Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VIII)

SE-8

AN EXPERIMENTAL STUDY OF THE EARTHQUAKE RESPONSE OF BULDING MODELS PROVIDED WITH ACTIVE DAMPING DEVICES

M.-I. Traina[1], R.J. Fournier[1], O.T. Hata[1], B. Mann[1]
S.F. Masri[1], R.K. Miller[1], and T.K. Caughey[2]

[1]Dept. of Civil Engin., Univ. of Southern California, Los Angeles, CA, USA
[2]Div. Engin., Calif. Institute of Technology, Pasadena, CA, USA

SUMMARY

A simple yet efficient method is presented for the on-line vibration control of nonlinear, multi-degree-of-freedom systems responding to arbitrary dynamic environments. The control procedure uses pulse generators located at selected positions throughout a given system. The degree of system oscillation near each controller determines the controller's activation time and pulse amplitude. Experimental studies with small laboratory models demonstrate the feasibility, reliability, and robustness of the proposed active control method. The actuators used relied on different forms of motive forces: pneumatic, hydraulic, and electromagnetic.

1. INTRODUCTION

1.1 Application of Control Theory to Large Civil Structures

Civil engineering researchers have applied both classical and modern control techniques to large civil structures, and have addressed many of the same major issues that have been prominent in the aerospace, electrical, and mechanical engineering fields. These issues include such topics as mathematical modeling of structures, identification techniques, reduced-order models, modal truncation and controller interaction with residual modes, placement of control actuators, multivariable controller design techniques, mathematical measures of desired system performance, and optimal control techniques.

1.2 Control of Flexible Structures Using Pulse Inputs

For reasons discussed in the work of Miller et al. (Ref. 1), the major difficulties encountered in the application of modern control techniques to building structural systems are the following:

1. Active control requires the ability to generate and apply large controlled forces to the structure.
2. Modern control theory often leads to feedback control laws, thus requiring on-line measurement (or estimation) of all the system state variables.
3. On-line control requires that both measurement and control be performed in real time.

From a practical standpoint, while the application of large control forces to a structure does not pose insurmountable problems, the generation of such forces over sustained periods of time (as often dictated by continuous optimal feedback control theory) may cause the concept of active control to become impractical. To bypass this possible drawback, the approach under discussion attempts to utilize pulses of relatively short duration to control the structural system.

Furthermore, building structures during strong ground shaking show strongly nonlinear and time variant (degrading) behavior. Even in the absence of nonlinearities, the motion of the structure is governed by a linear differential equation with time varying coefficient matrices. The use of such a representation would prevent the system from being decomposed, in general, into normal modes, thereby making the concepts of modal control difficult to apply.

It is thus evident that the available standard methods of control system design are not well suited to the structural control problem under seismic, or similar nonstationary random excitation, because they either fail to take into account the statistical nature of the earthquake disturbances, or they do not lend themselves easily to on-line implementation, or both. Perhaps the most serious problem of the standard design techniques is that they do not lend themselves readily to restricting the class of control signals to relatively narrow, high-energy pulses of the type suitable for active control of buildings.

Moreover, it has been demonstrated that a sequence of force pulses applied to a structure can be selected in such a way that the power spectral density of the displacement at a particular point within the structure matches the spectral density produced by earthquake ground motions as closely as desired (Ref. 2). This result naturally suggests the possibility of using the force-pulses to counteract or reduce displacements produced by earthquakes. The following section presents one approach to this problem.

2. PULSE CONTROL OF NONLINEAR SYSTEMS

Consider an arbitrary nonlinear system with support motion $\underline{S}(t)$ and dynamic load $\underline{F}(t)$. The relative motion at certain locations in the system is to be limited in magnitude. A simple way of accomplishing this objective is to apply control pulses at selected locations throughout the structure whenever the velocity at this location reaches a maximum and in a direction which opposes this velocity. The idea is to use actuators whose operation is triggered each time a zero crossing of the relative displacement at a point of interest is detected. The magnitude of the control pulse p_i will be given by

$$p_i(t) = \begin{cases} -c_i \operatorname{sgn}(v_i)|v_i|^{n_i}; & t_{o_i} \leq t \leq (t_{o_i} + T_{d_i}) \\ 0; & (t_{o_i} + T_{d_i}) \leq t \leq t_{o_{i+1}} \end{cases}$$

where

c_i	coefficient for scaling the needed control force at location i
sgn(.)	indicates the algebraic sign of its argument
v_i	is the absolute or relative velocity of the structure at location i, depending on the nature of the problem

n_i is some appropriate power of the velocity at location i

t_{o_i} is the zero crossing time at location i

T_{d_i} is the pulse duration of the controlling force at location i.

This simple nonlinear control law, which relates the needed control force to an arbitrary power of the associated system velocity, has some worthwhile features as discussed in Ref. (3). A stability analysis of the method using the Second Method of Liapunov has yielded constraints on the pulse amplitude in relation to the magnitude of excitation of load forces. Satisfaction of such constraints insures the asymptotic stability of the system (Ref. 3).

3. EXPERIMENTAL STUDIES

3.1 Pneumatic Actuators

A mechanical model resembling a 6-story frame was designed and fabricated to investigate the pulse-control algorithm under realistic laboratory conditions. To consider torsional effects, the structure was designed such that its first torsional mode lies between the first lateral modes in the x and y direction (see Fig. 1). The diagrams in Figs. 2 and 3 indicate the details of the $\approx$ 159 kg (350 lb) test structure, vibration exciter, instrumentation, pneumatic power supply, and the minicomputer used for digital control.

The electrodynamic exciter, control sensor, and actuators were located at the sixth (top) floor of the structure. The actuators consisted of two commercially available and relatively inexpensive solenoids (Fig. 3) which metered the flow of 0.862 MPa (125 psi) compressed air through a nozzle, thus generating the control thrusts. The control logic was implemented on a Z-80 based microprocessor using the FORTH language.

Fig. 4 shows sample measurements for the structure under harmonic excitation with a frequency close to the fundamental frequency. Due to coupling between the transverse and the torsional modes, excitation in the x direction leads to significant response in the x, y, and θ_{zz} directions. In spite of the limited thrust that the actuators can generate, they were able to significantly attenuate the structural response. It is seen from Fig. 4 that within $\approx$ 10 periods of turning the controller on, the response is reduced to $\approx$ 0.15 of its uncontrolled value. Because the control used in this experiment is to simply turn the controller on or off, this corresponds to using $n = 0$ in the control law (i.e., active Coulomb damping). Thus, it is not surprising that the envelope of the decaying oscillations at the initiation of the control process exhibits the same characteristics associated with Coulomb friction, namely a straight line decay envelope. On the other hand, it is seen from Fig. 4 that when the excitation is turned off (at t $\approx$ 90 s), the envelope of the free vibrations can be well approximated by an exponential decay curve, which is a well known characteristic of viscously damped systems.

A simplified flow chart for the control algorithm used to implement the pulse-control approach under discussion is shown in Fig. 5.

3.2 Hydraulic Actuators

Experiments involving hydraulic actuators were conducted by means of the apparatus shown in Fig. 6. Sample test results are shown in Figs. 7 and 8.

The on-line control of the free vibrations of the test apparatus is presented in Fig. 7 where the top graph shows the control forces generated by the hydraulic actuators, the middle graph shows the free vibrations of the system when using pulse-control, and the bottom graph shows the system free vibrations in the absence of any control forces.

The graphs in Fig. 8 show the results of the on-line control of the steady-state oscillations of the test apparatus: the top graph shows the control forces, while the bottom graph shows the steady-state displacement response without and with pulse-control.

3.3 Electromagnetic Actuators

Experiments utilizing electromagnetic actuators were also conducted. Sample test results are shown in Fig. 9. The system free vibrations without and with pulse-control are compared in the top portion of Fig. 9, while the bottom portion shows the normalized displacement, velocity and electromagnetically-induced control forces.

4. SUMMARY AND CONCLUSIONS

A simple, yet efficient method is are presented for the on-line pulse control of linear as well as nonlinear, multidegree-of-freedom systems responding to arbitrary dynamic environments. A worthwhile feature of the control method is that it is suitable for situations in which detailed knowledge of the system structure is not available; only *local* measurements of displacement and velocity are needed with this method to determine the control force to be applied at a specific location in the nonlinear flexible structure.

Some experimental results are presented in which a mechanical model resembling a 6-story building frame was provided with sensors and colocated actuators that were distributed throughout the structure and configured so as to simultaneously suppress the building structural vibrations in two orthogonal transverse directions as well as torsional oscillations. The actuators used relied on different forms of motive forces: pneumatic, hydraulic, and electromagnetic. The over-all active control procedure was implemented by means of a single minicomputer which handled all the distributed controllers.

Experimental tests with several mechanical models of different size and configuration demonstrate the feasibility, reliability, and robustness of the proposed pulse-control methods.

ACKNOWLEDGEMENT

This study was supported in part by a grant from the National Science Foundation. The assistance of MTS Corporation in the experimental studies with hydraulic actuators is appreciated.

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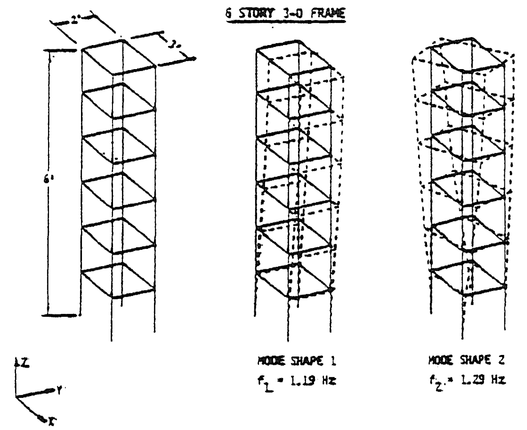

Fig. 1 Dynamic characteristics of building model.

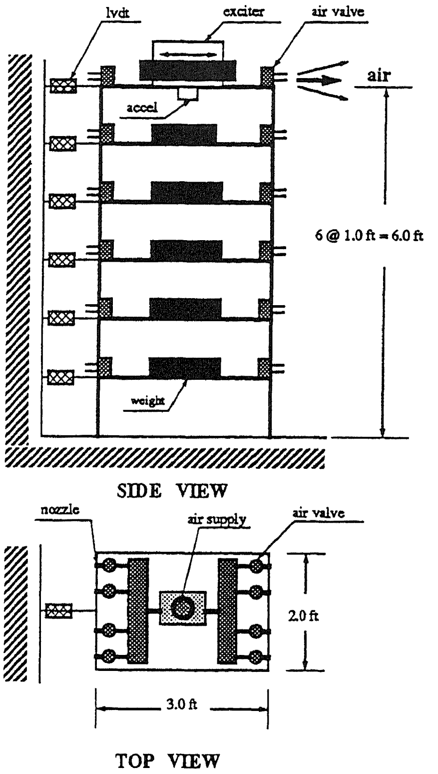

Fig. 2 On-line control test apparatus using pneumatic actuators to attenuate the oscillations of a 6-story frame model.

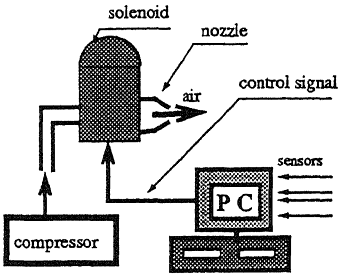

Fig. 3 Pneumatic actuator control diagram.

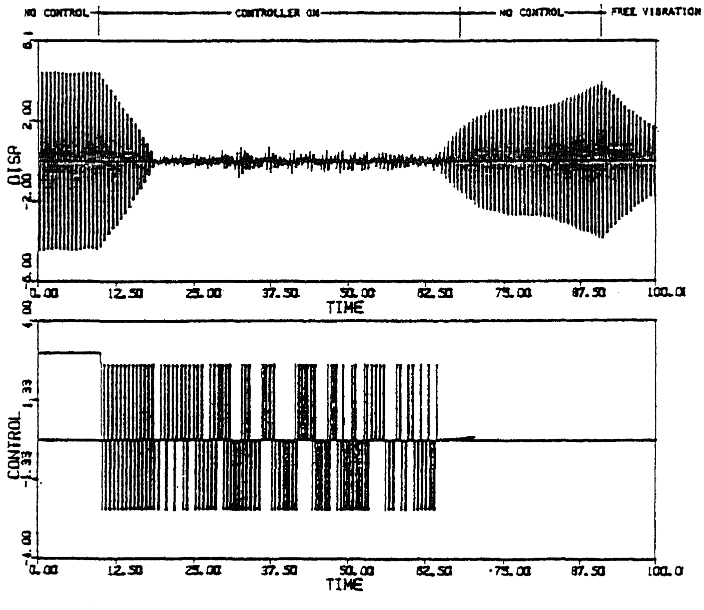

Fig. 4 Sample measurements from a harmonically excited structure with pulse-controlled pneumatic actuators.

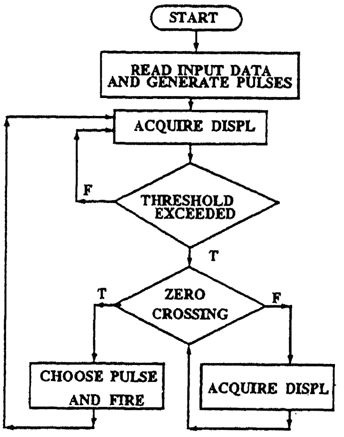

Fig. 5 Simplified flow chart of on-line pulse control algorithm.

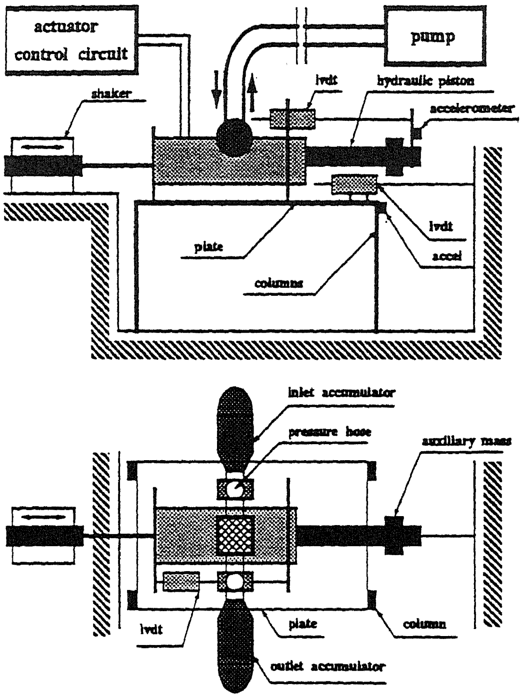

Fig. 6 Schematic diagram of the on-line control test using hydraulic actuators.

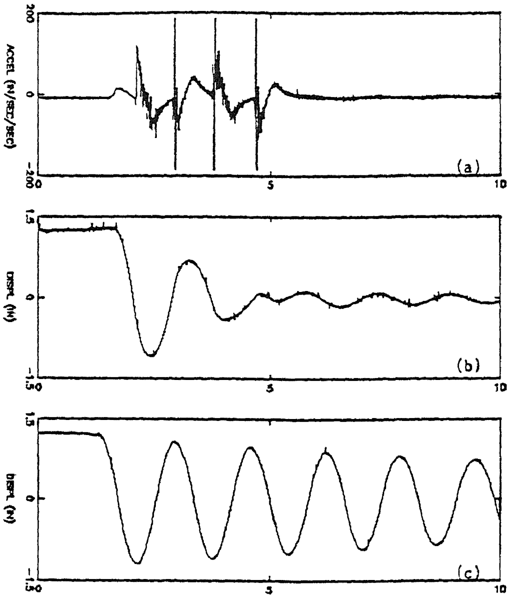

Fig. 7 On-line control of the free vibrations of the test apparatus using a hydraulic actuator, (a) control force ; (b) system displacement with pulse control, and (c) system displacement without any control.

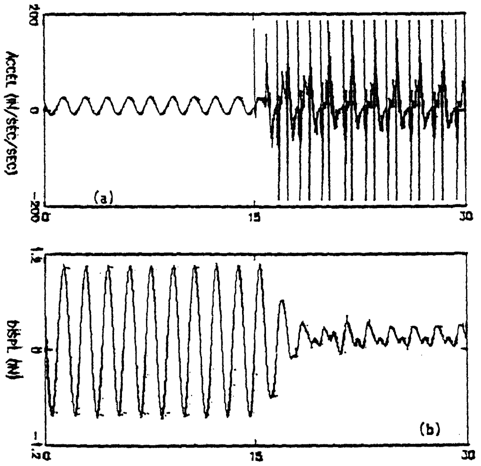

Fig. 8 On-line control of the steady-state oscillations of the test apparatus using a hydraulic actuator; (a) control force, and (b) displacement response without and with pulse control.

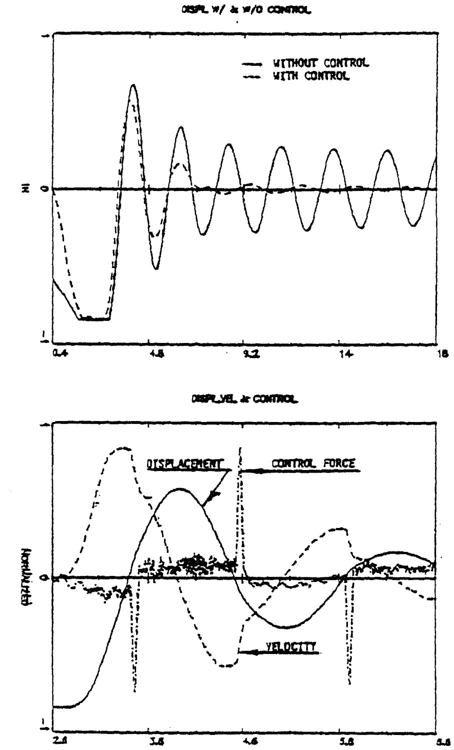

Fig. 9 On-line control of the free vibrations of the test apparatus using an electromagnetic actuator ; (a) normalized system displacement without and with control, and (b) normalized system displacement, velocity, and used control force.