Dynamic testing of structural active control system based on a hybrid test-simulation method

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Abstract

As civil engineering structures are usually very huge in volume and heavy in weight, full scale or large scale model tests are uneconomical or infeasible sometimes, therefore, small scale model tests have been widely used in previous relevant experiments for validating dynamic performance of structural active control systems. However, small scale models are not reliable due to its limitations in reflecting all properties of a full scale control system. From a practical point of view, this may potentially result in the loss of control efficiency and stability of structural active control system. Therefore, a compromise approach is quite necessary to examine and validate performance of a full scale structural control system, particularly active control system. In this paper, a comprehensive dynamic testing approach for evaluating structural active control system, i.e. Active Mass Driver (AMD), is proposed based on Real-time Substructure Testing (RTST) method, or so called Hybrid Test-Simulation (HTS) method. In this proposed approach, both physical subsystem and numerical subsystem are established independently. Partial structural response is feedback from the numerical structure, meanwhile AMD response is physically measured online. The optimal control force is calculated based on a certain control algorithm or control strategy. Then, the computed optimal force is commanded to the active control execution part and applied to the numerical structural model simultaneously. Repeating such procedures in the following time steps until the final time step or convergence error is reached. Such a kind of testing method is cost effective for evaluating active control system when it is considered to be installed into a full scale structure. Furthermore, multiple objectives can be achievable through whether or not incorporating structural control algorithm into dynamic performance tests.

Keywords: structural seismic response control; active control system; control structure interaction; dynamic performance evaluation; real-time substructure testing; hybrid test-simulation

1 Introduction

Within the last two years, there have been three major earthquakes worldwide: Haiti earthquake with a magnitude of 8.0, Chile earthquake with the magnitude of 8.8 and Japan Eastern earthquake with the magnitude of 9.0 which was the strongest ever recorded. Earthquake together with strong wind, volcano explosion, tsunami and flood have today become the most severe natural disasters and hazards faced by human beings. These natural hazards have always been imposing a significant threat to the safety of civil engineering structures and human occupants. One of the challenges faced by structural engineers is to develop safer civil structures to better withstand these natural hazards. Structural control for civil structures was born out of a need to provide safer and more efficient designs with the reality of limited resources.

Traditionally, section enlargement or higher strength material are common approaches to enhance local, and in most cases will contribute to overall safety of structures against these extreme loading conditions. However, such a kind of strengthening design method alone is not necessarily enough to ensure the expected safety or comfort under dynamic excitations, e.g. increasing mass may lead to increasing inertia forces etc. (Housner, et al., 1997). Yao introduced the concept of modern control into civil engineering field in 1972, which was acknowledged as the first initiative of structural active control. Among various structural control approaches, active control is viewed as the most efficient one, especially with multi-objectives achievable. Thereafter, intensive numerical and experimental investigations together with many engineering practices have been employed together to demonstrate that structural active control could be effective in reducing structural response and damages caused by earthquake excitations (Ou, 2003; Spencer and Nagarajaiah, 2003). In terms of practical applications, the Kyobasi Seiwa building, built up in Japan in 1989, which was the first building implemented with AMD control system. Thereafter, there have been more than 50 high-rising buildings, including television towers and nearly 15 large-scale bridge towers equipped with AMD control systems for reducing either wind-induced vibrations or earthquake-induced vibrations of civil structures (Spencer and Nagarajaiah, 2003).

Experimental verifications of active structural control are necessary to verify effectiveness of control strategies as well as to evaluate reliability of control devices. Aizawa (1988) carried out an active control experiment on a small scale model of a four-storey frame structure, which was the first recorded AMD control test. Kobori, *et al.* (1990) and Soong *et al.* (1994) completed small scale AMD control experiments almost at the same time period, respectively. Spencer *et al.* (1998) then developed a small scale three-storey, single-bay frame model which was accepted as a benchmark model for AMD control experiments. As civil engineering structures are usually very huge in volume and heavy in weight, full scale or large scale model tests, either limited by the available space or actuator equipment, are uneconomical or infeasible (Blakeborough, et al., 2001). Therefore, small scale model tests have been widely used in previous relevant experiments for validating dynamic performance of structural active control systems. However, small scale models are not reliable to reflect all properties of a full scale control system from a practical point of view, which may potentially result in the loss of control efficiency and stability. Therefore, a compromise approach is quite necessary to examine and validate performance of a full scale structural control system, especially for active control system. In the following section, a comprehensive dynamic testing approach for evaluating structural active control system, especially Active Mass Driver (AMD), will be proposed based on Real-time Substructure Testing (RTST) method or so called Hybrid Test-Simulation (HTS) method. Furthermore, the test method can also be developed to take practical working conditions and control-structure-interaction effect (Dyke et al., 1995; Zhang and Ou, 2008) of the huge active systems into consideration while at lower cost or else may merely require a numerical target structure.

2 Principles and testing procedures

Real-time Substructure Testing (RTST) method has been proposed by Nakashima et al. (1992), which is an online pseudo-dynamic test requiring a physical subsystem and a numerical subsystem. Based on the principle of RTST method, the AMD dynamic testing method is developed with the concept given in brief in Figure 1. For comparison, the traditional AMD control experiment system consisting of a physical structure subsystem and an AMD subsystem is shown in the left. Since comprehensive research on common behavior of structural members has been intensively carried out previously, both theoretically and experimentally, the accuracy of numerical structure models could be met and guaranteed in general. But for the active control system, i.e. AMD control system shown in figure1, comprehensive dynamic performance examination and evaluation must be carried out to evaluate its dynamic characteristics prior to its actual implementation. In the proposed testing method, the AMD subsystem is physically presented while the targeted structure subsystem is numerically built. Therefore, the experiment system is divided into two parts: physical subsystem (AMD device including its driver and data acquisition system etc.) and numerical subsystem (numerical structure model).

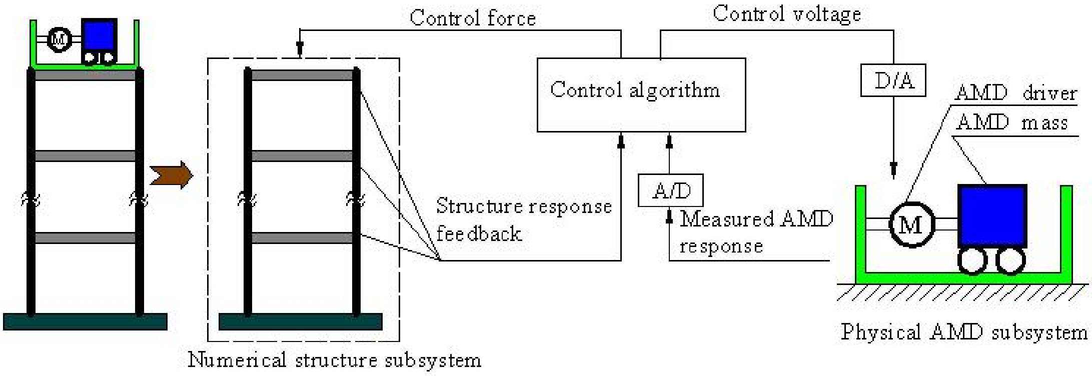


Figure 1. Scheme comparison of AMD testing methods

In the experiment, partial structural response will be calculated and fed-back from the numerical structure subsystem, while state variables corresponding to the physical AMD subsystem will be measured. According to the collected system information, the optimal control force u is calculated in a real-time sense based on an appropriate control algorithm. Then, the optimal control force u is “applied” to the numerical structure model to evaluate the structural response induced by the control force synchronous with external loadings for the next time step. Simultaneously, the optimal control force u is converted into a voltage signal to drive the AMD driver subsystem. The AMD driver receives the control command and drives the inertia mass moving towards the desired position during the next time step. Then the above procedures are iterated until the final time step or convergence error is reached.

According to the above principle and description, the anticipated advantages of such a testing method can be briefly summarized as: (1) Since it does not require the physical structural model, the ratio of efficiency to cost for conducting such a test can be greatly increased. (2) As different excitation cases can be considered to the numerical subsystem, full scale active control systems under various real working modes can be examined readily, to verify their effectiveness and reliability. This is especially useful to identify any faults or potential issues of a full scale active control system prior to its on-site installation. (3) Based on this method, one set of physical AMD subsystem could be numerically implemented into different numerical structure models to investigate its applicability as well as efficiency. (4) Although this method originally engages a numerical structure, based on proper arrangement this method can also be modified to conduct performance testing of an active control system due to the nature of its actuator. Therefore, a shaking table or any additional actuator is not necessary to conduct this AMD subsystem test. Besides, the stability of such a kind of AMD subsystem mainly depends on its own control algorithm which is also different from ordinary substructure testing of other systems, e.g. passive structural control devices.

3 Experimental setup

This section introduces the details of a real-time AMD subsystem test, which investigates a benchmark structure model controlled by an AMD subsystem subject to earthquake excitations. In this test, the numerical structure model is taken from the background of the first generation Benchmark structure (Chung, *et al.*, 1989; Spencer, *et al.*, 1998) at MCEER at SUNY Buffalo USA. While, the AMD control subsystem is a scaled prototype model of a linear motor based actuator which has been implemented in the Guangzhou New TV tower structure, which is one of the tallest buildings in China so far (Zhang et al., 2009).

3.1 AMD actuator

The AMD subsystem is driven by a linear motor. The linear motor mainly consists of a stator or primary which is made up of permanent magnetic blocks, and a mover or secondary which is electrical windings with coatings, linear bearings, chassis and connection wirings etc. The extra mass blocks (steel plates) are fixed to the mover of the motor, which all constitute inertia mass of the AMD subsystem. Hence, the AMD has all the hallmarks of a standard linear motor machine configuration. The standard motor test indicates that the time delay for this linear motor is less than 5ms and the friction force is about 38N. All other main parameters of the AMD model are listed in Table 1.

Table 1. Main parameters of the AMD model

Items	Parameters
Maximum stroke (mm)	±400
Rated thrust (N)	1105
Peak thrust (N)	2210
Moving inertia mass (kg)	46.9
Static mass of magnets (kg/m)	11.8

As given in Figure 2, the real-time AMD subsystem testing system consists of a computer which is used to simulate response of the targeted structure and generate command signals for the AMD subsystem; the AMD physical model is driven by a linear motor and controlled by an electrical amplifier; the NI-PXI 6255 data acquisition board is used for A/D acquisition, i.e. sampling AMD state variables, and D/A execution, i.e. output control command signals. Embedded sensors include a laser scale to measure the AMD position and an accelerometer to measure the acceleration of the AMD inertia mass. The test system runs under a Labview platform combined with the Matlab/Simulink. As shown in Figure 2, f_{cmd} is the calculated optimal control force; u_{cmd} is the command voltage to the electric amplifier; i_{drv} is the current that drives the linear motor; $x_{r,meas}$ and $v_{r,meas}$ are the relative displacement and velocity of the AMD inertia mass with respect to the base chassis, respectively.

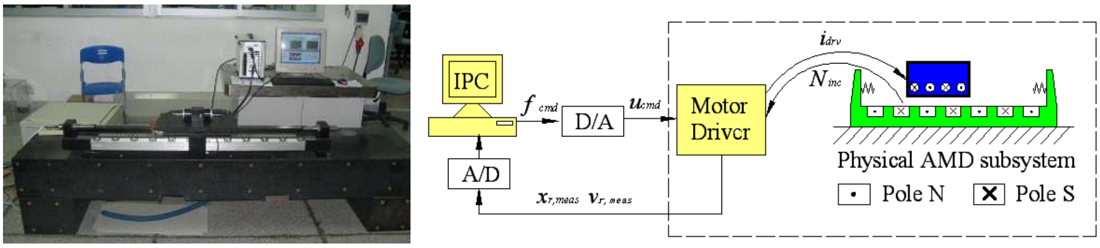


Figure 2. Experimental setup of AMD subsystem testing procedure

3.2 Numerical structure model

The MCEER benchmark structure is a scaled experimental model of an existing structure. The ratios of model quantities to the prototype structure, Q_m:Q_p, are listed in Table 2.

Table 2. Similarity ratios of the benchmark model

Physical quantities	Force	Mass	Time	Length	Acceleration
Scale ratios, Q_m:Q_p	1:16	1:16	1:2	1:4	1:1

The structure model has a mass of 2,950 kg, distributed evenly among three floors. The total height is 254 cm. The first three natural frequencies of the model are 2.27 Hz, 7.33 Hz, and 12.24 Hz, with corresponding damping ratios of 0.6%, 0.7% and 0.3%, respectively. Thus, the mass matrix $\mathbf{M}$, stiffness matrix $\mathbf{K}$ and damping matrix $\mathbf{C}$ for the numerical structure model can be constructed accordingly (Ou, 2003).

In practice, acceleration signals, rather than displacement and velocity signals of the structural response are more convenient to be directly acquired. Therefore, the calculated acceleration of the numerical structure model is utilized as feedback in this experiment.

3.3 System equations

Based on the above parameters of each part associated with the test system, the equation of motion for the whole structure-AMD system can be modeled as a second order differential equation (SODE):

$$\mathbf{M}_c\ddot{\mathbf{x}}+\mathbf{C}_c\dot{\mathbf{x}}+\mathbf{K}_c\mathbf{x}=-\mathbf{M}_c\left\{\mathbf{1}\right\}\ddot{x}_g+\mathbf{B}_s u \tag{1}$$

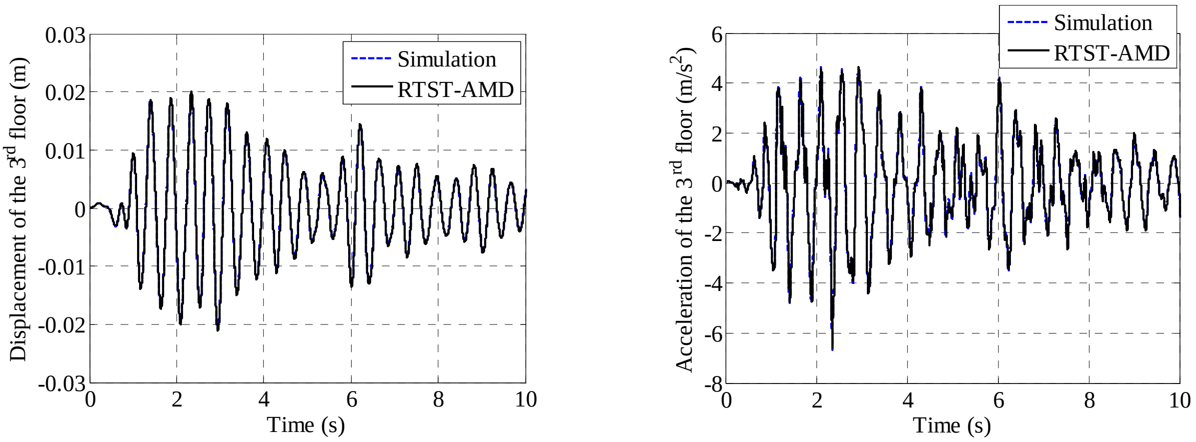
Where, $\mathbf{x}=\left[x_1,x_2,x_3,x_a\right]^T$ is the displacement vector including each structural floor's displacement and mass stroke, relative to the ground; $\ddot{x}_g$ is the acceleration of ground motion; u is the control force delivered by the AMD subsystem, $\mathbf{B}_s=\left[0,0,-1,1\right]^T$ is the location vector of control force according to the current test setup. $\mathbf{M}_c$, $\mathbf{K}_c$ and $\mathbf{C}_c$ are augmented system mass, stiffness and damping matrix, respectively. Then the system equations can be represented and converted into a discrete-time state-space based expression for real time control purposes.

4 Typical results and discussions

Four earthquake acceleration records, i.e. El Centro (1940, NS), Hachinohe (1968, NS), Kobe (1995, NS) and Northridge (1994, NS), which were also used for benchmark control problem (Spencer *et al.*, 1998), are adopted as excitation inputs for testing of AMD system. Acceleration peaks of each record are regulated to 200m/s^2 and also scaled into a 1:2 time sequence according to specifications outlined in table 2.

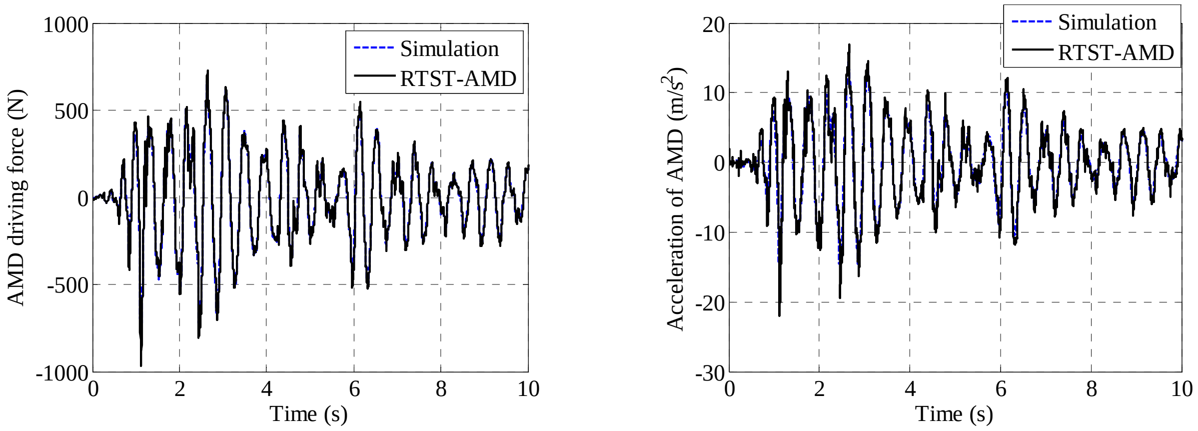
To validate the effectiveness of this proposed testing method, the results of real-time AMD subsystem tests are compared with simulation results, including both structural response and AMD subsystem response presented for evaluation. To be specific, the numerical structure is in an uncontrolled situation where the AMD actuator is utilized to excite the top of the structure model and cause it to fall into a pre-calculated response state which is normally achieved using a shaking table to excite the structure base. However, as previously discussed, no physical structure is involved in the test, therefore, all structural related states are generated according to measurements from the AMD system states and through calculations of the structure itself. Furthermore, if the control effectiveness of the AMD system is to be examined, then certain proper structural control strategy should be incorporated into the command signals to drive AMD actuator, and the effectiveness can be realized by the AMD subsystem. However, this is beyond the topic of the current paper and will be discussed separately. As a result, the following of this paper merely illustrates selected structural response and AMD response under pure simulation cases and hybrid testing simulation cases. Furthermore, the hybrid testing simulation method or the real-time substructure testing method has already inherently taken control structure interaction effect into consideration, i.e. including real AMD actuator and virtual structural model. This method is expected to be able to examine the dynamics of the actuator on a selected group of targeted structures with multi-range of dominant dynamics, and to quantify the control structure interaction effect. However, this idea needs to be validated with the support of further test results.

In the following, Figure 3 presents the structural response as well as states of the AMD subsystem corresponding to hybrid test-simulation and pure simulation cases. The results present an excellent consistency, which proves the feasibility of using such a kind of testing method. Moreover, Figure 4 shows the comparison of two independent test cases. The repeatability has been validated, which proves the reliability and robustness of such kind of testing method. Quantitative indexes can also be developed to further illustrate the differences in terms of, for example, amplitudes and wave forms or frequency domain components.



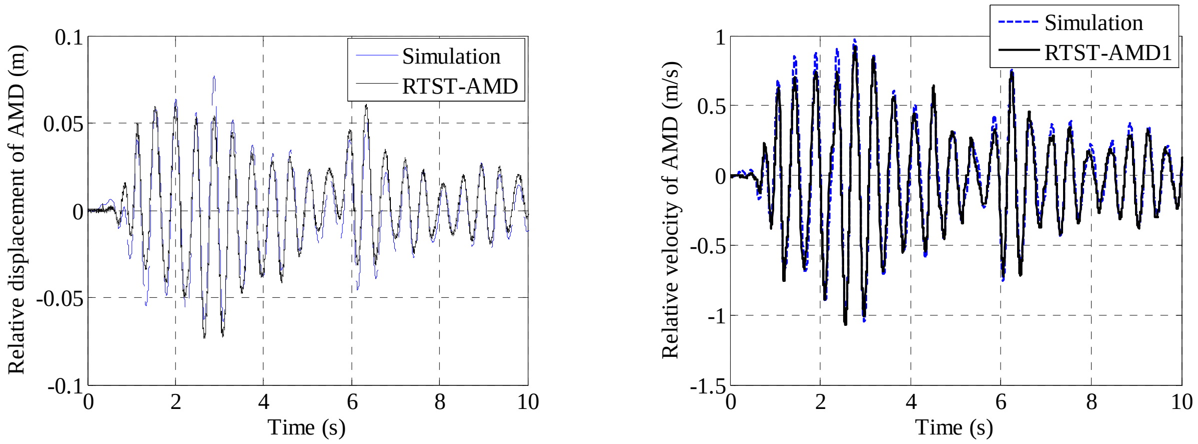
(a) Displacement of the structural third floor

(b) Acceleration of the structural third floor



(c) AMD driving force

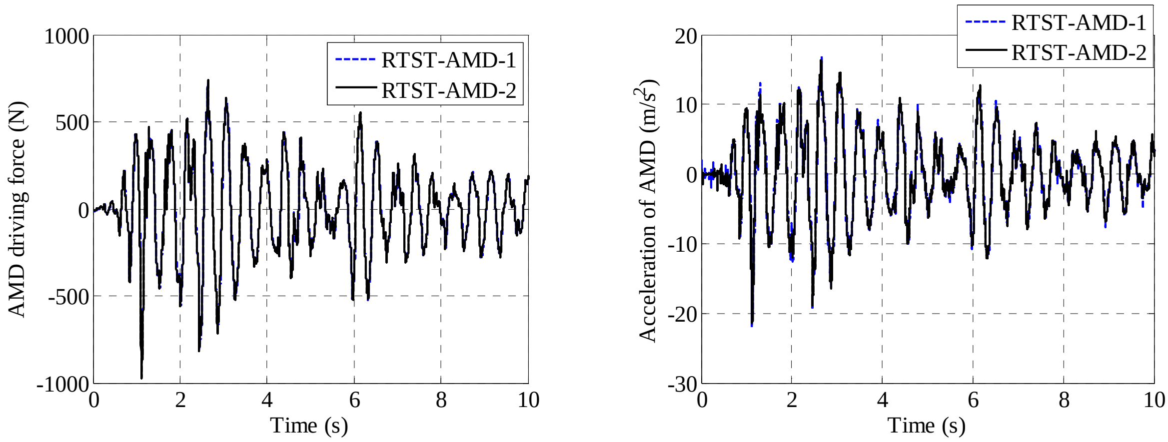
(d) Acceleration of AMD



(e) Relative displacement of AMD

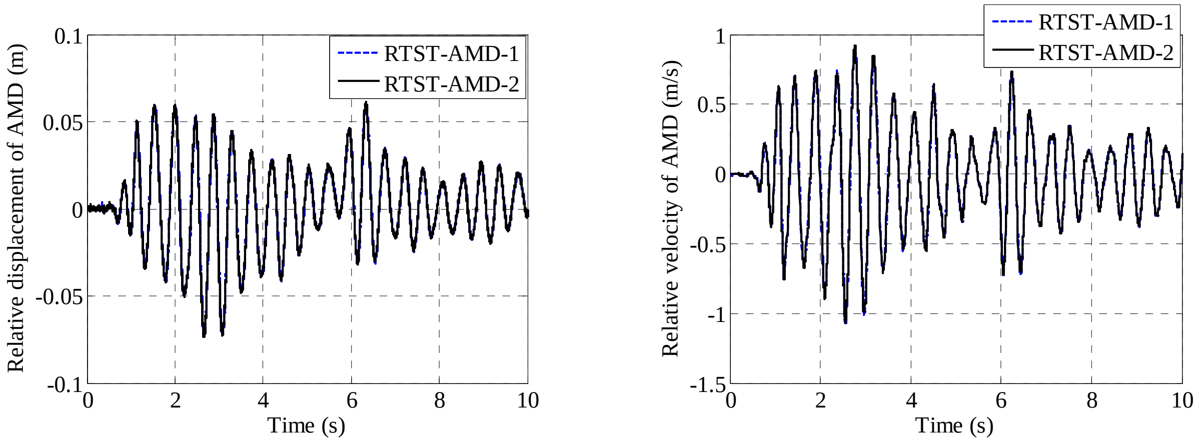
(f) Relative velocity of AMD

Figure 3. Comparison of hybrid test-simulation results with pure simulation results



(a) AMD driving force

(b) Acceleration of AMD



(c) Relative displacement of AMD

(d) Relative velocity of AMD

Figure 4. Repeatability of the hybrid test-simulation results

As can be identified, but will not be discussed in this paper, there are unsolved factors, to be quantified or qualified, which exists within the electrical-mechanical model of the AMD actuator or presents an evidence in support of the control structure interaction effect. For example, Figure 4(c) and 4(d) show that the repeatability for stroke and velocity of the AMD subsystem is acceptable, however, Figure 3(e) and 3(f) show considerable error between the hybrid testing simulation and pure simulation. As has been analyzed, the periodical ripple thrust force of such a linear motor based AMD actuator can be one factor causes the difference in mass strokes, while friction can be another factor causes velocity fluctuations. Therefore, further research is quite necessary to accurately model these effects or factors.

5 Conclusions

This paper proposes a hybrid test-simulation or so-called real-time subsystem/substructure testing method based approach for evaluating dynamic performances of structural active control systems.

The proposed testing method involves a physical AMD subsystem and numerical targeted structure model. Thus the stability of the whole test system can be guaranteed by the AMD subsystem only. Besides, the advantageous of such a kind of testing setup can be summarized in the following aspects: efficiency/cost effective, easy to realize working conditions, ready evaluation of effectiveness, guaranteed reliability, and capable of predicting relevant issues pre-hand etc. Of most importance, it is quite necessary and important to validate the performance of a full scale structural active control system prior to its actual implementation into a structure. The dynamics of an AMD subsystem can be fully examined based on the proposed test scheme without involving a control algorithm into the numerical structural model; on the other hand, the validation of control effectiveness can also be verified and fully examined by incorporating a proper control algorithm into the AMD and numerical subsystem. As a result, the control strategy can also be examined using such an approach.

Based on the selected test results, the feasibility as well as repeatability and robustness of the proposed testing method for AMD control system have been validated successfully. Furthermore, the potential ability of this proposed method in investigating the dynamics of the actuator towards, e.g. friction and ripple forces within the linear motor as well as other uncertainties or effect related to structural active control, e.g. control structure interaction etc., have been discovered, but not fully discussed in the current paper. It is expectable that the proposed hybrid testing simulation method is capable to investigate all aspects of structural active control system either major characteristics or effects which have yet not been taken into consideration.

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References

Aizawa Satoru, Fukao Yasuzo, Minewaki Shigeru, Hayamizu Yutaka, Abe Hiroshi and Haniuda Nobuyoshi. An Experimental study on active mass damper, Proceedings of 9th World Conference on Earthquake Engineering. 1988; 5:871-876.

Blakeborough A, Williams MS, Darby AP and Williams DM. The Development of Real-time Substructure Testing. Philosophical Transaction of the Royal Society: Theme Issue on Dynamic Testing of Structures 2001; A 359:1869–1891.

Chung L.L., R.C. Lin, T.T. Soong, A.M. Reinhorn. Experimental study of active control for MDOF seismic structures. Journal of Engineering Mechanics 1989; 115(8):1609-1627.

Dyke S. J., Spencer B. F.Jr., Quast P. and Sain M. K. The Role of Control-Structure Interaction in Protective System Design, ASCE Journal of Engineering Mechanics. 1995, 121(2): 322-338.

Housner G. W., L. A. Bergman, T. K. Caughey, A. G. Chassiakos, R. O. Claus, S. F. Masri, R. E. Skelton, T. T. Soong, B. F. Spencer, J. T. P. Yao. Structural Control: Past, Present, and Future. Journal of Engineering Mechanics 1997; 123(9):897-971,

Kobori Takuji. Technology development and forecast of dynamical intelligent building. Journal of Intelligent Material Systems and Structures 1990; 1:391-407.

Nakashima M, Kato H and Takaoka E. Development of Real-time Pseudo Dynamic Testing, Earthquake Engineering and Structural Dynamics, 1992; 21(1): 79–92.

Ou Jinping. Structural vibration control - active, semi-active and smart control. Science Press 2003, Beijing. (in Chinese)

Soong T.T., A.M. Reinhorn, S. Aizawa, M. Higashino. Recent structural applications of active control technology. Journal of Structural Control 1994; 1:5-21.

Spencer B.F. Jr., S.J. Dyke and H.S. Deoskar. Benchmark Problems in Structural Control, Earthquake Engineering and Structural Dynamics, 1998; 27(11), 1141-1147.

Spencer B.F. Jr., S. Nagarajaiah. Sate of the art of structural control. Journal of Structural Engineering 2003; 129(7):845-856.

Yao J. T. P. Concept of Structure Control. Journal of Structure Division, ASCE 1972, 98 (ST7): 1567~1574.

Zhang Chunwei, Ou Jinping. Control Structure Interaction of Electromagnetic Mass Damper System for Structural Vibration Control, ASCE Journal of Engineering Mechanics, 2008, 134(5), 428-437.

Zhang Chunwei, Xu Huaibing, etal., Recent advances on structural vibration control and blast resistance research in Hit blast resistance and protective engineering laboratory, 1st Asia pacific young researchers and graduates symposium, 26-28 February 2009, Kunsan National University, South Korea