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——理论与应用

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- Theory and Applications

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内容简介

在线混合实验方法是研究工程结构抗震最有效的方法之一，近30年来在线混合实验技术发展迅速，但关于在线混合实验的书籍在国内外均较少。本书旨在介绍在线混合实验技术的基本理论和工程应用，不仅介绍了常规在线混合实验，也介绍了在线混合实验在网络化以及复集有线元程序接合等方面的发展。

本书可供工程抗震实验研究人员在教学和科研工作中使用。

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前言

FOREWORD

Computer simulations play an important role in modern seismic design of structures, while experiments are commonly used to gain better insight into the structure behavior, and further to validate or calibrate the analytical models used in the computer simulations. This is the traditional understanding of computer and experiment. Recent years, however, an entirely new method to reproduce the seismic behavior of structures, which combines the computer simulations with the physical tests interactively, is developed. This method solves the dynamics of a structure in the computer domain using step-by-step time integration algorithms, while obtaining restoring forces from a physical specimen. The computer provides displacements to the specimen as the loading target, and the measured restoring forces are fed back to the computer to update the dynamic state. This interaction continues repeatedly until the end of the simulation. Because of the online communication and updating, this simulation technique is called the online hybrid test. Several benefits can be expected from this method. First, the inertial effect is simulated numerically in a computer. There's no need to construct massive physical payload on a specimen as it is loaded quasi-statically. Therefore, a large-scale specimen can be implemented. Second, because the loading rate is quite slow, one can closely observe the initiation and development of damages on the specimen, which is very important for better understanding on the seismic behavior. Finally, the online hybrid test can be realized by conventional load devices instead of sophisticated facilities such as shaking tables. This makes it rapidly developed in the past thirty years and become one of the standard approaches to examine the seismic performance of structures.

Recent development of online hybrid tests is classified into two categories, namely, real-time online hybrid test and substructure online hybrid test. Real-time online hybrid test requires very prompt response of loading devices. The dynamic interaction between the loading facility and the specimen must be considered explicitly because the response delay of the loading device may lead to divergence of the entire dynamic system. To compensate the delay is thus the key problem of the real-time online hybrid test, which is essentially a hydro-mechanical control problem. The discussion of real-time online hybrid test is beyond the scope of this book and will not be discussed hereafter. Substructure online hybrid test takes the most critical part of a structure as the experimental substructure while the rest with well-understood performance is numerically analyzed. The substructures are often distributed to different locations and connected through Network, thus being able to utilize resources of multiple laboratories. Substructure and Network render online hybrid test capability to investigate the seismic behavior of large-scale structures, as reported lately that the seismic responses of long-span bridges, braced frames, and concrete wall structures are reproduced.

In spite of the rapid growth of online hybrid test, little has been published in book form to guide the practitioner. The purpose of this book has been to provide comprehensive treatments of several topics pertinent to substructure online hybrid test. Emphasis has been placed on three frameworks, i. e., host-station framework, separated model framework and peer-to-peer(pzp) framework. They have been developed within Internet environment and particularly suitable for distributed hybrid testing. In order to help the readers to understand the essence of the online hybrid test and further to build up their own system, an engineering practice has been introduced at the end of this book with the source code appended. We address ourselves primarily to the readers with some background in structural dynamics, finite elements, and computer science. Efforts have been made to consolidate and simplify material that has ever appeared only in journal articles, and to provide the reader with a perspective of the state of the art.

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Authors

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CHAPTER 1

Introduction

1.1 Background, objective, and challenge

Two approaches are commonly used for simulating the earthquake responses of structures. One is the numerical simulation by which the equations of motion are formulated for a spatially discretized model, and solved numerically by the time integration algorithms in the time domain. The other is the experimental simulation by imposing the ground motions directly on the tested specimens. In the numerical simulation, a sophisticated model with huge degrees of freedom can be implemented, which is able to supply accurate responses. The solution procedure for this huge model, however, may be time-consuming, and the convergence of this solution procedure is always a critical problem, especially when great material nonlinearity and geometric nonlinearity are considered simultaneously. Furthermore, the existing analytical tools, such as finite element (FEM) programs, are often strong only for some types of structures, but not for all types. On the other hand, the experimental approach cannot handle full-scale structural models effectively either. It is very expensive and nearly impracticable to test a full-scale model of such a structural system, and a reduced-scale model is unable to duplicate the prototype behavior particularly when it involves strong nonlinearities. Therefore, it is not necessarily easy to accurately simulate the seismic responses of a huge and complex structural system by using either a single analytical method or a single experimental method.

The online hybrid test (OHT) [1-4] (also called the pseudodynamic test) is appealing since it can make use of the benefits of both the analysis and test. Such test has a history of more than thirty years, and many applications have demonstrated its effectiveness. The basic procedure of the first online test can be described as follows. First, the test specimen representing the structural system whose earthquake response behavior is being studied is fabricated and installed on the test bed. Assuming the specimen to be a discrete spring-mass system, a load-applying actuator is attached to the specimen at each mass position and in the direction in which the earthquake response of the specimen is to be examined. Then, the equations of motion are solved numerically in a computer by using time integration algorithms, while the restoring forces are obtained from a physical test. Therefore, the online test is a numerical technique utilizing the experimental information on the analyzed system's restoring force characteristics, which are difficult to model on a computer. Some of its major advantages are: (1) less actuator capacity is required than in the shake table because the loading can be quasi-static; (2) since the loading can be a repeated process of loading and pausing, conventional measuring devices used in quasi-static tests are sufficient; and (3) the loading can be stopped because of the discrete loading, enabling us to make close observation of the local behavior.

Since accurate displacement control and measuring are keys to the success of the test, the results given by the online test are more and more accurate due to the advancements in the technology of electronic devices, such as integration circuits and microprocessors. However, the online test is an approximate method including various assumptions and simplifications. The error sources are classified into two groups: intrinsic and experimental. Some of the major sources of intrinsic errors are: (1) the analyzed system is represented by a spring-mass discrete system; (2) the equations of motion are discretized with respect to the time domain and solved as difference equations; and (3) the damping is characterized as velocity-proportional viscous damping. Some of the major sources of experimental errors are: (1) the displacement value commanded to the servo controller differs from the computed displacement because of the finite resolution of the D/A converter; (2) the displacement reached after the actuator motion may be different from the command value because of the finite accuracy of the displacement sensor and the servo control limitation; (3) the force value measured may not be identical to the true force because of the finite accuracy of the load-measuring sensor; and (4) the measure force is changed to a digital value after the A/D conversion. Investigations on these error sources have been done by Nakashima and Kato to study and minimize them [5-8].

The online test has been improved over time by many researchers, using it with other techniques, hardware and software. The test, when combined with substructuring techniques, is called a substructure online hybrid test, and is particularly appealing for the earthquake response simulation of large-scale structures [9-17]. In the substructure online test, part of the structure whose restoring force behavior is too complex to model is tested, while the rest of the structure is modeled in the computer, and the equations of motion that represents the entire structure are solved. Most early applications of the substructure online hybrid test, however, have the following shortcomings: (1) the adopted numerical models used relatively crude assumptions and a limited number of degrees of freedom, a typical one of which was a stick model with lumped masses; (2) most applications implemented the numerical and experimental substructures at a local structural laboratory, where the limitation of analytical tools and loading facilities limit the applicability of online hybrid test systems for the seismic simulations of large-cale structures.

The online hybrid test is in essence a test with displacement control. The displacements for the next time step are predicted and applied to the test structure; the reaction forces corresponding to the target displacements are measured and fed back to the equations of motion for the prediction of the next displacements. Displacement control, however, is not practicable when the test structure is too stiff to accurately control the loading actuator's displacement. Also, we can find cases in which we wish to apply online tests to stiff structures, for example an online test applied to a base-isolated building using the substructuring techniques in which only isolation devices, say, rubber bearings, are tested. The isolation devices are commonly very stiff in vertical direction but relativelv soft in horizontal direction, and very stiff in compression but relatively soft in tension. Therefore, a system which can combine control by displacement and force is appealing [18].

Subsequent improvements to numerical analyses have been very positive for earthquake response simulation, and many general-purpose finite element (FEM) software applications have been made available. In such circumstances, it would very effective to use a FEM software application for the computation of the numerical substructures. Some important applications along this line are the online test system developed in European Laboratory for Structural Assessment (ELSA) [19], the Network for Earthquake Engineering Simulation (NEES) of the National Science Foundation of USA [20], and a portable online test system developed by Pan et al. [21]. The incorporation of the FEM source codes has been demonstrated to be capable of improving the accuracy of the numerical substructures and making the online hybrid test system more versatile. Two common features can be found from these applications: (1) only one numerical substructure was implemented in these proposed systems. The equations of motion of the entire structure were formulated based on the FEM model for the numerical substructure, and the restoring forces obtained from the experimental substructures were incorporated into the FEM model directly using the static condensation technique; and (2) the source codes of the FEM programs were modified to incorporate the experimental part into the entire analysis. This is, however, difficult, because the program is commonly so complex that modification of the source code involves huge efforts and needs special expertise. Furthermore, most commercial FEM programs are copyright-protected, and modifications to the source code have to resolve legal issues. Therefore, the developed online hybrid test systems are rather difficult to transfer from one laboratory to another, and the FEM programs employed in these systems are not easy to be replaced by the one most suitable for the concerned structures.

To geographically distribute the experimental substructures and analytical substructures to different locations and exchange necessary data through Internet is also desirable because this type of test environment will significantly increase the capacity of the substructure online hybrid test. The concept of "Internet testing" or "distributed testing" has been addressed over the past few years [22-24], and a few real applications have been reported: the distributed online tests conducted between Japan and Korea [25], in Taiwan [26], and in the United States as part of the George E. Brown, Jr Network for Earthquake Engineering Simulation (NEES) [27]. All these applications demonstrate the advantage of distributing substructures to different locations. To fully take advantage of "Internet testing" or "distributed testing", it is important to standardize and simplify the interfaces of diverse subsystems so that they can be effectively incorporated into an integrated Internet test system. Such standardization and simplification require the subsystems to be highly encapsulated. Therefore, in order to increase the flexibility and capacity of the substructure online hybrid test system, it would be feasible to treat all substructures equally and as independent as possible, and to develop a standard interface for the communication between all substructures.

One solution is to solve the equations of motion and obtain the hysteretic behavior of a structure by using separated models with different sophistication. The equations of motion are formulated for the entire structure and solved by using homemade source codes, while the hysteretic behavior is obtained from sophisticated FEM models or from physical tests. Disparity in the model sophistication would be reasonable in a situation like; a sophisticated static model is needed for accurate evaluation of member internal forces and deformations, while the dynamics of the structure are well-represented by the first several vibration modes, which may be determined from a model with much fewer degrees of freedom. In this framework, the only responsibility of each substructure is to provide the static force-displacement relationship to the dynamic model. Therefore, all substructures can be treated equally. This implementation makes the system more versatile, since various FEM programs or experimental facilities can be selected for different substructures according to their individual characteristics [28].

As another solution, the equations of motion can be formulated for each substructure rather than for the entire structure. Each substructure is treated equally and as an independent dynamic subsystem which can be selected for numerical simulation or physical test. Because of the independence and equal status of each substructure, this solution can be identified as a peer-to-peer framework. The equilibrium and compatibility at the boundaries between the substructures can be satisfied by an equation-solution procedure. Each substructure only exchange data with this equation-solution procedure, but does not matter with the other substructures. In this framework, each substructure is highly encapsulated, and only the standard input and output, i. e., the boundary displacements and corresponding reaction forces, are used as the data to exchange. Therefore, this substructure online hybrid test system is able to accommodate different simulation systems without much modification. Furthermore, the equations of motion are to be formulated independently for each substructure and solved in parallel. Indeed, parallel computing can increase the capacity and efficiency significantly for computation of large systems [29, 30].

The objective of this book is to provide the basis of the online hybrid test as well as an overview of recent developments with some applications. In this book, in addition to a summary of available algorithms and implementations of the online hybrid test, four online hybrid test systems based on the displacement-force mixed control, the host-station framework, the separated-model framework and the peer-to-peer framework, respectively, are presented. Each of them brings an improvement to the online hybrid test. Furthermore, some applications in engineering practice are also given.

1.2 Organization

This book consists of nine chapters. Chapter 1 is the background of this study, and Chapter 9 is the summary and conclusions. Chapters 2 to 9 constitute the main part of the book: (1) basics of time integration algorithms; (2) typical time integration algorithms; (3) online hybrid test using mixed control; (4) Internet online hybrid test using host-station framework; (5) separated-model framework and its demonstration examples; (6) peer-to-peer (P2P) framework, its preliminary demonstration test and its convergence speed investigation; (7) application in engineering practice. The key points of the seven chapters are summarized as follows.

In Chapter 2, the basics of time integration algorithms, which are important to solve the equations of motion of online hybrid tests, are introduced. The existing time integration algorithms are grouped into such families as: (1) linear multi-step methods, (2) Newmark's family, (3) collocation methods, (4) α-family, (5) ρ-family, and (6) mixed implicit-explicit methods. The superiority of one family over the others is summarized in terms of the following rules: (1) self-restart procedure, (2) second-order accuracy, (3) unconditional stability, and (4) optimal and controllable numerical dissipation. Besides, the typical analysis methods for stability and accuracy are formulated.

In Chapter 3, numerical characteristics, such as stability, accuracy, numerical dissipation, and period distortion, are examined and compared for some notable time integration algorithms usable to online hybrid test. Summarized also in this chapter are their algorithms and implementations, which include the implementations using the central difference algorithm, the hardware-dependent iterative schemes, the Newton-type iterative schemes, and the non-iterative mixed schemes.

In Chapter 4, an online test technique that employs mixed control of displacement and force is presented. Indeed, displacement control is not practicable when the structure is too stiff to accurately control the loading actuator's displacement. Two types of mixed controls. "displacement - force combined control" and "displacement - force switching control" are proposed. In displacement - force combined control, one jack is operated by displacement control, and another is operated by force-control. Validity of the combined control technique is demonstrated by a series of online tests applied to a base-isolated structure subjected to horizontal and vertical ground motions simultaneously. The substructuring technique is employed in the tests, and the base-isolation layer is tested, with the rest of the structure modeled in the computer. Displacement-control and force-control were adopted for simulating the horizontal and the vertical responses, respectively. In the displacement - force switching control, the jack was operated by displacement-control when the test specimen was flexible but switched to force-control once the specimen became stiff. Validity of the switching control technique was also checked by a series of online tests applied to the base-isolated structure subjected to vertical ground motions. Switching between displacement-control and force-control was achieved when the axial force applied to the base-isolation layer changed from tension to compression or from compression to tension.

In Chapter 5, an Internet online test system is developed in which a physical test is conducted in one location, the associated numerical analysis is performed in a remote location, and the two locations communicate over the Internet. To implement the system, a technique that links test and analysis domains located at different places is proposed, and an Internet data exchange interface is devised to allow data communication across Internet. A practical method that utilizes standard protocols implemented by operating systems for sharing files and folders is adopted to ensure stable and robust communication between remotely located servers that commonly protect themselves by using strict firewalls. Therefore, the system consists of the host, stations, and data exchange interfaces. To combine the online test with a FEM program formulated in an incremental form and adopting an implicit integration scheme, a tangent stiffness prediction procedure is proposed. In this procedure, a tangent stiffness is estimated based on a few previous steps of experimental data. Using the system devised, tests on a base-isolated structure were carried out.

In Chapter 6, the development of the separated-model framework is introduced, and its validity is demonstrated. In this framework, two models are set up for the dynamics and the static behavior of one structure, respectively. The incorporation of general-purpose FEM programs into the static model is realized by repeatedly using its inherent restart capability. The general-purpose FEM program thus can be viewed as a black box with a standard input/output interfaces, avoiding modification of the source code. Furthermore, a high-speed scheme using a socket mechanism based on TCP/IP protocol is developed for data exchanged through Internet. A proxy program is set up to solve the data exchange difficulties when strict firewall exists. An encoding-decoding procedure is also developed for various subsystems. The Internet online hybrid test environment based on this separated-model framework is developed, and three example structures are set up to demonstrate its effectiveness and validity. The one- and three-story braced frames are first examined by this system locally and numerically. Thereafter, an eight-