

Comparative Study on Distortion Evaluation Methods for Seismic Simulation Vibration Table

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Abstract: To address the inconsistency in distortion definitions for seismic simulation shaking tables, a comparative study was carried out on three distortion indices, namely the fundamental-referenced total harmonic distortion, the rms-referenced distortion, and the peak distortion, based on measured sinusoidal response data from a 2.4 m × 2.4 m biaxial seismic simulation shaking table. The results indicate that the fundamental-referenced total harmonic distortion and the rms-referenced distortion exhibit similar trends within the low-to-moderate distortion range, whereas the former has a clearer physical meaning and is more suitable as the primary index for evaluating sinusoidal waveform quality. The peak distortion is more sensitive to local abnormal spectral peaks and can therefore be used as a supplementary diagnostic index.

1. Introduction

Seismic simulation vibration tables serve as critical infrastructure for structural earthquake testing, equipment seismic evaluation, calibration of seismographs and vibration sensors, and environmental adaptability verification. The quality of their output waveforms directly impacts the authenticity of test loads, repeatability of control results, and reliability of experimental conclusions [1]. As application scenarios expand from traditional structural components to bridges, underground structures, nuclear power facilities, electromechanical equipment, and multi-degree-of-freedom complex systems, engineering communities have raised higher requirements for vibration tables' dynamic performance under wide-bandwidth, large-displacement, high-load, and high-fidelity simulation conditions [2]. Waveform distortion degree serves as a key indicator reflecting output deviations caused by combined effects of platform structure, hydraulic/electromechanical actuators, control algorithms, sensor-test linkages, and load coupling, acting as a critical bridge between equipment performance, control quality, and experimental accuracy [4]. However, distortion degree lacks unified definitions in existing standards, literature, and engineering tests, with varying expressions potentially leading to discrepancies in result interpretation and performance assessment.

Current research on distortion evaluation primarily focuses on three key aspects. First, it examines the conceptual framework, definitions, and calculation methods of distortion. Shmilovitz highlighted that total harmonic distortion (THD) can be defined in at least two common ways: using the

fundamental frequency as reference or the total effective value as reference. Different definitions directly impact the interpretation of test results and cross-comparability between experiments [5]. Dalali et al. further demonstrated that traditional THD metrics and DFT-based analysis methods may exhibit spectral leakage, fence effect, and interpretive bias when dealing with signals containing frequency fluctuations, interharmonics, or non-stationary components, necessitating signal-specific modifications to evaluation criteria [6]. Although these studies originated in power quality research, their discussions on discrepancies in distortion metric definitions, sources of spectral decomposition errors, and limitations in non-stationary signal evaluation provide valuable insights for analyzing distortion levels in sinusoidal output signals from vibration tables.

Secondly, the research focuses on the formation mechanisms of distortion in vibration tables and their control suppression strategies. Existing reviews indicate that waveform reproduction errors in hydraulic vibration tables are closely related to nonlinear flow characteristics, servo valve dead zones, friction, structural flexibility, oil source pulsations, and load variations. Control strategies typically employ approaches such as model inversion, three-parameter control, iterative learning, adaptive robust control, and online compensation [7]. Ramirez-Senent et al. proposed a control framework based on real-time state space model inversion to mitigate the impact of specimen load variations on system performance [8]; Liang et al. utilized Echo State Networks for online learning compensation to enhance the time-domain waveform reproduction capability of electro-hydraulic vibration tables [9]; Wang et al. improved harmonic parameter identification accuracy in hydraulic servo vibration tables through multi-innovation stochastic gradient algorithms from a dynamic estimation perspective [10]. In domestic studies, Song Qiong et al. demonstrated through nonlinear modeling of hydraulic vibration tables that low-frequency bands and resonance regions are particularly sensitive to distortion [11]; Hu Chunyan et al. implemented harmonic notch feedback methods to achieve distortion control in ultra-low frequency standard vibration tables, validating the effectiveness of harmonic compensation in reducing distortion [12]. These findings indicate that distortion degree is not a singular test result but rather a comprehensive representation of system dynamic characteristics and control performance.

Finally, the research focuses on the measurement techniques and engineering applications of distortion degree. Yang Qiaoyu et al. emphasized that distortion degree of low-frequency standard vibration tables serves as a critical indicator for evaluating technical performance. It is essential to specify whether displacement waves, velocity waves, or acceleration waves should be used for representation in low-frequency ranges to avoid confusion in results [13]. Studies by Ma Jiemei et al. demonstrated that acceleration harmonic distortion affects calibration results of velocity-type seismometers, indicating that distortion degree not only serves as equipment acceptance parameters but also significantly impacts measurement traceability accuracy [14]. From a measurability design perspective, Lü Qi et al. further proposed that transverse vibration ratio, acceleration harmonic distortion, and frequency indication error of low-frequency standard vibration tables should be considered as key measurement parameters for integrated evaluation [15]. In recent years, Ding Hongquan et al. have pioneered the use of non-contact methods such as machine vision to comprehensively test amplitude-frequency characteristics, repeatability, and distortion degree of low-frequency vibration tables, providing novel technical approaches for dynamic performance assessment under complex operating conditions [16].

Overall, existing research has sufficiently demonstrated the close relationship between distortion level and vibration table control accuracy, calibration capability, and the reliability of engineering tests. However, systematic discussions remain lacking regarding cross-comparisons of different distortion definitions, unified interpretations of the physical meanings of various indicators, and optimization of rapid testing procedures tailored for engineering applications.

Comprehensive analysis of existing research demonstrates that both domestic and international

standards and literature universally recognize distortion degree as a critical parameter in vibration table performance evaluation. However, comparability remains limited due to inconsistent definitions, waveform representations, and test protocols. Building on this foundation, this study conducts comparative analysis of various distortion calculation methods using measured sine wave excitation data from vibration tables, while examining their applicable scopes and characteristic differences in performance assessment contexts.

2. Distortion Evaluation Method

The key to evaluating the sinusoidal performance of vibration tables lies in determining whether their surface output can accurately reproduce target fundamental frequency excitation. ISO 5344:2004 defines distortion as unintended waveform variations, specifying that it can be measured for various physical quantities including current, voltage, acceleration, velocity, or displacement-with acceleration distortion exhibiting significant load dependence [17]. Therefore, in vibration table applications, distortion degree fundamentally quantifies non-ideal harmonic components in output signals rather than merely amplitude deviations. Current Chinese standards such as JJG 298-2015, JJG 948-2018, and JJG 638-2015 all list harmonic distortion or waveform distortion as critical performance requirements [19-21], though specification limits and reference objects vary across different vibration table types. Particularly in low-frequency and ultra-low-frequency scenarios, it is essential to clarify whether distortion degree corresponds to displacement waves, velocity waves, or acceleration waves to avoid confusion. Studies have shown that identical motion waveforms expressed through different physical quantities may yield distortion degree values differing by an order of magnitude, which could further affect seismometer calibration results [13,14]. Based on these findings, this paper categorizes vibration table distortion evaluation metrics into three types: fundamental reference-based total harmonic distortion, RMS reference-based distortion, and peak-to-peak distortion.

2.1 Fundamental Reference-Type Total Harmonic Distortion

The fundamental reference-type total harmonic distortion can be expressed by Equation (1):

$$\delta_1 = \frac{\sqrt{\sum_{i=2}^n A_i^2}}{A_1} \times 100\% \quad (1)$$

In the formula, A_1 represents the fundamental wave amplitude, and A_i denotes the amplitude of the i harmonic.

This formula corresponds to the most common THD_F definition, with its physical meaning being the ratio of the higher-order harmonic composite quantity to the main oscillation component. The total harmonic distortion specifications in ISO 5344 and JJG 298-2015 align with this conceptual framework, as Shmilovitz noted, since the fundamental component-based definition helps avoid interpretative ambiguities. For sinusoidal vibration table tests, this metric directly quantifies the deviation of non-fundamental components from target excitation, making it an ideal primary evaluation indicator for sinusoidal waveform quality.

2.2 Total Effective Value Reference-Type Distortion Degree

The total effective value reference-type distortion can be expressed by Equation (2):

$$\delta_2 = \sqrt{\frac{\sum_{i=2}^n A_i^2}{\sum_{i=1}^n A_i^2}} \times 100\% \quad (2)$$

This formula corresponds to the THD_R (rms-referenced THD) definition, where the normalized reference is based on the total signal RMS value. Its advantage lies in accurately reflecting the proportion of higher-order harmonics within the overall signal, aligning more closely with the direct reading logic of partial distortion meters or harmonic analyzers. Shmilovitz noted that THD_F and THD_R yield similar results under low distortion conditions, but the discrepancy widens significantly with higher distortion levels. Therefore, clear definitions must be established for practical engineering applications. This study incorporates this metric as a supplementary indicator to the fundamental reference-based total harmonic distortion measurement.

2.3 Peak Distortion Degree

Given that some engineering documentation still employs local abnormal peaks to characterize waveform distortion, this paper introduces the peak-to-peak distortion degree as an auxiliary metric, expressed by Equation (3):

$$\delta_3 = \frac{A_{peak}}{A_1} \times 100\% \quad (3)$$

In the formula, A_{peak} represents the peak value, and A_1 denotes the fundamental wave amplitude. Given that this study employs the spectral peak method to extract fundamental waves and major higher-order harmonic components, and considering Huang Haohua's observation that Japan also uses peak distortion degree to quantify distortion [3], we further specify: A_{peak} is calculated by subtracting the maximum value from the primary higher-order spectral peaks excluding the fundamental wave. This metric demonstrates greater sensitivity to individual abnormal spectral peaks, making it particularly suitable for identifying scenarios where overall distortion remains low but localized peaks are prominent.

2.4 Comparison of Three Distortion Degree Evaluation Methods

The fundamental reference total harmonic distortion (THD), total RMS reference distortion, and peak value distortion are all used to characterize the degree of output waveform deviation from an ideal sine wave, though they differ in normalization benchmarks and application scenarios. Current international standards and domestic regulations predominantly use harmonic-type metrics to describe vibration table distortion. ISO 5344, JJG 298-2015, JJG 948-2018, and JJG 638-2015 all prioritize harmonic distortion or waveform distortion as core performance requirements, while peak value distortion serves more as an auxiliary engineering indicator. The fundamental reference THD, measured against the fundamental amplitude, directly reflects the output waveform's deviation from the target fundamental frequency with the most explicit physical meaning, making it suitable as the primary evaluation metric. The total RMS reference distortion, based on the total signal RMS value, effectively supplements explanations regarding higher harmonic components' proportion in overall output. Peak value distortion focuses solely on prominent abnormal spectral peaks, demonstrating greater sensitivity to localized anomalies, making it ideal for fault diagnosis and anomaly identification. Therefore, these three metrics do not replace each other but correspond to three distinct levels: primary evaluation, supplementary comparison, and anomaly diagnosis.

3. Experimental Design and Result Analysis

3.1 Experimental Design

This study focuses on the measured input-output data of a 2.4m×2.4m bidirectional seismic

simulation shaking table under sinusoidal excitation conditions, as illustrated in Figure 1. The experimental data were derived from original sampling records obtained during the performance testing process of the shaking table, providing reliable representation of its actual output characteristics under varying frequencies, loads, and measurement point configurations.

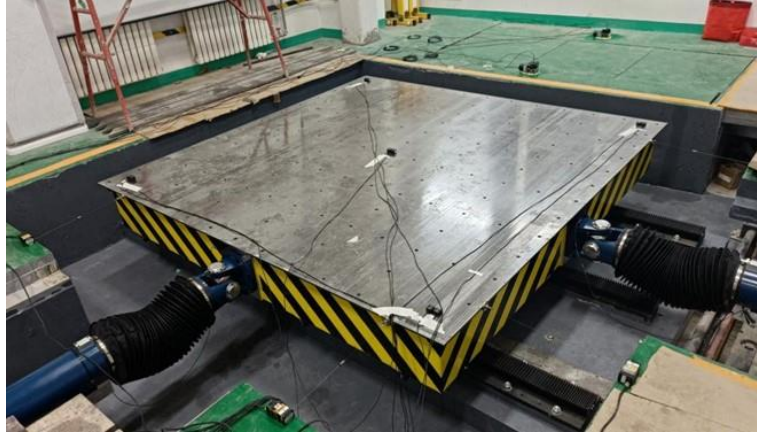


Figure 1: Photograph of 2.4 m × 2.4 m seismic simulation shaking table

The key performance parameters of the vibration table are listed in Table 1. For distortion measurement, laser displacement sensors and three-axis accelerometers were employed. Two displacement measurement points were installed in each of the two orthogonal horizontal directions, with a displacement measurement range of 500mm. Accelerometer measurement points were arranged at each of the four corners and the center of the vibration table surface.

Table 1: Performance indices of 2.4 m × 2.4 m seismic simulation shaking table

Worktop dimensions	2.4 meters × 2.4 meters
maximum bearing capacity	1 ton
service frequency	0.1~50Hz
Vibration direction	Horizontal bidirectional
Horizontal X-axis loading parameter	Maximum displacement: ±250 mm Maximum speed: ±1.6 m/s Maximum acceleration: ±1.5g (no load), ±1.3g (load of 1 ton)
Horizontal Y-axis loading parameter	Maximum displacement: ±250 mm Maximum speed: ±1.3 m/s Maximum acceleration: ±1.5g (no load), ±1.3g (load of 1 ton)
Maximum Sinusoidal Velocity of 1-ton Inertial Load	X-direction: 1.6 m/s Y direction: 1.3 m/s
Maximum velocity of unidirectional continuous sine wave	X-axis: ±0.8 m/s; Y-axis: ±0.8 m/s
maximum overturning moment	15kN m
maximum eccentric moment	15kN m

This study selected five representative frequencies (0.1, 1, 10,30, and 50 Hz) within the vibration table's operational range of 0.1–50 Hz, with operational conditions detailed in Table 2. Specifically, 0.1 Hz and 1 Hz were subjected to 125 mm large-displacement excitation to evaluate low-frequency displacement waveform distortion. 10 Hz and 30 Hz employed higher acceleration excitation to assess harmonic distortion levels in the mid-frequency range, while 50 Hz was positioned near the upper frequency band limit to test high-frequency control performance and distortion variations. Each

frequency point was tested under both no-load and 1-ton inertial load conditions with bidirectional X/Y loading, enabling comparative analysis of distortion metrics under different load configurations and loading directions.

Table 2: Test conditions for distortion measurement

Operating condition code	Condition name	pumping frequency /Hz	amplitude	loading condition	Excitation direction
T-01	displacement distortion degree	0.1	125mm	No load	X
T-02					Y
T-03	displacement distortion degree	1	125mm	No load	X
T-04					Y
T-05	acceleration distortion	10	0.75g	No load	X
T-06					Y
T-07	acceleration distortion	30	0.75g	No load	X
T-08					Y
T-09	acceleration distortion	50	0.3g	No load	X
T-10					Y
T-11	displacement distortion degree	0.1	125mm	1t inertia	X
T-12					Y
T-13	displacement distortion degree	1	125mm	1t inertia	X
T-14					Y
T-15	acceleration distortion	10	0.65g	1t inertia	X
T-16					Y
T-17	acceleration distortion	30	0.65g	1t inertia	X
T-18					Y
T-19	acceleration distortion	50	0.3g	1t inertia	X
T-20					Y

3.2 Data Processing and Distortion Degree Calculation Method

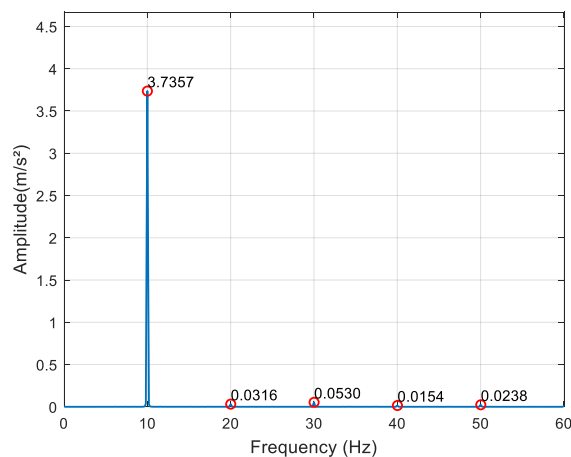


Figure 2: Frequency spectrum in X direction at 10 Hz under no-load condition

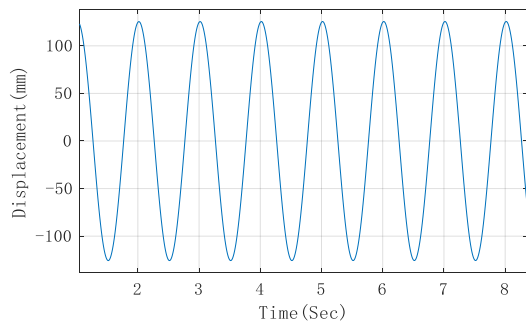
To ensure comparability of results across different operating conditions, this study employs a unified data preprocessing and spectral analysis workflow. Experimental data were sampled at 1024Hz with 0.1Hz sampling intervals, using 20-second intervals for specific conditions and 6-

second intervals for others. The process begins with mean removal from raw sequences to eliminate DC component interference, followed by Hanning window application to mitigate spectral leakage caused by limited sampling duration. The Fast Fourier Transform (FFT) is then utilized to obtain unilateral amplitude spectra, enabling identification of fundamental harmonics and dominant higher-order spectral peaks. For instance, the no-load X-direction 10Hz spectral diagram is illustrated in Figure 2. Bell's research on digital waveform measurement demonstrates that waveform parameter calculation methods based on digital sampling and spectral analysis exhibit excellent versatility, serving as a fundamental approach for harmonic parameter computation [18].

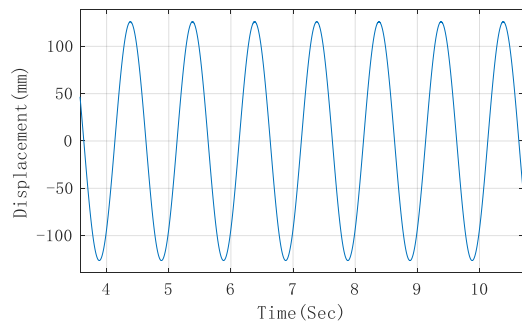
Based on unified spectrum analysis, this study sequentially identifies the fundamental peak A_1 and major higher-order spectral peaks A_2, A_3, \dots, A_5 for each dataset group, and calculates three distortion metrics using Equations (1) to (3). Partial time-history curves under specific operating conditions are presented in Figure 3, with the corresponding distortion calculation results summarized in Table 3.

Table 3: Calculation Results of Three Distortion Indices

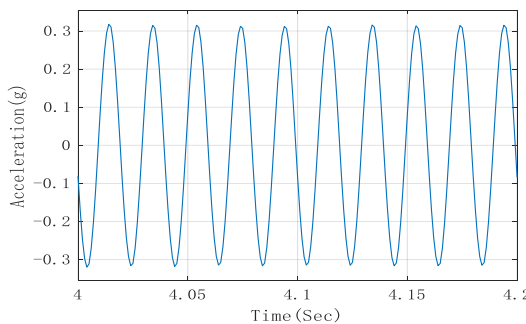
pumping frequency /Hz	amplitude	Distortion degree name	loading condition	$\delta_1/\%$		$\delta_2/\%$		$\delta_3/\%$	
				X	Y	X	Y	X	Y
0.1	125mm	displacement	No load	0.100	0.110	0.100	0.110	0.083	0.086
1	125mm	displacement	No load	3.181	2.030	3.179	2.030	2.326	1.736
10	0.75g	accelerated speed	No load	1.818	1.975	1.818	1.975	1.419	1.757
30	0.75g	accelerated speed	No load	1.412	1.351	1.412	1.351	1.195	0.746
50	0.3g	accelerated speed	No load	0.660	2.295	0.660	2.295	0.404	2.142
0.1	125mm	displacement	1t inertia	0.044	0.129	0.044	0.129	0.033	0.096
1	125mm	displacement	1t inertia	3.251	2.455	3.249	2.454	2.424	1.969
10	0.65g	accelerated speed	1t inertia	1.293	1.433	1.293	1.433	0.901	1.067
30	0.65g	accelerated speed	1t inertia	1.597	1.321	1.586	1.313	1.192	0.947
50	0.3g	accelerated speed	1t inertia	0.749	5.196	0.732	5.189	0.44	5.011



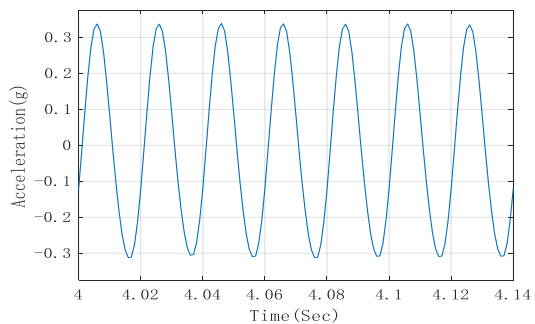
a) No load, X direction at 1 Hz



b) No-load Y-direction at 1 Hz



c) No-load X-direction at 50Hz



d) No-load Y-direction at 50Hz

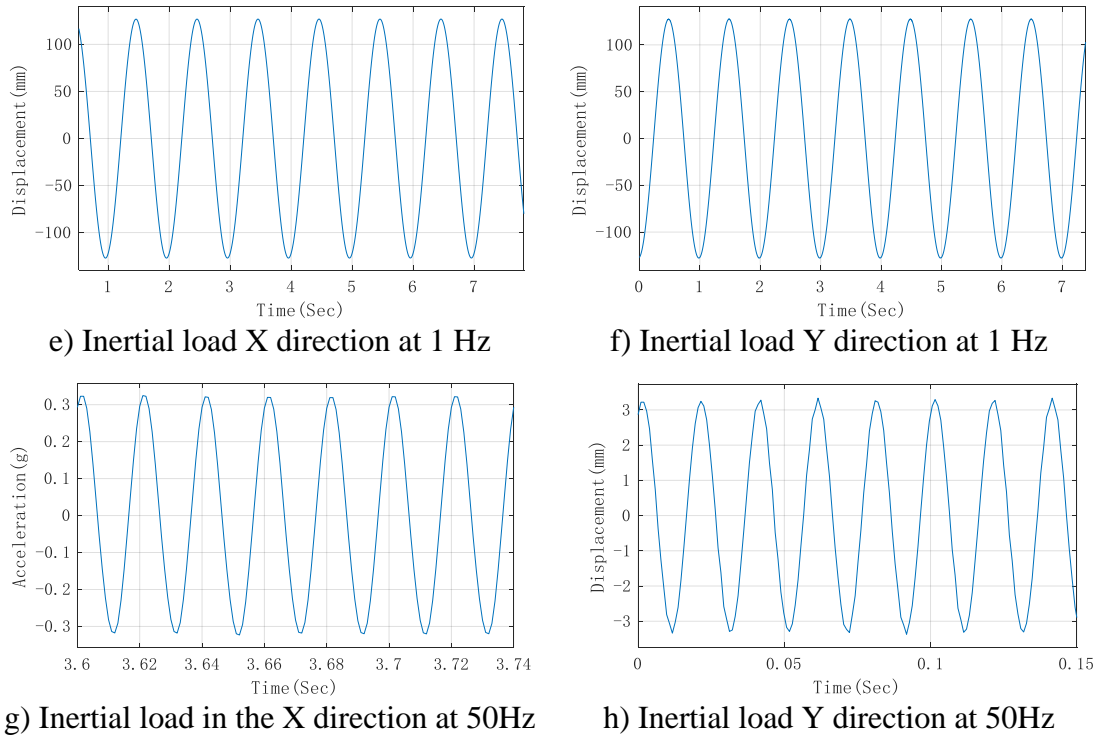
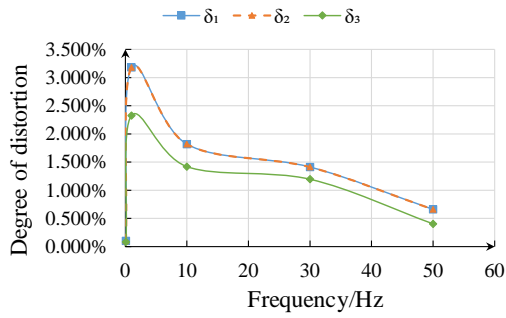


Figure 3: Distortion Time-History Curve

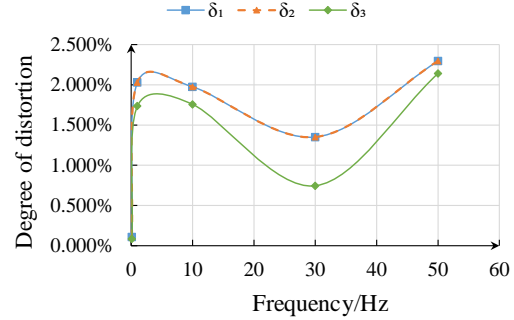
3.3 Comparison and Analysis of Three Distortion Degree Indicators

Generally, the fundamental reference-type total harmonic distortion (THD) δ_1 and the total RMS reference-type distortion δ_2 should exhibit consistent variation trends, as illustrated in Figure 4. However, due to differing normalization standards, the value of THD δ_2 typically remains below δ_1 . The observed consistency in experimental measurements indirectly validates the rationality of the computational approach.

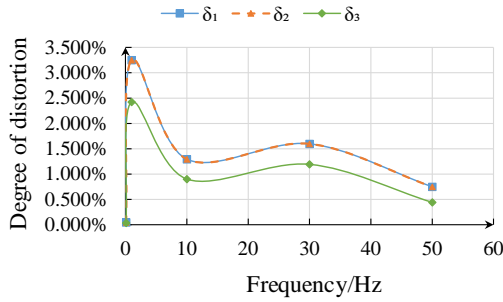
δ_1 and δ_2 exhibit essentially consistent variation trends across the four operating conditions with minimal numerical differences, indicating good consistency between the two harmonic distortion types within the low-to-moderate distortion range investigated in this study; δ_3 is generally lower than the former two but demonstrates greater sensitivity to localized abnormal spectral peaks. Both no-load X-direction and 1-ton load X-direction tests exhibited significant distortion at 1Hz with overall attenuation across the 10–50Hz frequency range, indicating greater sensitivity in low-frequency bands while demonstrating stable mid-to-high frequency control. The no-load Y-direction test showed renewed distortion increase at 50Hz, demonstrating localized harmonic amplification characteristics in high-frequency ranges. Under 50Hz load conditions, all three distortion metrics in the Y-direction for 1-ton load tests showed marked elevation, with metric δ_3 approaching values of δ_1 and δ_2 respectively. This indicates that distortion in this condition was predominantly driven by a single abnormal spectral peak, representing the most challenging operational scenario in the experiment. Overall, metric δ_1 should serve as the primary evaluation indicator, while metrics δ_2 and δ_3 are suitable supplementary analytical indicators.



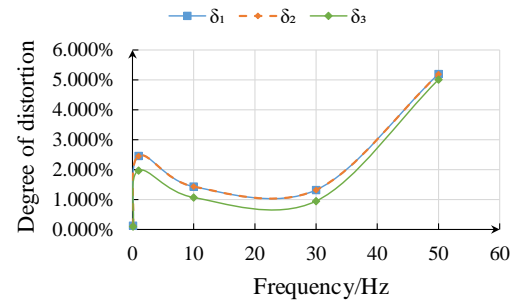
a) No-load X-direction distortion degree



b) No-load Y-direction distortion degree



c) X-direction distortion degree under a 1-ton load



d) Y-direction distortion degree under a 1-ton load

Figure 4: Overall comparison of three distortion indices

3.4 Analysis of Test Uncertainty and Discussion on Replicability

To ensure the reliability of comparative results among three distortion metrics, it is essential to analyze the sources of experimental uncertainty and methodological repeatability. The distortion measurements in this study are primarily influenced by sensor calibration errors, amplitude accuracy of acquisition systems, sensor installation conditions, limited sampling duration, spectral leakage caused by windowing processing, and control fluctuations of vibration tables. Since distortion calculations rely on extracting higher-order harmonic amplitudes—which are typically much smaller than the fundamental frequency—the results exhibit heightened sensitivity to harmonic identification errors. This sensitivity becomes particularly pronounced under low-distortion operating conditions, where noise interference and spectral leakage effects demonstrate more significant relative impacts.

From a computational perspective, both the fundamental reference-based total harmonic distortion (THD) and total RMS reference-based distortion are derived through multi-order harmonic synthesis, demonstrating low sensitivity to isolated spectral peak disturbances and overall robust performance. In contrast, the peak-to-peak distortion measurement exclusively utilizes the maximum abnormal spectral peak. While this approach enhances local anomaly detection capabilities, it remains more vulnerable to noise interference and spectral recognition errors.

Since this study did not conduct repeated loading tests under all operational conditions, rigorous statistical repeatability results cannot be obtained. However, based on methodological characteristics and existing findings, the first two harmonic-type indicators demonstrate consistent variation trends and comparable values under the test conditions, indicating good stability. The peak value distortion degree theoretically exhibits weaker repeatability compared to the aforementioned indicators. Therefore, the fundamental reference-type total harmonic distortion degree is more suitable as the primary evaluation metric for sinusoidal waveform quality in vibration tables.

4. Conclusion

Based on measured data from a 2.4 m × 2.4 m bidirectional seismic simulation shaking table with sinusoidal excitation, this study conducts comparative analysis on three key metrics: fundamental reference total harmonic distortion (THD), total RMS reference distortion, and peak value distortion. The results demonstrate that:

(1) The fundamental reference-based total harmonic distortion (THD) and total RMS reference-based distortion demonstrate nearly identical variation trends under the test conditions, indicating strong consistency between these harmonic metrics in the low-to-moderate distortion range.

(2) The fundamental reference-based total harmonic distortion (THD) directly quantifies the deviation of output waveforms from the target fundamental frequency, offering clearer physical interpretation. It serves as the primary evaluation metric for sinusoidal waveform quality in vibration tables. The total effective value reference-based distortion provides supplementary insights into the relative proportion of higher-order harmonic components in overall output. Peak-to-peak distortion demonstrates greater sensitivity to localized abnormal spectral peaks, making it an ideal auxiliary indicator for anomaly diagnosis.

(3) Test results indicate that the X-direction operating condition remains generally stable, while the Y-direction distortion significantly increases at 50Hz. Notably, the 1-ton inertial load under Y-direction 50Hz conditions represents the most challenging scenario in this test, demonstrating heightened load sensitivity at high frequencies in this direction.

In conclusion, the distortion evaluation of vibration tables should adopt a comprehensive analytical approach primarily based on fundamental wave reference total harmonic distortion (THD), supplemented by total effective value reference distortion and peak value distortion.

References

- [1] Ji Jinbao, Wu Jianfeng, Li Wenyue. *Comprehensive review on foundation design and construction technology for earthquake simulation shaking tables [J]. Journal of Beijing University of Technology*, 2022,48(8):888-897.
- [2] YAO J, DIETZ M, XIAO R, et al. *An overview of control schemes for hydraulic shaking tables[J]. JOURNAL OF VIBRATION AND CONTROL*, 2016,22(12): 2807-2823.
- [3] Huang Haohua. *Design and Application Technology of Seismic Simulation Vibration Table [M]. Seismic Publishing House*, 2008.
- [4] Liang Zhiguo, Zhu Jijie, Sun Jingyu. *An accurate evaluation method for waveform distortion of sine signal sources [J]. Journal of Metrology*, 2003(02):144-148.
- [5] SHMILOVITZ D. *On the Definition of Total Harmonic Distortion and Its Effect on Measurement Interpretation[J]. IEEE Transactions on Power Delivery*, 2005,20(1): 526-528.
- [6] DALALI M, JALILIAN A. *Indices for measurement of harmonic distortion in power systems according to IEC 61000-4-7 standard[J]. IET generation, transmission & distribution*, 2015,9(14): 1903-1912.
- [7] TANG Y, SHEN G, ZHU Z, et al. *Time waveform replication for electro-hydraulic shaking table incorporating off-line iterative learning control and modified internal model control[J]. PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS PART I-JOURNAL OF SYSTEMS AND CONTROL ENGINEERING*, 2014,228(9): 722-733.
- [8] RAMIREZ-SENENT J, GARCIA-PALACIOS JH, DIAZ I M. *Shaking table control via real-time inversion of hydraulic servoactuator linear state-space model[J]. PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS PART I-JOURNAL OF SYSTEMS AND CONTROL ENGINEERING*, 2021,235(9): 1650-1666.
- [9] LIANG J, DING Z, HAN Q, et al. *Online learning compensation control of an electro-hydraulic shaking table using Echo State Networks[J]. ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE*, 2023,123: 11.
- [10] WANG X, LI W, YAO J, et al. *Acceleration Harmonic Estimation for Hydraulic Servo Shaking Table Based on Multi-Innovation Stochastic Gradient Algorithm[J]. MATHEMATICAL PROBLEMS IN ENGINEERING*, 2020,2020: 13.
- [11] Song Qiong, Zhu Changchun, Niu Baoliang. *Modeling of hydraulic vibration table and analysis of acceleration waveform distortion [J]. Machine Tool and Hydraulics*, 2008,36(12):81-83.
- [12] Hu Chunyan, Li Xinliang. *Distortion control of harmonic trapping method ultra-low frequency standard vibration table[J]. Measurement Technology*, 2010(4):3-4,8.
- [13] Yang Qiaoyu, Shu Yulong. *Distortion degree and measurement of low-frequency standard vibration table[J]. World*

Seismic Engineering, 2011,27(2):185-189.

[14] Ma Jemei, Teng Yuntian, Zuo Aibin, et al. *Effect of acceleration harmonic distortion degree on vibration table calibration of velocity seismometers [J]*. *Journal of Seismology*, 2014(6):1124-1130.

[15] Lü Qi, Wang Junbo, Zhang Ying, et al. *Research on Measurable Design of Low-Frequency Standard Vibration Table [J]*. *Metrology Science and Technology*, 2022,66(4):101-107,88.

[16] Ding Hongquan, Chen Hongjiang, Bai Wenqi, et al. *Method for testing dynamic performance parameters of low-frequency vibration tables based on machine vision [J]*. *China Testing*, 2024,50(10):99-104.

[17] TC ISO. *Equipment for generating electric vibration. Performance characteristics: International Organization for Standardization*, 2004.

[18] BELL B A. *Standards for waveform metrology based on digital techniques[J]*. *Journal of Research of the National Institute of Standards and Technology*, 1990,95(4): 377-405.

[19] National Technical Committee on Vibration and Shock Speed Measurement. *Standard Vibration Table: JJG 298-2015[S]*. China Standards Press, 2015.

[20] National Technical Committee for Standardization of Testing Machines (SAC/TC 122). *Electric Vibration Table: GB/T 13310-2007[S]*. China Standards Press, 2007.

[21] National Technical Committee for Standardization of Testing Machines (SAC/TC 122). *Hydraulic Vibration Table: GB/T 21116-2007[S]*. China Standards Press, 2007.