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DEVELOPMENT OF SUBSTRUCTURED SHAKING TABLE TEST METHOD

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SUMMARY

Since various kinds of issues arise in the practical application of structural response control devices, such as the tuned mass damper, active mass damper etc. to the seismic response reduction of structures, experimental verification of the structural control device and the algorithm used for the control is becoming increasingly important. This paper describes the substructured table test method, which can be used with great advantage for experimental verification of structural control devices under simulated dynamic loading conditions. In the substructured shake table test method, a part of the entire structure is tested as the specimen while the response of the rest of the structure is numerically computed, and those two results are combined in a real-time basis. Based on the transfer function formulation, stability and accuracy of the algorithm is analyzed to give an insight to suitable choice of parameters and test specimen. A substructured shake table test system is developed with a set of hydraulic shake table and DSP-based controller, and representative test results that demonstrate the feasibility of the test concept are shown.

INTRODUCTION

In order to suppress undesirable structural vibration induced by the wind, earthquakes etc., structural control techniques have been investigated, and some of these techniques are used in the practical application to civil engineering structures. In course of the development of dynamic response control devices, it is becoming of greater importance to verify the performance of the control devices, and to establish the test method for this purpose. This paper describes the substructured shake table test method, which is a dynamic test method for structural components and control devices such as Tuned Mass Dampers (TMD), using a shake table controlled by a computer which performs numerical dynamic analysis. The substructure shake table test method utilizes the control of the shake table to simulate the response of the main structure to be controlled by means of numerical computation of the response including the interaction between the control device and the main structure.

In this paper, the basic concept and algorithm of the test method is presented. Stability and accuracy of the test method is investigated to establish acceptable test strategies and to clarify the fundamental properties of the algorithm. A hydraulic-type shake table is used for the development of the test method. The real time substructuring algorithm is implemented to a Digital Signal Processor (DSP) system that controls the shake table hardware through D/A and A/D channels. Representative test results using the developed test system and a TMD model are shown to demonstrate the feasibility of the test method and the actual performance of the algorithm.

CONCEPT OF SUBSTRUCTURED SHAKE TABLE TEST

The basic idea of the substructured shake table test is to divide the entire structural system to the experimental part to be tested by the shake table, and the numerical part for which the response is numerically computed by the computer, and those two processes are carried out exchanging the result of the two processes each other on a real time basis. For the experimental part, the substructure is selected so that the dynamic response of the tested part is significant and of great interest. For a typical test setup for control devices namely active mass dampers,

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Tuned Mass Dampers (TMD) etc. installed on a main structure, the device is tested as the experimental part in the substructured shake table test, and the rest of the structure that accommodates the device is treated as the computational part, as shown in Figure 1.

The flowchart of the test method is shown in Figure 2. For the test of a TMD, a load cell is installed between the contact surfaces of the table and the device to measure the base shear force. As an alternative approach, an accelerometer can be used to measure the inertia force generated by the auxiliary mass of the damper. Either of these is provided to the computational part that calculates the response of the main structure by the numerical time integration scheme such as Newmark's beta method, including the effect of the interaction between the device and the structure.

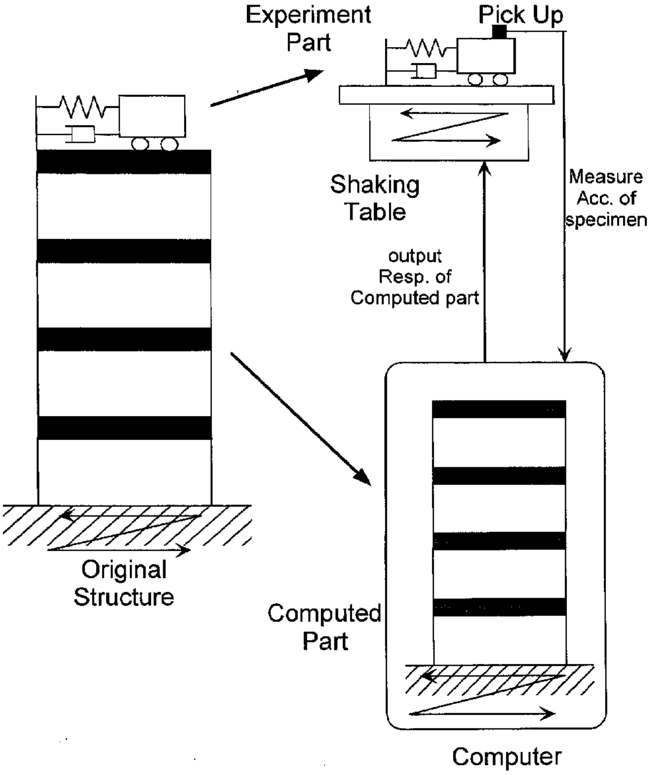


Figure 1: Substructured shake table test concept

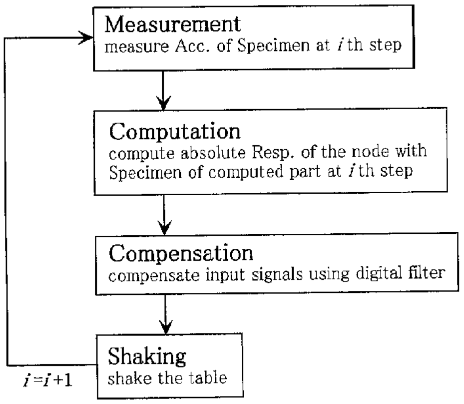


Figure 2: Test algorithm

Similar test concepts has been proposed by several researchers for other applications, such as the testing of structures with soil-foundation interaction effects [Konagai et al. 1998], mechanical systems [Inoue et al. 1998] etc. This method would be particularly advantageous for the testing of structural response control devices and to verify the response reduction effect, since the dynamic property of the main structure can be easily changed without preparing different hardware settings.

STABILITY ANALYSIS

The substructured shake table test algorithm involves the numerical integration algorithm, shake table hardware, and experimental specimen that interact in a real time basis. These test components bears different dynamic characteristics, and the result of the tests is sensitively affected by the properties of each test components. In the past experiments, the test process occasionally indicates severe unstable behavior [Nakano et al. 1997], and the mechanisms and the stability characteristics of the test algorithm must be investigated in order to obtain reliable and accurate test results using the proposed test methods.

Figure 3 shows the block diagram representing the overall dynamic interaction and external disturbances to be considered in the analysis. The numerical algorithm part, which is basically a step-by-step numerical integration, is a discrete time components, while the shake table and the experimental substructure specimen are regarded as continuous time dynamic components, and the stability and the accuracy must be checked by treating the whole system as a mixed discrete-continuous time system.

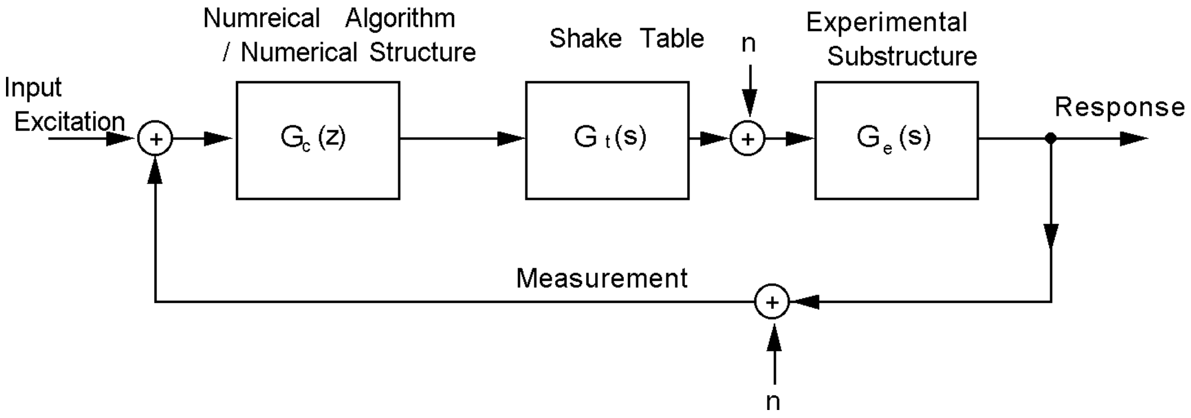


Figure 3: Modeling of the dynamics of the test process

One of the most important characteristics within the algorithm which play key roles in the stability of the entire system is the time delay in the shake table hardware. This can easily be demonstrated with the simulation of the test process, which shows unstable behavior by giving a certain amount of time delay to the shake table components. It can also be pointed out that the numerical part also involves time delay in nature because it is a step-by-step process in which the output is computed using the information at the previous step.

In this study, the stability and accuracy of the test algorithm is discussed by deriving the input/response transfer function of the entire system represented by the block diagram in Figure 3. In the derivation, Newmark's (method is assumed as the numerical time integration scheme, and dynamics of the shake table with the time delay and the experimental substructure specimen are approximated by discrete-time components, and the resulting system transfer function is thus obtained as a discrete time transfer function with respect to the variable z. Once the transfer function is obtained, it is possible to calculate the poles of the system, and the stability criterion is to check whether any of the poles locate outside of the unit circle centered around the origin in the plane. In the ideal situation, the location of the poles exactly corresponds to those of the poles of the original total structural system in the plane. Therefore, the accuracy of the test can be evaluated by the degree of the proximity between the poles of the original system and the test process dynamics either in the *s*-plane or in the *z*-plane.

RESULT OF STABILITY ANALYSIS

An example of the stability analysis is performed using the model of a 2-story structure in which the lower story is designated as the numerical substructure, and the upper story is assumed as the experimental substructure to be tested, as shown in Figure 4. The transfer functions of the algorithm/numerical substructure and the experimental substructure are explicitly formulated, and the transfer function of the test process as a discrete system and its poles are numerically evaluated with rational function manipulation using MATLAB. The locations of the poles are represented in terms of the radius (distance from the origin) $|p|$ where p is the poles of the transfer function of the test process. In the case of this representation, the stability criterion can be specified by $|p|<1$ for all modes, as described in the previous section.

Results of the analysis for this 2-story structure is shown in Figure 5. In Figure 5a, the plot of the location of the poles vs. natural period of the structural system is shown for the case mass, inter-story stiffness and damping of the experimental and computed parts are equal. The damping ratio for each part is 0.01. In this analysis, is the constant time delay in the shake table hardware δt is taken into account, and the case of $\delta t=0.01$ sec is compared with the case of no time delay. This figure indicates that in the case of $\delta t=0.01$ sec, the test process is unstable if the natural period T is shorter than 1.5 sec, and the unstable mode is the 2nd mode. Therefore, T=1.5 sec or greater is the requirement for the choice of system parameters as well as the characteristics of the test specimen.

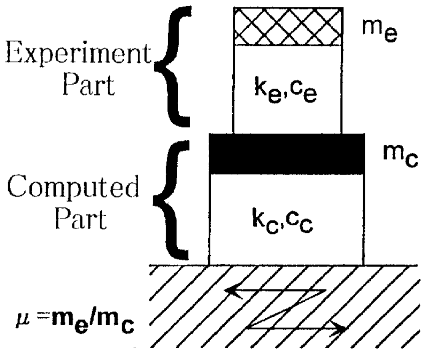
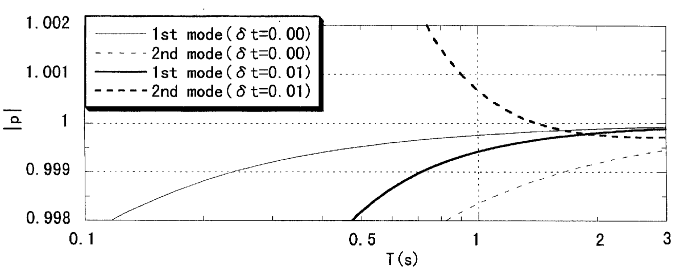
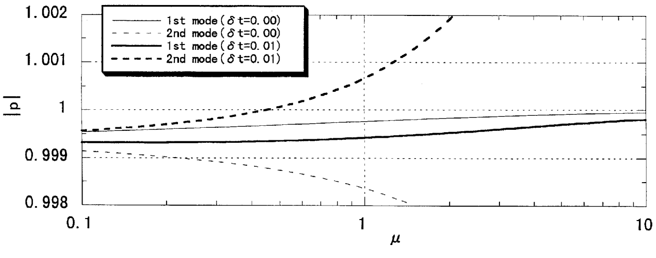


Figure 4: 2-story structural system



(a) Stability for natural period



(b) Stability for mass ratio

Figure 5: Stability analysis for the 2-story model

In Figure 5b, the influence of the mass ratio μ on the location of the poles the case the natural periods of the both substructures are set equal to 1.0 sec. As can be seen in the figure, the test process is unstable if $\mu>0.44$. It is worth noting that the difference between the two cases $\delta t=0$ and $\delta t=0.01$ becomes smaller as the mass ratio decreases. Since this difference directly indicates of the accuracy of the test result, it means that if the mass ratio is sufficiently small, a reliable test result can be expected. Considering that the mass ratio for a typical TMD, for example, is of the order of 0.01, the application for the testing of such devices can suitably take advantage of the substructured shake table test method.

IMPLEMENTATION AND TEST RESULT

In this section, actual application of the test method using the real shake table and representative test results based on the substructure hybrid shake table test method are described. The test algorithm was implemented to a test system consisting of a hydraulic shake table (manufactured by Shimadzu Corp.) of dimension 1.5m by 1.5m with the capacity of 1 ton, and a DSP based controller. The test system outline is shown in Figure 6.

The numerical simulations assuming various experimental errors show that the most influential experimental error is that in the control signal and shake table response, and the phase lag taking place between the control signal and the shake table response is found to be of the greatest significance [Suwa et al. 1998]. Therefore, appropriate compensation of the phase lag must be considered in the testing algorithm. In order to overcome the problem of the instability and insufficient accuracy of the test result, digital filtering technique was employed in the compensation of the dynamics of the shake table control. The digital filter incorporated into the algorithm was designed by determining the parameters of an IIR filter using the concept of least squares approximation to the target response in the frequency domain. With the use of this implementation method of the test algorithm, the test system achieved a sufficient performance in the frequency range between 1.5 and 4 Hz.

In order to demonstrate and verify the actual performance of the test system, a series of verification tests were carried out. The 2-DOF structural system consisting of a TMD installed on the top of a SDOF system, as shown in Figure 7, was assumed as the tested structure, in which the TMD part of the structural system is treated as the "experimental" substructure. The test specimen (Figure 8) is a model of the mass damper designed to simulate the dynamics of various types passive and semi-active mass dampers by the moving mass (weight = 35.40kg) supported by a linear roller bearing and restoring force supplied by four springs. Viscous damping was added by the mechanism of electro-magnetic damper to minimize the nonlinear effect caused by friction force acting between the moving mass and the support. The natural frequency T is 2.01 Hz, and the damping ratio of the specimen can be adjusted within the range up to 0.07. In most cases, the damping of the specimen was set to the maximum value, corresponding to the damping ratio 0.07.

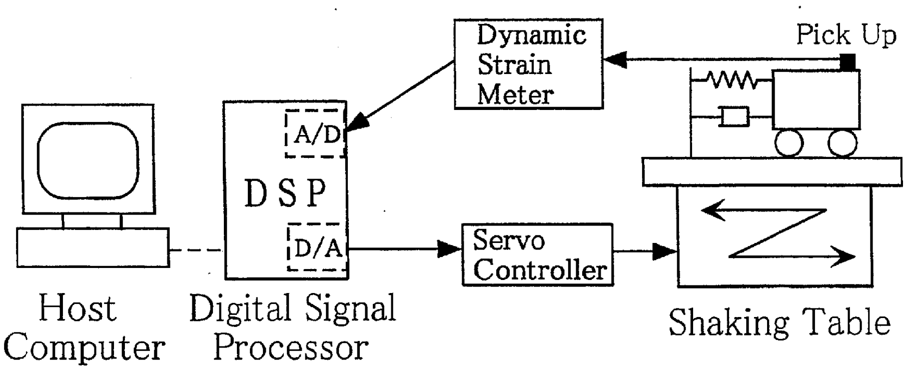
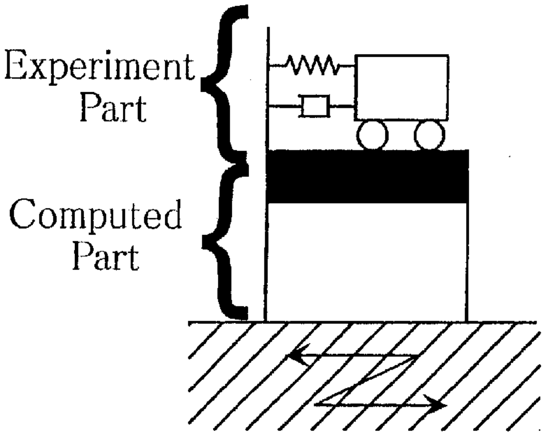


Figure 6: Experimental system for substructured shake table test method



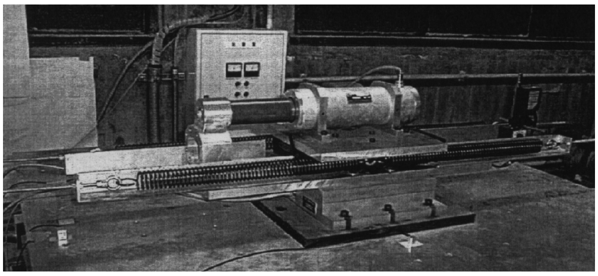


Figure 7: Model of the structural system with TMD

Figure 8: Mass damper specimen

In the first test to verify the accuracy and reliability of the test method, sinusoidal input acceleration of amplitude 4.1 Gal and of frequency 2.0 Hz was used. The response acceleration of the mass damper specimen obtained from the test is shown in Figures 9. The mass of the computed part was selected so that the optimal damping condition for the case of sinusoidal excitation is satisfied. As a result, the mass ratio μ (i.e. the ratio of the mass in the experimental parts to that of the computed part) was found to be 0.1315. The stiffness of the computed part was determined from the natural frequency of the computed part 2.01 Hz (the ratio of the natural frequencies was 0.9935) so that the tuning condition of the mass damper be retained. The control step size was 0.001 sec. The response of the system can be well simulated by the test method, as shown in Figure 9. From this result, the reliability of the test method and the test system was verified.

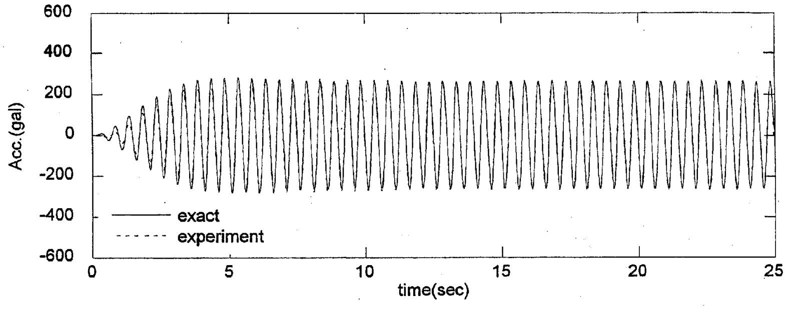
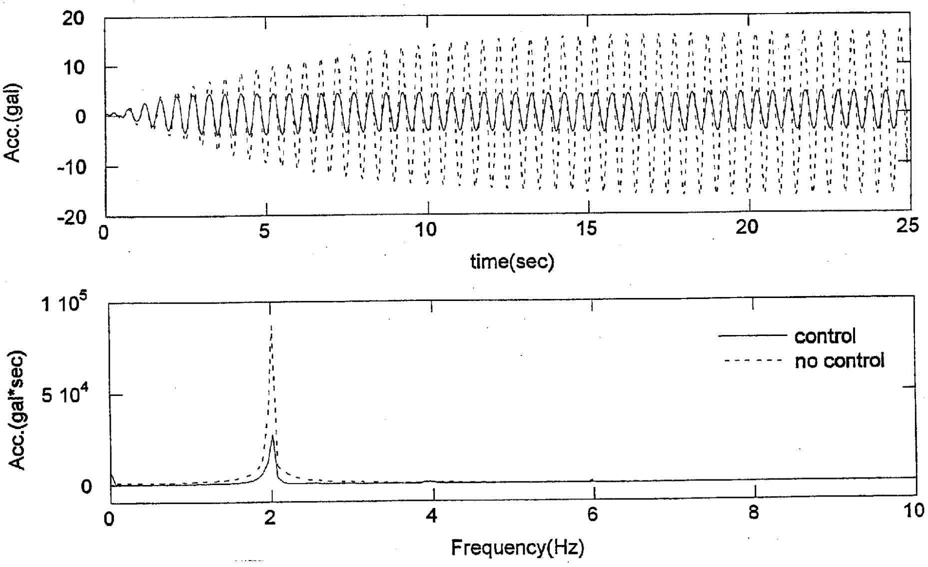


Figure 9: Comparison between the numerical solution and the test result

Using the test system, the response reduction effect of the TMD model was investigated. Figure 10 shows the comparison of the shake table accelerations, which represents the response of the main structure, for the case in which TMD was used (solid line) and for the case without TMD (dotted line). The test for the case without TMD was conducted by locking the sliding mechanism of the specimen to allow no movement in the specimen. These test results clearly indicate that the TMD effectively reduces the response of the structure.

Figure 10: Test result for specimen's acceleration (sinusoidal input excitation)



Similar tests were performed with an artificial acceleration record input which contains a wide range of frequency contents. In this case, the parameters for the computed part were chosen so that the TMD should be tuned for stationary random excitation. The mass ratio μ is 0.020 and the natural frequency ratio is 0.9951. The peak acceleration of the table is reduced to approximately 50% by activating the TMD, representing the expected response reduction for the assumed main structure if the same device is installed to the structure.

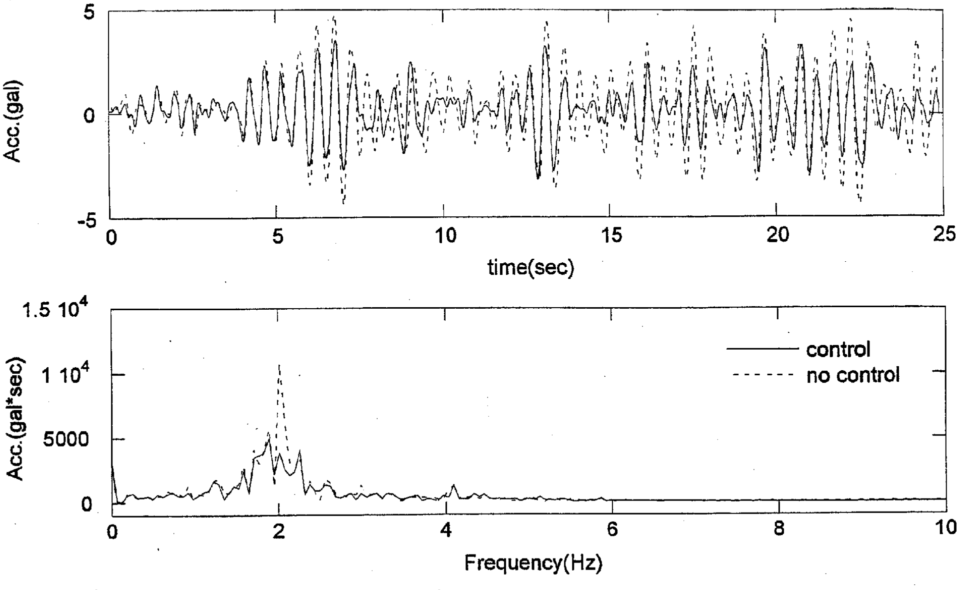


Figure 11: Test result for the specimen's acceleration (random input excitation)

CONCLUDING REMARKS

For testing response control devices, namely Tuned Mass Damper (TMD) etc., the substructured shake table test method is developed. The substructure shake table test method utilizes the control of the shake table to simulate the response of the main structure to be controlled by means of numerical computation of the response taking the interaction between the control device and the main structure into account. As demonstrated by the test results shown in this study, the proposed method is feasible as long as the test specimen and the test parameters satisfy the stability condition which can be numerically determined. The most important point is to keep the mass ratio (experimental / computational) reasonably low. 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 application of this method to other devices and situations should also be of great interest.

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