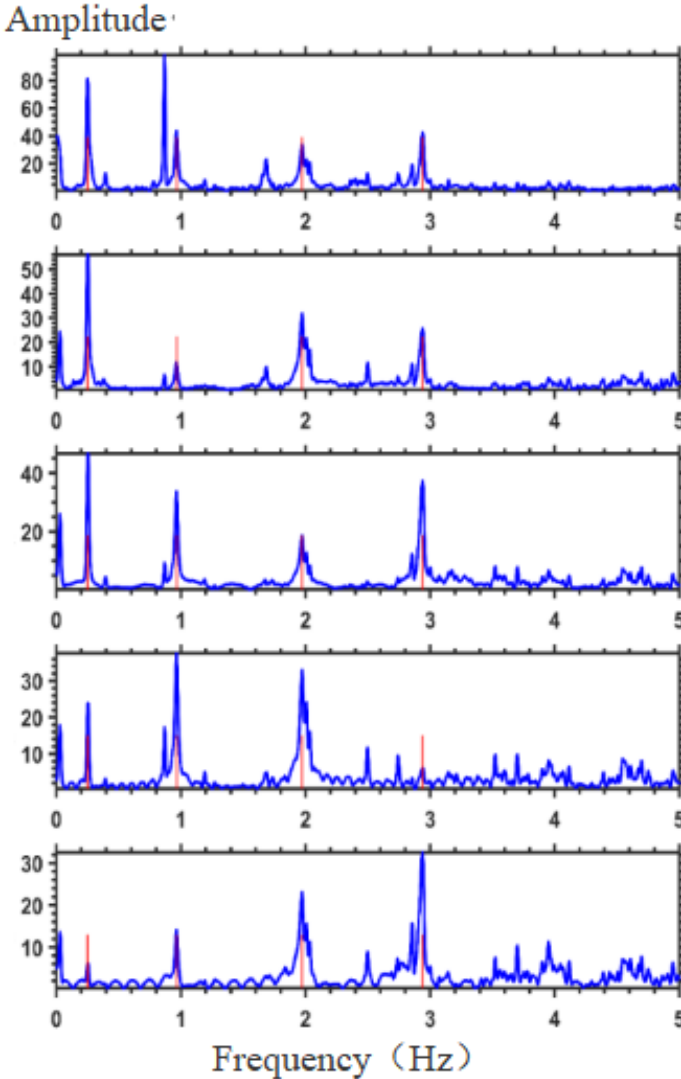


Fig. 9. Cross-power spectrum of seismic signals of M5.8

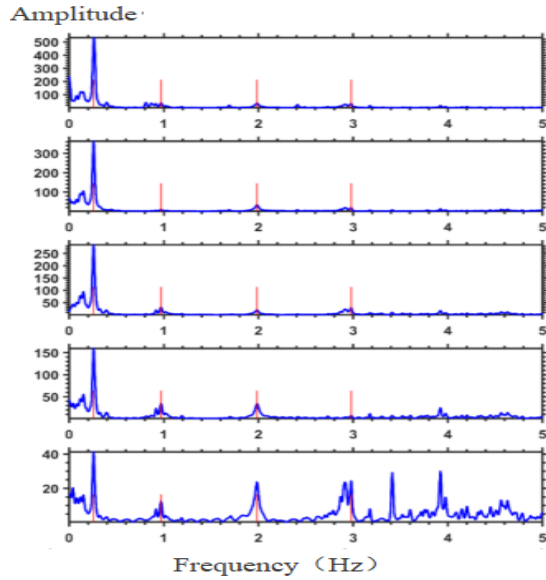


Fig. 10. Cross-power spectrum of seismic signals of M3.8

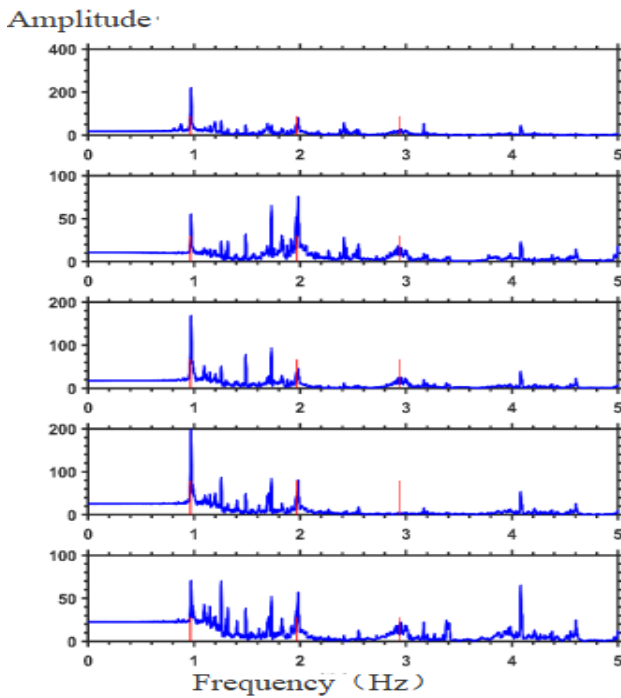


Fig. 11. Cross-power spectrum of air gun signals

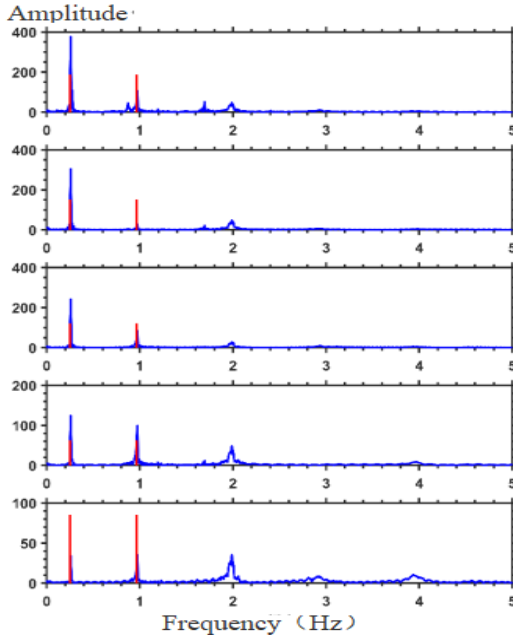


Fig. 12. Cross-power spectrum of noise signals

Through conducting modal analysis on the seismic, air gun, and noise signals captured by the structural array, the cross-power spectral density of seismic events, air gun sources, and noise sources at various floors of the Xiamen Fortune Center were calculated. The findings indicate that earthquakes exhibit a range of frequencies, spanning from low to relatively high values. In contrast, noise predominantly manifests lower frequencies, whereas the air gun source predominantly exhibits a relatively higher main frequency.

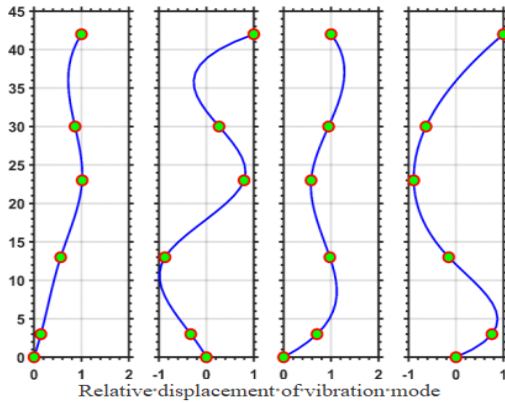


Fig. 13. The vibration types of M5.8

By analyzing the cross-power spectral density between the acceleration response at the basement level and the responses from other measurement points, the translational vibration modes of the structure were determined, as depicted in Figure 13. This figure reveals that the first-mode vibration represents a global translational mode, while the second and third modes depict anti-phase translational modes between the middle and upper and lower parts of the structure. Additionally, it is observed that the maximum displacement occurs at the vertex for the first four modes.

5 Conclusion

The Xiamen Fortune Center utilizes a circular steel tube–concrete column–steel support structure with innovative materials and forms. Modal parameters are important parameters that play a crucial role in assessing the reliability of structural analysis results and analyzing the seismic performance of the building. By employing suitable sensors and data acquisition systems, the difficulties of long periods and weak signals can be overcome. Modal vibration analysis was conducted using seismic, air gun, and noise signals, yielding the first four vibration frequencies and modes of the structure. This information serves as a basis for verifying or enhancing the structural analysis results obtained during the design phase by structural engineers. Furthermore, it lays the groundwork for subsequent seismic response simulation and analysis. The measured modal frequencies exhibit the following characteristics. (1) Seismic signals offer comprehensive results for the first four modes of the structure. Air gun and noise signals, as non-destructive sources, can provide results comparable to those obtained from seismic signal analysis, indicating that their combination can serve as a supplementary approach to traditional structural modal analysis. (2) Considering the Xiamen Fortune Center's configuration as a circular steel tube–concrete column–steel support structure with 42 floors and a height of approximately 200m, the first natural period extends up to 4.0 seconds, offering valuable insights for future designs of super high-rise buildings with similar materials, heights, and structural forms. (3) The ratios of the first three translational natural periods closely align with the ratios of the homogeneous shear deformation mode.

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