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Research Article

Development of the Shaking Table and Array System Technology in China

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Shaking table is important experimental equipment to carry out antiseismic research. Research, conclusion, comparison, and analysis concerning the developmental history, constructional situation, performance index, control algorithm, and experimental technique of the internal shaking table were reviewed and compared. Such functional parameters as internal shaking table's tableboard size, bearing capacity, working frequency, and maximum acceleration were given. Shaking table's constructional status quo and developmental trend were concluded. The advantages and disadvantages of different control algorithms were contrastively analyzed. Typical shaking table test, array system tests, and experimental simulation materials were induced and contrasted. Internal existing shaking table and array system test's structural type, reduced scale, and model-material selection were provided. Analysis and exposition about the developmental tendency of shaking table's enlargement, multiple shaking tables array, full digitalization, and network control were made. The developmental direction, comparison of technical features, and relevant research status quo of shaking table with high-performance were offered. The result can be reference for domestic or overseas shaking table's design and type selection, control technique, and research on experimental technique.

1. Introduction

At present, the structural seismic research methods include the pseudostatic test, pseudodynamic test, and shaking table test. The test method of the shaking table test can recreate the structural response and seismic oscillation in the lab accurately and reproduce the whole process of seismic oscillation effect or artificial effect in real time. The development of shaking table provides an accurate and effective way to study structural elastic-plastic seismic response [1–3].

Japan and the United States are the first two countries to establish shaking tables in the world. And, China initially built a shaking table in 1960 [1] when Institute of Engineering Mechanics, Chinese Academy of Sciences, built one-way horizontal vibration [4–7] with a specimen size of 12 m × 3.3 m. So far in China, there are a lot of shaking tables [1]; some were made in China, some were systematically remodeled from imported parts, and some were totally imported. In recent years, many scholars [8, 9] and Wang et al. [2] conducted abundant research on the development and control technology of China's shaking tables and also got some research achievements. However, such results are mostly summaries of the test technologies or control technologies of shaking table [10], while there are few summaries concerning the construction history and usage of domestic shaking tables. This paper makes a comprehensive summary of the development and application of domestic shaking tables and array test technologies in terms of the development, control technology, test application, and development trend of shaking table and array system based on current collected information, so as to provide some reference and basis for the construction and development of domestic shaking table.

2. Development of Shaking Table and Array

2.1. Construction Situation of Shaking Table. The development of shaking table in China came relatively late

[1, 3, 11–14]. It can be roughly divided into four stages. In 1960s, the mechanical shaking table was the main stream with a working frequency of 1 Hz~40 Hz, of which the characteristics of the specimens in low segment are difficult to be controlled [2, 10, 11]. Electrohydraulic shaking table was then rapidly developed with its high frequency. In 1966, departments of machinery and electronics collaborated with each other to build China's first exclusive shaking table for national system of defense in three years [2, 10, 13]. Thereafter, many domestic colleges and universities as well as scientific research institutes also begun to conduct researches. For example, Tongji University brought in the 4 m × 4 m two-horizontal dimensional identically dynamic electrohydraulic shaking table developed by American MTS, which has been transformed into three- to six-degree-of-freedom identically dynamic shaking table [1]. At the beginning of the 70s, the research on shaking table in China was continuously carried out and quickly developed. Our country also started to develop one-way electrohydraulic servo shaking table but rarely hooked into multiaxis shaking table [15–20]. And, foreign shaking tables were introduced only when the test was demanding, so the introduction quantity of shaking tables was sharply decreased. Domestic institutes that conduct researches on shaking table mainly include China Academy of Building Research, Xi'an Jiaotong University, HIT (Harbin Institute of Technology), Institute of Engineering Mechanics, and Tianshui Hongshan Testing Machine Co., Ltd. [21, 22]. The shaking table construction situation in China is shown in Table 1.

The work frequency of electrohydraulic shaking table in the early stage of our country was about 50 Hz. At present, at home and abroad, the work frequency of high-thrust shaking table with over 50 t can reach more than 1000 Hz. For instance, the work frequency of Y2T.10c shaking table developed by 303 Research Institute of China Aviation Industry Corporation is as high as 1000 Hz, and the wide band random vibration control precision is 2.0 dB [23] within the frequency range of 20 Hz~1000 Hz.

In 2006, Beijing University of Technology built a nine-sub-building block array system with a size of 1 m × 1 m, which along with the original 3 m × 3 m single-array system composed the 10-subarray system, which can be used to constitute testing systems with any several subarray systems and many optional positions; at the end of 2006, Institute of Electro-Hydraulic Servo Simulation and Test System of Harbin Institute of Technology (HIT) developed successfully the first domestic multiaxis independent intellectual property rights (the hydraulic vibration test system with shaking table system is shown in Figure 1) and got identification, which changed the history of depending on importing shaking tables [24]. In 2012, Jiangsu Suzhou Dongling Vibration Test Instrument Co., Ltd. successfully developed the world's largest single electromagnetic shaking table test system (http://www.cnki.net/kcms/detail/11.2068.TU.20130124.1608.001.html) with a thrust of 50 tons.

The development trend of the shaking table since the 1960s is shown in Figure 2. So far, there are more than 50 self-made, systematically remodeled, and totally imported shaking tables in China.

2.2. Construction Situation of Shaking Table Array System. With the 9-subarray system of Beijing University of Technology as an example, this paper introduces the construction situation of shaking table array system. In 2003, The State University of New York built the first set of two-subarray systems. In the same year, the University of Nevada-Reno built the three-subarray system with three movable two-direction shaking tables. The size of the table and the maximum bearing capacity of the shaking table are introduced. The array system (shown in Figure 3) is suitable for experimental research on spindly space structure.

In 2004, Chongqing Jiaotong Institute of our country completed the constitution of the two-subarray system with a specimen size of 6 m × 3 m, of which one is fixed and the other is movable (shown in Figure 4). And, in 2008, National Key Laboratory of Bridge Dynamics was established.

In 2011, Beijing University of Technology began to prepare to construct nine-subarray system (shown in Figure 5) and has built 12 sets of actuator building block array systems till 2006, which was increased to 16 sets in 2009 and is now the array system with the largest number of single-array system in the world. Each single shaking table is composed by mesa, 5 connecting rods, a vibrator, and a base. The array system can be made into various combinations by 16 sets of vibrators and connecting rods to conduct varied shaking table array tests with different layouts and forms. The performance indicators of nine-subarray system are shown in Table 2. The system uses four piston pumps to offer oil. The rated oil supply pressure of the seismic simulated shaking table system is the same as the maximum oil supply pressure. In addition to 4 oil pumps, the system also has energy storage to supplement the oil supply when the oil supply of the oil supply pump is insufficient.

In recent years, many colleges, universities, and research institutes were planning to construct multiarray systems. The construction situation both at home and abroad is shown in Table 3.

2.3. Development of Shaking Table Control Technology

2.3.1. Traditional Control Algorithm. There are two main types of traditional shaking table control technology: one is PID control based on displacement control and the other is three-parameter feedback control (also known as the three-state feedback control) synthesized by the displacement, velocity, and acceleration [25]. It is essential for feedback theory to adjust the system after making the right measurement and comparison. In 1950, the PID control method mainly composed of unit P proportion, integral unit I, and differential unit D was developed. The traditional PID control method is simple in control algorithm, good in stability, and high in reliability and thus has been widely applied in the practical engineering. The PID control method is especially suitable for deterministic control system. Yet, as the target signal of shaking table is acceleration signal, high-frequency control performance is poorer when

Table 1: Shaking table construction in China.

Time	Sector	Dimension	Amount of model (t)	Frequency (Hz)	Maximum acceleration (g)	Vibration direction
In the 70s	China Academy of Building Research Foundation	1.5 × 1	3	0.1~30	1.0	Unidirectional vibration
	Academy of Railway Sciences	1.5 × 2	2	0~80	2.0	Unidirectional vibration
	Nanjing Hydraulic Research Institute	2 × 2	1	10~300	1.0	Unidirectional vibration
	Institute of Engineering Mechanics	1.2 × 1.2	0.75	0~50	1.0	Unidirectional vibration
In the 80s	Institute of Engineering Mechanics	5 × 5	30	0.1~50	1.0	Three-way vibration
	Academy of Water Resources and Hydropower	5 × 5	20	0.1~120	1.0	Three-way vibration
	Tongji University	4 × 4	15	0.1~50	1.2	Two-way vibration
	Institute of Architectural Engineering	4 × 3	15	0.1~25	1.0	Unidirectional vibration
	Institute of Seismic Engineering, Chinese Academy of Architectural Sciences	3 × 3	15	0.1~20	1.0	Unidirectional vibration
	Dalian Institute of Technology	3 × 3	10	0.2~50	1.0	Two-way vibration
In the 90s	Ministry of Posts and Telecommunications	1.5 × 2	2	0.4~50	2.0	Unidirectional vibration
	Shanghai Youth Culture Center	5 × 5	5	0.1~15	0.5	Two-way vibration
	Tongji University	4 × 4	15	0.1~50	1.2	Three-way vibration
After 2000	Beijing University of Technology	3 m × 3 m	10	0.1~50	1.0	Unidirectional vibration
	Nuclear Power Institute of Chengdu	6 m × 6 m	60	0.1~50	1.0	Three to six degrees of freedom
	Chongqing highway	6 m × 3 m	20	0.1~50	1.0	Three to six degrees of freedom
	China Academy of Building Research	6 m × 6 m	60	0~50	1.0/1.5	Three to six degrees of freedom
	Harbin Institute of Technology	2 m × 4 m	7	0.5~80	1.5	Three to six degrees of freedom
	Nuclear Power Institute of China	6 m × 6 m	70	0~100		Three to six degrees of freedom

Figure 1: Six-DOF electrohydraulic vibration table produced by IEST.

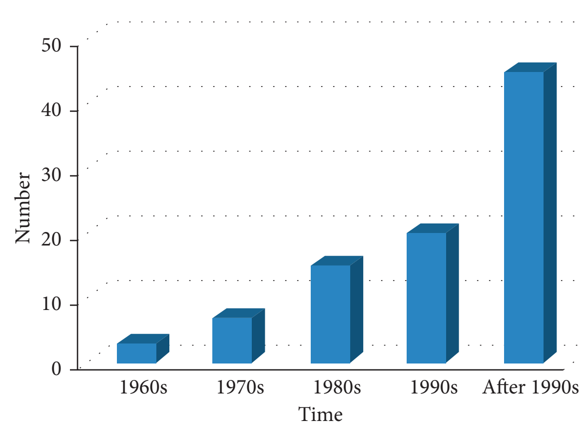

Figure 2: The development trend of shaking table in China.

the displacement PID control is adopted, while the mesa cannot be located if acceleration PID is used. Meanwhile, in the process of control, nonlinear behavior exists in every specimen; thus, the effect of traditional PID control is not ideal due to the large waveform distortion [24, 26–29]. As the structure sets higher requirement for control accuracy, three-parameter feedback control synthesized by the displacement, velocity, and acceleration was put forward in 1970s (the control principle is shown in Figure 6), which makes up for the narrow frequency band and the inability to realize acceleration control of single displacement control. Acceleration feedback can improve the system damping, and velocity feedback can improve the oil column resonance frequency. Adopting the displacement to control low frequency, speed to control midfrequency, and acceleration to

Figure 3: Seismic array of the University of Nevada, Reno.

Figure 4: Seismic array of China Merchants Chongqing Communications Research and Design.

Figure 5: 1 m × 1 m 9-table seismic array of BJUT.

control high frequency plays an important role in improving the dynamic behavior and bandwidth of the system. The introduction of three-parameter control technology greatly improved the playback accuracy of seismic time history, but due to the complexity of transfer function in the system, the correlation of input and output waveform is still not high. Power spectrum emersion control algorithm modifies drive spectrum utilizing system impedance and the deviation of the reference spectrum and the control spectrum, so as to get a relative high consistency of response spectrum and reference spectrum of the system [30, 31]. Power spectrum retrieval principle diagram is shown in Figure 7. This method belongs to the nonparametric method, which has nothing to do with any model parameters. But the matching degree of estimated power spectral density and real power spectral density is very low, so it is an estimation method with low resolution.

Another kind of the parametric estimation method, using the parameterized model, can give a much higher frequency resolution than period gram methods. The power spectrum control method based on the parameter model has high resolution and can improve the system control convergence speed and power spectrum estimation precision, yet it is sensitive to noise with higher computation requirements. Therefore, in the vibration test control, it has not reached practical stage [32].

2.3.2. Intelligent Control Algorithm. The traditional control algorithm is based on the linear model of vibration table and specimen [33], and the parameters in the process of test are assumed unchanged, but the actual test object is very complex. The components experience elastic-plastic phase and then the failure stage in the process of the test, and the parameters that were assumed to be unchanged turn out to have been changed in the process of test. The change of the parameters influences the accuracy of the input seismic signal, which is the biggest defect in the traditional control technology. From the 1970s to 80s, intelligent control is a new theory and technology with strong control ability and great fault tolerance. The introduction of the adaptive control improved the robustness and control precision of the system, such as adaptive harmonic control theory (AHC), adaptive inverse function control theory (AIC), and the minimum control algorithm (MCS) [34]. At present, the fuzzy control algorithm of the structure control attracted the attention of more and more scholars with its advantages of powerful knowledge expression ability, simple operational method, and the adoption of fuzzy language to describe the dynamic characteristics of the system. As early as 1996, some scholars abroad has carried out the induction and comparison of structural seismic control methods and summarized the advantages and disadvantages of various control methods, particularly expounding that the fuzzy control and neural network control algorithm could better solve the problem of nonlinear. The application of domestic intelligent control algorithm in the engineering structure control is relatively late. In 2000, Ou [29] and other scholars proposed the control algorithm which can realize fuzzy control according to the control rules and fuzzy subset, which greatly improved the practicability and efficiency of fuzzy control algorithm.

Most of the fuzzy control rules are established based on experience, leading to great difficulty in structure control. In view of this, Wang and Ou [35], in 2001, put forward the method of extraction, optimization, and generation of fuzzy control rules with the basis of structural vibration fuzzy modeling and genetic algorithm. Qu and Qiu [36] came up with a kind of active feed forward control method based on adaptive fuzzy logic system method, which better solved the nonlinear control problems of reference signal and external interference in the feedforward control. Wang [30] for flexible structure completed the application of the fuzzy PID control method in the structural vibration and conducted the active control experimental verification of beam vibration.

Table 2: Performance indices of 9-table seismic array.

Table size	Table weight	Maximum load	Frequency	Maximum velocity	Displacement accuracy	Actuator stroke	Actuator number	Control	Maximum acceleration
1 m × 1 m	1 t	5 t	0.4~50 Hz	60 cm/s	≤0.005	±75 mm	16	Acceleration	$2.0g/1.0g$

Table 3: Multiple shaking table construction.

Construction	Table size (m)	Number	Bearing weight (t)	Frequency (Hz)	Vibration direction
Buffalo, USA	7 × 7	2	50	0~50	Bidirectional six DOFs
Reno, Nevada	4.5 × 4.3	3	45	0~50	Three DOFs
Saclay, France	6 × 6	2	100	0~100	Bidirectional six DOFs
Taiwan Earthquake Engineering Center	8 × 8	1	150	0~50	Three to six DOFs
	3 × 3	3	25		
Chongqing Research Hospital	6 × 3	2	35	0.1~50	Three to six DOFs
Beijing University of Technology	1 × 1	9	5	0.4~50	Unidirectional
Fuzhou University	4 × 4	1	22	0.1~50	Bidirectional four DOFs
	2.5 × 2.5	2	10		
Tongji University	4 × 6	4	50	0.1~50	Bidirectional four DOFs
Institute of Engineering Mechanics	5 × 5	1	30	0~100	Bidirectional six DOFs
	3.5 × 3.5	1	10		
China Nuclear Power	6 × 6	1	50	0~100	Bidirectional six DOFs
	3 × 3	1	12		
Central South University	4 × 4	4	30	0~50	Three to six DOFs

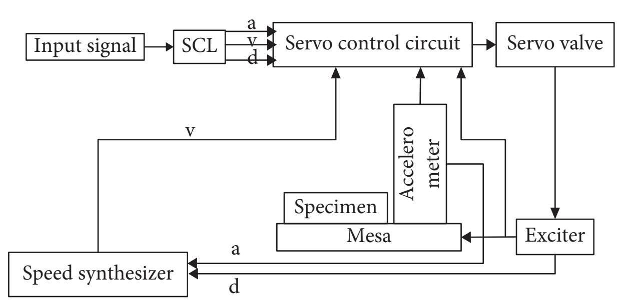

Figure 6: Schematic diagram of three-parameter control system.

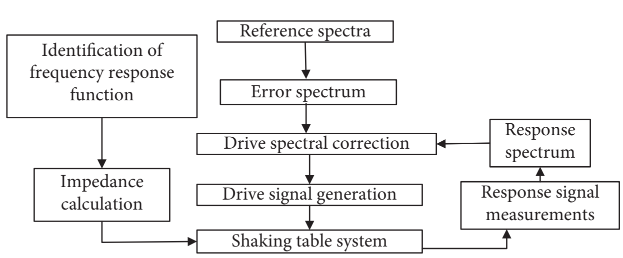

Figure 7: Schematic diagram of control algorithm for power spectrum of PSD replication.

The efficiency of fuzzy control depends on the selection of function parameters and the establishment of the fuzzy control rules. Therefore, the adaptive fuzzy control is of great research significance for the nonlinear structure system. Because of the functions of self-adaptation and self-study of artificial neural network, the application of neural network in seismic control in civil engineering began in the 60s, which adopts a simple neural network controller to control the movement of the inverted pendulum, and achieved good effect. In 2003, Mo and Sun [31] implemented numerical simulation of active vibration control on the beam vibration control model by using genetic algorithm with the minimum energy storage structure as the goal, compared with the exhaustive method, and achieved good control effect. Chen and Gu [37] carried out simulation research on the application of frequency adaptive control algorithm based on the least square method in the domain of vibration control, and the simulation got the damping effect of about 50 db. Li and Mao [38] achieved evolutionary adaptive filtering algorithm with strong instantaneity and applied it into the vibration control of structures to conduct simulation calculation based on genetic algorithm and moving least mean square algorithm of transient step, and the simulation obtained the damping effect of about 30 db.

2.3.3. Research on Hybrid Test Technology of Shaking Table. To solve the limit bearing capacity of shaking table for large structure test, scholars from all over the world conducted a wide variety of researches. The combination of substructure technique and shaking table test is an effective way to solve this problem [39]. Hybrid vibration test divides the structure into test substructure and numerical substructure. Test substructure is the complex part in experiment on shaking table, while numerical substructure is the simple part to carry out numerically simulation. Test substructure can carry out full-scale or large-scale model test, avoiding the influence of the size limit of shaking table with large-scale structure, and thus was widely used in the study of the engineering seismic test. The domestic researchers Chen and Bai [33] implemented preliminary exploration into structural seismic hybrid test technique on account of the condensation technology. In 2008, Chen and Bai [33] also embarked on the hybrid vibration test on the hybrid structural system of commercial and residential buildings, of which the bottom commercial district was put into a full-scale experiment on shaking table and other parts were involved in numerical simulation.

In 2007, Mr. Wu Bin from Harbin Institute of Technology applied the center difference method into the change of the acceleration calculation formula in hybrid real-time test which takes consideration of the quality of test substructure and analyzed the stability of the algorithm. The test results show that the stability of the center difference method in real-time substructure application is poorer than that of the standardized center difference method. Such scholars as Yang [40] in the same year made the numerical simulation analysis on the shaking test substructure test, and the analysis results show that the integral step change is sensitive to the influence of experimental stability. At the same time, he verified the validity of the theoretical research results.

3. Applications of Shaking Table and Array

3.1. Typical Shaking Table Tests. In recent years, the structural styles of shaking table test research were developed from masonry structure, frame structure, tube structure to bridge structure, structures with the consideration of some isolation and damping measures, and structural foundation interaction experiment. The application of shaking table tests on the structure seismic resistance made it possible to establish structure nonlinear model with various structural styles [2]. Many shaking table tests have been carried out in recent years in China, which, according to the testing purpose, can be roughly divided into three categories: the first type is to determine structural earthquake-resistance performance as the test purpose; the second type is to determine the dynamic characteristics of structure, obtain such dynamic parameters as the natural vibration period and damping of structure, seek for weak parts of the structure damage, and provide the basis for super high-rise and supergage designs; the third type is to verify the applicability of certain measure or design theory in the structure. This paper drew a conclusion of typical shaking table tests in recent years in terms of building types, model dimensions, and so on (shown in Table 3).

3.2. Typical Array Tests. Shaking table experiment diversifies the structural styles in experiment, makes it possible to establish the nonlinear damage model, and provides a reliable basis for all kinds of structures to establish the corresponding destruction specification. But large span structure tests on bridges, pipes, aqueduct, transmission lines, and so on may produce traveling wave effect under the action of earthquake due to large span, and a single shaking table will not be able to simulate the real response of the whole structure under seismic action. Array system can better solve these problems. For example, the State University of New York-Buffalo did damper damping effect research on Greek Antiliweng Bridge using 2-subarray system; conducted shaking table array test research on two continuous steel plate girder bridge and concrete girder bridge by using the 3-subarray system of University of Nevada. Many domestic scholars also carried out shaking table array test research on different structures of array systems. For instance, in 2008, Gao Wenjun made shaking table array test research of organic glass model on Chongqing Chaotianmen Bridge with the 2-subarray system of Chongqing Traffic Academy; conducted a multipoint shaking table array test research on concrete-filled steel tubes arch bridge with the 9-subarray system in Beijing University of Technology.

At present, the typical tests of array system are shown in Tables 4 and 5.

4. Development Trend of Shaking Table and Array System

4.1. Maximization. According to the size of mesa, shaking tables can be divided into large, medium, and small ones; in general, specimen size less than $2\,\text{m} \times 2\,\text{m}$ for the small, $6\,\text{m} \times 6\,\text{m}$ for the medium, and over $10\,\text{m} \times 10\,\text{m}$ for the large. Due to the size limitation of a small seismic simulation vibration table, it can only do small-scale tests, and there is a certain gap with the prototype test. In the seismic simulation vibration table test of scale model, all parameters are required to meet the similarity principle, but it is difficult to do in practical engineering. For some important structures, especially the important parts of large structures, to accurately reflect the dynamic characteristics of the structure, within the permitted scope of the condition of capital, it is necessary to increase the specimen size and the maximum load as much as possible to eliminate the size effect of the model, so the large full-scale test must be the development trend of shaking table. China Academy of Building Research developed a shaking table with a mesa dimension of $6.1\ \text{m} \times 6.1\ \text{m}$ and the maximum model load of 80 t.

4.2. Array Orientation. Due to the great investment, high maintenance cost, and test fees as well as long production cycle of large-scale shaking table, infinite increase in size of shaking table is obviously unreasonable, and likewise, it is not possible to fully meet the actual requirements only by increasing the size of shaking table. For large-span structure tests on bridges, pipes, aqueduct, transmission line, and so on array systems composed of many sets of small shaking table can be adopted. Shaking table array can either conduct a single test or make seismic resistance test on the structure of large-scale, multidimensional, multipoint ground motion input with varied combinations according to various needs. Therefore, the array system composed of many sets of small shaking tables must be the development trend of shaking table.

4.3. Intellectualization. In terms of control mode, power spectral density control was mostly adopted before 1975. After 1975, Huang Haohua and other scholars used the time-history playback control to finish the seismic wave control research in a broad band. In the mid-1990s, digital control

Table 4: Typical shaking table test.

Purpose	Building type	Model dimension	Total mass (t)	Building height	Peak acceleration (g)	Reduced scale	Experimental result
To determine the structure of the earthquake resistance for purpose	Rural timber frame bearing adobe wall structure	3.28×4.9	41	2.60 m	0.035	1 : 1	Shaking table test of the house; seismic performance test is simple and economic
	Light wood composite structures	6.1×3.7		8.4 m	0.1~0.5	1 : 1	This structure has good seismic performance, and the stiffness model has larger seismic response than the less rigid structure
Determination of dynamic characteristics of structure for the purpose	Brick house of Xinjiang	1.785×1.335	3.2	3.2 m	0.36	1 : 4	Summary of the failure mechanism of this kind of buildings under seismic action and the weak link in the earthquake
	Large-span arch bridge structure	1.2×0.3		$120\ m \times 30\ m$	6.968	1 : 100	The structure of the natural frequency of vibration and damping and dynamic parameters such as formation have been determined
	Tube structure	3.32 m	2.24	166m	0.15	1 : 50	Understanding from elasticity to damage under ground motion response provides important basis for tall overall design
The applicability of the validation of a method or theory	Reinforced concrete tall building	3.32 m	2.237	166m	0.16	1 : 50	The results of the shaking table and the use of TBSAP linear elastic finite element analysis program for calculation coincided basically with the results of the prototype structure
	Especially irregular all steel structure	1.5 m	8.315	30 m	0.09	1 : 20	SAP2000 is adopted to conduct three-dimensional force analysis on the structural model, along the most unfavorable vibration direction of the theoretical analysis results and the shaking table test results, to verify the validity of the SAP2000 program

Table 5: Typical array shaking table test.

Structure	Test name	Model size	Ratio of reduced scale	Number	Test results
Span bridges	Yitong River Bridge	3.2 m + 9.8 m + 3.2 m	1 : 16	3	The effects of wave velocity and field are considered, and test results obtained agree well with the simulation results
	Rion Greece Antioch Bridge	57.6 m	1 : 50	3	This experiment studies the effect of force dampers on the seismic response of the abnormal structure under seismic excitation
	Chaotianmen Bridge	18.64 m	1 : 50	2	As long as the main parameters of the model meet similar requirements, model test can achieve better results
Large span space structure	Bidirectional National Stadium roof beam string structure	11.4 m × 14.4 m	1 : 10	9	In order to obtain the seismic response of the structure, the acceleration response, velocity response, and strain characteristics of the structure are measured
	Olympic badminton gymnasium dome	$R = 9.3$ m	1 : 10	8	The influence of the traveling wave effect is considered in the shaking table test
Transmission tower-line architecture	Transmission tower-line system	5.39 m	1 : 10	3	Structural response obtained under the laws and the characteristics of multidimensional seismic action
Soil-structure interaction	Bridge-soil structure interaction	16 m × 1.2 m	1 : 10	4	This experiment verifies the structural dynamic characteristics of soil under seismic action considering the interaction between pile and soil
Tunnel system	Immersed Tunnel	7.3 m × 3.2 m	1 : 60	4	The seismic performance and multipoint boundary effects of excitation tunnel joints are verified

and analog control are widely used in the shaking table control, of which digital control is mainly applied in the system signal and compensation and the analog control is the basis for the control, whose control mode is complicated in operation with too much manual adjustment. After 1990s, Fang Zhong and other scholars developed a full digital control technology which has been widely used in the hydraulic servo control system with the rapid development of digital technology. Other than the valve control device and feedback sensor which adopt analog circuits, the rest utilize digital software to fulfill implementation. This control method can make up for some flaws in the analog control with simple test operation, being able to improve the accuracy, reliability, and stability of the system. Full digital control is the inevitable development trend of hydraulic servo system control.

4.4. Networking. With the appearance of slender and shaped structures and the application of new materials in building engineering, the seismic test methods of structures are put forward with higher and higher requirements. To meet the requirements of actual engineering and seismic research, scholars from all over the world are active in exploration and attempt and put forward some new testing methods. In recent years, countries around the world greatly invest in seismic research. From 2000 to 2004, the United States Science Foundation Committee spent eighty million dollars of research funding on the NEES plan; Europe established a collaborative research system "European Network to Reduce Earthquake Risk (ENSRM)"; South Korea established a virtual structure laboratory using grid technology, which includes the wind tunnel, the shaking table, and other scientific research equipment. Furthermore, Internet ISEE Earthquake Engineering Simulation System in Taiwan of China was the earthquake engineering research platform developed by National Earthquake Engineering Research Center of Taiwan, China, with the Internet. The platform not only allows several laboratories to interconnect each other to

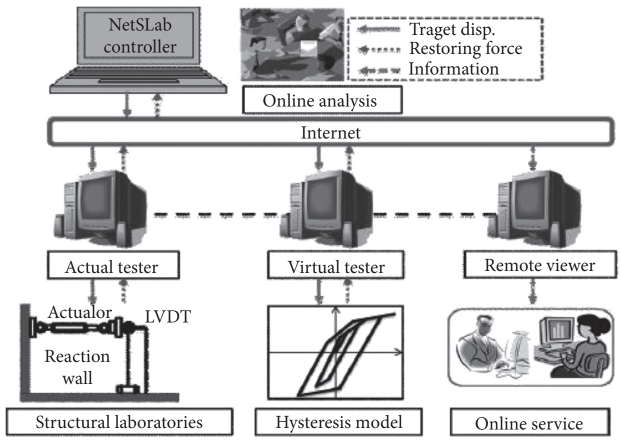

Figure 8: Primary module and interface of NetSLab.

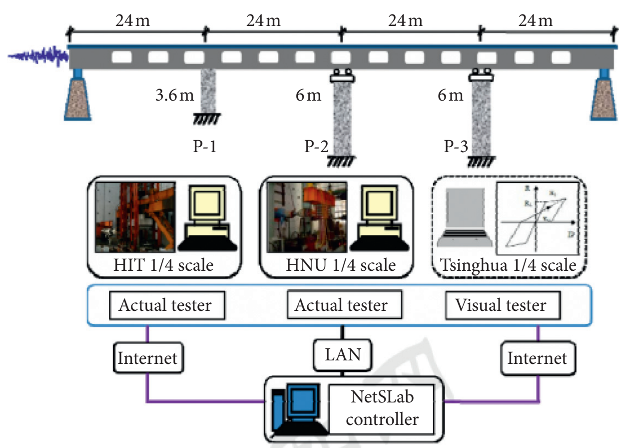

Figure 9: Remote collaboration testing in China.

implement large-scale shaking table test but also permits different laboratory researchers around the world to observe the test simultaneously and synchronously.

In China, Hunan University firstly put forward the structure network synergy test research and cooperated with Vision Technology Co., Ltd in 2000 to develop the network structure laboratory (NetSLab is shown in Figure 8). The main module and interface are shown in Figure 8. Thereafter, Hunan University cooperated with Harbin Institute of Technology to accomplish secondary development to establish the network collaborative hybrid test system and conducted a structure remote collaborative test along with Tsinghua University, Harbin Institute of Technology. Three domestic universities firstly completed remote collaboration pseudodynamic test, which is shown in Figure 9.

5. Conclusion and Discussion

This paper drew a conclusion of the construction, history, and status quo as well as application and research of shaking table and array. The main conclusions are as follows:

(i) On account of factors of actual application demand and economy, the size of the shaking table is between 1 m and X m, among which 3 m~6 m are the majority. For large span structures such as bridges and pipes many sets of small array mode of vibration table can be used.

(ii) Shaking table mesa acceleration and speed are about $2g$ and 80 cm/s, respectively. Through statistics, the remarkable frequency of previous ground motion records is mainly within 0.1 Hz~30 Hz, and the frequency range of medium shaking table should be in 0 Hz~50 Hz according to the requirements of the similar rule. Moreover, tests with special requirements need to be above 100 Hz.

(iii) With the appearance of slender and shaped structures and the application of new materials in building engineering, the seismic test methods of structures are put forward with higher and higher requirements.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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