PSEUDO DYNAMIC TEST METHOD
FOR INELASTIC BUILDING RESPONSE

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SUMMARY

The pseudo dynamic test method provides a means for static testing full scale structures subjected to simulated earthquake ground motions. The method uses an online computer to calculate the appropriate inertia forces which are experimentally applied to the structure. Experimental and theoretical research has been continuing in the United States and Japan to apply this method to buildings subjected to damaging level earthquakes. This paper summarizes studies on the characteristics of the actuator controller and the need for careful implementation of the method.

INTRODUCTION

Much recent work has been carried out in Japan and in the United States to develop an experimental procedure to determine the response characteristics of building structures to seismic excitation. The pseudo dynamic test method (PDTM) uses an online computer to monitor and control a building so that the structural displacements imposed closely resemble those that would occur if the building were subjected to a seismic excitation. Experimental measurements are made of the building restoring forces during the test; these measured forces are used by the computer, together with a set of mathematical equations for the building response characteristics, to determine changes in the structural displacement that should be imposed on the building as a consequence of a given ground acceleration. The PDTM has been proposed as one way of simulating the dynamic responses of a building structure that is too large for existing shaking table tests. The PDTM differs from classical computer based structural dynamics simulation in that it depends on experimental use of the building for structural restoring forces which are experimentally measured rather than computed from a mathematical model and physical force actuators are used to cause the displacements of the building to track the computed structural displacement. Pseudo dynamic test facilities are in current operation at the Building Research Institute, Ministry of Construction (Ref. 10-12) and the University of Tokyo (Ref. 15-17) in Japan and at the University of California, Berkeley (Ref. 3-4,14) in the U.S.A. A test facility is currently being developed at the University of Michigan;

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but this paper presents a theoretical view of the pseudo dynamic test method based on experience at the existing facilities.

The PDTM has been demonstrated to be a viable testing procedure for single story buildings (Ref. 15) however, there has been some difficulty in using the PDTM for testing multi-story buildings (Ref. 10). It appears that some of the practical difficulties which have arisen in application of the PDTM to multi-story buildings may be due to inadequate control of the structural dynamics. The important issues of control of the structural dynamics in implementing the PDTM have received little attention. In particular, the following issues are suggested as important in developing and verifying the appropriate application of the PDTM: (a) development of suitable control of the electro-hydraulic actuators used in the tests; displacement and pressure (or load) feedback is desirable and development of an actuator controller system should take into account the effects of multi-story and inelastic structural coupling; (b) suitable selection of appropriate test parameters based on a theoretical understanding of the PDTM; (c) evaluation of the PDTM, taking into account the controlled structural dynamics, including all instrumentation and controllers; (d) analysis of the effects of test errors and inaccuracies on the overall validity of the PDTM.

These issues have been addressed previously, in some detail in (Ref. 5), but it was assumed there that the structural motion of the building remains elastic. In this paper the methods of (Ref. 5) are extended and the results of a computer simulation of the PDTM, for an inelastic structure, are presented. The emphasis throughout is on development of a suitable understanding of the dynamic relationships between the various physical subsystems that comprise the PDTM. Questions of acquisition and processing of data obtained from pseudo dynamic tests are not considered.

In this paper an implementation of the pseudo dynamic test method is viewed as an interconnection of physical components. Particular attention is given to the selection of a pseudo dynamic test control algorithm, whereby the test is performed recursively, and to selection of an actuator controller, which automatically regulates the displacements of the electro hydraulic actuators/building combination as desired. Particular design conditions are suggested; the importance of pressure (or load) feedback in the actuator controller is emphasized so that stability of the controlled actuators/building is guaranteed. Computer simulation experiments have been performed, and selected results are presented. Finally, the importance of a careful implementation of the method is emphasized, and it is suggested that the accuracy of the pseudo dynamic test data as equivalent earthquake response data be interpreted carefully.

DESIGN OF PSEUDO DYNAMIC TEST METHOD

The logical subsystems which define the PDTM are interconnected as shown in the schematic in Figure 1. The pseudo dynamic system is completely described in terms of the indicated subsystems. The parameter values in the PDTC and the AC, namely the dimensions and value of the mass matrix M, the value of the earthquake time increment T_e and the values of the feedback gain matrices G^a and G^d need to be specified.

Because the focus of the test is on the development of pseudo dynamic responses of a multi-story building, the building is extensively instrumented so that measurements of its motion (displacement) and restoring forces at various locations on the building can be made. In addition, a number of electro hydraulic servo actuators are located to apply suitable forces to the building using a rigid reaction wall. The building and associated instrumentation constitute the core of the PDTM.

In order to complete the physical implementation of the test method a pseudo dynamic test controller (PDTC) and an actuator controller (AC) must be selected. The PDTC, implemented as a digital computer, carries out the computations of the desired structural displacements of the building which would arise from the specified ground acceleration; these computations are based on a PDTC algorithm. In order to cause the building to actually deform according to the computations of the PDTC the electro hydraulic actuators must be properly controlled; this is the function of the actuator controller (AC). Physically the AC is implemented as an electronic "black box". It is suggested that the AC be based on feedback of the displacements and forces of the building at the actuator locations according to

$$u = -G^d(x-d)-G^f f \qquad (1)$$

where u is the n-vector of currents applied to the actuator servo valves, x is the n-vector of measured building displacements, f is the n-vector of measured forces between the actuators and the building, and d is an n-vector of (desired) building displacements obtained from the PDTC algorithm. The n x n matrices G^d and G^f represent feedback control gains. Thus the AC electronics generate the input currents to all actuator servo valves, based on measured values of the building displacements and forces at the actuator locations. Note that either load cells or hydraulic pressure transducers can be used to obtain the force measurements. The focus here is on explicit force feedback as an important part of the AC. However, leakage of fluid around the actuator piston has the same effect as force feedback; hence the gain matrix G^f should take into account the leakage effects.

The appropriate earthquake time increment T_e is selected to guarantee that numerical errors are not amplified and is based on the same criteria used for standard numerical integration procedures, Ref. 2. The usual second order differential equation describing earthquake dynamics

$$M\ddot{x} + F(x) = f = -M\ddot{z} \qquad (2)$$

is used where M is an n x n symmetric, positive definite mass matrix, F(x) is the building restoring force and $\ddot{z}$ is the ground acceleration. Knowledge of the building restoring force function F(x) is not required to implement the PDTC. It is also assumed that the lumped parameter model for the building is consistent with the instrumentation in the sense that (a) measurements of x and f can be explicitly made and (b) the force f is explicitly generated by the electro hydraulic actuators. These assumptions are rather restrictive but they could be relaxed at the expense of somewhat greater mathematical complexity.

Conditions for choosing the AC parameters will now be examined. In order to obtain a complete description of the inner loop part of the pseudo dynamic system it is necessary to include a suitable mathematical model for the hydraulic actuators. It is assumed that the force f in equation (2) is directly due to a set of n suitably located hydraulic actuators. The dynamics of the hydraulic actuators can be described by Ref. 8,

$$\dot{f} = -K_h\dot{x} + K_hK_qu \qquad (3)$$

where K_h is a diagonal, positive definite stiffness matrix which depends upon the geometry of the actuator design, the bulk modulus of the hydraulic fluid and the stiffness of the elastic connection between the actuator and the building (Ref. 6); and K_q is a nonsingular diagonal current influence matrix which depends upon the geometry of the actuator design, and the hydraulic servo valve characteristics.

Thus the actuator and building dynamics are described by the coupled equations (2) and (3). Substituting the controller equation (1) into equation (3) the closed loop equations for the inner loop are obtained

$$\begin{aligned} M\ddot{x} + F(x) &= f \\ \dot{f} &= -K_h\dot{x} + K_hK_q[-G^d(x-d)-G^ff] \qquad (4) \end{aligned}$$

These equations form the basis for selection of the feedback gain matrices G^d and G^f so as to guarantee that the closed loop of building/actuators/controller has desired response characteristics.

Actuator Control Design Condition, Ref. 6,7: The feedback gain matrices G^d and G^f in the AC should be chosen as diagonal matrices to satisfy the conditions

$$K_hG^f > G^d > 0 \qquad (5)$$

As shown in Ref. 7, satisfaction of such conditions guarantees that the closed loop is stable, for a wide class of building restoring forces. But in addition, accurate tracking is desired in the sense that on a given step the test displacement should approach the desired displacement. Even for a stable closed loop perfect tracking accuracy is not achievable and the steady state tracking error depends on the nonlinear restoring force function. To achieve a small steady state error the feedback gains should be chosen to satisfy

$$G^f K << G^d \qquad (6)$$

Thus there is a trade-off in achieving satisfaction of the two conditions of stable operation and accurate tracking. This tradeoff is a key-feature in achieving a proper implementation of the AC in the PDTM.

These observations also suggest that it is important that the electro hydraulic servo values be selected so that their hydraulic stiffnesses significantly exceed the maximum stiffness of the building to be tested.

EXAMPLE SIMULATION OF PSEUDO DYNAMIC TEST METHOD

Extensive computer based simulation experiments of the PDTM have been performed to evaluate the method when the building is deformed into its inelastic range. These simulations have typically used two degree of freedom systems with nonlinear inter-story springs which followed the Q-hyst, Ref. 13, hysteretic force-deformation relationship. In one of these cases the complete pseudo dynamic system was simulated, including the inner loop actuator/structure/actuator controller dynamics. For the purposes of assessing the effects of realistic AC on the error propagation an ideal inner loop controller case was performed. The results of this reference experiment is illustrated in Figure 2. From this result and other simulation data as well, it appears that the PDTM error variance increases approximately linearly with the duration of the test. This casual observation for an inelastically deformed building is consistent with the theoretical analysis in Ref. 5, where the same conclusion was reached for an elastically deformed building.

It is clear that the comparison indicated in Figure 2 suggests that it would likely be desirable to improve the steady state accuracy of the inner loop test cycles. As has been mentioned, this is easily achieved by appropriate selection of the feedback gain parameters, but at the expense of the speed of the test. The particular simulation data given in Figure 2 is not meant to imply that the AC implementation is particularly good; but rather it does indicate that any realistic AC implementation will give rise to cumulative errors in the PDTM.

CONCLUSIONS

The main emphasis in this paper has been on the design and development of suitable Pseudo Dynamic Test Control (PDTC) and Actuator Controllers (AC). Most previous work has focused on selection of a PDTC algorithm, with specification of the earthquake time increment so that the algorithm is numerically stable. A careful design of the AC is critical, for otherwise the actual building displacements may be quite erratic without tracking the desired displacements. A specific form for the AC has been suggested. AC performance depends on careful and accurate measurements of the building displacement and force vectors. Selection of the AC gains is more difficult. Particular conditions for choosing the gains to stabilize the closed loop have been presented; but the gains should also be chosen to minimize the steady state tracking error; so that an overall trial and error tuning of the parameters is required.

Even in the most carefully implemented PDTM the limitations of the method must be realized. There are inevitable measurement errors and inner loop tracking errors. The computer simulations, as well as previous theoretical work, indicate that the errors in the PDTM responses are cumulative. Statistically speaking, it appears that the error variance of the PDTM responses increase approximately linearly with the test duration (number of cycles). At this point, an exact numerical specification of the rate at which these errors increase is unavailable. But the qualitative conclusion is that as the test duration increases the accuracy of the PDTM response data decreases.

The PDTM may prove to be a valuable method for evaluating building design and analysis techniques. However, great care is necessary in implementing the method and in interpreting the pseudo dynamic test data.

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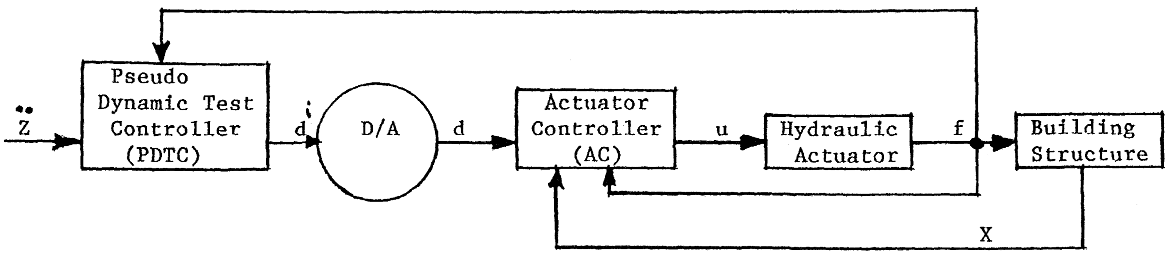

Figure 1. Schematic Diagram of Pseudo Dynamic System

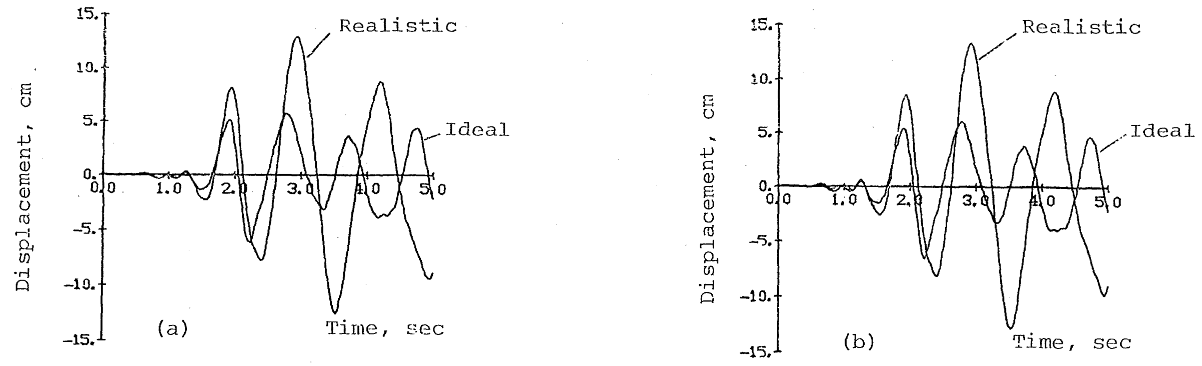

Figure 2. Comparison of Inelastic Response with Ideal and Realistic Actuator Controllers (a) First Floor and (b) Second Floor