FULL-SCALE VERIFICATION TEST OF DYNAMIC RESPONSE CONTOROL TECHNIQUES FOR STRONG EARTHQUAKES

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SUMMARY

In order to verify the applicability and feasibility of various active control algorithms for the seismic response control for structures, a full-scale active control test facility using a real size steel frame structural system has been set up at the campus of Disaster Prevention Research Institute, Kyoto University. The test facility consists of two frame structures so that the testing of interaction interface joint damper control can be conducted. The outline of the test facility and representative verification tests for the full-scale application of a nonlinear control algorithm for Active Mass Damper (AMD), and the joint damper control are presented. The development of the nonlinear AMD control algorithm is motivated by the fact that the high level of excitation in the event of strong earthquakes possibly induces auxiliary mass displacement that exceeds the stroke capacity of the AMD device. The control algorithm for the real size multi-story steel frame test structure takes advantage of a nonlinear control scheme based on a variable gain method to overcome this difficulty. The nonlinear control used in the test achieves effective use of AMD with a limited displacement range of the auxiliary mass for structures under various levels of seismic input. The test result using a seismic record shows the effectiveness of the control method, especially when subjected to a strong earthquake excitation. For the verification of joint damper control, a hydraulic damper device is installed between the two adjacent full-scale frame structures. Viscous type passive Joint Damper shows different efficiency on dynamic response reduction depending on types of earthquake ground motion, which may be improved with application of active control algorithm.

INTRODUCTION

A university-industry joint research project sponsored by Japan Society for Promotion of Science (JSPS) was conducted in order to develop intelligent seismic response control systems for strong earthquakes with a large capacity and a wide dynamic range, thus drastically enhancing the seismic safety of various structures, using the experience of the industry, university researchers and the academic resources in this field. As the structural model control experiment phase in this project, a verification test program using a real size 5-story steel frame at the campus of Disaster Prevention Research Institute, Kyoto University was conducted. An active Mass Damper (AMD) and an excitation system were installed on the steel frame structure, which was built about 20 years ago, for the verification tests.

The objective of the development of the control algorithm used in this test program is to satisfy the constraint on the displacement of the auxiliary mass in the AMD system independent of the excitation level. The displacement of the auxiliary mass is mostly limited by the size of the space provided to the AMD device, as well as the size

of the device itself. In some cases, such requirement can be a crucial factor when introducing a mass damper type dynamic response control device. On the other hand, the displacement requirement of the auxiliary mass of the AMD device is usually evaluated as a result of the trial-and error response simulation to select proper control

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parameters. Therefore, if the auxiliary mass displacement is an explicit critical factor in the design requirement of the dynamic response control system, the control parameters cannot be directly determined, necessitating tedious repetition of response simulation using a number of parameter combinations.

In order to solve these two problems, a nonlinear control scheme using variable control gain is employed. This method allows a stable operation of an AMD device in case of strong earthquakes, as well as a direct parameter setting without using a trial-and error approach, since the control parameters can be explicitly determined based on the displacement range value of the auxiliary mass.

Since the fundamental properties of the control algorithm has been investigated by means of numerical simulations and shake table tests of a scale model (Igarashi et al., 1995) (Iemura et al. 1996), the objective of the test program is to verify the feasibility of the control device and algorithm used with a full-scale frame structure, and to investigate the response reduction effect under the simulated seismic excitation.

Furthermore, the test facility has been extended to a two-structure system, in order to test the Joint Damper method, in which two adjacent structures are connected by a damper device. Since a hydraulic actuator is installed in the test facility as the Joint Damper, it allows test not only of passive type, but also the active Joint Damper system, by taking advantage of digital control of the hydraulic actuator that is able to simulate the predefined behavior of the connecting device used as the Joint Damper.

REAL SIZE FRAME STRUCTURE AND TEST SYSTEM

The outline of the test system is shown in Fig.1. Lateral response of the frames was generated by excitation devices installed on the 4^{th} floor level of the 5-story frame and on the top floor of the 3-story frame. The excitation device, or shaker used an auxiliary mass driver mechanism in order to allow excitation with arbitrarily specified waveforms. Although the sensor outputs were shared by the control and the instrumentation for the structural frame response measurement, the output signal processing in the two systems was completely separated so that the control procedure and measurement procedure work independently.

Test Structural Frames and Natural Frequencies

The full-scale structural control test facility consisting of the 5-story steel frame structure (1 × 2 spans) and the 3-story frame (1 × 2 spans) at the campus of DPRI, Kyoto University is shown in Fig.2. The dimensions and other data are summarized in Table 1. The total weight of the 5-story structure is approximately 150 tons, equivalent to the effective mass of 75 tons. Measured natural frequencies for each structure is also indicated in Table 1.

Table 1. Summary of the full-scale structural frames

Total Height		17.22 m	10.65 m
Weight of Each Floor		Approx. 30.0 t	Approx. 20.0 t
Floor Plan Dimensions		3.75 m × 15.0 m	3.75 m × 9.8 m
Total Weight		150 t	60 t
Natural Freqs.	1^{st} mode	2.05 Hz	2.44 Hz
	2^{nd} mode	6.28 Hz	7.63 Hz
	3^{rd} mode	11.01 Hz	12.82 Hz

AMD, Shaker and Instrumentation

The photograph of the Active mass driver is shown in Fig.3. This device was intended to be used as AMD device or shaking device, depending on the situation and test setups. For this reason, the spring constant for the AMD was set to a minimal value to allow the use of the device for general purposes. The weight of the auxiliary mass of the driver used as an AMD system was approximately 2 tons, corresponding to the mass ratio of 2.5%, and the maximum stroke is 50cm.

The device used as the shaker for the 5-story frame uses the auxiliary mass weight of 5 tons, and the stroke of 100cm, and the shaker for 3-story frame is one of the same specification as the AMD device. In order to excite the test frame structures as though they are subjected to the earthquake ground motion, it is necessary to determine the appropriate input signal to the shaking device by taking properties of the structure and device into account. In this study, the appropriate input signals are firstly determined for each vibration mode of the structure and then the summed up input signal is applied to the shaker. (Iemura et al., 1999)

The accelerations and velocities at all floor levels were measured to capture the response of the frame structure. The response of the devices (the AMD and shaker) was visually monitored by video cameras, in addition to the measurement of the displacement, acceleration and velocity of the auxiliary mass for each device.

VERIFICATION TEST OF NONLINEAR CONTROL ALGORITHM FOR AMD

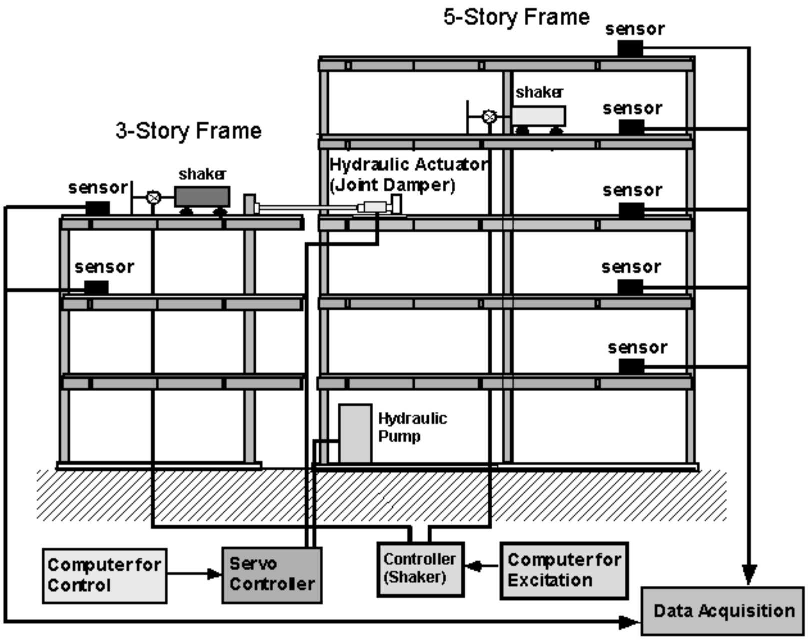
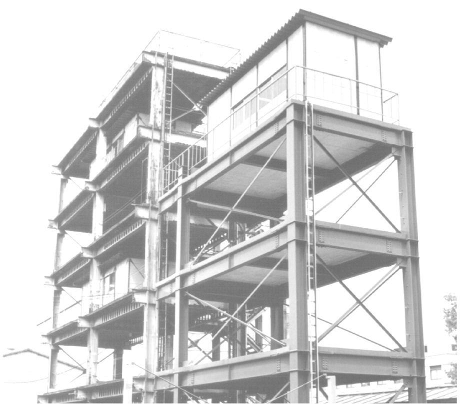


Fig.1: Outline of the real-size test system



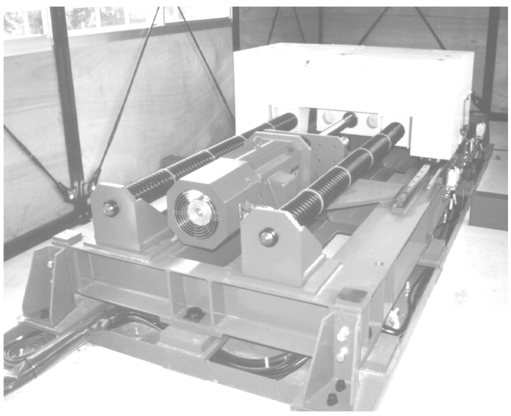


Fig. 2: Full-scale structural frames   **Fig.3: Active mass driver used as shaker and AMD**

The first example of the test using this test facility is the verification of nonlinear control algorithm for AMD using variable gain control strategy. The test setup is shown in Fig.4. The control device i.e. the AMD system, is installed on the top floor.

The variable gain control algorithm was implemented to the control system of the AMD. The sinusoidal input and the El Centro record were used as the acceleration inputs. The theoretical background of the variable gain control is explained in the reference (Iemura et al., 1996)

Fig.5 shows the representative test result using the El Centro record as the input. The El Centro record was first scaled to the peak acceleration of 50 Gal, and was used as the standard reference input level. Furthermore, the scale factor of 0.7 was used. It should be noted that the response reduction is comparatively lower in the neighborhood of 4.0 sec (see Fig.5a), due to the limitation of the AMD displacement stroke (Fig.5c) and also to the low control gain shown in Fig.5d. In the test using other scale factors, the displacement amplitude of the auxiliary mass is shown to be similar in spite of the difference of the input excitation level, indicating that the displacement range of AMD is constant for different levels of input excitation. The detail of the test is described in reference (Iemura et al., 1996 and 1997).

TEST FOR JOINT DAMPER SYSTEM

The Joint Damper system test is currently conducted, using the hydraulic actuator connecting the two adjacent

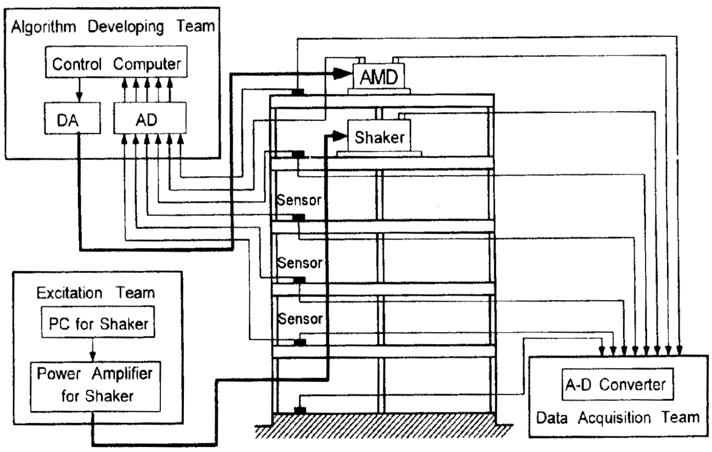


Fig.4: Test setup for verification of nonlinear AMD control algorithm

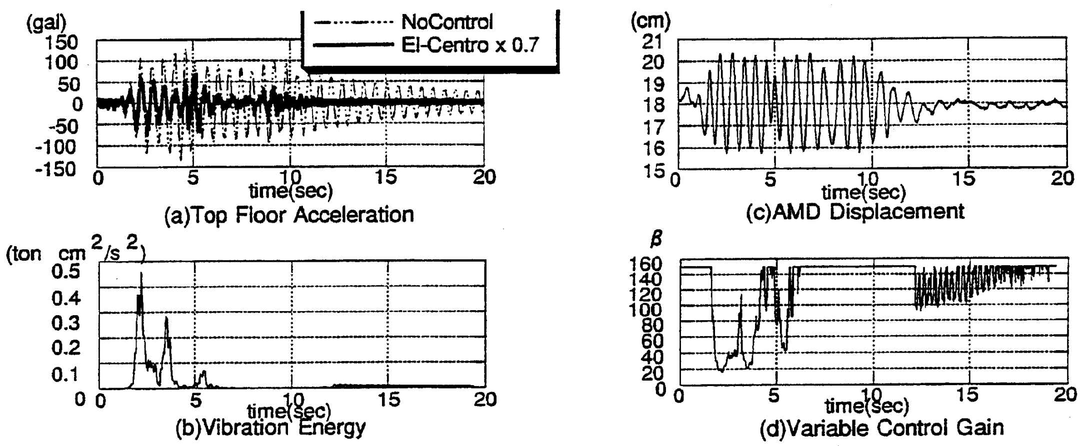
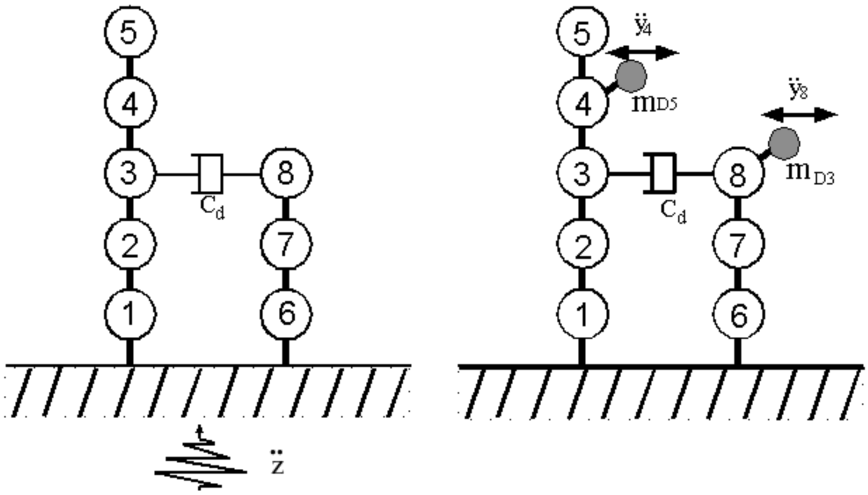


Fig.5: Test Result: El Centro record input, Scale Factor=0.7

steel frames. The test setup is as already shown in Fig.1, where the shakers on both steel frames are used to generate the simulated seismic response of the structural system, and the response of the two structures are controlled by the joint damper.

The advantage of the Active Joint Damper system is effectiveness in reducing the structural response that is difficult to be coped with AMD type control devices. The objective of the test is to verify the advantage of this type of control method in a full-scale experiment.



(a) Base Excitation (b) Excitation using shakers

Fig.6: Modelling of the excitation of the two structural frames

In the case of the two-structure system with a Joint Damper, the excitation method of the entire system needs special attention, since the responses of the two structures interact each other through the connected device. The modeling of the excitation is shown in Fig.6. The excitation in the test is intended to simulate the base excitation as shown in Fig.6a, although the actual excitation mechanism of the shaker is modeled as Fig.6b. In the current test setup, the excitation inputs are determined so that the acceleration of the auxiliary mass for each shaker corresponding to the response of each frame is calculated assuming the classical damping and model analysis, neglecting the interaction between the two frame structures through the Joint Damper (which generally introduces nonclassical damping to the structural system). The influence of this simplification of the shaker input as well as the use of shakers as the excitation method is examined by numerical simulation based on the identified characteristics of the full-scale frames. Fig. 7 shows the change of the value of base shears in each structural frame as the damping coefficient of the Joint Damper is increased, assuming that the behavior of a viscous damper in the Joint Damper system. The test result shows that it is justifiable to use this simplified input calculation method in the range of damping coefficients that is effective in reducing the dynamic response of the two structural frames simultaneously.

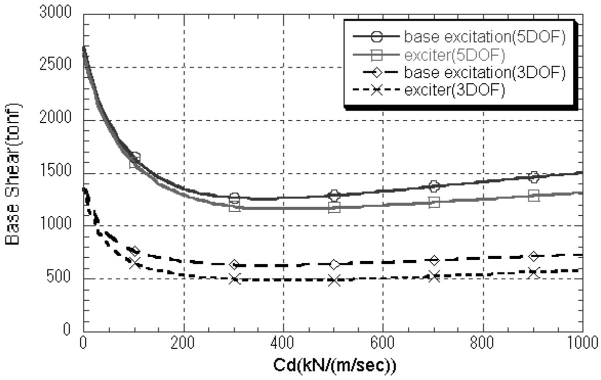


Fig.7: Relationship between base shear and Damping coefficient of the Joint Damper

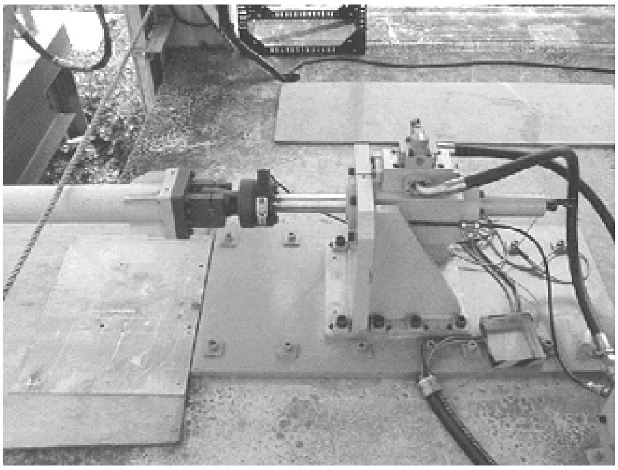
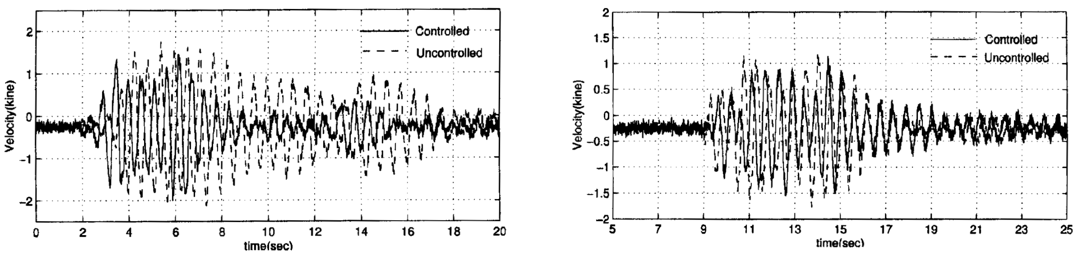


Fig.8: Joint Damper System



(a) El Centro Record Excitation **(b) Kobe Record Excitation**

Fig.9: Reduction of Velocity Response at the top of 5-story structure with the Joint Damper

Effects of the Joint Damper to reduce dynamic response of the structural frames subjected to the El Centro NS Record (1940) and the Kobe Record (1995) are tested. The active joint damper of which photo is shown in Fig.8 is controlled to work as a passive viscous damper of which viscous coefficient is set as 300 (KN sec/m) from discussions in Fig.7.

Tested results are shown in Figs.9(a) and (b). The dynamic response against El Centro Record which have relatively long duration is fairly well suppressed by the Joint Damper. However, the response against Kobe Record which is a shock like ground motion with short duration is not effectively reduced. The efficiency of the active Joint Damper may be increased with application of modern control algorithms, which is now under investigation.

CONCLUSIONS

For testing response control devices, namely Active Mass Damper (AMD), Tuned Mass Damper (TMD) etc., full-scale test method using shaker is developed. A full-scale test of an AMD device using a real-size structural frame and shaker device clearly indicates the performance of the device and the nonlinear variable-gain control algorithms under a practical situation. This method is a very promising testing approach for a control device such as TMD, since it is possible to test the device with various characteristics of the main structure, without changing the hardware settings. The Joint Damper system is tested in order to discuss the performance of the joint damper system regarding the capability to effectively reduce the structural response that is difficult to be coped with AMD type control devices.

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