

Recent Progress on Control Techniques of Shaking Table and Array Systems in China: An Overview

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Received August 16, 2020; Revised September 19, 2020; Accepted September 28, 2020

Abstract Shaking table is one of the important equipments for seismic research. It can accurately reproduce the seismic wave in the laboratory to accurately study the structural response. Based on the summary of domestic shaking table and array system control algorithms, the applications of various control algorithms and their advantages and disadvantages are summarized. The development trend of the shaking table control algorithm is analyzed and explained. It can be used as a reference for research on control technology of shaking tables at home and abroad.

Keywords: seismic research, shaking table, control algorithm, development trend

Cite This Article: Gao Chunhua, Yuan Xiaobo, Wang Jieqiong, and Zhang Yonghe, "Recent Progress on Control Techniques of Shaking Table and Array Systems in China: An Overview." *American Journal of Civil Engineering and Architecture*, vol. 8, no. 3 (2020): 119-130. doi: 10.12691/ajcea-8-3-5.

1. Introduction

At present, the seismic research methods of structures include pseudo static test, pseudo dynamic test and seismic simulation shaking table test [1]. The shaking table can reproduce the desired seismic waveform and can simulate the seismic response in the laboratory, and then study the seismic performance of components and structures. Therefore, compared with the pseudo static test and pseudo dynamic test, the shaking table test is a true seismic simulation test and it is one of the most accurate and direct experimental methods for studying the seismic performance of structures [2]. The earliest construction of the shaking table in the world was Japan [3] and the United States. The construction of the shaking table in China can be traced back to 1960. The table size built by the Institute of Engineering Mechanics of the National Seismological Bureau in 1960 was 1.2m × 3.3m. It is the one of the early earthquake simulation shaking tables in China [4]. In 1992, the Institute of Engineering Mechanics of the National Earthquake Administration successfully built a three-way six-degree-of-freedom electro-hydraulic servo seismic simulation shaking table. This is the first three designed and manufactured by China. To six-degree-of-freedom large-scale earthquake simulation station [5]; in 2018, China's major national science and technology infrastructure in the field of seismic engineering-large-scale engineering simulation research facility was led by Tianjin University. After completion, it will become the

world's largest and most powerful seismic simulation research facility for major projects, which is of great significance for ensuring the safety of major projects such as civil engineering, water conservancy, ocean, and transportation. Typical shaking tables at home and abroad are shown in Figure 1.

In recent years, the construction of shaking table has been developed rapidly, but the problem of low localization level is outstanding, and the high construction cost of imported instruments severely limits the development of domestic earthquake simulation shaking table. In addition, the waveform reproduction accuracy is one of the main performance indicators considered in the construction of the shaking table, and the waveform reproduction accuracy is mainly affected by the hardware performance and the control algorithm: for the built earthquake shaking table, the hardware performance is basically fixed, it can hardly be changed, so improving the accuracy of waveform reproduction needs to start with the control algorithm. In recent years, improving the accuracy of waveform reproduction in seismic shaking table has become a research hotspot. Based on the above analysis, this article mainly starts with the control technology, summarizes the development process of the control algorithm of the domestic shaking table, and divides the control algorithm into two categories: traditional control algorithm and intelligent control algorithm. It summarizes the application of various control algorithms and their advantages and disadvantages. And the development trend of this field is prospected, which provides reference and basis for the application of seismic shaking table control algorithm at home and abroad.

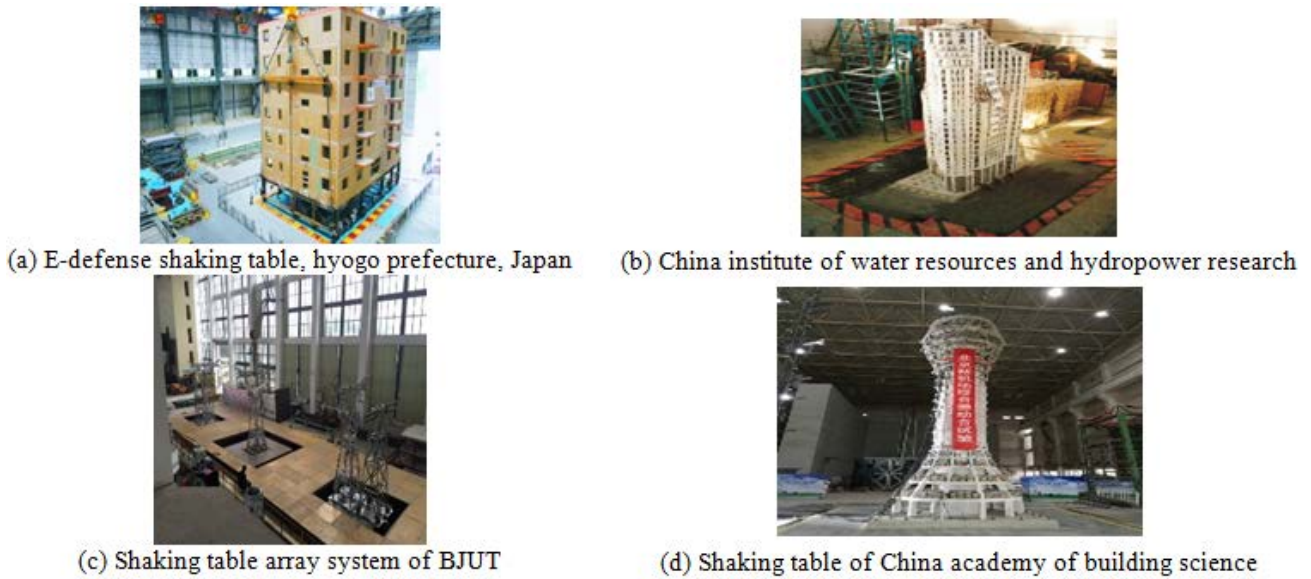


Figure 1. Typical shaking table at home and abroad

2. Traditional Control Algorithm

2.1. PID Control Algorithm

PID control is one of the earliest control methods applied to seismic simulation shaking tables, where P is Proportion, I is Integral, and D is Differential. The principle of PID control is shown in Figure 2, $r(t)$ is the system input signal, $u(t)$ is the control system output signal, used to control the controlled object, and $c(t)$ is the controlled object feedback signal.

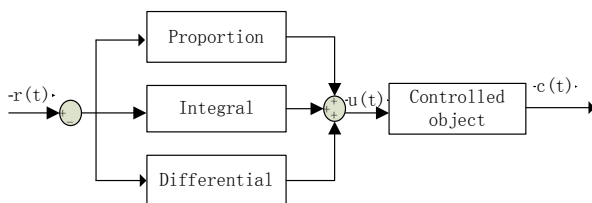


Figure 2. PID control principle

PID control is widely used in different fields such as industry and machinery because of its simple principle and other characteristics. PID parameter setting is to find the best combination of parameters through experimental or theoretical calculation methods, so as to achieve the purpose of improving the dynamic and static characteristics of the system. In [6] the critical scaling method, attenuation curve method and empirical method were proposed for parameter tuning. Subsequently, engineering tuning methods and Ziegler-Nichols tuning methods appeared. In [7] the unit negative feedback system of a typical second-order controlled object is taken as an example. From the perspective of root locus and frequency characteristics, the impact of PID controller parameter changes on system control performance was analyzed in detail. The complexity of parameter setting and reasonable selection of PID controller parameters have certain reference value. In [8] a method of using fuzzy systems to accurately tune PID controller parameters is given. The knowledge base of fuzzy control rules consists of tuning knowledge and expert experience

rules. However, for general complex systems, it is difficult for expert experience to grasp its uncertainty, so this method has certain limitations. With the development of computer technology, people began to use artificial intelligence to self-adjust PID parameters. In [9] a PID parameter self-tuning controller based on BP neural network is designed. This controller combines neural network and PID control, and uses neural network to approximate the characteristics of complex nonlinear system, and then self-tuning PID parameters. However, the neural network has problems such as slow learning speed. To solve this problem, in [10] the improvement of the basic BP algorithm is carried out and its application research in PID optimization control, so that the PID controller has better dynamic characteristics, thereby improving the control effect. On this basis, in [11] neural network is introduced into fuzzy PID control, and a PID parameter tuning method based on improved fuzzy neural network is proposed. The two algorithms of fuzzy control and neural network were organically combined, and the simulation result shows that this method can further reduce the control error. In addition, domestic scholars have also carried out corresponding research work on PID parameter tuning of genetic algorithms, wavelet transforms, and particle swarm optimization: in [12] an improved cross-over and select the operation algorithm is proposed and apply it to the PID controller parameter tuning. The results show that the algorithm improves the accuracy and convergence performance, but this method can only adjust the PID parameters offline, the practicability remains to be studied; in [13] the wavelet transform is applied to the PID parameter tuning of the control system, and it is found that the wavelet transform can accurately determine the system lag time and better parameter tuning to improve the control effect; in [14,15] two improved particle swarm optimization algorithm is proposed for PID parameter tuning optimization. The simulation results show that the improved particle swarm optimization algorithm can quickly find the optimal PID parameters and has certain practical value. In addition to the above commonly used algorithms, the related literature also has some new intelligent algorithms, such as artificial

fish school algorithm [16], multi-universal parallel genetic algorithm [17], maximum/minimum ant system algorithm [18], Big Bang big convergence algorithm [19], bacterial foraging algorithm [20] for PID tuning research.

In summary, PID control is widely used because of its simple principle. In the seismic simulation shaking table system, due to the existence of nonlinear factors such as friction, PID control has a large overshoot, parameter adjustment takes a long time, and the control efficiency is low. The actual effect of PID control and PID control after parameter tuning is not ideal, the waveform distortion is large. Taking into account the control requirements and characteristics of the seismic simulation shaking table itself, scholars then proposed a three-variable control algorithm.

2.2. Three-variable and Multi-variable Control

In the 1970s, a three-variable control composed of displacement, velocity, and acceleration was proposed. The control principle is shown in Figure 3.

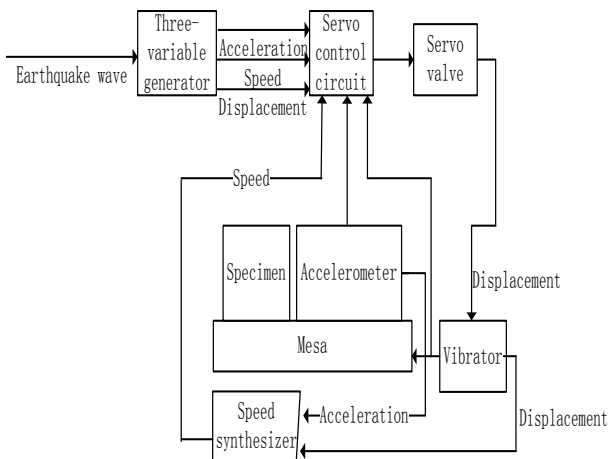


Figure 3. Three-variable control principle

In [21] the role of the three-variable feedback and feed-forward link in the three-variable controller by studying the three-variable control algorithm are determined: acceleration feedback can improve system damping, speed feedback can increase the oil column resonance frequency, and provide flatness System performance; the three-variable feedforward parameter cancels the pole closer to the imaginary axis in the closed-loop transfer function of the system, further expanding the system bandwidth and greatly improving the frequency response characteristics of the system.

The earliest research on three-variable control in China is the Department of Mechanical Engineering of Harbin Institute of Technology, and it is called three-state control. In order to solve the problems of low damping and poor stability of the servo system, the pole configuration is used to design the structure and parameters of the three-state feed-forward and three-state feedback controller, and the controller is applied to the three-way six-degree-of-freedom vibrating table control system developed by China [22]. Since then, Chinese scholars have successively carried out three-parameter control related research, and achieved a series of research results.

Considering that the electro-hydraulic servo system has complex nonlinearity, when the 90° phase shift frequency of the servo valve is close to the resonance frequency of the oil column of the system, the servo valve will resonate with the oil column, which seriously affects the effective frequency range of the system. The effective frequency band of the existing electro-hydraulic servo seismic simulation shaking table system is mostly 0.4-50 Hz, which is not enough to meet the requirements of seismic tests for large-scale scale-down structures. In order to reduce the effect of the servo valve characteristics of the existing seismic simulation shaking table system on the system performance and widen the effective frequency band of the shaking table system, in [23] the original negative velocity feedback in the three-variable control is changed to positive velocity feedback to increase the open-loop gain and the system damping ratio while appropriately reducing the system's oil column resonance frequency, the simulation results show that the three-variable control with positive speed feedback has a fast response speed and enhanced system stability; for the control accuracy of electro-hydraulic position servo system, in [24] a two-degree-of-freedom composite control strategy combining three-parameter feedback control and feedforward inverse model control is proposed. The feedforward inverse model control is used to improve the dynamic response characteristics of the experimental system and expand the system bandwidth. At the same time improve the vibration table waveform correlation.

Domestic scholars have also conducted research on three-variable control parameter tuning: in [21] a fast three-variable control parameter tuning method is proposed, and through computer simulation and field tests, the three-variable control parameter rapid tuning results and compare the results of the traditional trial and error method. The comparison shows that the two results are basically the same, which guarantees the effectiveness of the algorithm; at the same time, it is proved that the method can effectively shorten the parameter setting time and realize the rapid setting of the three-variable control parameters. At the same age, in [25] a frequency domain identification method around the three-variable parameter tuning problem is proposed. After using a simple harmonic signal to sweep the vibration table system, the system transfer function was obtained by least square method frequency domain fitting identification, and then carried out three-parameter theoretical control parameters are obtained through theoretical calculations, and actual system parameters are obtained through fine-tuning. Simulation results show that the algorithm can obtain more ideal control parameters; in [26] computer simulation expert manual tuning algorithm is proposed. The setting process makes the parameters reach the optimal value quickly and accurately. Summarizing the current research results, it is found that the current three-variable tuning algorithm still has limitations such as cumbersome derivation process, inconvenient practical operation, and low degree of intelligence.

Based on the three-variable control, the scholars introduced some other parameters and developed a multi-variable control algorithm: in 1997 [27] a three-variable controller design study on an electro-hydraulic servo system with differential pressure feedback is conducted.

The results show that the the controller can adapt well to changes in system parameters and has certain practicality. In [28] force, displacement, velocity and acceleration errors is added to the control loop with certain weights based on the internal closed-loop control of the FIGT controller displacement of the vibration table of the former Hunan University Structural Laboratory, forming an acceleration waveform tracking external closed-loop multi-variable controller; and for the continuous changes of structural physical parameters during the experiment, neural network is added to the online adjustment process of multi-variable control weights, and finally high-frequency and high-precision tracking of acceleration waveforms is achieved. After the bench model test, the multi-parameter control outer closed loop has a better adaptive effect.

In [29] the acceleration feedback signal and the acceleration feedforward signal is introduced into the control link on the basis of three-variable control to form a acceleration multi-variable control algorithm for shaking table, the results show that acceleration feedback can reduce the impact of system oil column characteristics on system performance while expanding the system frequency band; in [30] on the basis of the three-variable control, the interaction between the specimen and the table is consider and the force feedback compensation control of the interaction between the specimen and the table is introduced, the simulation analysis of the shake table of the single-degree-of-freedom and multi-degree-of-freedom specimens is completed. The results show that the force feedback compensation control effectively compensates the influence of the interaction between the test piece and the table on the vibration table control eliminates the peaks and notches of the fourier amplitude spectrum of the table acceleration at the natural frequency of the test piece and its nearby frequency. However, the control algorithm is based on the ideal assumption of real-time and accurate measurement of actuator output and table acceleration. In actual application, the error of the acceleration sensor and the force sensor need to be studied.

With the use of seismic simulation shaking table, its inherent parameters will change. The traditional control algorithm mainly relies on parameter adjustment to achieve control. The parameter tuning algorithm has limited tracking of changing parameters, resulting in the poor control effect of the three-variable control algorithm on the seismic simulation shaking table.

2.3. Feedforward Control

During the research of the three-variable scholars found that the design of the three-variable controller is based on feedback control. The feedback control is based on the error between the target input and the actual output of the system, so it has a certain lag problem. For the shaking table servo system with requirement of high waveform reproducibility, it is necessary to consider the accuracy effect brought by the lag problem. In response to the lag problem caused by feedback control, scholars have developed a feedforward control algorithm. Compared with feedback control, a major feature of feedforward control is that it can respond in advance according to the input signal, so that the system can have a certain predictability, and then improve the tracking accuracy of

the system. The principle of feedforward control is shown in Figure 4. Among them, $P(s)$ is the controlled object, $C(s)$ is the feedback controller, $G_b(s)$ is the feedforward controller, $R(s)$ is the system input, $Y(s)$ is the system output, $E(s)$ is a systematic error.

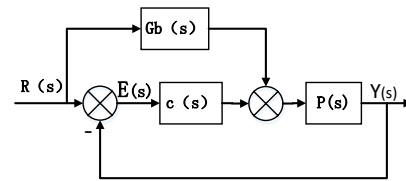


Figure 4. Feedforward control principle

In [31] a resonant electro-hydraulic vibration table feedforward controller based on the principle of zero phase difference feedforward compensation is designed. The principle of the controller is shown in Figure 5. Among them, $y_{in}(k)$ is the input signal, $r_{in}(k)$ is the control signal, $y_{out}(k)$ is the output signal, and $G(s)$ is the feedback signal. The sine wave simulation results show that the performance of the controller has been significantly improved. However, the research algorithm only compensates for PID control, and the simulation waveform is sine wave, zero phase difference feedforward three-parameter compensation technology and seismic wave simulation research needs further development.

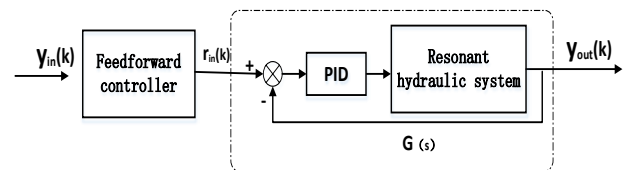


Figure 5. Structure of feedforward controller

In [32] the influence of the flexibility of the seismic test structure is considered and the feed-forward control strategy is applied to the electro-hydraulic seismic shaking table: using feed-forward control to compensate the zero point of the system to suppress the anti-resonance peak generated by the flexible foundation and put the pole offset to the virtual axis to further expand the system bandwidth. Experimental results show that the algorithm compensates the influence of structural flexibility and improves the bandwidth of the vibration system. The disadvantage is that the feedforward control strategy relies on accurate estimation of the vibration system, and the control of complex multi-degree-of-freedom shaking table and array systems still needs further study. On the basis of feedforward control, in [33] a function chain adaptive control that can deal with the changing dynamics, inherent nonlinearity, external uncertainties and disturbances of the system in order to improve the reproducibility of acceleration recurrence performance of shaking table is introduced. The experimental results of one-way electro-hydraulic seismic simulation shaking table verify the feasibility and superiority of the algorithm.

With the development of computer technology, a variety of intelligent control algorithms such as neural network control, fuzzy control, and adaptive control have been applied to the control of seismic shaking table.

3. Intelligent Algorithm

3.1. Iteration Control

In 1978, Japanese scholar Uchiyama (Uchiyama, Tohoku University) proposed iterative learning control (ITC). Its control principle is shown in Figure 6.

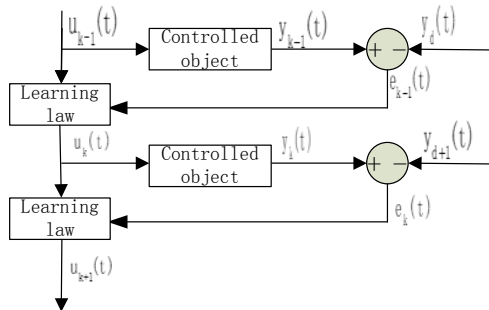


Figure 6. Iteration control schematic

In the iterative control, the learning law adjusts the output error $e_k(t)$ to obtain a better control signal $u_k(t)$. To achieve efficient control of the controlled object. The output error is shown in equation (1):

$$e_k(t) = y_{d+1}(t) - y_k(t) \quad (1)$$

Where $y_k(t)$ is the actual output signal of the second iteration of the system, $y_{d+1}(t)$ is the control input signal of the second iteration of the system.

Later, Kawamura, Miyazaki (Osaka University) and other scholars further research promoted the development and improvement of iteration theory [34]. Because the iterative control has good learning ability, the performance increases with the increase of the number of control system operations, so this method quickly receives great attention [35]. In 1985, the Institute of Engineering Mechanics of China Earthquake Administration used microcomputer and digital iterative method to control a one-way 1.5T electro-hydraulic shaking table for the first time. The results show that this method can meet the requirements of the output waveform of the shaking table. Since then, domestic scholars have carried out research on iterative learning control laws and system forms. Especially since the 21st century, relatively rich research results have been achieved: in [36] an iterative algorithm model is built and simulation experiments on the basis of traditional PID control is completed, exploring iterative algorithms in the seismic simulation shaking table control system. The application of the given engineering implementation scheme promotes the engineering application of the iterative algorithm in the electro-hydraulic servo system. On this basis, in [34] iterative control theory is applied based on the PID control of the internal displacement of the horizontal single-degree-of-freedom seismic simulation shaking table, an external acceleration iterative closed loop is built to form a double closed loop control, and the shaking table reconstruction is completed successfully. The algorithm is simulated and tested, the simulation results show that the correlation coefficient between the system response and the expected response is increased from 0.858 to 0.995, which meets the engineering accuracy requirements (the correlation

coefficient is greater than 0.95). This research work provides a theoretical basis for the application of iterative control to the seismic simulation shaking table control system. Double closed-loop iterative control is of great significance to the research of seismic simulation shaking table control technology in my country, but the actual test results of the control algorithm cannot fully meet the engineering requirements. In [37] a control strategy combining offline iterative control and improved internal model control is proposed. Experimental results show that compared with the traditional pure iterative learning controller, the algorithm has better tracking accuracy and faster convergence speed, and improves the waveform reproduction accuracy of the electro-hydraulic vibration table. Later, in [38] the input link system with non-linear characteristics of the dead zone is discussed, and a filtering initial correction iterative learning control method is proposed, which has important reference value for the shaking table control technology including the dead zone of the servo valve. In [39] the iterative learning control algorithm based on displacement-acceleration shaking table to solve the problem of low accuracy of the acceleration waveform of the shaking table is proposed. Simulation and experimental results show that the algorithm is more accurate than the displacement-displacement iterative learning control algorithm for higher waveform reproduction and faster iteration. In [40] considered the influence of the dynamic characteristics of the specimen on the accuracy of the waveform reproduction. On the basis of the original frequency domain iterative correction of the vibration table, a frequency domain inverse compensation correction algorithm is developed. The test and simulation results show that the algorithm is under control. The response of the specimen can well represent the real response. However, at present, the algorithm only performs experimental verification on linear structure specimens, and the seismic test of nonlinear structure specimens needs to be completed.

In [41] an iterative learning control algorithm based on uncertain factors such as the dead zone of the servo valve, the oil temperature change of the hydraulic system, and the inherent gap of the mechanical system in the actual work of the three-axis loading hydraulic servo system is proposed. Compared with the full digital control control system, this method improves the control accuracy of the system and promotes the research and development of the iterative algorithm under the influence of nonlinear factors. Based on the identification of the seismic control station servo control system, in [42] an iterative learning control algorithm based on time delay estimation is proposed to prove the algorithm for the control lag problem in the practical application of the seismic simulation shaking table. After convergence, the waveform reproduction accuracy was improved from 0.8949 before iteration to 0.9314 through multiple iteration control experiments. The improvement of the waveform reproduction accuracy proved the effectiveness of the algorithm application.

In addition, many domestic scholars have also studied the problem of iterative control convergence: in [43] iterative control algorithms is introduced in complex nonlinear systems, simulation results and test results from the frequency domain perspective shows that the

control algorithm not only widens the system frequency band, but also improves the tracking accuracy of the system output and the expected signal; in [44] the design of the quantitative feedback theory (Quantitative feedback theory, QFT) iterative control algorithm is also carried out. These two algorithms have opened up a new way for high-performance real-time control of hydraulic angular shaking table, and also brought a new control method for iterative control of shaking table. Since the 21st century, the research of domestic scholars has also considered the combination of iterative control and intelligent control algorithms such as adaptive and flexible control [45], and an iterative learning control algorithm with high control accuracy is proposed. Although the iterative learning control algorithm improves the shaking table waveform reproduction accuracy, its long iteration time and incompatibility with the control software still need further study. Neural network control that processes information in parallel to reduce the length of information processing has attracted people's attention.

Neural network (NN) is an algorithm for distributed parallel information processing. The basic neural network structure is shown in Figure 7, which is the system input signal and the control system output signal, used to control the controlled object; the connection weight between the p-th neuron in the input layer and the q-th neuron in the hidden layer is the connection weight between the p-th neuron in the hidden layer and the q-th neuron in the output layer. The neural network control principle is shown in Figure 8. Since the 1980s, research results such as BP neural network, RBF neural network, Hopfield neural network have emerged.

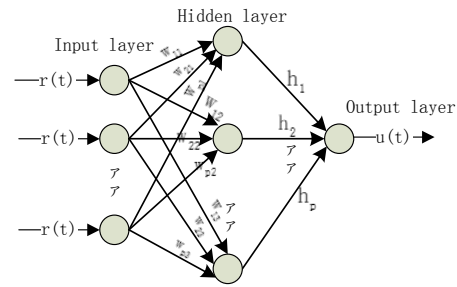


Figure 7. Basic neural network structure

3.2. Neural Network Control

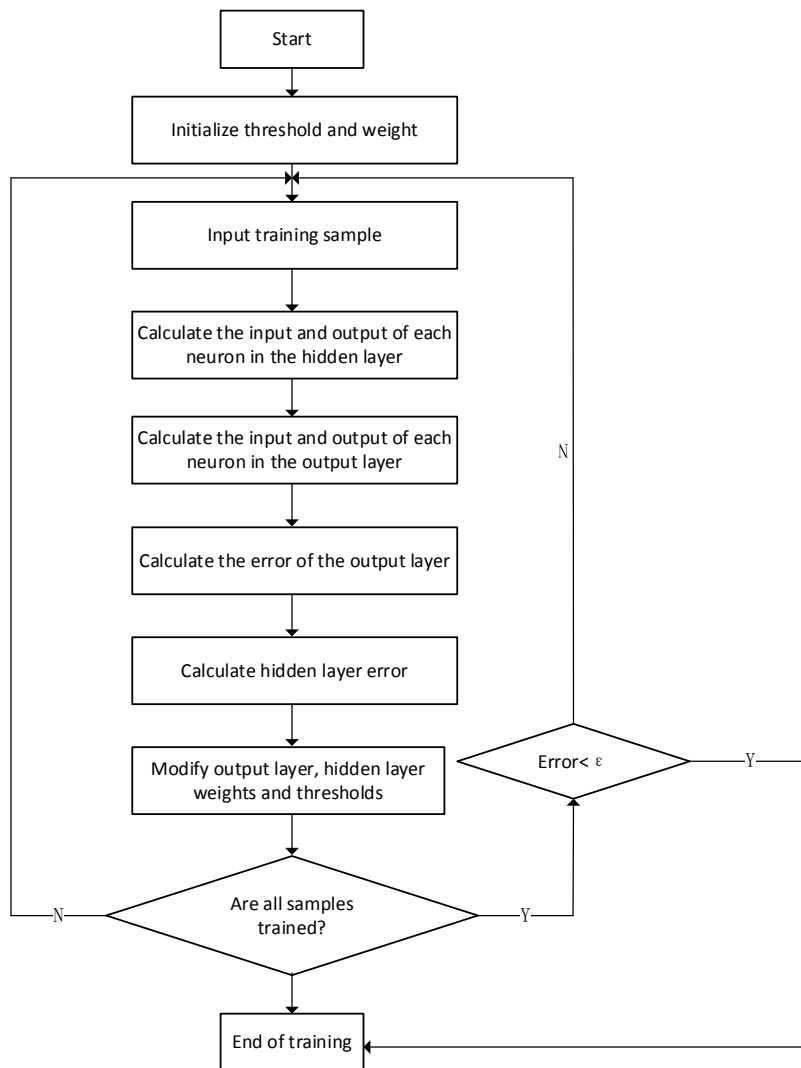


Figure 8. Neural network control principle

In [46] the BP neural network is used to optimize the local minimum problem for the amplitude and displacement deviation of the electro-hydraulic vibration table under traditional control, so that the output peak was the same as the input peak, and the waveform reproduction accuracy was improved. In response to the same problem of displacement deviation of the shaking table, in [47] an improved PID neural network is used to optimize the control of the shaking table. The results show that the output displacement and frequency of the shaking table can quickly track the input value under the control algorithm, and the waveform related degree is higher. In [48] responded to the needs of the earthquake simulation shaking table of the Structural Laboratory of Hunan University, the neural network outer closed loop control was added based on the basis of the original PID inner loop control. The effectiveness of the algorithm was verified through experiments. This research work successfully completed the physical reconstruction of the earthquake simulation shaking table, and promoted the practical application of the neural network in the shaking table control system. In [49] a real-time acceleration tracking strategy combining inverse compensation technology and neural network controller is proposed to improve the acceleration tracking performance of a typical electro-hydraulic shaking table system. The effects of inherent nonlinearity, dynamic changes and external uncertainties of the system. In the same year, in [50] an adaptive compound dynamic surface control strategy based on neural network for low-speed and high-accuracy tracking control of electro-hydraulic shaking table system in response to the problem of poor control of the shaking table due to nonlinearity is proposed. In addition, in [51] neural networks is used to solve the time lag problem of the vibration table substructure test system. The simulation results show that the control algorithm has a significant time delay compensation effect, and better improves the vibration table substructure test accuracy.

The neural network approximates the nonlinear system of the real seismic simulation shaking table by virtue of its strong function approximation capability and good fault tolerance, thus achieving efficient control. However, at present, most of the research on neural network control of seismic simulation shaking table focuses on theoretical simulation research, and the practical application of neural network on the shaking table needs to be further studied by scholars.

3.3. Fuzzy Control

Fuzzy control is a computer digital control technology based on fuzzy set theory, fuzzy linguistic variables and fuzzy logic reasoning. The basic principle is shown in Figure 9. Generally speaking, fuzzy control is suitable for complex nonlinear systems like the shaking table, where the mathematical model is unknown or difficult to accurately represent [52].

In the early 21st century, Chinese scholars carried out research related to fuzzy control: in [53] first aimed at nonlinear uncertain systems represented by shaking tables, and applied fuzzy control theory to construct fuzzy models of nonlinear systems. The system fuzzy control provides a theoretical basis; in [54] the fuzzy control algorithm is applied to the electro-hydraulic shaking table control

system, which suppressed the influence of various nonlinear factors and improved the control accuracy; in [55] the control theory and PID control theory are combined to design a fuzzy PID controller and apply it to the servo system simulation model. The results show that the control performance is significantly better than the ordinary PID control, and a good control effect is achieved.

In summary, the current research on fuzzy control of shaking table in China: on the one hand, the research direction is single, and currently only focuses on PID fuzzy control, which still has a large gap compared with foreign countries; on the other hand, there is a lack of research on the control rules in fuzzy control. To realize the fuzzy control of shaking table, it is necessary to refer to a large number of foreign studies to carry out basic research on fuzzy control, and thus broaden the research field.

3.4. Adaptive Control

Adaptive control as an intelligent control algorithm, integrates the three links of system modeling, inversion function and control into a control system, and online modification of control parameters through the adaptive algorithm has the guarantee of the system. The advantages such as stability and reducing the burden of manual debugging can automatically compensate for unpredictable changes in model order, parameters and input signals. It is very suitable for shaking table. After the working conditions change, their dynamic parameters and the system control of the structural changes of the model, adaptive control is considered to be the best method and future development direction to solve the high-precision time-domain acceleration waveform reproduction of multi-axis electro-hydraulic vibration table. Adaptive control algorithms are mainly divided into variable gain adaptive control and model reference adaptive control. In [56] Lyapunov stability theory is used to design a position loop adaptive controller for a high-precision servo system. The controller is shown in Figure 10. The application effect of the controller shows that the controller has good robustness. The research results provide a valuable reference for the research on the adaptive control of the shaking table servo system.

In [57] LMS filters is used for the first time to establish an adaptive model of the shaking table system, and realized the acceleration table tracking of the shaking table. On this basis, in [58] Model Reference Adaptive Control is applied to the electro-hydraulic shaking table servo control system, giving the shaking system better stability, robustness, and autonomy. In [59] adaptive part is used to eliminate parameter uncertainty in servo system control. In model reference adaptive control, the minimum control synthesis algorithm has attracted wide attention from scholars by virtue of the fact that it does not require any dynamic parameters other than the degree of freedom and system dimension. The principle of the minimum control synthesis algorithm is shown in the Figure 11. Minimal control synthesis has been applied to several multi-channel hydraulic shaking tables, such as those from Bristol University and the Technical University of Athens [60].

In [61] the minimum control synthesis algorithm is applied to the shaking table control and set the outer loop controller as shown in Figure 12. The simulation results

show that the system can still track the expected signal well when the internal parameters of the system change. However, this research object is only a single-degree-of-freedom system, and further research is needed for multi-degree-of-freedom shaking table.

In [62] an adaptive inverse control framework for

shaking table is proposed as shown as in Figure 13. The framework promotes the development of adaptive control of the shaking table to a certain extent by formulating a set of key design specifications corresponding to safety, robustness, and ease of use, and standardizing adaptive design theory standards.

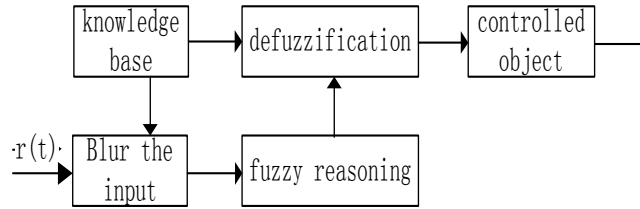


Figure 9. Fuzzy control principle

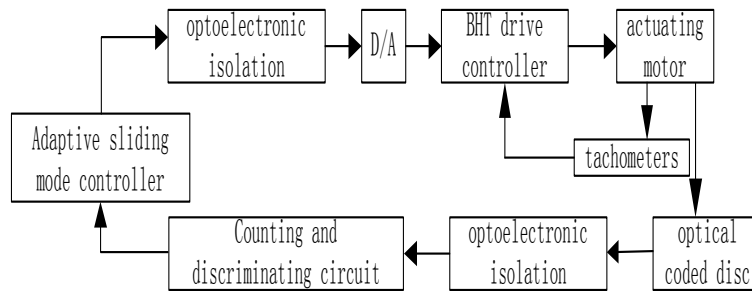


Figure 10. Position loop adaptive controller

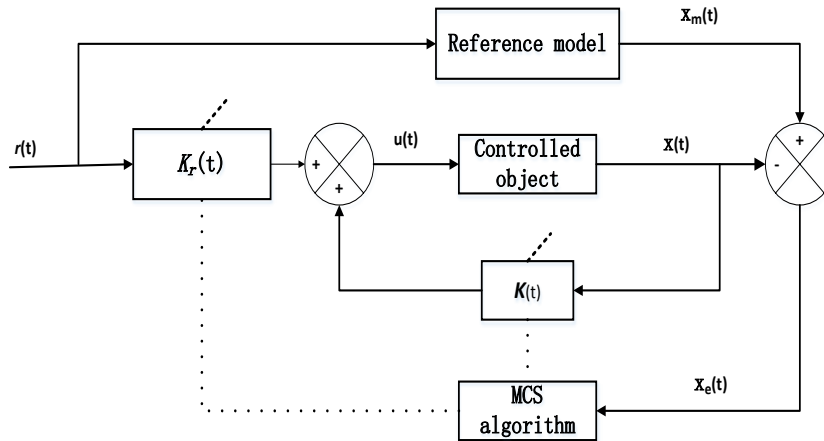


Figure 11. Minimal control synthesis algorithm schematic

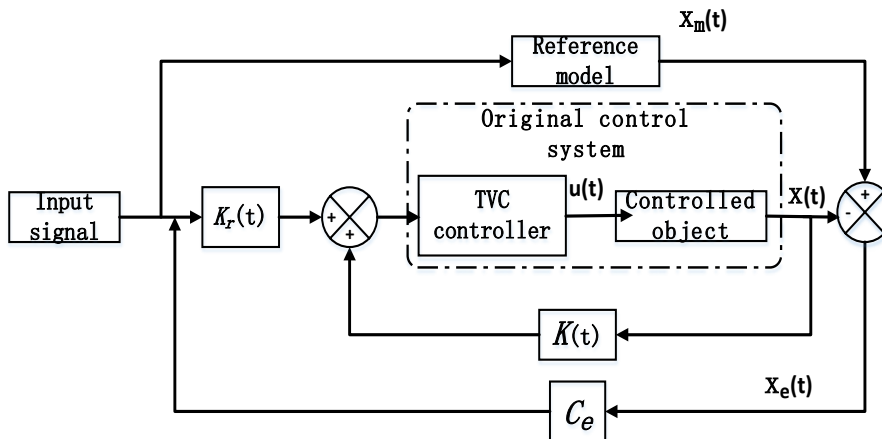


Figure 12. Outer loop controller

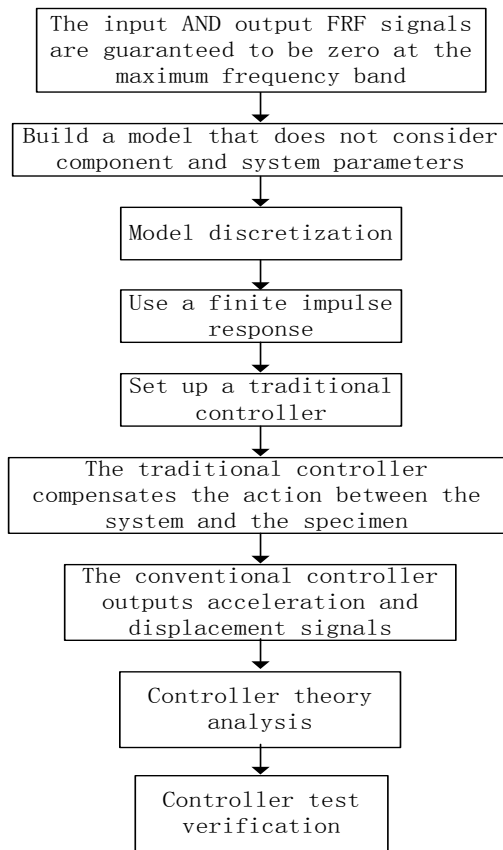


Figure 13. Adaptive inverse control framework

During the research of adaptive control, some scholars found that the uncertainty of algorithm parameters and the modeling uncertainty of nonlinear friction hindered the development of high-performance controllers for hydraulic servo systems. In response to this problem, in [63] an adaptive control method for seismic simulation tests is proposed. This method overcomes the time-varying nature of the hydraulic system by continuously identifying the transfer function of the system to improve the accuracy of waveform reproduction. In [64] the six-degree-of-freedom electro-hydraulic vibration table of Harbin Institute of Technology is taken as the research object, and the offline adaptive control is designed to replace the three-variable feedforward for the complex problem of three-variable feedforward parameter tuning, and further combined with X-filtering. This control strategy reduces the number of parameters to be tuned, and the experimental results show that the time domain waveform reproduction accuracy is further improved, proving the effectiveness of the control method. In [65] a non-linear factor such as interference suppression and unmodeled dynamics is considered, and a multi-model robust adaptive control algorithm is proposed. The experimental results show that this method solves the problem of traditional adaptive control sensitive to the initial value of parameters, overcomes the effects of nonlinearity and parameter uncertainty, and improves the transient response performance of the system. In [66] the nonlinear adaptive controller using the inverse method is designed to deal with the nonlinearity of the servo valve and the parameter uncertainty of the control algorithm. At the same time, the xPC/Target rapid prototyping technology was used on the single-axis shaking table. A comparative experiment was carried out to verify the

feasibility of the developed controller. In response to the problem of the system band formant caused by the additional mass of fluid-structure coupling in the underwater vibrating table, in [67] an adaptive pole placement control method is adopted to adjust the parameters of the three-variable control scheme online. Simulation results show that the control scheme widens the frequency range of the shaking table system and suppresses resonance peaks. This control algorithm provides a positive attempt for adaptive pole placement to solve the system formants, and the next step can use this control algorithm to study whether it can solve the bandwidth problem caused by the formants of the ground simulation shaking table.

In recent years, adaptive harmonic identification [68], adaptive refined modeling feedforward control [69], feedforward minimum control integrated algorithm [70], and adaptive internal model control [71] have emerged. At present, adaptive control theory has achieved fruitful results and has achieved good simulation results, but experimental research is relatively rare. Promoting adaptive control experimental research has far-reaching significance for the engineering application of adaptive control.

3.5. Decoupling Control

The real earthquake has a three-dimensional space effect, so compared with the unidirectional horizontal shaking table, the three-axis six-degree-of-freedom shaking table can simulate the translation and rotation in three directions of space, and the simulation effect is closest to the real earthquake. However, in its multi-degree-of-freedom hydraulic servo system, multi-input and multi-output are interrelated and affect each other, and there is a coupling phenomenon that affects the actual control effect of the three-axis six-degree-of-freedom shaking table. In order to solve the coupling problem, each output is controlled by only one input, and different outputs do not affect each other. Scholars have studied the decoupling control algorithm. In [72] aiming at the internal force coupling effect caused by the pressure difference of the exciter, the internal force coupling compensation control algorithm is introduced to eliminate this coupling effect. The experimental results show that under the action of the control algorithm, not only the differential pressure output of each excitation system when the vibration table is in a balanced state, but also the waveform distortion of the acceleration output of the shaking table is significantly reduced.

In [73] the transfer function of the matrix-type multi-axis electro-hydraulic vibration table is analyzed and the system inverse model is designed. Shaking table experimental verification results show that the performance of the system after decoupling is greatly improved, and the coupling signal is reduced to a certain extent. In order to improve acceleration tracking performance and achieve motion decoupling, in [74] a six-degree-of-freedom electro-hydraulic shaking table system was proposed. The decoupling control algorithm comprehensively transforms the coupled dynamics into modal control of six independent systems and the inverse dynamics model used to eliminate differences in actuator

dynamics. Shaking table experiments prove that the algorithm reduces the coupling effect of the horizontal axis compared with the three-variable control, greatly improves the control accuracy of the seismic simulation shaking table, and reduces the number of parameters that need to be adjusted from 36 to 4. This control strategy provides a feasible way to improve the accuracy of seismic testing in the future. However, the performance of this control method is related to the accuracy of the model, and the influence of modeling parameter errors needs to be further considered.

4. Development Trend

In summary, after a long period of research, the seismic shaking table has made considerable progress in the field of civil engineering, and has achieved certain research results. Especially the combination of traditional control algorithms and intelligent control has significantly improved the accuracy of the shaking table control. It has laid a good foundation for the follow-up seismic research. However, with the development of high-rise and super-high-rise buildings, prefabricated buildings, and large-span structures, higher requirements are imposed on the application of vibration table in structural seismic resistance. The author believes that the contents of the vibration table control that need further research are mainly reflected in the following aspects:

4.1. Intelligent Tuning of Control Parameters

At present, most of the seismic shaking table adopt three-variable control. It is extremely time-consuming to complete the control parameter adjustment before each test, which greatly increases the test cost; and as the properties of the test piece change during the test, the control parameters given before the test affect the control Precision and test results. The current parameter setting algorithm has the problem of low intelligence, so it is necessary and important to develop an intelligent control parameter setting algorithm.

4.2. Nonlinear Overall Control Algorithm

The commonly used seismic shaking table exhibit strong nonlinear behavior [75], so it is of great significance to carry out research on nonlinear control algorithms. Domestic scholars have reviewed the research progress of electro-hydraulic servo nonlinear control technology [76], and related algorithms have also been studied in industry [77]. However, most of the researches on the nonlinear control of seismic shaking table focus on a single nonlinear behavior [78,79,80]. Later research work should consider the overall influence of nonlinearity and conduct more extensive research on nonlinear control algorithms.

4.3. Array System Control

The array system uses a combination of multiple sub-units to complete the test, which has obvious cost advantages. The vigorous construction of the array system has been widely recognized in the industry. Therefore, the

control of the array system is also a research hotspot of the current seismic shaking table control. Compared with a single unit, in addition to the problems of a single vibration table, the array control system is mainly due to the coupling and cooperative control between multiple units. Due to the internal mechanical coupling [81] and the test accuracy requirements, the control of the array system is difficult. At present, the research on the domestic vibration table array hardware system has become more mature, but there is less research on the control algorithm and array cooperative control. In [82] ultra-high-speed EtherCAT technology is used to design a real-time high-performance servo control system for the seismic simulation shaking table array system. Although the position, velocity, and acceleration of the shaking table were eventually synchronized, the control system used advanced communication, and it has high technical content and high cost, and has not yet entered the practical stage. The level of control of the domestic array system is still far behind that of foreign countries. Work in this area needs further exploration and research.

4.4. Multi-degree-of-freedom Shaking Table Control

The multi-degree-of-freedom shaking table is widely concerned because the simulation effect is closest to the real earthquake. At present, China's multi-degree-of-freedom shaking table is booming, but the research of multi-degree-of-freedom shaking table control algorithm is at the preliminary theoretical stage: due to the existence of redundant constraints, the traditional control algorithm control effect is not good; in addition, multi-degree-of-freedom shaking control also needs to be considered different degrees of freedom synthesis and decomposition processes from traditional control algorithms increase the difficulty of developing control algorithms. To improve the level of earthquake resistance in China, the multi-degree-of-freedom shaking table control algorithm needs further study.

4.5. Experimental Verification

Scholars at home and abroad have proposed more corresponding algorithms to improve the control performance of the shaking table. Simulation analysis is often used to verify the feasibility and effectiveness of the algorithm. It is rare that the algorithm is embedded in the controller and used in seismic simulation of the shaking. It is very important to improve the empirical research level of algorithms and promote the practical application of algorithms.

5. Conclusion and Discussion

This paper summarizes the construction of domestic seismic simulation shaking table and the development of control algorithms, and draws the main conclusions:

(1) For traditional control algorithms—PID control and three-variable control, which have poor control effect, domestic scholars have proposed parameter tuning algorithms and compound controller algorithms to improve the waveform reproduction accuracy.

(2) With the help of the development of computer technology, the domestic intelligent control algorithm research has achieved fruitful results. The simulation results show that the waveform reproduction accuracy has been improved, and some algorithms have been successfully applied to the upgrading of seismic shaking table.

(3) Efficient control parameter adjustment algorithm, nonlinear control algorithm, array system control, multi-degree-of-freedom shaking table control, and experimental verification are the future development trends of seismic shaking table control technology.

Acknowledgements

Thanks to the Henan Provincial Science and Technology Research Project (182102210539) and Henan Provincial Higher Education Key Project (18B560009) for funding. Thanks to the help of the team members.

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