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Methodologies of Electromagnetic Shaking Table Seismic Test on Reduced Scale Specimen of Building Structures

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Abstract: The performance of shaking tables and their control systems are key elements to achieve the objects of a seismic vibration test simulation. In this paper, the methodology of a vibration test on reduced scale test specimens with a small scale electromagnetic shaking table has been proposed. For the influence of test specimens and table structure over the table output signal, this method optimizing the non-linear correction of signals driven by the shaking table so as to reduce the distortion degree of the table output excitation parameters has been discussed. The solutions of the preprocessing of input signals, post-processing of output signals, and analyzing test data targeted at the structural features of reduced-scaled test specimens has also been put forward.

Keywords: Random vibration, Shaking table driven by electromagnetism, Nonlinear correction, Servomechanism, Total harmonic distortion.

1. Introduction

The shaking table test is an important approach to study structural failure mechanisms under earthquake action, as well as to assess structures' seismic performance. Since the 1940s, hundreds of large-scale shaking tables simulating earthquakes have been established worldwide. Most of them have been equipped with electro-hydraulic servomechanisms [1-3]. An electro-hydraulic shaking table features high precision, quick response and high power, and is applicable to the shaking table test of simulating earthquake response on large-scale structures. The electromagnetic type is characterized by a broad band of frequency, high quality wave shape, and easy controllability. However, its load capacity is much smaller than an electro-hydraulic shaking table. There is a six-Dof electro-dynamic shaking table of three axes in the U.S. with the maximum test specimen weight of 2500 kg, the maximum displacement of 50 mm, and the frequency range of 5-2000 Hz. The equipment system and control technology on the shaking table have been greatly improved in recent years [4]. A digital-to-analog converter based on corresponding principles could be able to convert digital signals operated and processed by computer into analog signals. Moreover, the method of random vibration power spectrum reproducing tests makes it possible for the computer to control the vibration equipment accurately. However, further study should be conducted on controlling the algorithm stability and convergence rate, as well as controlling precision. The development of various apparatus, such as sensors of acceleration, velocity and displacement, and cameras with high frame rate, make it easier to collect and record the parameters and process of vibration response from test specimens. In addition, the related primary dynamic behaviors of the structure can be obtained through processing of the collected data by means of specialized software [5]. The testing time, expenditure, and other influential factors in the shaking table seismic test lead to substantial limitations of the number of test specimens and comparing research of test results. Hence, identifying an appropriate method for conducting large quantities of vibration tests, especially to determine the relevance between influential factors, requires additional exploration.

This paper mainly discusses how to configure the software system and hardware system of a small electromagnetic shaking table and the methodologies of the shaking table test on reduced-scaled structures, and tries to provide references for shaking table seismic tests on reduced-scaled structures.

2. Technical Parameters on the Hardware of an Electromagnetic Shaking Table System

2.1. Shaking Table Body and Driving Device

The components of a shaking table seismic test system are shown in Fig. 1. The moving parts act as the actuator of the control unit. They are the physical basis and carrier of vibration environment to be simulated.

A small electromagnetic shaking table is composed of the table body and supporting device, as well as the driving coil, moving parts, suspension, directing device of moving parts, charge amplifier, integrated vibration controller, etc. (as shown in Fig. 2).

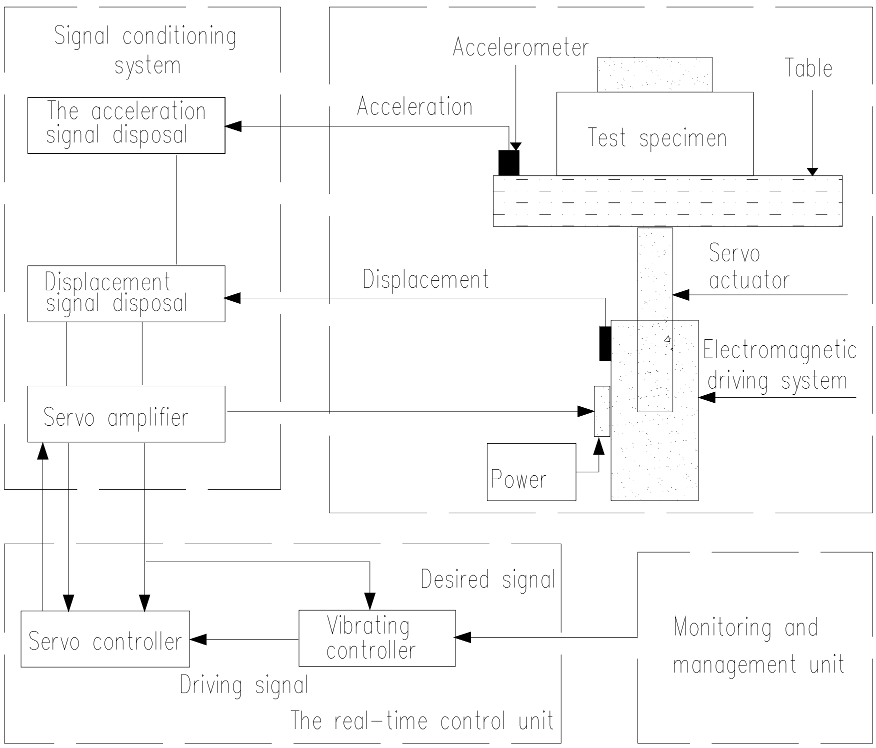


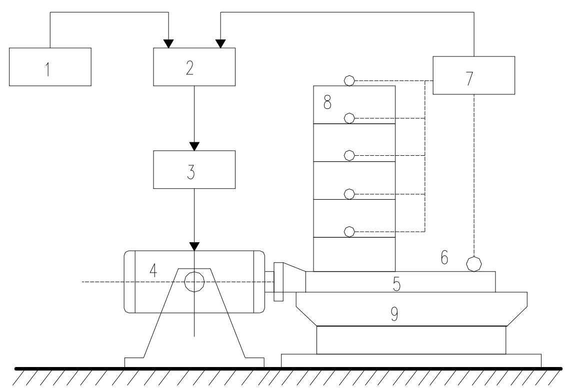
Fig. 1. Components of shaking table seismic test system.

The structure of the electromagnetic vibration exciter is shown in Fig. 3. Its construction features indicate that the specially designed shaking table could be applicable to simulate earthquake vibration on reduced-scaled test specimens accurately, and could meet the precision and relevant technical indicator specifications required by the test.

Considering that the natural vibration frequency of the reduced-scaled structure at each step is usually several times more than that of the prototype structure, the upper limit of working frequency of the shaking table should be no less than 200 Hz, the lower limit should be no more than 0.1 Hz, and the frequency accuracy should be within 0.01 Hz. It is feasible to meet the requirements for the electromagnetic shaking table. Existing academic achievement indicates that a double-magnet driving structure can make the lower limit of the working frequency of the shaking table be less than 0.01 Hz [6]. In order to reproduce seismic waves during the seismic test, it is necessary to keep the amplitude-frequency fluctuation range of the shaking table within ±3 dB. The driving coil, moving parts, table body, and supporting device are key elements of the shaking body. The shaking table should provide enough strength and stiffness required for the seismic test to install the test specimen. The natural vibration frequency of the shaking table should be no less than 500 Hz, so as to ensure that the intrinsic vibration mode will not be stimulated within the working frequency range. The natural vibrating frequency of the table body can be estimated with equation (1):

$$[K]\{\phi_i\} = \omega_i^2 [M]\{\phi_i\}, \tag{1}$$

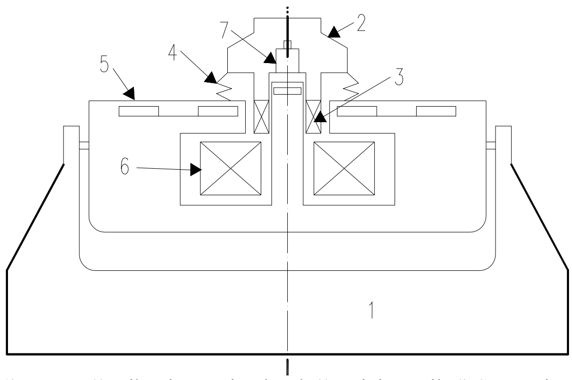
where [K] represents the stiffness matrix; $\{\Phi_i\}$ is the vector of the vibration mode at step *i*; ω_i is the intrinsic frequency of the mode at step *i*; and [*M*] is the mass matrix.



1) Signal generator; 2) Automatic controller; 3) Power amplifier; 4) Electromagnetic exciter; 5) Shaking table; 6) Vibration measuring sensor; 7) Vibration measurement and record system; 8) Test piece; 9) Table foundation.

Fig. 2. Composition system of the shaking table.

The table size limits the maximum dimension of the structural test specimen. The dead weight of the table body is related to the table structure, the bearings' weight of the test specimen, and working frequency range. The ratio between the test specimen weight and the table body weight is recommended to be no more than 2 times. The weight of the shaking table foundation shall be 10-20 times that of the moving parts or the exciting force. These requirements can improve the high-frequency character of the system and reduce impacts from surrounding buildings or other equipment. The shaking table shall also be able to vibrate vertically and horizontally, so as to meet the requirements of the three-dimensional and six-Dof (degree of freedom) seismic test. The maximum loaded weight of the shaking table shall be determined according to the expected exciter power. In order to be more feasible and economical, the test specimen weight shall be within 100 Kg, the maximum acceleration under full load shall be no less than 2 g, and the maximum displacement may be controlled within ±30 mm, so as to complete a seismic test for reduced-scaled test specimens with a higher cost performance ratio.



1) Frame; 2) Vibration exciter head; 3) Driving coil; 4) Supporting spring; 5) Magnetic shield; 6) Exciting coil; 7) Sensor

Fig. 3. Structure of the electromagnetic vibration exciter.

2.2. Data Acquisition Unit

1) Sensor.

The vibration sensor will be calibrated before being applied to the seismic test and marked with such indicators as sensitivity, frequency response curve, linear dynamic features, transverse susceptibility, temperature response, etc. The requirements are as follows: sensitivity error is ±0.5 %; sensitivity stability is ±0.5 %/year; frequency response and relative motion sensitivity change is -2 %; sensitivity change is ±4 %; and strain sensitivity is 0.001 g/με. To calibrate a sensor, precision could be achieved with sine wave as the calibration excitation signal, and frequency bandwidth could be obtained with random waves, such as white noise wave [7].

2) High-speed Camera.

The high-speed camera can record the details of how a test specimen becomes destroyed during vibration, so as to play back and research the vibrating response of a structure. The camera frame frequency should be no less than 5 times the frequency of the high-order mode, so that the response process of the high-order mode during each vibration period can be recorded clearly, which makes it possible to identify dynamic response details of the structure in later study. Because certain high-order frequencies of small-scaled test specimen can reach up to about 150 Hz, the high-speed camera to record the vibration test video should have a frame frequency of at least 1000 fps [8, 9].

2.3 Control Equipment

Control of the shaking table is performed through computer, controller, signal generator, charge amplifier, data acquisition unit, etc. The computer configuration should match the software operating environment, and the interface should be designed for ease of communication with the controller. The analog signal output interface (D/A) of the signal generator should be connected to the power amplifier directly through a double BNC cable. The power amplifier magnifies the input electric signal through the amplified current to provide the driving force for the vibration exciter. The charge amplifier should feature functions, such as charge magnification, voltage amplification, low pass filtering and integration, in order to be able to amplify the piezoelectricity acceleration sensor signal of the control shaking table and import the output voltage analog signal to the control shaking table and data acquisition unit directly.

3. Software System and Function

3.1. Control Software

The software system of the shaking table includes two components: the monitoring and management unit, and the real-time control unit. The monitoring and management unit is responsible for system management and data monitoring. It interacts with the power management unit by serial communication bus. The real-time control unit is responsible for running the real-time control program and logic management, data acquisition (A/D), and signal output (D/A). It makes servo control and vibration control possible. The structural composition and the relationship of the shaking table system software are shown in Fig. 4.

The key element of the shaking table is servo system that controls the whole system. A schematic diagram of the shaking table servo system is shown in Fig. 5.

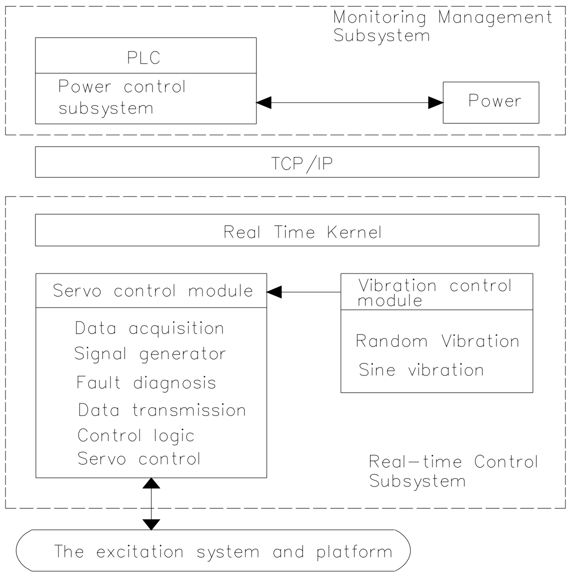


Fig. 4. System software structure.

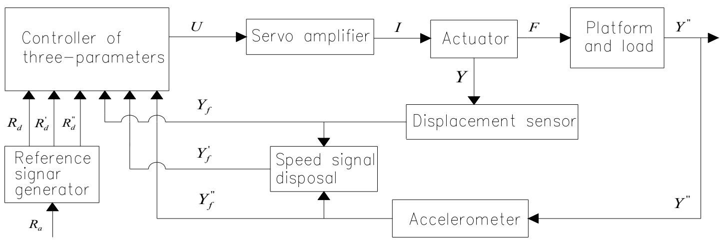


Fig. 5. Schematic diagram of the shaking table servo system with the controller of three parameters

Specifically, R_a is the reference acceleration signal; R_d is the reference location signal; U is the control voltage (V); I is the control current (A); K_a is the servo amplifier gain (A/V); F is the actuator load; and the three parameters, respectively, correspond to displacement Y, speed Y', and acceleration Y" of the shaking table system. Depending on the seismic vibration parameters to be simulated, the vibrating controller synthesizes the corresponding drive signal. Then, the drive signals are conveyed to the input terminal of the servo controller. The servo amplifier then converts the voltage signal generated from the servo controller to the current signal that will be applied to control the reciprocating movement of the servo actuator. The response signals are fed back to the servo controller through the displacement conditioner and acceleration conditioner. Thus, the closed-loop control of the motion platform is performed. The response signal of the shaking table under servo control will have a large deviation compared with the expected signal, and exhibits a nonlinear relationship. For this reason, an input seismic wave signal cannot be directly used to stimulate the test specimen on the shaking table. A vibration control loop is formed in the outer ring of the servo control loop, which feeds back to the vibrating controller the answer signal of analog quantity, such as seismic acceleration, displacement, etc. Special vibration control technologies are implanted into the vibrating controller so that nonlinear iterative compensation to the drive signal could be conducted, and the answer signal of the system can reproduce the seismic analogy signal with high precision [10].

Noise signals generated by the shaking table system may affect control precision. An anti-aliasing filter system must be installed between the A/D and D/A convertor, and the shaking table analog control system to eliminate noise signal and improve control precision.

3.2. Data Analysis and Processing Software

The recorded seismic original wave data can be processed with a correction filter using specialized software, such as Seismosignal. The control signal, pick-up feedback signal, and experimental data can be analyzed and processed with Vib Control+ Vib SQK, which is system software provided by a shaking table manufacturer. The experimental results data can also be processed by programming based on MATLAB. Image data recorded by high-speed camera can be processed with specialized software, such as ProAnalyst, to measure movement data and to extract corresponding relationships.

4. Seismic Vibration Simulation Test

4.1. Test Scheme for Small-scale Specimen

The test objective of the shaking table seismic test is to explore a certain seismic performance of a building structure. According to the test objective, the test scheme is as follows: 1) to design small-scale test specimens based on the structural features of a prototype building and the working frequency band, maximum displacement, velocity acceleration, and load bearing capacity of the shaking table; 2) to inspect whether or not the shaking table meets the test requirements [11]; 3) to make the test loading scheme and determine the contents of structural dynamic behavior, and seismic dynamic response to be tested in different working phases (crack, yield, and damage stages); 4) to manufacture and fix the test specimen according to test rules; 5) to calibrate and arrange acceleration sensor, displacement meters and gauge transducers, so as to gain various data related to a test objective; 6) to set some mark points on the test specimen to make tracking analysis on the recorded image data; and 7) to take some pre-protective safety measurements, so as to ensure the safety of personnel and apparatus during the process of the crack and damage stages under simulated seismic action.

4.2. Preprocess of Input Seismic Signal

To conduct the shaking table test, at least two actual recorded seismic waves and one seismic simulated acceleration time-history curve should be chosen as the seismic excitation signal based on site geographic conditions, seismic fortification intensity, and the structural features of the prototype structure. For example, if seismic test specimens are related to the building that lies in the Shanghai area with seismic fortification intensity 7 and class IV ground soil. In addition, their seismic driving signals should be from ElCentro wave, Pasadena/San Fernando wave, and Shanghai artificial seismic wave II. If original record data from an actual seismic wave are applied to the test, the process of filtering and correction should be conducted with specialized software, such as Seismosignal. According to the given similarity relation, the sampling frequency is adjusted, and the correct seismic wave is corrected again. The seismic wave TXT file is also changed into the needed input data format of a shaking table controlling system, the input amplitude (A_{gm}) is determined by formula (2):

$$A_{gm} = S_A * A_{gp}, \qquad (2)$$

where A_{gp} is the ground maximum acceleration corresponding to prototype design intensity level; and S_a is the similar coefficient of acceleration.

4.3. Correction on Control Parameter of Shaking Table

There are certain parameters that should be calibrated and corrected in the operation software of the shaking table, such as sampling frequency, controlling freedom, controlling scheme, frequency resolution, calibration coefficient, and dimensional unit. Frequency resolution is determined by formula (3):

$$\Delta f = \frac{S_f}{2 \times N_{sl}}, \qquad (3)$$

where S_f represents sample frequency (Hz); and N_{sl} represents the spectrum line numbers in the frequency domain.

As a seismic wave file is read into the system, a corresponding desired signal could be defined. Moreover, the controlling vibration amplitude should be examined so that the excitation could be appropriate for test and observation. Generally, the correction steps are as follows: 1) to input the desired signal file; 2) to examine the time domain curve and spectrum curve in the system control software; 3) to filter the desired signal to the range that requires control with the low-pass filter; 4) to set identification parameters in the system operation software and to generate white noise; and 5) to conduct synchronous identification on the shaking table to judge whether it is synchronous through the superposition situation of the characteristics of curve and phase of white noise by the pre- and post-synchronous operation.

Fig. 6 shows the seismic wave chosen for the test. Fig. 7 shows a white noise wave generated by the computer control system. By means of correction, the white noises are almost coincident (as Fig. 9 shows).

It could be evaluated by the corresponding phase curve (as Fig. 11 shows). If the alignment chart is nearly with a certain fixed value, the controlling system has been synchronous.

If the white noises are not coincident (as Fig. 8 shows), the phase curves fluctuate sharply (as Fig. 10 shows), and the iteration error will very large [12].

Based on the feedback signal of white noise, the performance of the shaking table could be corrected and transformed. According to characteristics of the test specimen and seismic wave, the frequency band, which is out of range, could be removed. Non-linear curve could be smooth-processed by multiplied coherence function. If the coherence function were weight-processed, the deficiency of the non-linear identification curve could be compensated, and the poor coherence characteristics could be suppressed. One of the compensation function curves is shown in Fig. 12.

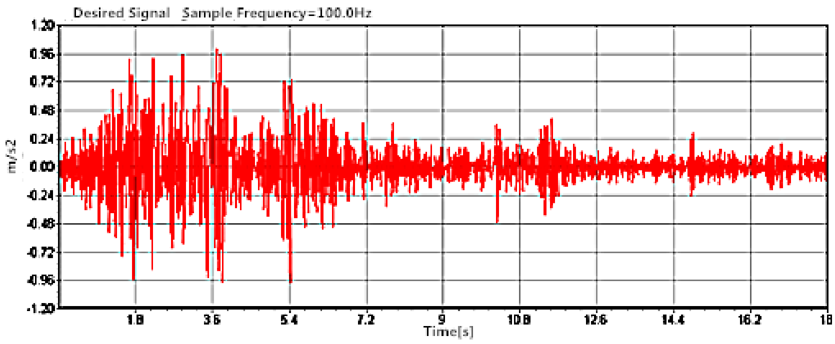


Fig. 6. Input practical seismic waveform.

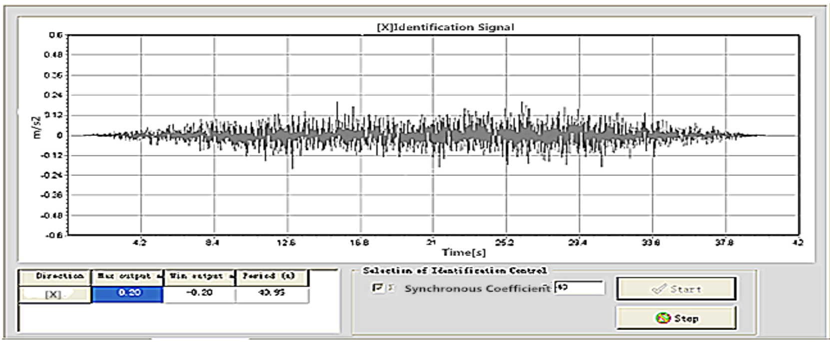


Fig. 7. Generated white noise.

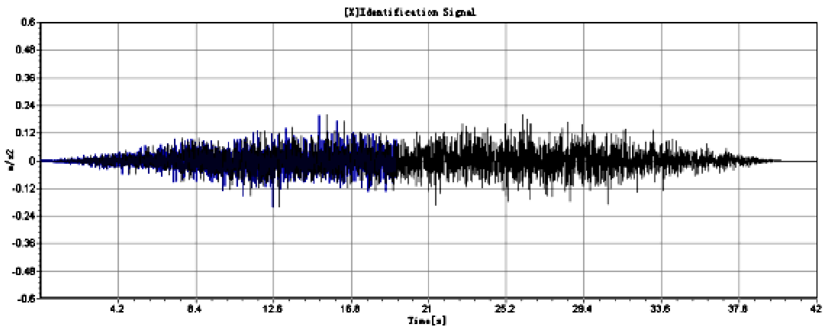


Fig. 8. Non-synchronous white noise sweep-frequency graph.

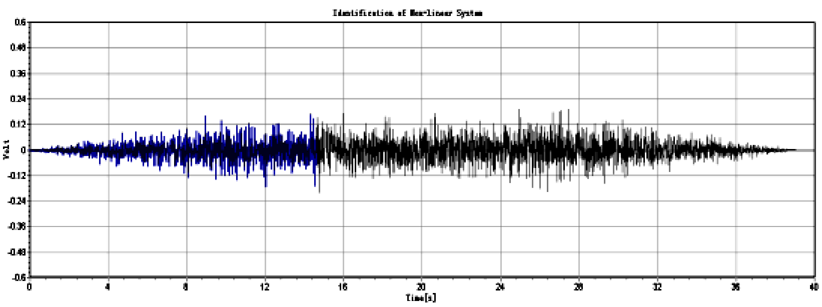


Fig. 9. Synchronized white noise sweep-frequency graph.

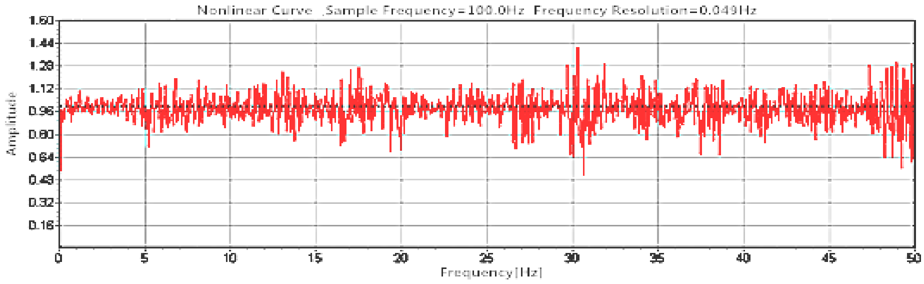


Fig. 10. Non-synchronous phase.

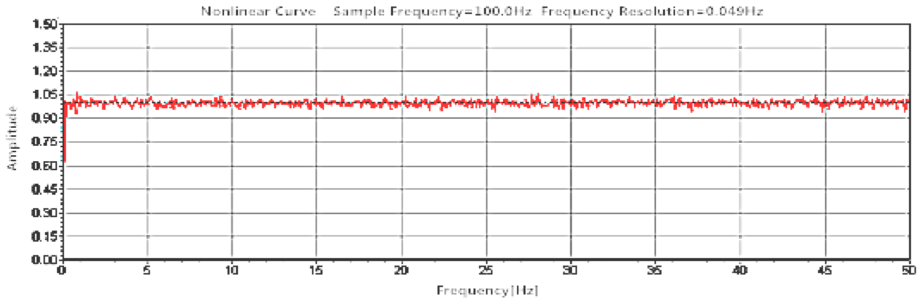


Fig. 11. Synchronized phase.

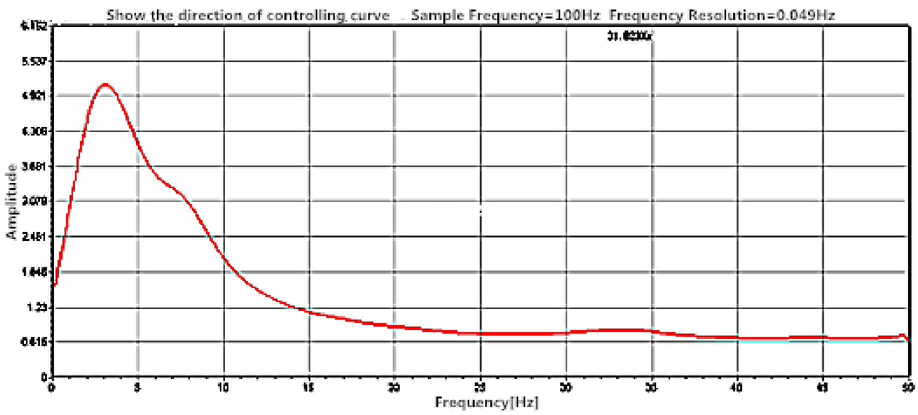


Fig. 12. Compensation function curve.

4.4. Generation and Correction of Drive Signal

The desired control signal could be corrected based on the non-linear curve of the system. The control drive signal with less error could be obtained after multiple iteration compensation. The iteration process can conduct iteration compensation on control signals of different groups.

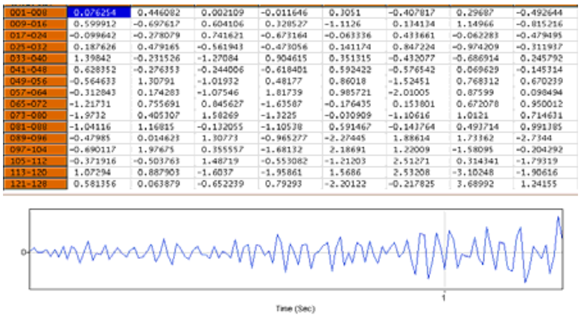
The compensation process can be conducted several times, which is determined by the error between the desired signal of the iteration result and the response signal. If the average error is within 5 % and shows a decreasing trend, and the average decibel no longer has any changes, the iteration result can be recorded as the final drive signal. The calculation of the maximum iteration error is as formula (4):

$$ERR_{\max} = \left[X_n(t) - X_{n-1}(t)\right]_{\max}, \quad (4)$$

The average error is calculated as formula (5):

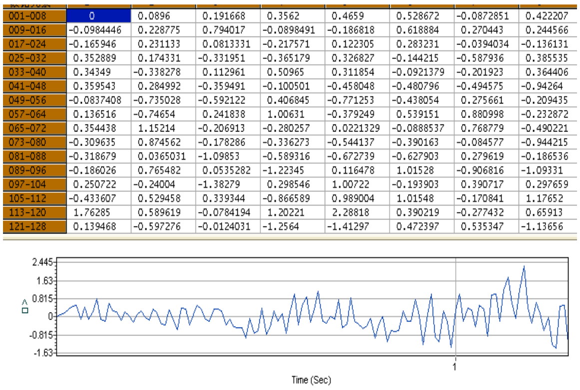
$$ERR_{avg} = 0.8\frac{\int_0^T \left[X_n(t) - X_{n-1}(t)\right]^2 dt}{\int_0^T \left[X_n(t)\right]} + 0.2\frac{\left\|\varepsilon_1(t)\max\right\|}{\left\|X_n(t)\max\right\|} \quad (5)$$

The above drive signal should be further corrected, so as to make the initial value be zero and to avoid test specimens from vibrating suddenly when a test starts. Fig. 13 shows an initial drive signal of a test. After the correction on the initial value, its complete drive signal could be obtained (as shown in Fig. 14).



001-008	0.076254	0.446082	0.002109	-0.011646	0.3051	-0.407817	0.29687	-0.492644
009-016	0.599912	-0.697617	0.604106	0.328527	-1.1126	0.134134	1.14966	-0.815216
017-024	-0.099642	-0.278079	0.741621	-0.673164	-0.063336	0.433661	-0.062283	-0.479495
025-032	0.187626	0.479165	-0.561943	-0.473056	0.141174	0.847224	-0.974209	-0.311937
033-040	1.39842	-0.231526	-1.27084	0.904615	0.351315	-0.432077	-0.686914	0.245792
041-048	0.628352	-0.276353	-0.244006	-0.618401	0.592422	-0.576542	0.069629	-0.145314
049-056	-0.564633	1.30791	-1.01932	0.48177	0.86018	-1.52451	0.768312	0.670239
057-064	-0.312843	0.174283	-1.07546	1.81739	0.985721	-2.01005	0.87599	0.098494
065-072	-1.21731	0.755691	0.845627	-1.63587	-0.176435	0.153801	0.672078	0.950012
073-080	-1.9732	0.405307	1.58269	-1.3225	-0.030909	-1.10616	1.0121	0.714631
081-088	-1.04116	1.16815	-0.132055	-1.10538	0.591467	-0.143764	0.493714	0.991385
089-096	-0.47985	0.014623	1.30773	-0.965277	-2.27445	1.88614	1.73362	-2.7344
097-104	-0.690117	1.97675	0.355557	-1.68132	2.18691	1.22009	-1.58095	-0.204292
105-112	-0.371916	-0.503763	1.48719	-0.553082	-1.21203	2.51271	0.314341	-1.79319
113-120	1.07294	0.887903	-1.6037	-1.95861	1.5686	2.53208	-3.10248	-1.90616
121-128	0.581356	0.063879	-0.652239	0.79293	-2.20122	-0.217825	3.68992	1.24155

Fig. 13. Pre-corrected drive signal.



001-008	0	0.0896	0.191668	0.3562	0.4659	0.528672	-0.0872851	0.422207
009-016	-0.0984446	0.228775	0.794017	-0.0898491	-0.186818	0.618884	0.270443	0.244566
017-024	-0.165946	0.231133	0.0813331	-0.217571	0.122305	0.283231	-0.0394034	-0.136131
025-032	0.352889	0.174331	-0.331951	-0.365179	0.326827	-0.144215	-0.587936	0.385535
033-040	0.34349	-0.338278	0.112961	0.50965	0.311854	-0.0921379	-0.201923	0.364406
041-048	0.359543	0.284992	-0.359491	-0.100501	-0.458048	-0.480796	-0.494575	-0.94264
049-056	-0.0837408	-0.735028	-0.592122	0.406845	-0.771253	-0.438054	0.275661	-0.209435
057-064	0.136516	-0.74654	0.241838	1.00631	-0.379249	0.539151	0.880998	-0.232872
065-072	0.354438	1.15214	-0.206913	-0.280257	0.0221329	-0.0888537	0.768779	-0.490221
073-080	-0.309635	0.874562	-0.178286	-0.336273	-0.544137	-0.390163	-0.084577	-0.944215
081-088	-0.318679	0.0365031	-1.09853	-0.589316	-0.672739	-0.627903	0.279619	-0.186536
089-096	-0.186026	0.765482	0.0535282	-1.22345	0.116478	1.01528	-0.906816	-1.09331
097-104	0.250722	-0.24004	-1.38279	0.298546	1.00722	-0.193903	0.390717	0.297659
105-112	-0.433607	0.529458	0.339344	-0.866589	0.989004	1.01548	-0.170841	1.17652
113-120	1.76285	0.589619	-0.0784194	1.20221	2.28818	0.390219	-0.277432	0.65913
121-128	0.139468	-0.597276	-0.0124031	-1.2564	-1.41297	0.472397	0.535347	-1.13656

Fig. 14. Corrected drive signal.

4.5. Vibration Loading Test

According to loading scheme, the shaking table test is conducted, and the vibrating response of the shaking table and test specimens are measured. Natural frequency, damping ratio, and some other dynamic parameters of test specimens are abstracted through spectral analysis of the transfer function and power spectrum. A multi-stage loading test is usually adopted for the convenience of observing seismic response of the test piece under different seismic intensity. Dynamic parameters of the specimen are measured in each test stage, specifically: 1) undamaged; 2) initial cracking; 3) moderate cracking; 4) full cracking throughout the entire section; and 5) damage and collapse.

4.6. Analysis and Organization of the Test Result

By processing the test data, the vibrating period, damping, deformation, stiffness degradation, energy absorption ability, and hysteresis behaviors of a specimen in each test stage could be calculated. The processing on video and picture recorded from the high-speed camera by specialized software could help to analyze the test phenomena and summarize the time-order character of vibrating damage and the dynamic response of a test specimen under seismic action.

5. Conclusions

According to the above analysis, the methods of the electromagnetic shaking table seismic test on a reduced scale specimen are feasible. 1) The natural vibration frequency of a small scale specimen is usually bigger than that of a prototype structure. If the software and hardware system of the electromagnetic shaking table were well configured, the shaking table could completely play its role in simulating seismic impact with wide frequency band and good waveform. If there is ultralow frequency demand to a shaking table, double magnetic body structure could significantly reduce the frequency band lower limit of the shaking table to 0.1 HZ. 2) The shaking table can induce aberration to seismic wave signal and lead to distortion of vibration excitation by the shaking table. Non-linear correction could obtain the desired excitation signal output from the shaking table. 3) The multi-stage loading test may cause damage accumulation in the test specimen, which will affect the test precision of dynamic behaviors. 4) Filter correction of the input seismic wave can remove noise from the original seismic wave. To choose an appropriate similarity ratio and adjust the sampling frequency of the input seismic wave can effectively stimulate the small scale model and fully exhibit its dynamic characteristics. 5) The high-speed camera is useful to record video data of the shaking table test and is helpful to research the damage time-order and evolution of the test specimen under seismic impact. 6) Period, damping, vibration deformation, stiffness degradation, and hysteretic behavior acquired from the reduced-scale test are greatly helpful to qualitatively evaluate the dynamic behaviors of prototype structures.

Acknowledgements

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