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State University of New York at Buffalo

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ABSTRACT

This report presents a structural vibration reduction system which includes control algorithms and example devices. The concept of this system is to adaptively change the physical parameters of a structure based on dynamic information such as ground motions and the structure's response to these motions. This approach is referred to as Real-time Structural Parameter Modification (RSPM). A structure implemented with RSPM capacity is called an innervated structure. An innervated structure consists of three integrated functions or components: a sensory unit to measure the dynamic signals, a decision-making unit to analyze the signals and responses of the structure with added innervating elements, and an action unit consisting of certain functional switches and/or actuators. The basic functions are self-monitoring, self-decision-making and self-tuning.

The innervating action of structures is modeled after human body motion control principles, which is conceptually different from the various structural control schemes presently defined by the structural engineering community. This report presents only the basic concept and preliminary theoretical and experimental results to demonstrate the feasibility of introducing innervating actions to structures. It emphasizes a research direction to establish the necessary engineering knowledge base for the design and construction of man-made structures with features and characteristics similar to those of living systems.

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The project to develop innervated structures was initiated in 1991. The design of the functional switch and the concept of the four-loop hierarchical model were established in 1992. A first prototype system was built and tested in the laboratory in 1993. A second test structure was built and tested with improved sensors in 1994. Because this study involves the development of three components of a system (sensors, algorithms and functional switches) and the fact that several major challenges had to be overcome, it took the authors more than three years to reach the present stage, which has resulted in this technical report about the decision and switching subsystems of RSPM. (The monitoring subsystem will be reported separately.) During this period, the authors have received much assistance and suggestions from their colleagues in Civil, Mechanical and Electrical Engineering as well as from Physiology both on and off the University at Buffalo campus, and from the technical support staff of the Seismic Simulator Laboratory at the University at Buffalo, particularly D. Walsh, R. Cizdziel and M. Pitman. To all of them the authors express their sincere gratitude. In addition, the authors would like to acknowledge the helpful comments and advice of Professors T.T. Soong and M. Shinozuka for improving this report.

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BACKGROUND

1.1 Introduction

Structures designed against static loading conditions usually only consider the proper distribution of structural stiffness. Such a design principle is insufficient for earthquake or other time-dependent loading conditions. If stiffness is chosen based on static actions alone, the dynamic magnification factor can increase. That is, the amount of increase of deformation due to dynamic loading can be greater than the amount of deformation reduced due to increased stiffness. To overcome this difficulty, the concept of absorbing energy through inelastic deformation of the structure has been pursued. However, design based on ductility alone is considered undesirable since it carries high repair and/or replacement costs.

In recent years, many research efforts have been devoted to establishing earthquake engineering design approaches by absorbing energy using devices/protective systems rather than utilizing inelastic deformation of the structure. Such structures are referred to as structures with energy-absorbing-means (EAM).

As early as 1969, viscoelastic (VE) dampers were installed in the World Trade Center to reduce wind-induced vibrations (Mahmoodi 1972). Subsequently, three tall buildings have also been installed with VE dampers for the same purpose. Using VE dampers to control earthquake induced vibrations has been examined by many authors (Lin et al., 1991, Aiken et al., 1990, Chang et al., 1991, Liang et al., 1989, 1990, 1991a,c,d, Tong 1991, and Tsai et al., 1992, 1993a). Friction dampers have also been used for other applications and extended to earthquake protection (Pall et al., 1981, 1986, Filiatrault et al., 1985, Aiken et al., 1993, Constantinou et al., 1993a,b, and Soong 1994b). Fluid dampers that primarily provide viscous damping have been used in the past for mechanical engineering applications. In 1993, Constantinou published the results from a comprehensive study on the earthquake applications of fluid dampers (1993a).

The metallic yielding method is another type of energy absorbing device, first installed for base isolation purposes (Tyler 1978, Buckle et al., 1990, and Kelly 1993). Later this method was referred to as "Added damping and stiffness" or ADAS by Whittaker et al. (1991). More recently, the feasibility of using two or more devices together on the same structure were examined by Tsai and Lee (1993b) and Pong et al. (1994).

In order to further develop EAM and apply them to engineering practice, researchers are examining how to use them within the context of existing building codes. The direct design parameter of most EAM is typically the damping ratio. However, both theoretical analysis and experimental tests have shown that introducing higher damping may not be a superior choice over increasing stiffness, that a higher damping ratio does not necessarily result in reduced deformation, and that the design of the damper cannot be separated from the overall structural system. This is not only true for the design of dampers, but also for theoretical modeling, such as finite element analysis. It may be readily shown that for a given number of dampers installed in the same structure, different results can be obtained for different configurations of damper locations. This issue is addressed in a separate report by the authors entitled "Damping of Structures: Part II - An Application of Complex Energy Theory in Structural Monitoring" (to be published).

An Application of Complex Energy Theory in Structural Monitoring

Another important issue regarding the application of EAM is establishing their limit of effectiveness. When the damping ratio of a structure is small (say, less than 2%), its ability to dissipate energy is low. In this case, added passive damping is effective. When the damping ratio of a structure is high (say, more than 5%), added passive damping becomes less effective. To extend the capability of passive EAM, various active controls have been investigated (Liu 1993, Inaudi et al., 1994, Soong 1990a,b, 1994a,b, Reinhorn et al., 1985, Yang et al., 1992, and Yao 1972). These authors have shown that a larger dynamic range of control can be achieved by active control devices. In most active control cases, the control forces are determined through velocity-feedback. In structural dynamics, the force proportional to velocity is the damping force.

Therefore, generally speaking, most active controls are related to EAM. In this report, this kind of active control is referred to as active EAM.

At the same time, many researchers pursued an alternative method of vibration control. Instead of applying active force to structures, this approach either changes structural parameters or simulates active forces by certain switching mechanisms. This method is referred to as parametric control, semi-active control, semi-passive control, hybrid control or innervating control by different researchers. (Examples include Kobori et al., 1990, 1991, 1994, Feng et al., 1992, Nemir et al., 1992, Inaudi et al., 1993, Kawashima et al., 1993, Lee et al., 1994 and Sack et al., 1994.) In the following, this approach will be discussed.

1.2 Recent Developments in Structural Control

In this section, definitions in structural control are reviewed to facilitate subsequent discussions.

Basic Concept

In engineering approaches, the control process is often described by a *state equation*, namely,

$$\dot{X}(t) = A(t)\, X(t) + B(t)\, U(t) \tag{1.1}$$

where the vector X(t) is the *state* variable describing the current state of the system to be controlled. The vector U(t) is the input variable including the control quantities. A(t) is the state matrix containing the physical parameters of the system. For application in civil engineering structures, the physical parameters are mass, damping and stiffness of the structure. B(t) is the input matrix, usually describing the location of the control action. Generally, all the quantities are functions of time. However, in most control technologies currently available, A and B do not vary with respect to time. In this case, Equation (1.1) is said to be a first-order, linear, time-invariant system. From Equation (1.1), within a limited duration, t_0 to t_1, if there exists a $U(t_0, t_1)$ with limited bound, such that any state $X(t_0)$ can be transferred to zero, the system denoted by A(t) is *controllable* at time t_0.

The above definition is not quite suitable for this purpose. To reduce structural vibrations due to earthquake ground motions, the response of a structure, usually the deformation, should stay within certain bounds, such as the limit of the drift between two floors. In this sense, the concept of controllability, and therefore the control theory, is not appropriate for aseismic design, because 1) such a control process cannot guarantee the response bound all the time, and 2) it is not necessary to bring the structural response to zero, in other words, the response bounds is being regulated but not the response itself.

The motion of a structure excited by earthquake ground motions may be approximated by a linear mechanical vibrating system:

$$M\,Y''(t) + C\,Y'(t) + K\,Y(t) = F(t) \tag{1.2}$$

where M, C and K are the *mass, damping and stiffness coefficient matrices*. $Y(t)$, $Y'(t)$ and $Y''(t)$ are the displacement, velocity and acceleration vectors. The superscript ' and " stand for the first and second derivative with respect to time t. $F(t)$ is the forcing function vector. For earthquake ground motions, $F(t)$ may be written as

$$F(t) = -M\,\{1\}\,y''_g(t) \tag{1.3}$$

where, $\{1\} = [\,1, 1, \ldots 1]^T$ and $y''_g(t)$ is the ground acceleration.

For the control scheme that applies forces directly to the structure, the equation of motion can be expressed by

$$M\,Z''(t) + C\,Z'(t) + K\,Z(t) = F(t) + F_c(t) \tag{1.4}$$

where $Z(t)$ is chosen to be the relative displacement, $Y(t) - \{1\}\,y''_g(t)$. Regular control forces $F_c(t)$ are often set to be linear functions of $Z(t)$, $Z'(t)$ and $y''_g(t)$. It can also contain a force P, not relating to the state variable

$$X(t) = [\, Z'(t), Z(t)]^T \tag{1.5}$$

and the input force F(t). In other words, P can be a continuous impulse with high frequency. It can also be time invariant, such as a prestress force, etc. For convenience, P is used to denote P(t) in subsequent considerations. Furthermore, the control force may be expressed as:

$$F_c(t) = \alpha\, Z(t) + \beta\, Z'(t) + \gamma\, y''_g(t) + \delta\, P \tag{1.6}$$

Comparing Equations (1.4) and (1.5) with (1.2), we have

$$A = \begin{bmatrix} -M^{-1}C & -M^{-1}K \\ I & 0 \end{bmatrix}, B = \begin{bmatrix} I \\ 0 \end{bmatrix} \tag{1.7}$$

The effort described by Equations (1.4) and (1.6) can be further shown in figure 1-1 (a), which provides an example of active structural control (Scheme 1). Figure 1-1 (b) is the logic diagram of figure 1-1 (a).

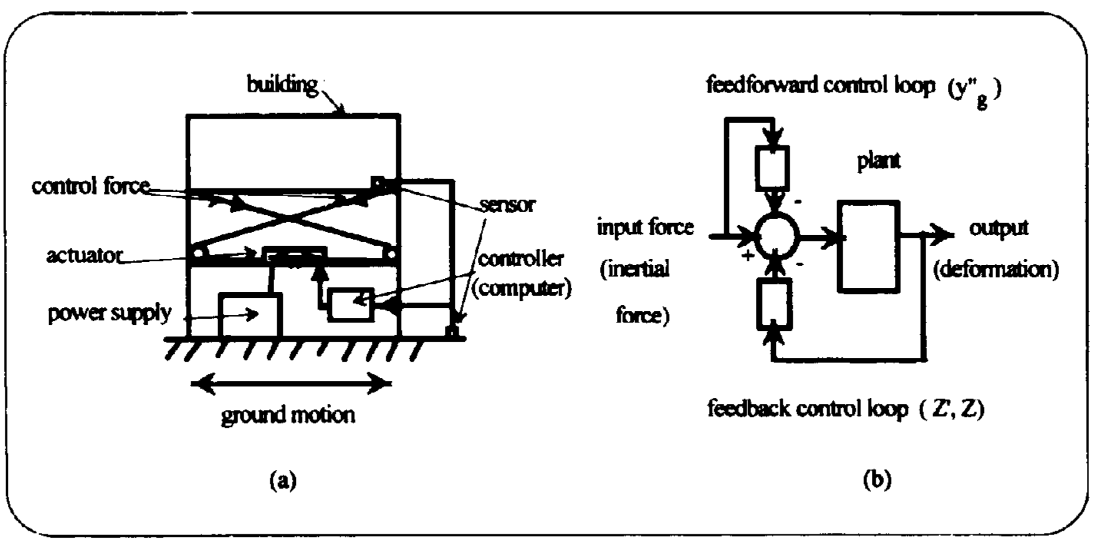

FIGURE 1-1 Active Control (Scheme 1)

When

$$F_c(t) = \alpha\, Z(t) + \beta\, Z'(t) \tag{1.8a}$$

the control force is determined according to the output state, such as the deformation at a specific location. From figure 1-1(b), it can be seen that the process of input-plant-output-feedback gain-input forms a loop, known as a feedback loop. This is defined as *feedback* control.

When

$$F_c(t) = \gamma\, y''_g(t) \tag{1.8b}$$

the control force is determine according to the input variable. From figure 1-1 (b), it can be seen that the process of input-feedforward gain-input forms a different loop, known as a feedforward loop. This is defined as *feedforward* control.

In general, a system may contain both feedback and feedforward loops, so that in this case,

$$F_c(t) = \alpha\, Z(t) + \beta\, Z'(t) + \gamma\, y''_g(t) \tag{1.8c}$$

Sometimes, a system may contain more than one feedback or feedforward loops. However, all the "loops" can be closed loops. Therefore, they are defined as *closed loop* control.

When

$$F_c = \delta\, P \tag{1.9}$$

the control force is applied neither according to the feedback nor the feedforward signals. Thus, no closed loop exists. Equation 1.9 describes an *open loop* control.

In most cases, the control system described by Equations 1.8 (a), (b) and (c) and 1.9 engages the application of certain external force or energy to the structure. This is referred to as the *active* control. In practice, active forces are introduced by actuators, such as hydraulic actuators or electromagnetic actuators.

On the other hand, the state variable of a structure such as the deformation can be reduced without the application of any external forces. For example, certain dampers can be installed in strategic locations on a structure to increase damping to a desirable level. This is usually referred to as *damping* control. Sometimes, the mass or stiffness of a structure can be modified to change its natural frequencies to avoid resonance. They are referred to as *mass* and *stiffness* controls, respectively. These cases, for which no external force or energy is added to the structure, are said to be *passive* controls. There are other types of passive control, such as base isolation. In addition, the vibration energy of the structure can be used to generate the control force described by Equation 1.9.

A structure may be controlled by using both active and passive components. This is called *hybrid* control. As mentioned before, combinations of different passive devices have been presented (for example, Tsai and Lee, 1993b), which are also referred to as a hybrid approach.

The above definitions can be found in technical publications and textbooks. However, they are not yet unified. For example, control described by Equation 1.8(a) is called closed loop control and the one described by Equation 1.8(b) is called open loop control (Soong, 1990a). The word "semi-active" is used to express hybrid control and also to explain control that does not directly apply forces to the structure but instead applies it to elements or devices, such as actuators.

Active Stiffness

The concept of *active* stiffness, or *variable* stiffness was first introduced in aerospace engineering structures. It is conceptually shown in figure 1-2.

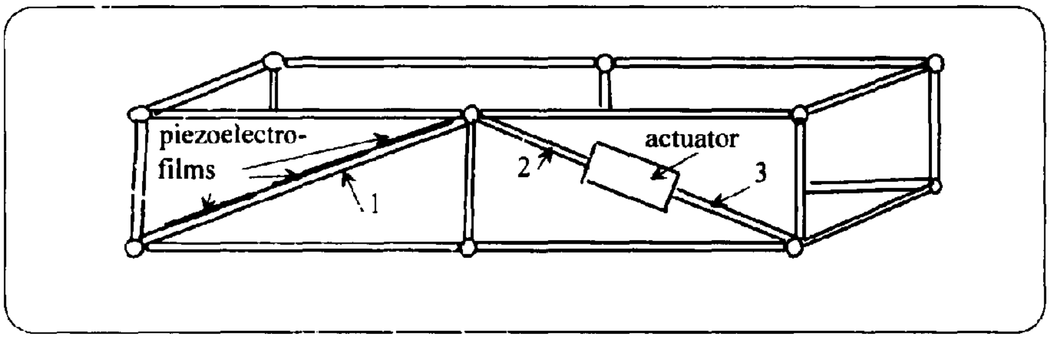

FIGURE 1-2 Active Stiffness

In figure 1-2, two possible methods to vary the stiffness of a structure are shown. On member 1, piezoelectric films are attached. Both sensors and actuators can provide the forces. In the right hand side panel, an actuator is installed in the diagonal (2-3) direction to provide the variable axial force. With these two actuators, the system becomes active. In this case, energy is applied to the structure in the two diagonal directions through active control.

If the actuator functions like a "cylinder lock" (Kobori et al., 1990) the stiffness of member 2-3 can have two possible statuses: a certain value or zero. There are various control laws to determine the value of stiffness. One major effort carried out by Kobori was to change the stiffness of the structure according to its change of natural frequency. For an SDOF system, the natural frequency is proportional to the square root of the ratio of stiffness and the mass. For MDOF systems, the relationship between the natural frequency and the stiffness is approximately the same. Therefore, by changing the stiffness, the natural frequency of the structure can be changed to avoid resonance under given excitations. For this method, it would be desirable to describe an earthquake by a harmonic wave. However, most earthquake ground motions are random in nature. Thus, changing the stiffness consistent with the natural frequency becomes less effective.

Kobori et al., (1991) subsequently suggested an earthquake forecasting system to remotely measure the earthquake wave and to analyze the frequency component of ground motion in real-time. This method is an improvement, however, its accuracy greatly depends on the similarities of the characteristics of the ground at the measured location and the local site.

A further development of Kobori is to perform FFT on the ground motions locally to determine what kind of natural frequencies a structure should have. However, the FFT is, mathematically speaking, an integral transformation. The integration requires a certain time duration, which slows the response of the control system. In addition, since the earthquake ground motions are random in nature, the FFT results obtained from first few seconds may not be suitable for the entire duration.

Kobori et al., (1994) further advanced their active variable stiffness (AVS) approach by using cylinder lock. As shown in figure 1-3, the cylinder lock is mounted at certain locations of the structure which are subjected to vibration. If the displacement increases, the cylinder is locked and thus provides some stiffness. If the displacement decreases, the cylinder is unlocked. In this scheme, the absolute value of the displacement is used.

The above mentioned active stiffness methods are focused on controlling the displacement of structures, however, they are not as effective in controlling vibration at all times. Since earthquake ground motions are random events, it is difficult to determine under what condition the control command would be issued. Among all the above mentioned approaches, the strategy shown in figure 1-3 exhibits the best possible results. However, no rigorous explanation can be given as to why this strategy works. Intuitively, the control law can be explained as follows.

Consider the motion of a point on the structure to be controlled. At any given time, there exists the inertial, damping and restoring forces in a state of dynamic equilibrium with the external force. For the active (variable) stiffness control, the inertial and damping forces remain unchanged. First, the point moves away from the equilibrium position driven by the external force. If an additional stiffness is added, the restoring force against the external force becomes larger. In this case, this point will move slower and the resulting displacement will be smaller. That is, the distance between positions 1 and 2 in figure 1-3 is shorter. Next, if at exactly the peak position 2, the external force is reduced to zero, the point is driven back by the restoring force. If the amount of stiffness is reduced, the restoring force will become smaller. This point will then move slower and the resulting displacement will also be smaller. That is, the distance between positions 2 and 3 is shorter. From position 3 to 4, the external force is applied to the structure at exactly position 3 and it discontinues at exactly position 4. The same process can be repeated.

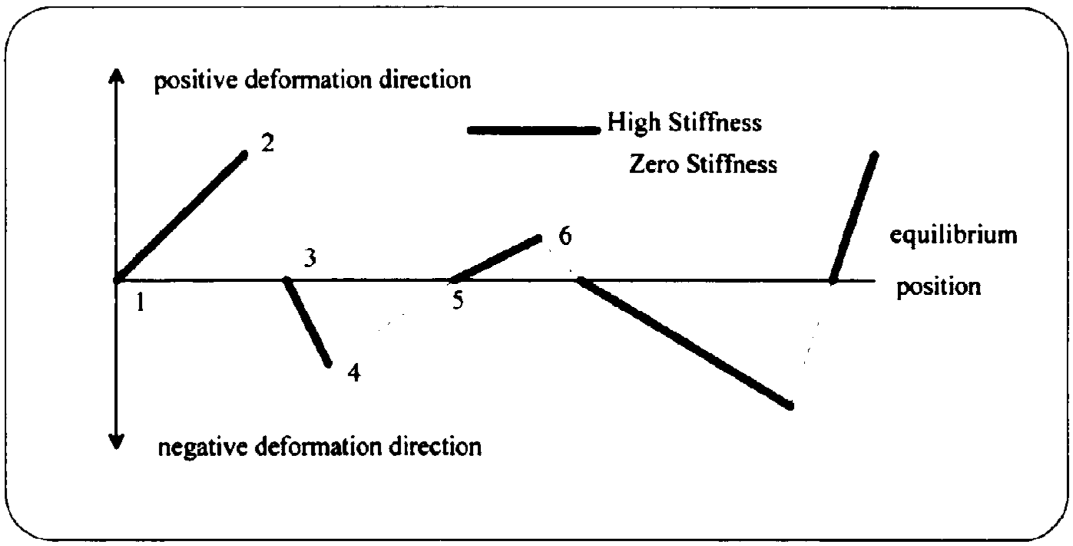

FIGURE 1-3 Active Stiffness Control Law Suggested by Kobori

Although the above strategy works in principle, there are a few problem areas in earthquake engineering applications. Most importantly, since the external forces generated by the earthquake ground motions are random in nature, it cannot be ensured that the external forces are applied exactly at position 1 and discontinued exactly at position 2, etc. It is possible that shortly after position 2, a large external force is suddenly applied to the point in the reversed direction (from 1 to 2), and the point will move outward resulting in a larger displacement, because the control law commands a decrease of the stiffness and thus a weaker restoring force. In practice, any control action has a certain time delay, and the additional displacement due to the time delay cannot be avoided by the strategy presented in figure 1-3.

The corresponding action scheme for RSPM is shown in figure 1-4. Here, the stiffness is not disconnected exactly at position 2 but at a later time such as position 2'. It also may be dropped sooner than reaching position 4, at an earlier position 4', and so on.

The proposed RSPM scheme shown in figure 1-4 is intuitively sound. The proper positions 2', 4', etc. can only be decided through dynamic analysis of the structure-device system in real-time.

Another problem area of the strategy of figure 1-3 is that minimizing the displacement at certain local positions of a structure does not necessarily mean that the vibration of the entire structure is properly controlled. Larger displacements permitted to occur at certain locations may reduce the

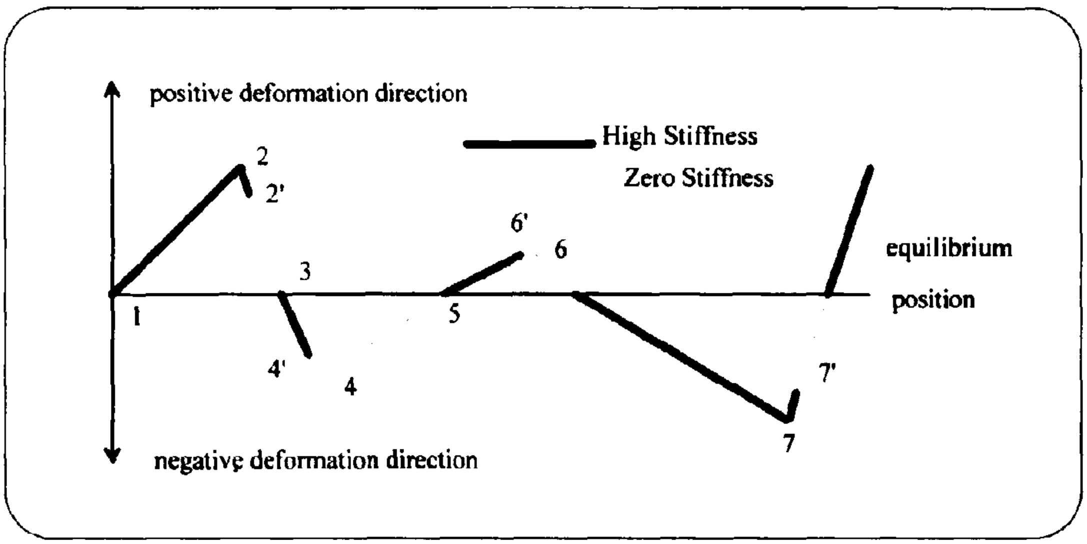

FIGURE 1-4 Proposed Modification Law for Random Vibration

vibration at other more critical points of the structure. The tuned mass damper is a good example: to reduce the deformation of the entire building, the displacement of the tuned mass may be increased as much as possible. Sometimes, a region in the building vibrates just like the tuned mass, while vibration of the rest of the building is reduced. For an MDOF system, this phenomenon may very often be seen. Thus, the control law shown in figure 1-3 cannot be used for "tuned-mass-control."

Active Mass

The concept of active mass is first mentioned in the tuned mass damper method. Passive tuned mass dampers are designed with fixed mass added to the structure in order to lower the natural frequency of the system. Since a given mass can only work for one specific frequency, the method of active mass damping has been pursued by researchers to cover a wider frequency range.

Active Damping

The equation of motion (1.4) is expressed as equilibrium of forces. MZ'', CZ' and KZ are the inertia, damping and spring forces, respectively. Comparing Equations (1.4) and (1.3), the control force $F_c(t)$ contains two components that act as damping and spring forces. The conventional force-actuator method, applying direct forces, will require an instant power supply. For large structures, the required power supply will be large. To avoid using heavier actuators, the weighting factors α and β may be chosen such that the feedback force αZ is not significantly larger than $\beta Z'$. This means that the main function of $F_c(t)$ is to increase the damping function. However, in so doing, this form of active control faces the same limitation as passive damping control. That is, they are both most effective when the damping ratio is small, say less than 5%.

Another method of active damping is to use *variable dampers*. A number of investigators believe that the response $X(t)$ of a mass-damping-stiffness system described by Equation (1.2) can be controlled by changing the damping coefficient. (Inaudi and Kelly, 1993 and Kawashima and Unjoh, 1993) They presented computer simulations to indicate the potential of this approach. Future research efforts are necessary to establish the physical meaning of variable damping and relate them to possible design parameters.

Active Members

Both active stiffness and active dampers can be referred to as active structural members. Actuators are one kind of active member.

Another kind of active member is represented by Kobori's cylinder lock. This kind of active member has more potential for practical applications than actuators. In any case, the use of active members is an important and promising approach. The field, however, requires continued research and development efforts.

The above brief review is by no means exhaustive. It is presented to provide an orientation for introducing the basic concepts of RSPM, which is discussed in the following sections.

SECTION 2
REAL-TIME STRUCTURAL PARAMETER MODIFICATION

2.1 Theory of Complex Energy

It has been shown that the theory of complex energy (Liang et al., 1991c) offers an important quantitative description of the dynamic responses of multiple degree-of-freedom structures. The theory of complex energy is briefly summarized in this section.

If a structure is non-proportionally damped, the *Caughey criterion* (Caughey and O'Kelly, 1965) cannot be satisfied, that is, the relationship

$$C M^{-1} K = K M^{-1} C \tag{2.1}$$

does not hold.

When a system is non-proportionally damped, its equation of equilibrium cannot be decoupled in the normal modal space. This means that, in a vibrating system, a certain amount of energy is transferred among the vibration modes. To analytically quantify the energy of the vibrating systems, the concept of *complex energy* was introduced by Liang et al., 1992 and Liang and Lee, 1991d. The real part of the complex energy stands for the energy dissipated, whereas the imaginary part represents the energy transferred. This latter amount of energy remains conservative. For a dynamic system, let the mass M = I, the identity matrix. If Q denotes the eigenvector of the stiffness matrix, it can be written:

$$K = Q^T \Delta_K Q \tag{2.2}$$

where Δ_K is the diagonal eigenvalue matrix,

$$\Delta_K = \mathrm{diag}(\omega^2_{mi}) \tag{2.3}$$

where ω_{ni} is the i^{th} *natural frequency* of the corresponding proportional damped system that satisfies the criterion Equation (2.1).

The following generalized Raleigh quotient can be shown to be complex valued,

$$Q_i^T \; C \; P_i \,/\, Q_i^T \; P_i = 2\,\omega_i\,(\,\xi_i \; + j\,\zeta_i\,) \tag{2.4}$$

where j is the square root of -1, P is the mode shape of the system, the subscript i stands for the i^{th} mode, and ω_i is the i^{th} natural frequency of the system.

It can be proved that in Equation (2.4), ξ_i is the conventionally defined *damping ratio* of the i^{th} mode, which is proportional to the ratio of the energy dissipated during one cycle of vibration, W_{di}, and the energy stored before this cycle, W_i, that is,

$$\xi_i \; = W_{di} \,/\, 4\,\pi\, W_i \tag{2.5}$$

In Equation (2.4), ζ_i is the *modal energy transfer ratio* of the i^{th} mode, which is proportional to the ratio of the energy transferred during one cycle of the vibration, W_{ti}, and the energy stored before this cycle, W_i, that is,

$$\zeta_i \; = W_{ti} \,/\, 4\,\pi\, W_i \tag{2.6}$$

With the help of Equations (2.4) and (2.5), the modal energy equation can be obtained,

$$\omega_i \; = \; \omega_{ni} \exp\,(\,\zeta_i\,) \tag{2.7}$$

where ω_{ni} is defined by Equation (2.3).

In Equation (2.5), the term of natural frequency, ω_{ni} or ω_i , actually stands for the *generalized modal energy*.

The damping ratio ξ_i is always a positive number, since there is always energy dissipation in each mode. The modal transfer ratio ζ_i can be positive, when energy is transferred into this mode; or it can be negative, when energy is transferred out of this mode; ζ_i is zero, when no energy is transferred. In this case, the complex mode reduces to normal mode. If the first mode is complex, then the energy transfer ratio is always greater than zero, that is

$$\zeta_1 > 0 \tag{2.8}$$

The energy transfer ratio for the last mode, ζ_n , is always less than or equal to zero, where the subscript n stands for a system having n degree-of-freedom.

The modal energy Equation (2.7) provides the basis for designing proper control laws to achieve a desired modal energy status for a dynamic system. For example, if a structure is designed to be flexible, its first few natural frequencies must be lower in value. This design lowers the dynamic magnification factor. It can be seen from Equation (2.7) that the modal energy transfer ratio for such a case should be as small as possible. In other words, the non-proportionality of the damping for such a flexible system must be minimized.

When the damping ratio of a structure is very small, say less than 2-3%, the effect of complex energy can be neglected. However, when the damping ratio is higher than 5%, especially when using various EAM to enhance the value of the damping ratio, the effect of complex energy must be examined.

2.2 Real-Time Structure Parameter Modification (RSPM)

Most current active control schemes in earthquake engineering directly apply forces to a structure to suppress the vibration level. The innervating action proposed by the authors modifies the physical parameters (such as the mass, damping, or the stiffness coefficients of the structure and/or certain friction force equal to the normal force times the friction coefficient) to optimally reduce the vibration due to the input forces in real-time. That is, the structure performs an adaptive function against external excitations through nonlinear modification laws (conceptually shown in figure 1-4). Structures that consist of real-time structure parameter modification (RSPM) capabilities in strategic locations are called *innervated structures*. Structures with self-adjusting abilities are referred to as adaptive structures by some authors. RSPM may also be referred to as one of the approaches of adaptive structures.

Innervating action is further explained by figure 2-1, which is different from the conventional active control scheme shown in figure 1-1(b) in several ways. First, innervating action simultaneously changes the mass, damping and stiffness coefficients of the structure. Therefore, the feedback quantities are no longer the forces. The second important characteristic of innervating action and its associate theory, laws and evaluating measures for structures are to contain the structural response within desired limits.

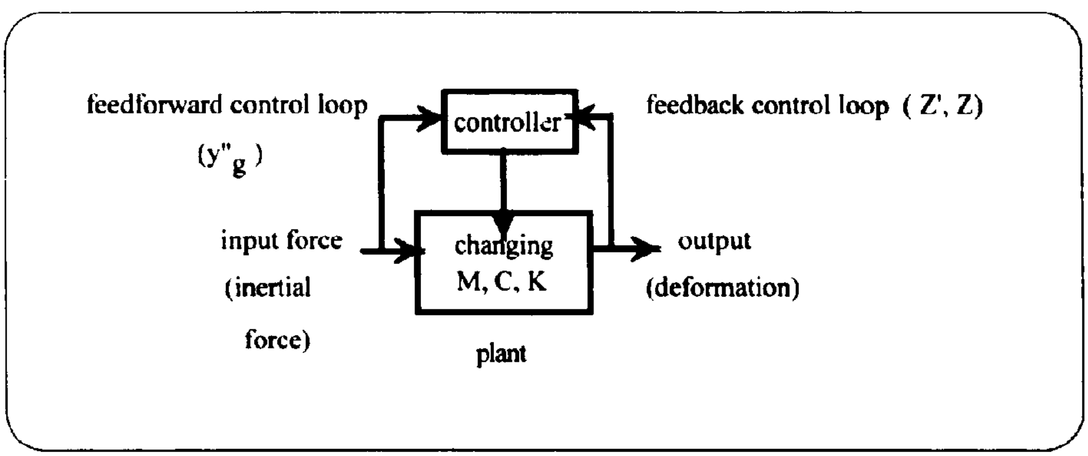

FIGURE 2-1 Innervating Action

Conceptually, the scheme of changing the mass, damping and stiffness may be seen from figure 2-2 by a simple selection system. With a selecting or switching mechanism, the main structure can be connected/disconnected with certain mass/damping/stiffness functions. These functions can be provided by certain substructures, or additional members, supports, bracings, weights, dampers, etc. The selecting mechanism is implemented by "functional switches." It is noted that regardless of which physical parameter is modified, damping is always involved in the RSPM approach. This is illustrated in figure 2-2.

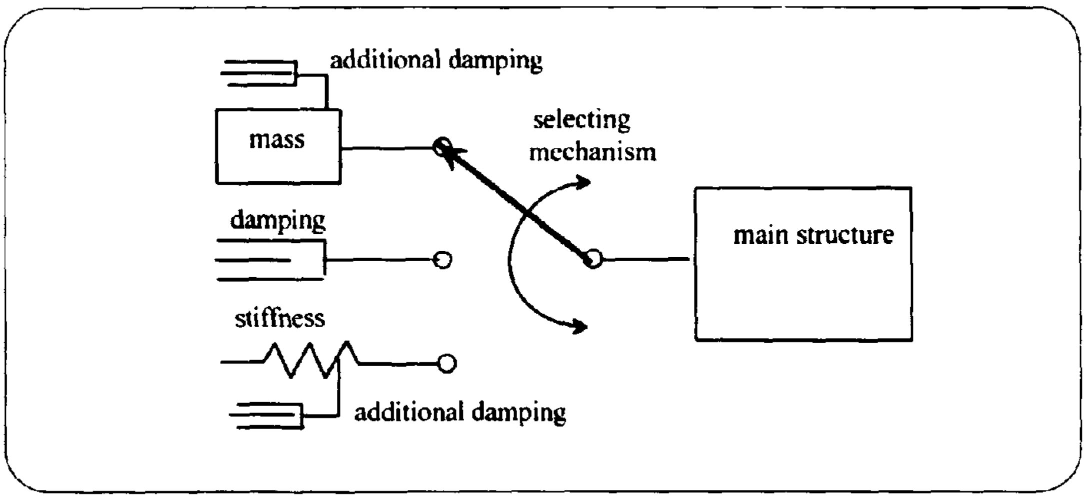

FIGURE 2-2 Selecting Mechanism and Parameter Modification

Consistent with figure 2-2, the equations of motion defined by Equation (1.4) may be rewritten as

$$M(x'', x', x, t)\, Z''(t) + C(x'', x', x, t)\, Z'(t) + K(x'', x', x, t)\, Z(t) = F(t) \qquad (2.9)$$

Equation (2.9) expresses that the mass, damping and stiffness are all functions of time. The function is feedforward/feedback controlled. This equation is not used for the design of innervating action. It is only used to provide a comparison with conventional active controls described by Equation (1.6). In other words, for innervating action, the term $F_c(x'', x', x, t)$, although mathematically equivalent to the control force, does not appear in the control process.

$$F_c(x'', x', x, t) = \alpha(x'', x', x, t)\, Z(t) + \beta(x'', x', x, t)\, Z'(t) + \gamma(x'', x', x', t)\, y''_g(t) + \delta(x'', x', x, t)\, P \tag{2.10}$$

Comparing Equations (2.10) and (1.6), it is seen that all the feedforward and feedback coefficients, α, β, γ and δ are both spatial and time variants. However, the terms $\alpha\, Z(t)$ and $\beta Z'(t)$ (in many cases, also including the coefficient of acceleration) are not active forces. They are not applied to the structure by devices or other external means.

The innervating action does not input any energy into the structure and does not have the stability problem of conventional control. On the other hand, functional switching is a nonlinear process. Although the algorithm can generally be made piece-wise linear, good modification schemes are the key to success in innervating action design.

2.3 Minimal Conservative Energy

Proper innervating action requires rigorous operating laws. These may be examined from an energy consideration viewpoint. Consider the modal energy status of a structure. First of all, there is the energy input from the ground motion. This energy created by an external force is denoted by $W^i_e(x'', x', x, t)$, where the superscript stands for the i^{th} mode because the vibration is considered from the viewpoint of modal energy. Using the method of *modal analysis* is beneficial in structural modification, because the first few vibration modes often contain a major portion of the energy. By proper modal truncation, the dynamic response of structures can be obtained in a relatively simple fashion with sufficient accuracy.

Traditionally, $W^i_e(x'', x', x, t)$ is considered to be the entire input energy to the i^{th} mode of the structure. In 1991, Liang and Lee presented the complex energy theory (1991c,d), in which they advanced the theory of energy transfer among vibrating modes (see Equation (2.7)). This amount of energy, denoted by $W^i_m(x'', x', x, t)$, is the work performed by other vibrating modes of the structure. They have shown that by ignoring this term, significant errors may be introduced in the dynamic analysis of MDOF systems.

Within the structure, there are the kinetic energy, $E^i_m(x'', x', x, t)$ represented by the inertial force; dissipated energy, $E^i_c(x'', x', x, t)$, contributed by the damping force; and the potential energy, $E^i_k(x'', x', x, t)$, generated by the spring force. The kinetic and potential energies are usually conservative. When the coefficients α, β, γ and δ are both spatial and time varying quantities, the equations of motion of the structure become nonlinear. In this case, the term E^i_m can be separated into two parts: a conservative part, $E^i_{mc}(x'', x', x, t)$ and a variable part, $E^i_{mr}(x'', x', x, t)$. Thus, the modal mass $m^i(x'', x', x, t)$ can be represented by a permanent part, m^i_p, and a variable part, $m^i_r(x'', x', x, t)$. That is,

$$m^i(x'', x', x, t) = m^i_p + m_r^i(x'', x', x, t) \qquad (2.11)$$

and

$$E^i_m(x'', x', x, t) = E^i_{mc}(x'', x', x, t) + E^i_{mr}(x'', x', x, t) \qquad (2.12)$$

Similarly, the modal damping coefficient $c^i(x'', x', x, t)$ can be written as the sum of a permanent part, c^i_p, and a variable part, $c^i_r(x'', x', x, t)$,

$$c^i(x'', x', x, t) = c^i_p + c_r^i(x'', x', x, t) \qquad (2.13)$$

and the dissipative energy can be expressed by

$$E^i_d(x'', x', x, t) = E^i_{dp}(x'', x', x, t) + E^i_{dr}(x'', x', x, t) \qquad (2.14)$$

where the subscript p for the term E^i_{dp} represents the energy dissipated by permanent loss of energy due to damping.

Following the same process, the modal stiffness coefficient $k^i(x'', x', x, t)$ can be represented by a permanent part, k^i_p, and a variable part, $k^i_r(x'', x', x, t)$,

$$k^i(x'', x', x, t) = k^i_p + k^i_r(x'', x', x, t)$$

and likewise the potential energy can be expressed by

$$E^i_k(x'', x', x, t) = E^i_{kc}(x''. x', x, t) + E^i_{kr}(x'', x', x, t) \tag{2.15}$$

Thus the energy equation for innervating action may be written as follows,

$$E^i_{mc} + E^i_{mr} + E^i_{dp} + E^i_{dr} + E^i_{kc} + E^i_{kr} = W^i_e + W^i_m \tag{2.16}$$

Here, all the energy terms in Equation (2.16), as well as in the following equations are both spatial and time variables.

The conservative portion of the energy stored in the structure still needs to be minimized, as expressed in Equation (2.16), namely,

$$\min [E^i_{mc} + E^i_{kc}] = \min (E_{conservative}) \tag{2.17}$$

Equation (2.17) is referred to as the Principle of Minimum Conservative Energy.

From Equations (2.17) and (2.16), we have

$$\min(E_{conservative}) = \min[(W^i_e+W^i_m) - (E^i_{dp}) - (E^i_{mr} + E^i_{dr} + E^i_k)] \tag{2.18}$$

In Equation (2.18), the two terms in the first bracket on the right hand side are energy input. The third term represents the energy dissipated by the damping force. The remaining three terms on the right hand side of Equation (2.18) are the energy quantities which can be removed by adjusting the mass, damping and stiffness.

From Equation (2.18), it is clear that the energy dissipated by damping force, E^i_{dp} should be maximized. That is, the damping effect should be increased as much as possible.

Now, all the other energy terms are examined. First, the work performed by the external force, W^i_e is considered. This energy can be affected by two factors. First, the work performed by the external force is a function of the static force and the corresponding static displacement. Most structures are proportioned based on static loads and the static stiffness will not be affected by EAM. In other words, the EAM will not change the static force and displacement. This amount of energy and the corresponding displacement is the lower limit of any EAM. To evaluate an EAM, one may compare the deformation under dynamic loading against the static deformation.

The second factor affecting the term W^i_e is the dynamic magnification, or its reciprocal, the *dynamic impedance*. Any EAM will somewhat influence the dynamic impedance. Structural parameter modification will also influence this factor. Therefore, minimizing the conservative energy maximizes the dynamic impedance in real-time. For example, the mass and stiffness control schemes of Kobori et al., (1991, 1994) are measures of increasing the dynamic impedance. In a later section, it will be shown that there are additional issues to be addressed to increase the dynamic impedance.

Compared to the work performed by the external force, the term W^i_m in Equation (2.18) is a more complicated quantity, because the energy transfer ratio ζ_i can be either positive or negative (see Equation (2.4)). In a real control process, a higher level command for choosing the globally optimal ζ_i (i = 1, or i = 1,2,..) must be issued in order to guarantee that the lowest amount of $W^i_m(t)$ is realized.

The energy quantities (E^i_{mr} +E^i_{dr} + E^i_{kr}) in Equation (2.18) can be removed from the structure by varying the mass, damping and stiffness. For example, consider a component of a member of a structure with a certain amount of mass m shown in figure 2-3. When this component is connected by the functional switch FS_1 to the main structure, the latter gains a certain amount of kinetic energy, because now the two structures vibrate together. When the substructure is disconnected from the main structure, by the switch FS_1 , the added mass is dropped, and the corresponding kinetic energy is removed from the main structure. Similarly, when the switch FS_3 is "on," the stiffness k is connected to the main structure. The change in stiffness k means that certain potential energy is stored. If FS_3 is disconnected later, this amount of energy is removed from the main structure.

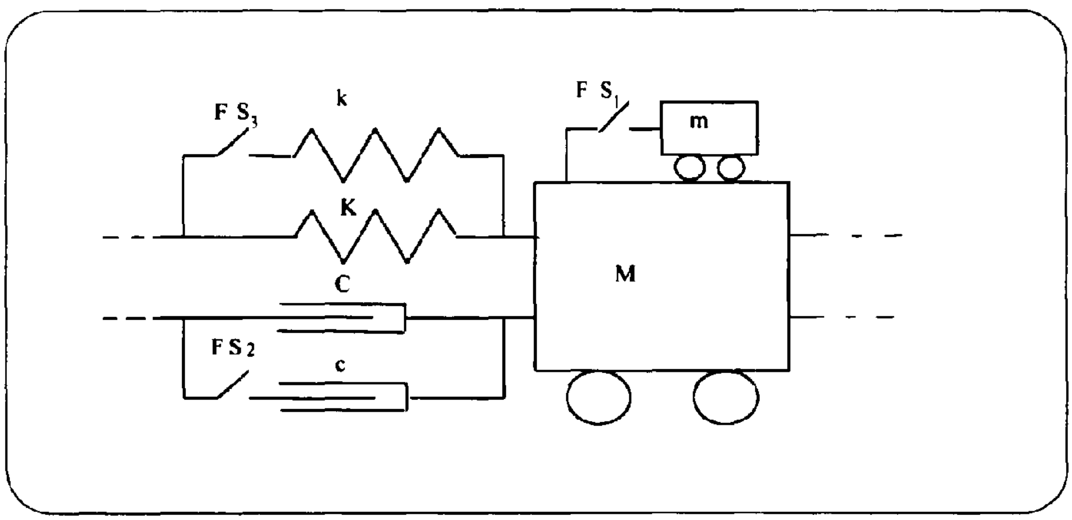

FIGURE 2-3 Energy Removal Mechanism

Changing the status of the switch FS_2 cannot perform the energy-storage-discharge functions. However, it changes the capability of energy dissipation for the main structure. Intuitively, it can be seen that the terms E^i_{mr}, E^i_{dr} and E^i_{kr}, should be maximized. However, maximization of (E^i_{mr} +E^i_{dr} + E^i_{kr}) may also affect the term W^i_m. Therefore, a hierarchical check in the RSPM operating loop must be carried out. The commands for maximizing the terms (E^i_{mr} +E^i_{dr} + E^i_{kr}) are in the lower rank. Another important consideration is that the damping mechanism can be used to remove this amount of energy from the main structure. Or, a portion of this amount of energy may be used to perform certain work against the external force, resulting in an increase in the dynamic impedance.

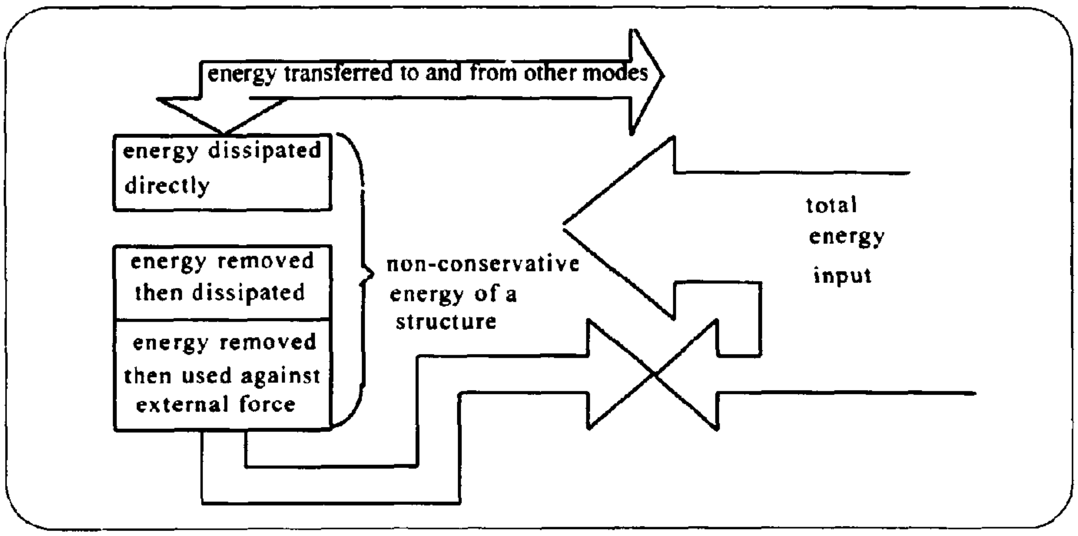

FIGURE 2-4 Energy Status of a Vibrating Structure

In figure 2-4, the energy status of a structure installed with innervating devices is shown conceptually. First of all, the dynamic impedance is increased to minimize the energy input by the external force; then the energy already imported is dissipated as much as possible. One portion of the imported energy is removed, through dissipation by using damping mechanisms. At the same time, the energy removed is used to work against the external force. Meanwhile, the amount of energy transferred by nonproportional damping effect is controlled.

As stated above, innervating action requires the minimization of the algebraic sum of all energy terms:

$$[(W'_e+W'_m)-(E'_{dp})-(E'_{mr}+E'_{dr}+E'_{kr})]$$

without such a global consideration, a reduction of energy may not be achieved.

SECTION 3
INNERVATING DEVICE, FUNCTIONAL SWITCH

It has been established that modifying the physical parameters of a structure can minimize the total conservative energy. Although the principle of minimization of conservative energy is applicable to any active control scheme, for this purpose, the innervating action of RSPM is realized by certain special devices. They are referred to as functional switches.

3.1 Basic Functions

The functional switches work as structural/mechanical connectors, which can be bi-directional or single-directional. Their functions are:

1) Completely rigid
2) Completely relaxed (zero stiffness and damping) and/or
3) Adjustable damping.

The above three functions are called status. For convenience, status 1) is said to be "on," 2) is said to be "off" and 3) is said to be "damp."

One type of functional switch can be a completely stiff connector in one direction and act as a damper in the other direction. The direction and status can also be controlled. One such example is shown in figure 3-1.

Different types of connectors can be subject to 1) tension-compression; 2) torsion; 3) bending and 4) shear, as shown in figure 3-2.

The operational status can be 1) repeated control or 2) monogenetic control. The deformation of the connector can be 1) more than 1 cm up to several dm's, which is considered to be a long stroke functional switch or 2) less than 1 cm, which is considered to be a short stroke functional switch.

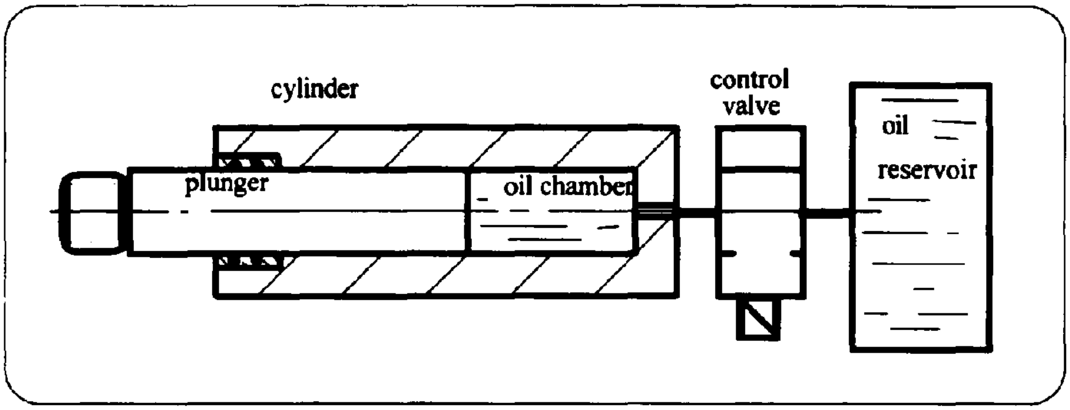

FIGURE 3-1 Single Direction Functional Switch

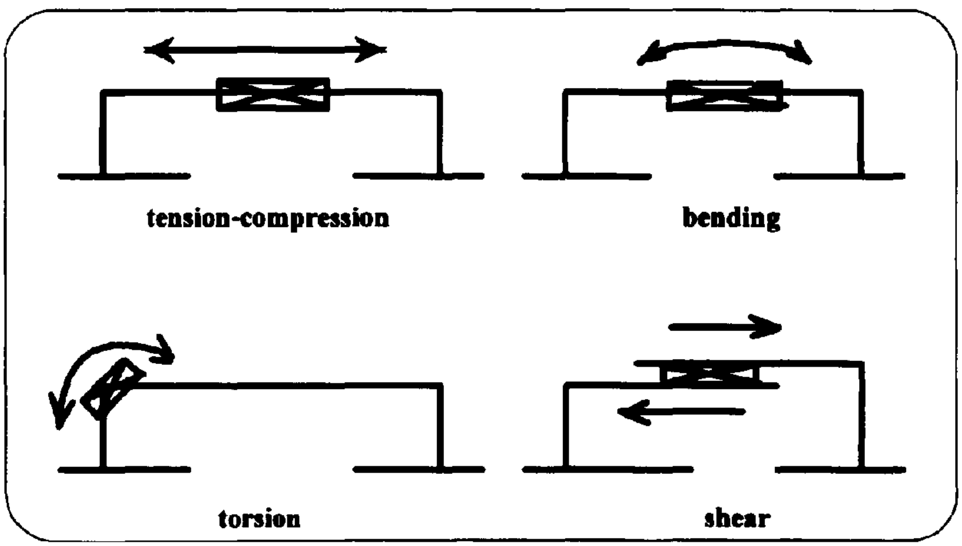

FIGURE 3-2 Different Types of Functional Switches

3.2 Prototype Designs

Monogenetic Functional Switch

The monogenetic type functional switch is used only once. It can be controlled by a safety valve, or a safety bar, or other such device. When the working stress exceeds the allowed stress, the safety bar will be broken and the switch is released to "off." Figure 3-3 shows a tension monogenetic functional switch. A torsion monogenetic functional switch can be designed using the same principle.

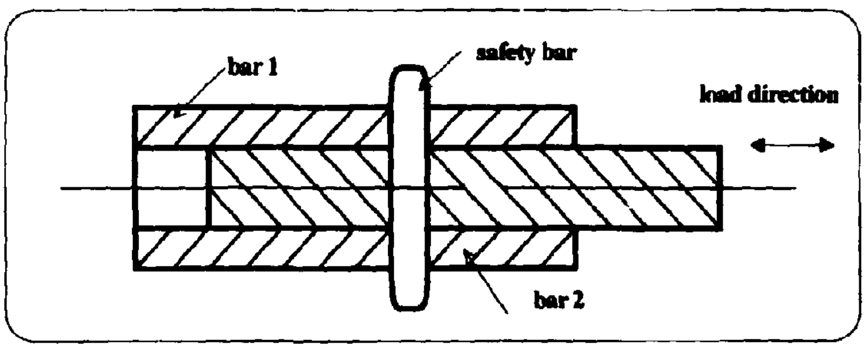

FIGURE 3-3 Monogenetic Functional Switch

Single Direction and Repeated Type Functional Switches

The single direction functional switch has been fabricated and examined (shown in figure 3-1) in a pilot experimental program which is described later in this report. The advantage of using a single direction switch is that they are simple to design and install and, two single direction switches can be used to form a bi-directional switch, which will be discussed in the next section.

As shown in figure 3-1, the single direction switch is assembled by a plunger fitted into an oil chamber. At the end of the chamber, there is a short path to a single direction control valve, which is connected to an oil reservoir. The prototype single direction control valve is assembled by a regular single valve and a regular electric magnetic control valve.

Repeated and Bi-Directional Type Functional Switches

Figure 3-4 shows a scheme for repeated bi-directional functional switches. This design has been used in "semi-active control" for truck vibration absorbers. Recently, Kobori et al., (1990) have used it in active variable stiffness systems. They called it "cylinder lock."

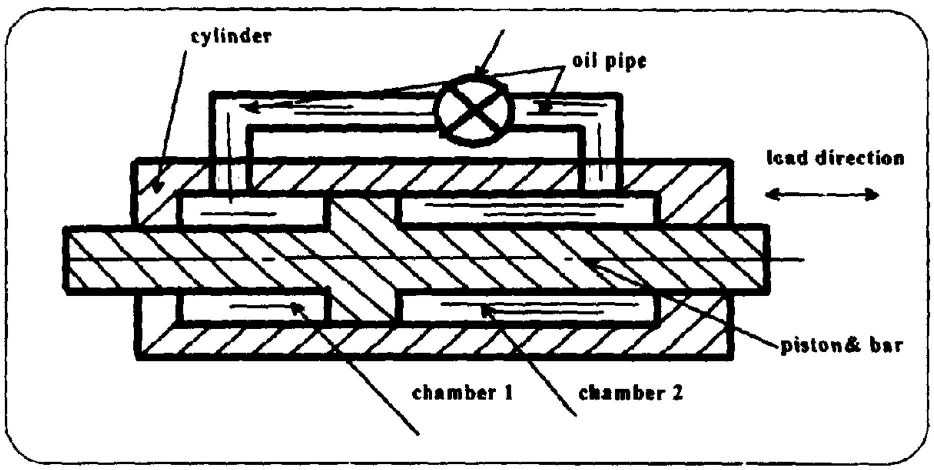

FIGURE 3-4 Repeated Type Functional Switch (Used by Kobori)

The major disadvantage of the "cylinder lock" shown in figure 3-4 is that the oil path may be too long for fast and accurate temporal and position responses. In earthquake vibration reduction, at least several hertz frequency response and several millimeter spatial reaction are needed.

3.3 Design Principles of the Functional Switches

Dynamic Behaviors of the Switches

The dynamics of a functional switch can be understood from examining the behavior of a single direction switch working under an idealized condition. Other types of dynamic behavior of the switches can be easily extended from this basic analysis.

Theoretically speaking, the "switching" action of the device should consume virtually no time. The idealized process can be seen in figure 3.5.

At the time t_0, the switch is initially set at "on." At time t_1, it is predetermined to be "off" and the switch disconnects immediately. The switch is set to "on" at time t_2 and t_4 and set to "off" at time t_3.

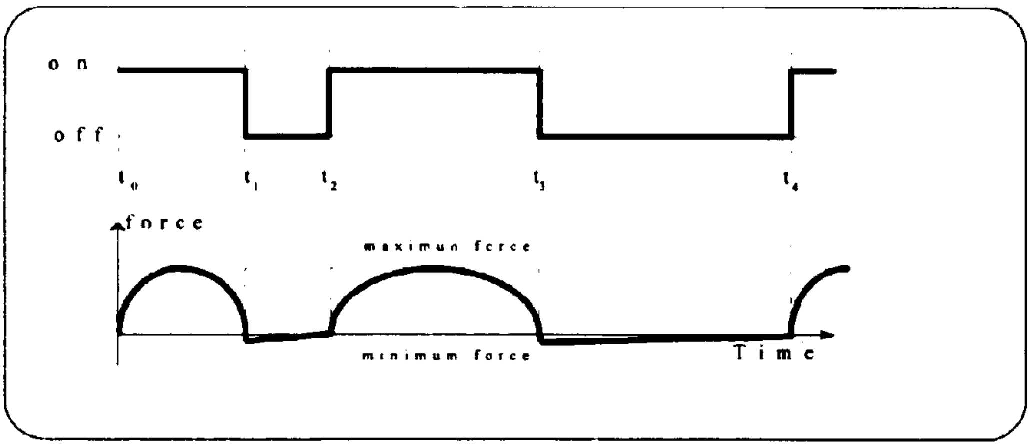

FIGURE 3-5 Idealized Time History Response of a Functional Switch

SECTION 4
MODIFICATION SCHEMES

4.1 Actions of Innervated Structures

The innervating action of Real-time Structural Parameter Modification (RSPM) consists of two major operations. First, the actions of the valves of the functional switches are controlled by an adaptive algorithm. Second, the switching modifies the physical parameters of the structure. The difference between an innervated structure and one with an added active system using actuators is shown conceptually in figure 4-1.

An innervating action, described in this report, is different from typical passive control schemes because it has a sensory system, a decision making unit and switching mechanisms. From the viewpoint of control law, innervating action is also different from the conventionally defined adaptive control, because the directly controlled quantities are the physical parameters. Finally, the innervating action limits the responses of structures to preset bounds while structural control is based on the control theory that targets zero responses for the structure.

When the functional switch of an innervated structure is switched to the "on" position, a heavy mass (to add a significant amount of mass) may be connected to the structure to reduce its natural frequency. The functional switch can also be used to increase the stiffness of the structure in order to reduce the displacement and thereby increase the natural frequency. When the switch is turned "off", the added mass and/or stiffness is released. When the switch is set at "damp," with adjustable damping, the energy dissipation capacity of the structure can be increased as needed. When this state is eliminated, the damping force can be reduced.

In RSPM, there are only three output states, so that the innervating action algorithm can be much simpler than those of regular actuator methods. Thus, the speed for real-time computing can be increased significantly, which is a key issue in active or adaptive control. And, since no energy input is applied to the structure by the control device, stability and robustness are no longer important issues in RSPM.

To command RSPM actions, a hierarchical model consisting of several loops is established, based on the behavior of human body motion control from local reflexes to different levels of body motion controls with and without using the central nervous system (see, for example, McMahon 1984). The following describes this four loop control procedure in more detail.

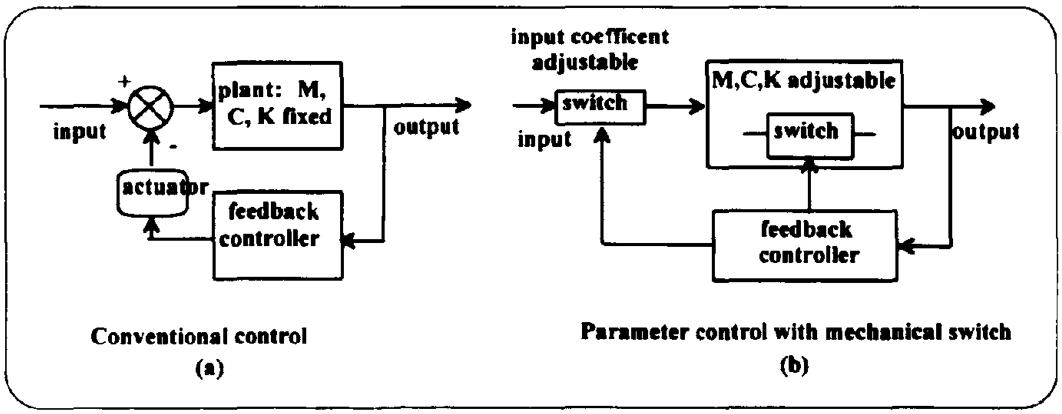

Figure 4-1 RSPM with Functional Switches Compared with a Typical Active Control Scheme

4.2 Innervating Action Hierarchy

To realize the RSPM process described in figure 4-1(b), the functional switches must perform according to certain hierarchical commands. The lowest level of the command is issued for specific purposes at the local level. For example, when a switch is dedicated to changing the stiffness of a structural member, it will receive the command from a special local unit. This unit consists of sensors that detect certain given quantities which are locally controlled. It also contains a decision-making module that can be a dedicated computer or a simple logic circuit. This local unit also has its own amplifier to issue the command with low electrical impedance. Another example of this lowest level command unit is a switch to change the mass of the structure by connecting it to a given mass.

The above loop of sensor-decision making- voltage amplifier-power amplifier-valve of the switch is the lowest hierarchical loop, called the L_1 loop. This loop acts all the time, except when it is overridden by loops of higher ranks. Since the feedback quantity for this loop is the velocity, it may also be called the velocity loop.

In actual practice, when the stiffness of a structure is changed, the mass and/or damping should also be changed. Therefore, it is reasonable to see many L_1 loops in action simultaneously.

A second loop of command is introduced to adjust the unbalanced forces, which cause the increase of velocity and acceleration of the structural responses at the local regions. A good example of the influence of the unbalanced force is to examine the method of variable stiffness (Kobori 1994), which is shown in figure 4-2. If the input is sinusoidal, the velocity and force are equal to zero when the displacement is at its peak value. Under this ideal condition, Kobori's variable stiffness method works, because virtually no overdraft can occur. However, at such a position of zero velocity, just after the stiffness is reduced, a force acting in the direction of greater displacement (or reduced stiffness) can suddenly develop.

This unbalanced force cannot be predetermined in the control algorithm, because earthquake ground motions are random in nature. What can be done is to prevent the increase of displacement by not letting the stiffness decrease. To carry out this function, a separate loop is established, the L_2 loop, to provide feedback of the force information. This loop is called the force loop. After sensing the undesired force, a command will be issued to the control valve of the functional switch such as the one shown in figure 3-1 to delay the opening time of the valve. This command can override the L_1 loop, although the L_2 loop is also a local loop. It is to be noted that the L_2 loop is also concerned about the direction rather than quantitative measures of the motion. This may be explained by the forward motion of a human body caused by an unexpected "push" from the back. The reaction of the body is first to adjust its muscle system and weight distribution to reverse the forward momentum to avoid "falling on the face" (see Pollack 1990).

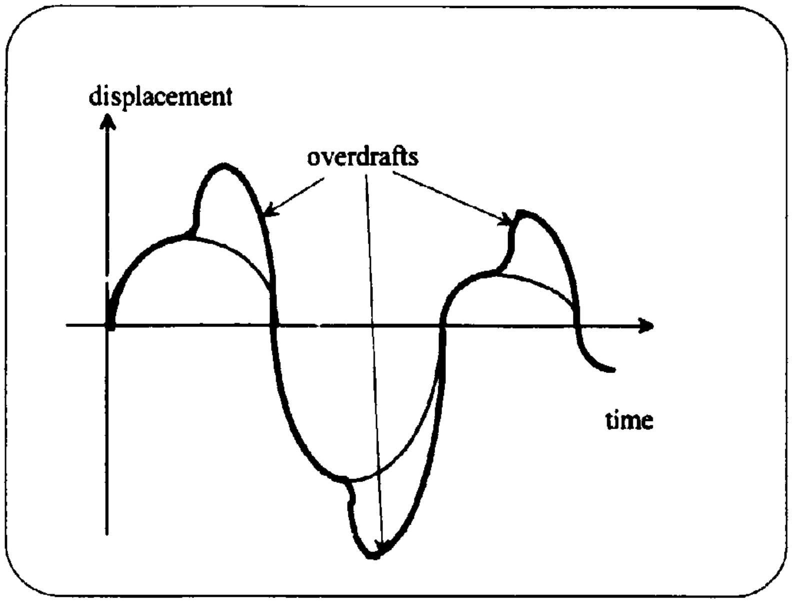

FIGURE 4-2 Improper Control at Level One Caused an Overdraft Condition to Occur

The next higher level of command is issued by a control module which calculates the amount of necessary changes in mass, damping and stiffness simultaneously. The principle of minimal conservative energy is used as a criterion to deduct proper operation commands. This is the third loop, referred to as the L_3 loop. The basic function of the L_3 loop is to check the efficiency of the performance of the L_1 and L_2 loops by calculating the energy status of the system. In general, it does not issue commands very often, unless certain highly ineffective actions (from the structural systems' viewpoint) are initiated by the L_1 loops. Theoretically speaking, the L_3 loop should be the main control loop. However, the current state-of-the-art of determining the energy status of a system is based on the signals of the displacement and/or acceleration, which have 180^0 phase difference. These signals are either measured and/or calculated. To date, it is still difficult to consider them globally in real-time for system optimization. This "displacement" loop may be improved when the fundamental knowledge base in structural dynamics is expanded.

The highest level of command of RSPM is a safety-check loop, the L_4 loop. This loop works under criteria totally different from those of the other three loops. The criteria are established by various safety concerns that are not directly related to the improvement of structural performance. They may be internal stress, absolute acceleration, energy accumulation, and so on. When the structure is in its linear region, these quantities may be a linear transformation of the structural deformation. However, a structure is often designed to deliver ductility (inelastic deformation), which is more difficult to describe analytically. An alternative measurement/ calculation system may need to be introduced to monitor these quantities. Whenever any critical quantity is reached, commands are issued by the monitoring module to override the lower level commands, in order to ensure stability and safety of the modification process. Returning again to the example of a human body subjected to an unexpected "push" from the back, if "falling forward" is inevitable, the decision of the body to stiffen and to raise the upper limbs to protect the face and head are typical actions commanded by the L_4 loop (see Berne and Levy, 1993).

The hierarchy for the innervating action is described in figure 4-3.

To realize the hierarchical actions, first consider one of the basic schemes of seismic vibration reduction for an MDOF system, shown in figure 4-4. Initially, all the switches are set to "On". The structure is then subjected to a multi-dimensional ground motion input. The dynamic responses, the internal and external forces, the modal energy status and/or ground motions are subsequently measured and/or calculated. A system identification unit may be used to obtain certain modal parameters. All measured/calculated information is kept in the storage unit. When a response level exceeds the preset value, the central decision unit will trigger the action of local decision units. Another important function of the central decision unit is to identify the optimal set of specific functional switches and their on-off status with respect to global demands. For example, a local region in a structure may achieve a minimal response but this minimal response may lead to undesirable deformation at a different location/region of the structure. On the other hand, a local region may develop a large deformation and absorb a significant amount of energy so that the level of global vibration may be reduced. Thus it is important to consider the optimal performance of a structure at the global level.

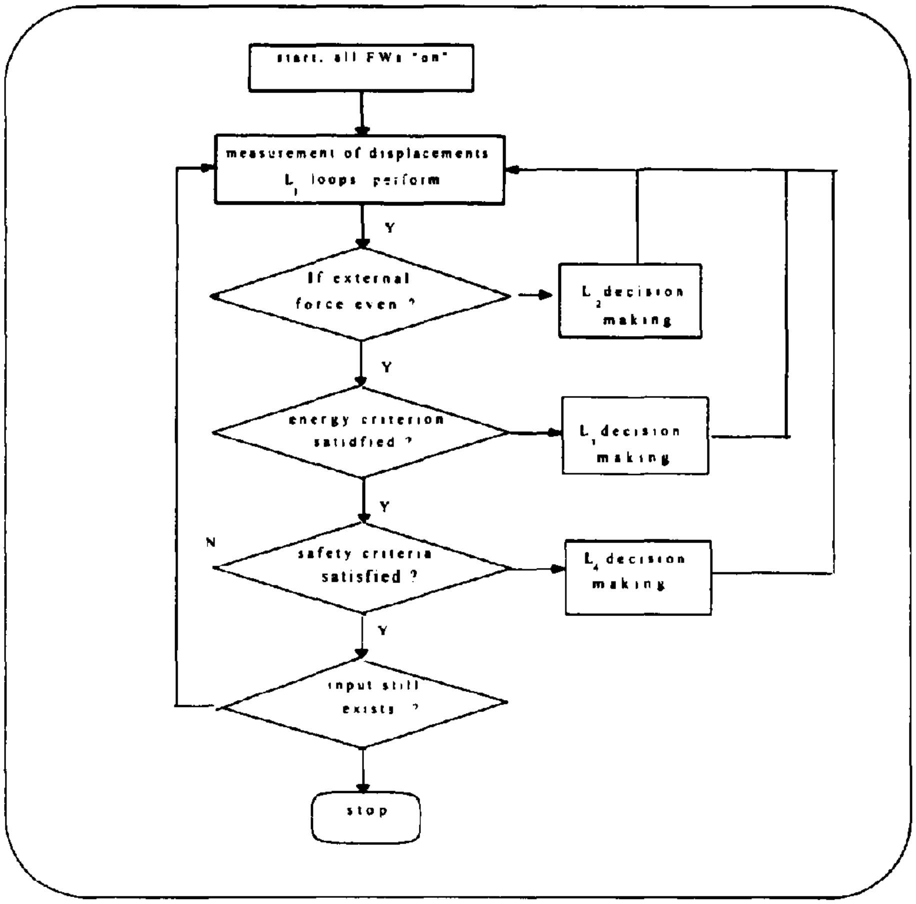

FIGURE 4-3 Hierarchy of Innervating Action

Upon receiving the commands from the central unit, the local decision units then calculate the optimal results and give the on-off orders to the functional switches individually. This process will be repeated at every subsequent time interval until the external excitation and the structural vibration levels are reduced to values within the bounds. Again, a safety unit is provided to safeguard possible malfunctions of the RSPM system.

Some details of the different levels of innervating action are given below.

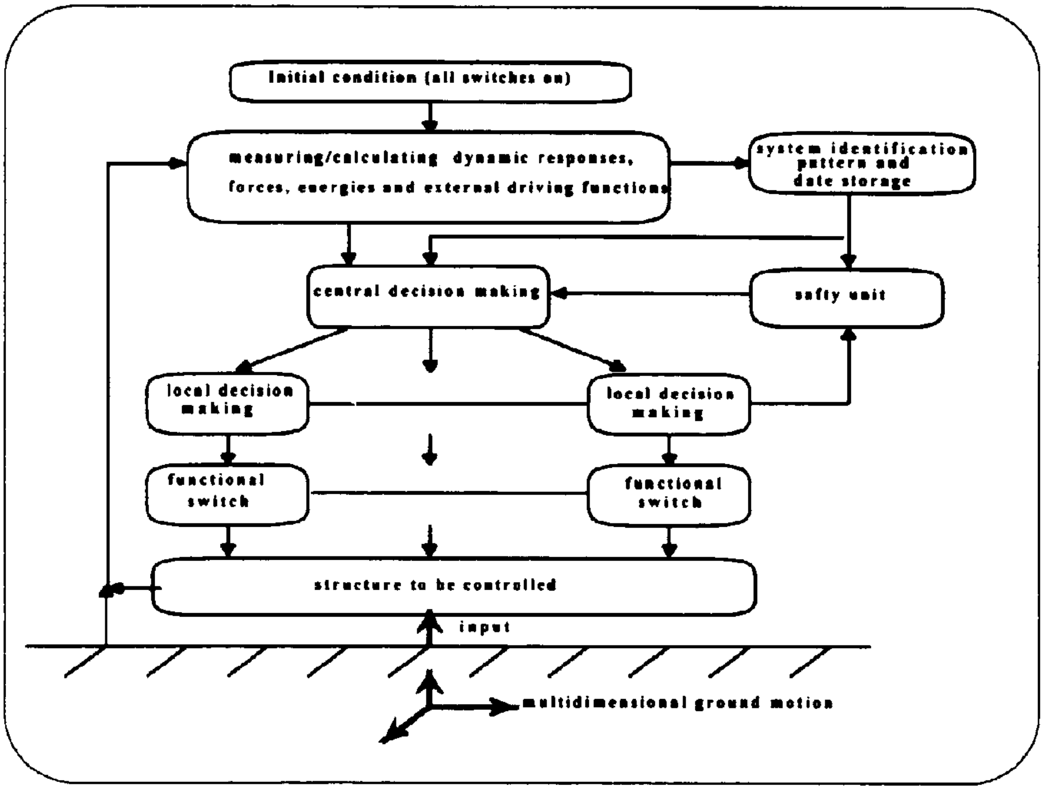

FIGURE 4-4 Vibration Reduction Scheme for an MDOF System

4.3 Functions of the L_1 loop

Stiffness-Switching

The L_1 loop is the most frequently activated loop in a typical RSPM scheme. Figure 4-5 shows one of the methods of switching stiffness suggested by Kobori et al. (1990), which can also be used in the L_1 loop.

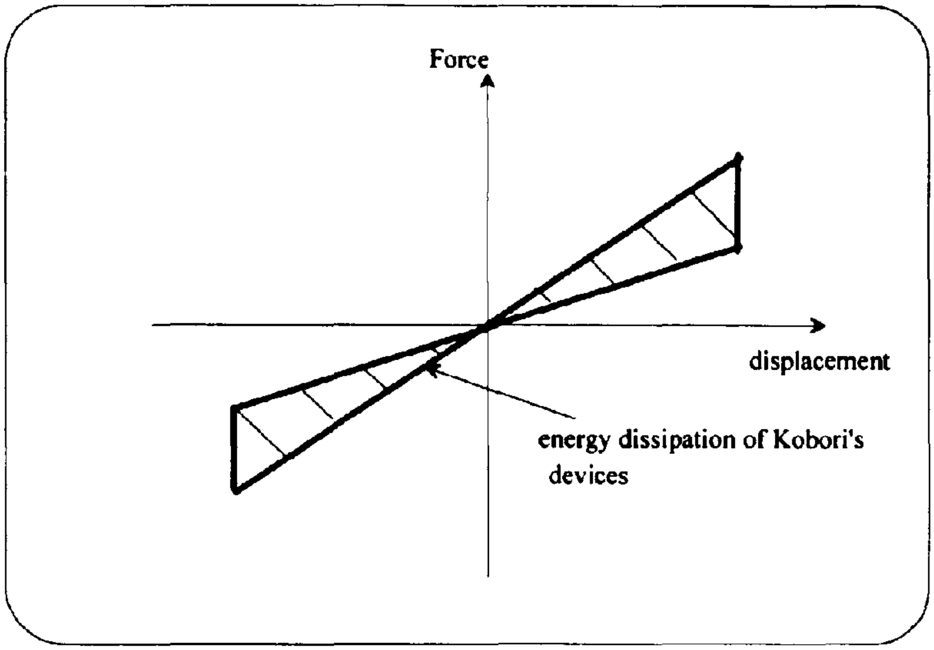

FIGURE 4-5 Characteristics of Push Pull Switches

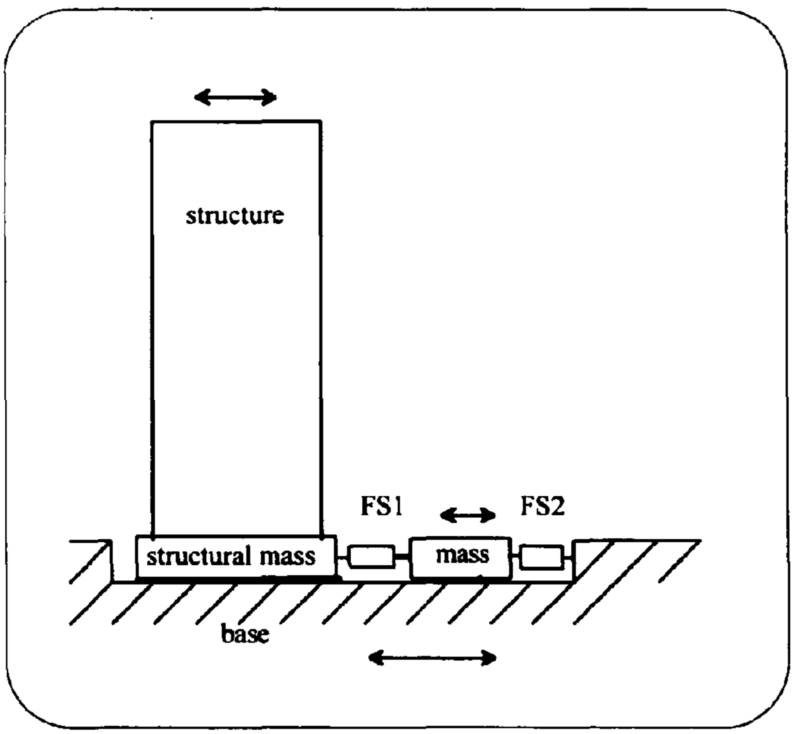

FIGURE 4-6 Example of Mass Switching

Mass Switching

Similar to stiffness-switching, switching of mass is also determined from velocity feedback. Figure 4-6 shows examples of mass modification. The additional mass is connected to the main structure through the switch FS1. Initially, FS1 is set at the "on" position and FS2 is "off." When the structure moves, the added mass supplies an inertial force against the movement. When the added mass gains the maximum speed and hence the maximum kinetic energy, switch FS1 is disconnected, separating this added mass from the main structure. The corresponding amount of energy is later dissipated through switch FS2, which is switched to the "on" position immediately after FS1 is switched "off."

Damping Switching

There are various methods in damping switching (see Kobori et al., 1990, 1991, 1994). At the local level, when more energy is damped, smaller displacement will result. Therefore, it may appear that damping switching is not necessary at first. However, damping switching is needed when optimal performance of a structure at the global level is considered. This will be discussed in a later section.

4.4 Functions of the L_2 Loop

The basic function of the L_2 loop is to handle the overshoot problem in the structural dynamic response. This loop does not initiate any action, if the incoming excitation is not likely to make an undesirable input to the response when a switching action is executed.

When an unbalanced force is about to develop on overshoot, a command will be issued to override the action of the L_1 loop. This control loop, together with the L_1 loop, is shown in figure 4-7, in which the displacement loop is a feedback loop and the force loop is a feedforward loop. When the force exceeds a certain preset value, the switch will be commanded to change its status either to move ahead or to delay a certain amount of time as shown in figure 1-4. That is, with the L_2 loop, the control law shown in figure 1-4 can be achieved.

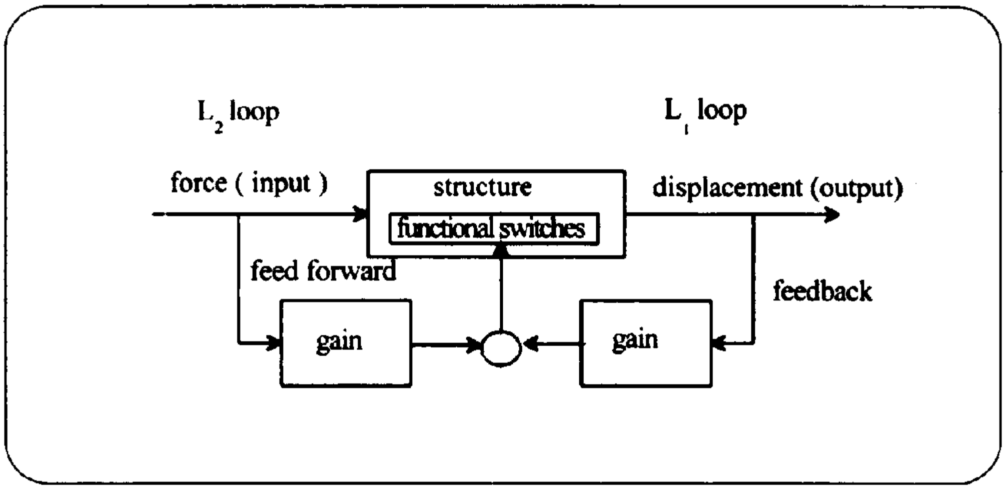

FIGURE 4-7 Action Scheme for Two Local Control Loops

4.5 Functions of the L_3 Loop

Often, all the displacements are reduced at the local region according to the prescriptions of the L_1 and L_2 loops. However, with these two loops, the structure may not necessarily operate in an optimal fashion. Sometimes, larger displacements are allowed at some local regions to further reduce displacements at critical locations. In fact, it is sometimes more desirable to magnify the displacements at selected locations to achieve a desired response configuration. Thus, a global optimal view to properly distribute the displacements throughout the structure is necessary. This is the purpose of the L_3 loop.

To accomplish desirable distribution of displacement, the criteria must first be established. In Section 3, the principle of innervating actions was presented. Based on these principles, certain control criteria governing structural modification can be deduced regarding internal force; displacement (velocity and acceleration); structural energy (including modal energy) and input energy. To mathematically realize the desired displacement distribution, constraints must be introduced such as the residual displacement and the maximum force (displacement, acceleration).

The same operation criteria can also be applied to quasi-static loading considerations, such as the controllable ductile connections, and others. The corresponding control algorithm can be a regular proportional integration and differentiation (PID) feedback, a state space feedback system, modal space method, an optimization scheme, or an adaptive and intelligence control algorithm. Some specific approaches for L_3 loop actions are given below.

Action of L_3 Loop Based on Energy Criterion

Based on results of computer simulations, one of the desirable approaches to optimally distribute the displacement is to realize an even rate of energy dissipation. Such a direct energy criterion can be implemented into the L_3 loop to balance the modal energy (conservative energy). The distribution can be easily realized in the spatial domain, which is approximately equivalent (but not precisely) equal to distribution in the modal domain. In this case, the L_3 loop is used to check the modal energy status and to prevent large amounts of energy transfer from other modes into the first mode by issuing a command to adjust the distribution of the energy absorbing actions. At present, an analytical model and/or mathematical solution for this displacement adjustment is still under development. A neural network model is used in a pilot experimental program, which will be discussed later. One of the drawbacks of direct energy criterion is the slow reaction speed due to the required integration related to the calculation of energy quantities. Successful implementation of the energy criterion will be an important milestone to achieve better results for optimal displacement distribution of the structure.

Action of L_3 Loop Based on Velocity-Displacement Criterion

Besides the direct energy criterion, the maximum velocity-displacement criterion may also be used in global considerations. The basic idea is, wherever the velocity and/or displacement exceed the preset bound, the L_3 loop is activated to adjust the displacements at specific portions of the structure. The method is faster than the direct energy method. It is still in the development stage.

Modified Associative Memory Approach

A self-learning algorithm by Modified Associative Memory Modification (MAMM) method has been developed for the L_3 loop. Associative memory control may be regarded as an improved neural network control. Instead of using the three-layer neural network, an associative memory (AM) algorithm uses a two-layer intelligent database network. It contains self-learning, on-line identification and decision making functions. Its computing speed can be a thousand times faster than a regular neural network. Because of the speed, it can be used with regular PC's (with math co-processor) (Xu et al., to be published). For most civil engineering structures, precision control is not required. It is reasonable to lose a certain degree of accuracy for simplicity and speed. This is the motivation for using the modified associative memory approach. Figure 4-8 shows a general scheme of the MAMM for structural parameter modification.

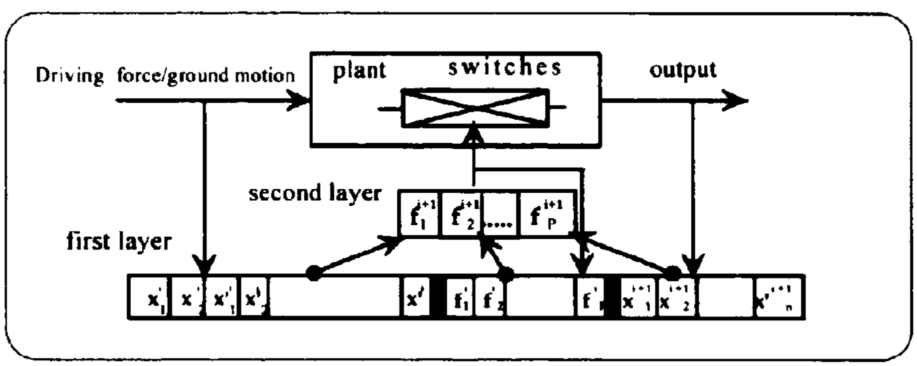

FIGURE 4-8 Scheme for MAMM

The advantages of MAMM are that it does not need precise system identification to model the system, and that it works with both linear and nonlinear structures. The main disadvantage of MAMM is low accuracy when demanded by the speed of computing for complex structures. The basic idea of the MAMM is as follows: The input signals, such as earthquake ground motions, driving force induced by wind gusts, etc., are treated as input states which are stored in an input layer. The control status, such as an "on," "off" and several degree of "damp" (the number of the status are three or more, but less than 10) are treated as an output layer. The two layers are associatively linked by given functions, such as a sharp-hat function. Figure 4-9 shows a block diagram of an MAMM system.

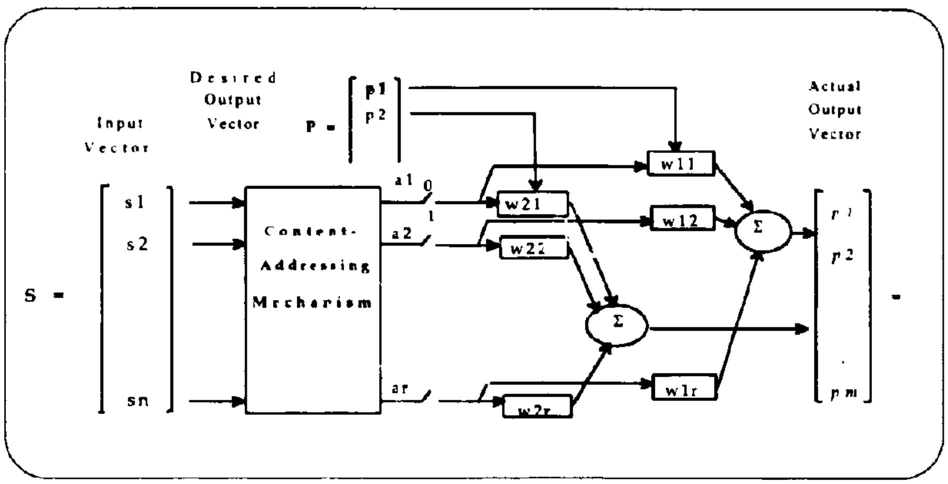

FIGURE 4-9 Block Diagram of a MAMM System

Theoretically speaking, if the initial conditions and the forces acting on the structure are given, (input), the displacement, velocity and acceleration of the structure at any time (output) can be determined. The input and output have a deterministic one-to-one relationship. In real engineering structures, the relationship is very complex because of the random nature of the input excitation and the irregular distribution of the mass and stiffness of the structure. However, for a typical structure, the input-output relationship is still approximately deterministic. The AM control will be an on-line learning of this kind of relationship and decision making (output status). The decision making process can be in milliseconds by using regular PCs and thus, the speed is fast enough to control up to 50 Hz vibrations.

Quasi-Dynamic Control

In plastic design, the ductility of structures is obtained through permanent plastic deformation. A quasi-dynamic approach is developed to increase the ductility of the structure by controlling the rotation capacity of a plastic hinge. The basic idea is the parallel connection of a functional switch to the plastic hinge (see figure 4-10).

When "plastic hinge rotation of a given location is not needed, the switch is turned "on" so that the rotational stiffness of the connection is increased. When rotation of the plastic hinge is needed, the switch is shut off. Figure 4-11 shows the benefit of being able to reestablish full elastic behavior of a moment connection after the formation of a plastic hinge. This feature not only can contribute to achieving desired overall structural performance but also can be installed as a fail-safe switch against structural collapse when the rotation capacity of a connection is exceeded (see L_4 loop).

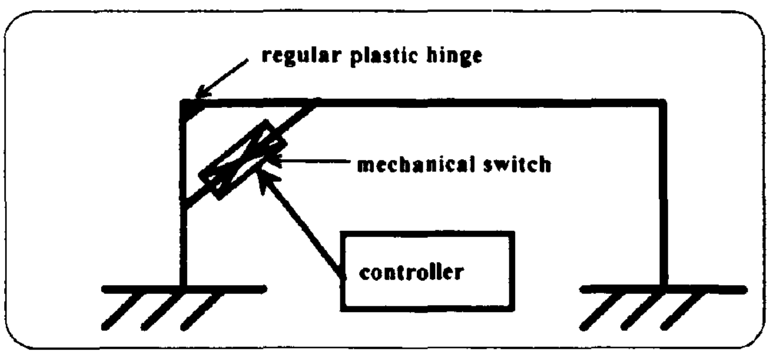

FIGURE 4-10 Plastic Hinge and Functional Switch Design (Illustrated by a single bent)

Quasi-dynamic control can be used in combination with other types of functional adaptive controls. It is also useful under single-direction loading such as wind gusts.

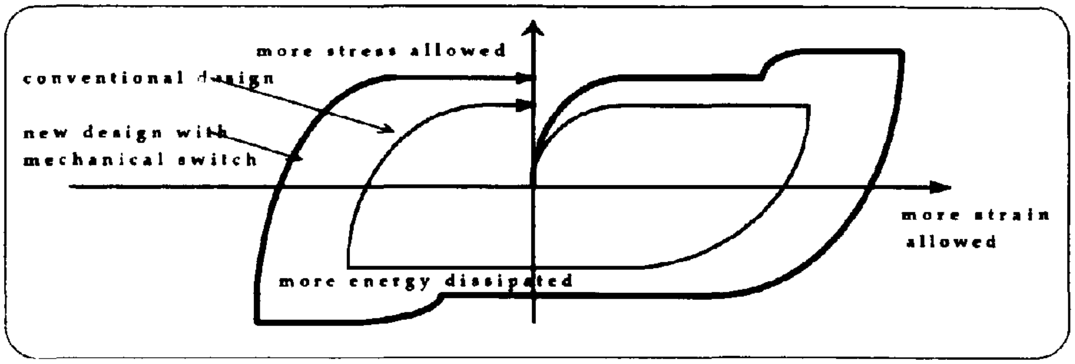

FIGURE 4-11 Typical Stress (stress resultant) vs. Strain (Displacement) Relationship of Quasi-Dynamic Control

4.6 Safety Checks in the L_4 Loop

To prevent possible accident, such as malfunctions in the lower level loops, or the occurance of forces beyond the structure's design values, the L_4 loop is employed to shut down the system. The feedback signal is either the relative deformation and/or the absolute acceleration. However, stress, strain, bending moment, rotation, energy accumulation, or other parameters may be used.

The basic function of this loop is, whenever these quantities exceed preset values, it will temporarily shut down all the on-line controls and change the functional switches to positions to protect the integrity of the structure according to certain preset criteria. These positions and their corresponding criteria are determined to ensure that the structure suffers minimum damage or that it does not collapse.

Energy Criterion

The energy criterion can mainly be used in structures with brittle materials, such as concrete or masonry. The basic idea is that if the energy accumulation exceeds certain pre-calculated levels, all the switches will be turned to "damp" status, to dissipate the energy unsuccessfully controlled by previous efforts.

The all "damp" status is also used when the structure resonates.

High-Frequency Criterion

Suppose a structure vibrates with natural frequencies considerably higher than the main frequency component of the input force, and that the actions taken at the local levels fail to bring the deformation of the structure down to a safe level, the L_4 loop will command the switches to a temporary status so that the structure has the highest stiffness.

Low-Frequency Criterion

Suppose a structure vibrates with natural frequencies considerably lower than the main frequency component of the input force, and that the actions taken at the local levels fail to bring the deformation of the structure down to a safe level, the L_4 loop will command the switches to a temporary status so that the structure has the largest mass.

Another function of the L_4 loop is self-diagnosis. It periodically checks the function of the sensors, different levels of control functions and power supplies, and issues warnings for possible malfunctions.

SECTION 5
RESULTS OF PILOT TESTS

The principles and algorithms described in the previous sections concerning real-time structural parameter modification were implemented in a pilot experimental program. In this section, the test results from a model structure subjected to excitations in one or two directions are presented.

Two kinds of excitations were used: the sweep sine input and the earthquake input. The former is used to seek the equivalent damping ratio and to determine the maximum possible reduction of the vibration level. Earthquake ground motion records were used to examine the effectiveness and capability of the RSPM systems.

In the tests, various input levels were used to examine the linearity of the responses. Various added stiffness were also used to determine the effectiveness of the stiffness-switching methods.

For this preliminary experimental program, results were quite close to theoretical predictions.

5.1 Test Setup

Shaking Table

A small two-directional shaking table in the Seismic Simulator Laboratory at the University at Buffalo was used in the preliminary experimental program. Figure 5-1 shows the shaking table. The dimensions of the table are given in figure 5-2.

The static and dynamic characteristics of the shaking table are given in table 5-I.

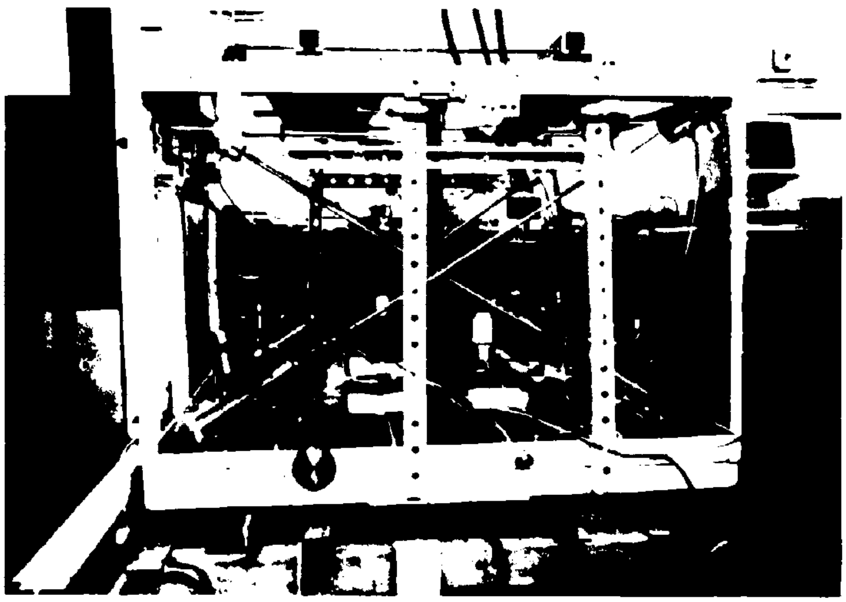

FIGURE 5-1 Two-Directional Shaking Table

Table 5-1 Characteristics of a Two-Directional Shaking Table

Length (mm)	1050
Width (mm)	950
Height (mm)	400
Stroke (N-S) (mm)	250 (peak-peak)
Stroke (E-W) (mm)	350 (peak-peak)
Maximum weight capacity (Kg)	1000
Maximum Frequency (Hz)	30
Harmonic distortion (0-10 Hz)	< 10%
(0-20 Hz)	< 15%
(0-30 Hz)	< 15%

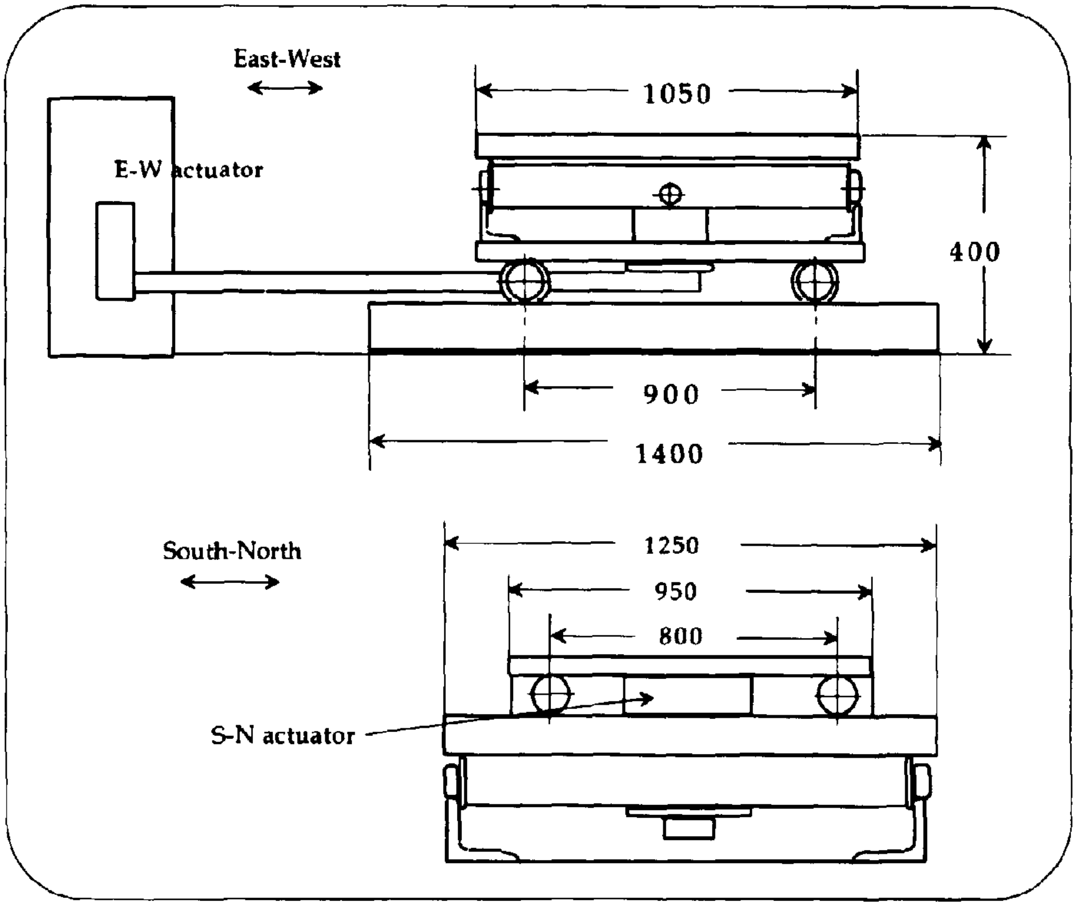

FIGURE 5-2 Dimensions of the Shaking Table

Instrumentation-Sensors

The sensors used in this pilot experimental program consist of the following:

Velocity sensor: Velocity sensors were used primarily in the L_1 loop. For the preliminary tests, several coil type velocity sensors were assembled in the laboratory. The function of these sensors was to output signals proportional to the relative velocity. Whenever relative velocity occurred, the coil moved and cut a magnetic field. Voltage was then generated by the coil.

Displacement sensor: The displacement sensors were mainly LVDT type sensors. Direct recording by pen was also used to calibrate the displacement. For convenience, some records generated by using the pen were used to evaluate the test results.

Acceleration sensors: Two types of acceleration sensors were used. PCB 393C earthquake accelerometers were used to measure the ground motion and the absolute acceleration of the test structure. High sensitivity low-cost accelerometers (pseudo-actuators), developed by the authors, were used for modal testing. They were also used for the same purpose as the PCB 393C accelerometers.

Force sensors: The PCB 204M, 214A, force transducers were used to measure the force. A PCB 108M82 pressure transducer was used to measure the hydraulic pressure inside the functional switches.

Data Acquisition System

A Vax II/GPX and MTS 420.3 data acquisition system with 128 channels was used for A/D converting. PCB Data Harvest 420 signal conditioner was used as anti-aliasing filter.

In addition to the MTS system, two PC/486-based data acquisition systems were also used. The system with an AT-MIO-64F-5 A/D board had 32 channels and the system with DT-2801 board had 16 channels.

Test Structure

The first test structure was a small scale metal frame. It is shown in figure 5-3(a). In the following, it is referred to as Structure 1. The static and dynamic characteristics of Structure 1 are given in table 5-II. The second test structure was a scaled down three-story metal frame. It is shown in figure 5-3(b). In the following, it is referred to as Structure 2.

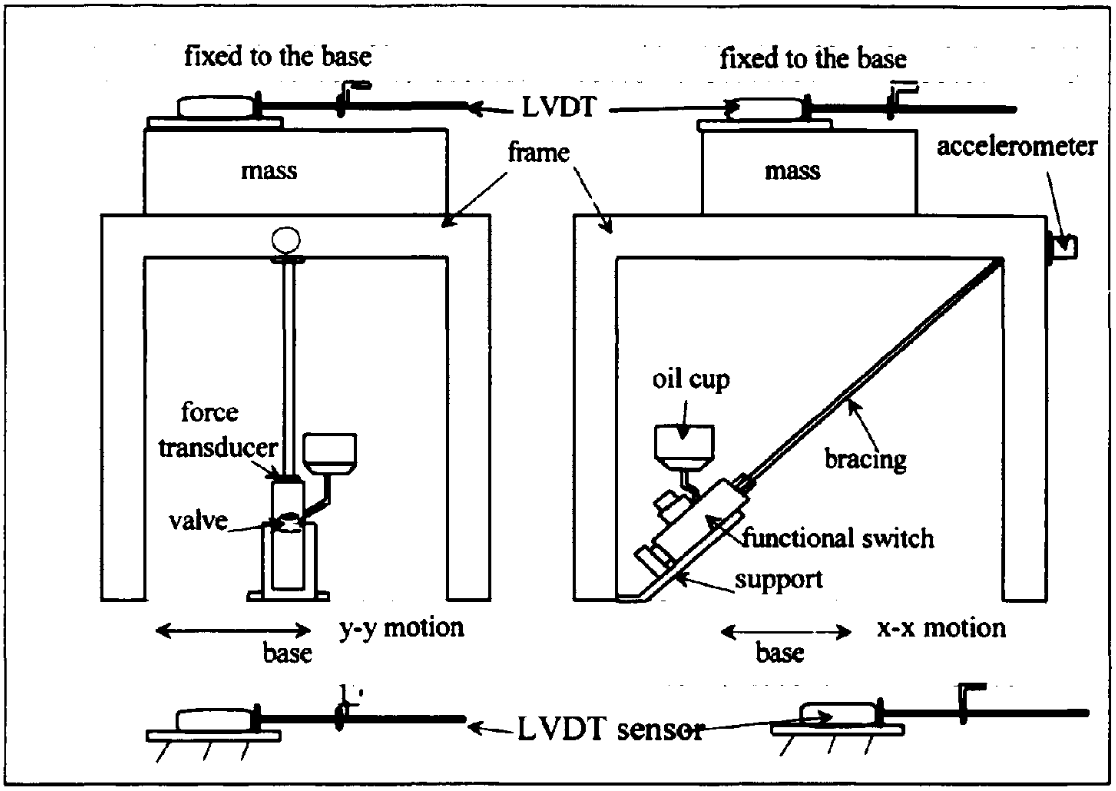

FIGURE 5-3 (a) Test Structure Showing Instrumentation and a Single Functional Switch

Table 5-II Characteristics of the Test Structure

Length (mm)	1000
Width (mm)	900
Height (mm)	1500
Weight (Kg)	250
Stiffness (N/mm) (E-W)	40000
Natural frequency (Hz)	First mode: 2.1 Second mode: 5.5 Third mode: 17.5
Damping Ratio (%)	First mode: 6.9 Second mode: 5.5 Third mode: 7.9

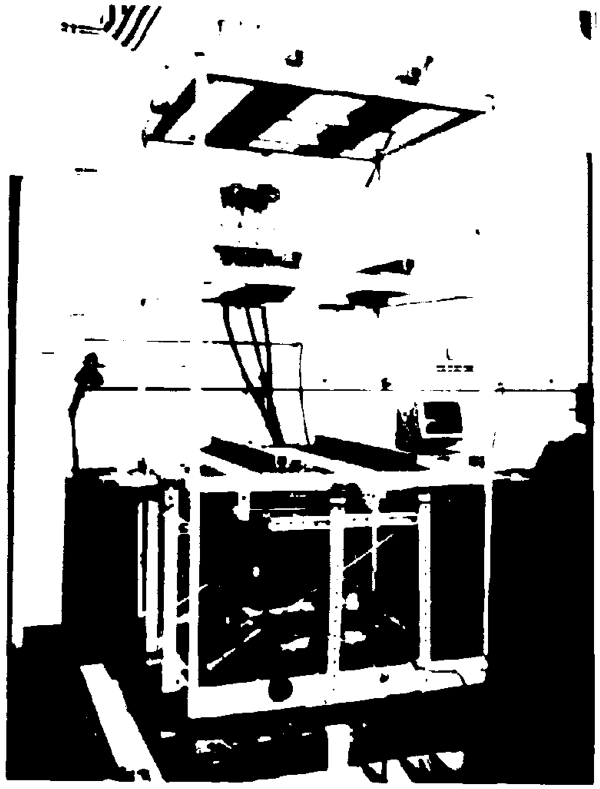

FIGURE 5-3 (b) Three-Story Test Structure (Structure 2)

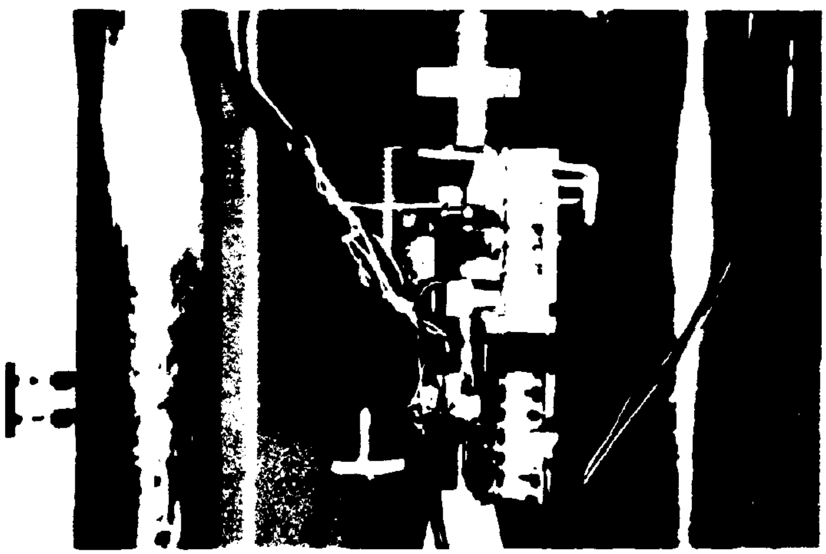

FIGURE 5-3(c) Functional Switches

5.2 Sweep Sine Test of Structure 1 with a Single Functional Switch

In this section, test results of the structure with a single functional switch are presented and discussed. The purpose of using only one functional switch (shown in figure 5-3 (c)) was to examine its performance and the efficiency of using L_1 commands for the innervating action. During the tests, several inputs were used, which include constant acceleration, and constant displacement input at different levels.

Figure 5-4 shows the peak values of the relative displacement between the ground level and the roof level with constant acceleration input. The input level was 0.1g. In figure 5-4, five cases were compared: 1) the structure with a single RSPM functional switch; 2) the structure with one rigid bracing whose stiffness was the same as that of the switch in the "on" position; 3) the structure with one viscous damper which was a functional switch in the "damp" position, (damper #1); 4) the structure with two viscous dampers which were two functional switches in the "damp" position (damper # 2); and 5) the structure with the same dampers as those used in case 4) plus two additional viscoelastic dampers (damper # 3). Table 5-III gives the equivalent damping, maximum deformation and percentage reduction of these five cases.

Table 5-III Sweep Sine Test with a Single Functional Switch, Constant Acceleration Input

	Rigid Bracing	Damper 1	Damper 2	Damper 3	Functional Switch	
					Experimental	Theoretical
Damping ratio (%)	8.1	13.5	18.6	23.1	33.0	34.0
Maximum deformation (mm)	47.5	28.0	26.9	26.3	11.9	10.0
RSPM reduction (%)	75.0	57.5	55.8	54.8		

The actuator of the shaking table is controlled by an MTS controller that has a built-in displacement feedback loop, and is therefore able to compare the displacements more precisely than the acceleration. To examine the linearity of the RSPM systems, constant displacement input at different levels was used, as described in the following.

Figure 5-5 shows the peak values of the relative displacement between the ground level and the roof level of the test structure. The constant displacement input level was 4 mm. The equivalent acceleration level at the resonant frequency was about 0.1 g. Similar to the cases shown in figure 5-4, five cases were compared in figure 5-5: 1) the structure with a single RSPM functional switch; 2) the structure with two rigid bracings whose stiffness was the same as that of the switches in the "on" position; 3) the structure with one viscous damper which was a functional switch in the "damp" position, (damper # 1); 4) the structure with two viscous dampers which were two functional switches in the "damp" position (damper # 2); and 5) the structure with the same dampers as those used in case 4) plus two additional viscoelastic dampers (damper # 3). Table 5-IV lists the equivalent damping, maximum deformation and percentage reduction of these five cases.

Table 5-IV Sweep Sine Test with a Single Functional Switch, Constant Displacement Input (4mm)

	Rigid Bracing	Damper 1	Damper 2	Damper 3	Functional Switch	
					Experimental	Theoretical
Damping ratio (%)	7.9	12.9	17.2	19.4	32.7	34.0
Maximum deformation (mm)	32.0	15.1	12.6	12.0	8.2	7.5
RSPM reduction (%)	74.4	45.7	34.9	31.7		

When the constant displacement input level was increased up to 12 mm, the peak values of the relative displacement between the ground level and the roof level of the test were also recorded. The equivalent acceleration level at the resonant frequency was about 0.3 g, which was about three times the value used in the test described in figure 5-4. In this case, three cases were compared: 1) the structure with a single RSPM functional switch; 2) the structure with two rigid bracings whose stiffness was the same as that of the switches set in the "on" position; 3) the structure with two viscous dampers which were two functional switches set at the "damp" position and with various additional viscoelastic dampers.

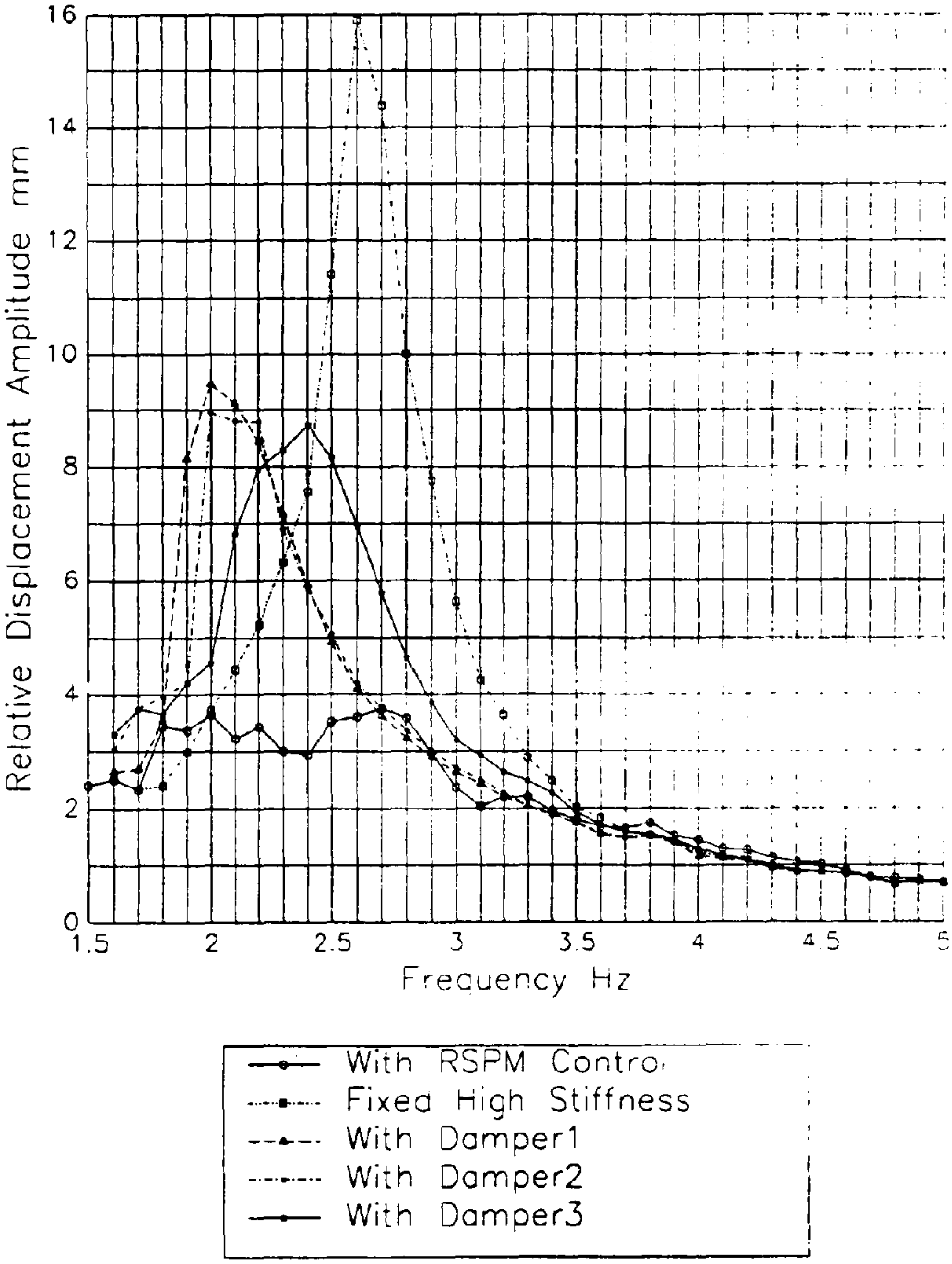

FIGURE 5-4 Single Switch RSPM, Constant Acceleration Input

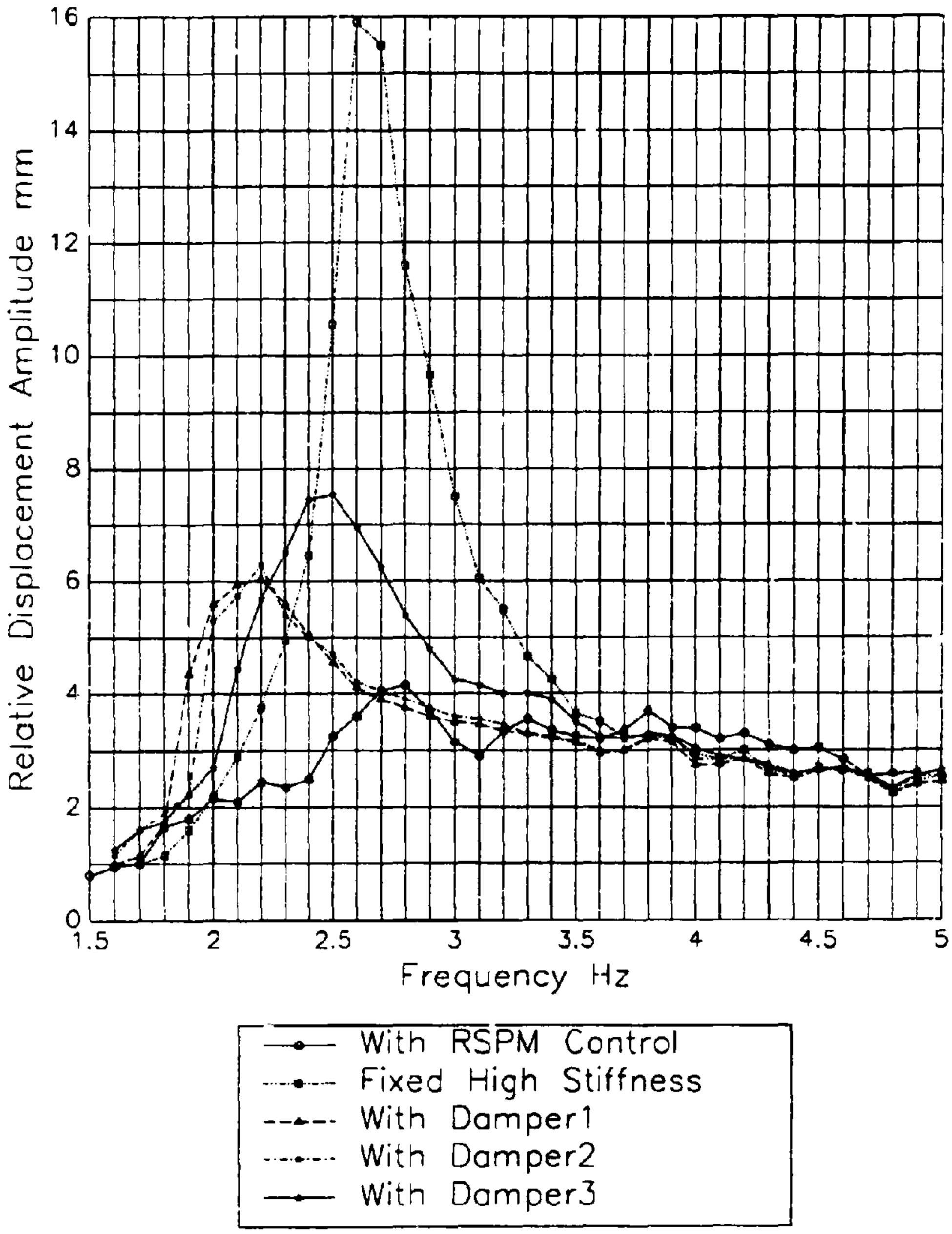

FIGURE 5-5 Single Switch RSPM, Constant Displacement Input

In this test, damper # 3 was chosen (previously explained), which provided the largest damping ratio. It is because RSPM can yield a considerably higher damping ratio than that contributed by passive control. Therefore, it is no longer necessary to compare with the case with small damping.

Table 5-V lists the equivalent damping, maximum deformation and percentage reduction for these three cases.

Table 5-V Sweep Sine Test with a Single Functional Switch, Constant Displacement Input (12mm)

	Rigid Bracing	Dampers	Functional Switch	
			Experimental	Theoretical
Damping ratio (%)	8.3	17.2	32.2	34.0
Maximum deformation (mm)	88.2	68.1	25.4	25.0
RSPM reduction (%)	71.2	62.7		

The above tests were carried out to examine the dynamic behavior of the functional switch. In order to properly realize the RSPM, many functional switches will be used in practice. However, from the above results, of only one functional switch with the L_1 command, it was clear that RSPM can provide significant vibration reductions. Compared to a stiffness added design (rigid bracing), the RSPM can achieve more than a 60% vibration reduction. In this pilot test program, the damping ratio of the test structure was about 8%, which was in general larger than the regular damping ratios of real world structures. In the latter, the damping ratio of the first mode of a structure was probably within 2% to 4% (see Liang and Lee, 1991d). Most building codes suggest a 5% damping ratio. The reason a high damping ratio was used in this pilot test program was to ensure that the structure did not collapse when large input levels were used. This means that the reduction percentages listed in the above tables were conservative.

Another observation made from the pilot tests was the good agreement of the RSPM results between the theoretical analysis and experimental data. For maximum displacements and the damping ratios, the errors were less than 10%.

The linearity of the RSPM was examined by increasing the input level. The basic process of RSPM was nonlinear in nature, because of nonlinear feedback algorithms. However, the output (the displacement) of the innervated structure was almost linear. This may be an important characteristic of RSPM for engineering applications once it fully developed.

The above results were only for one functional switch and with only the L_1 level command. In the following, the test results from two functional switches will be discussed.

5.3 Sweep Sine Test of Structure 1 with Double Switches

In this section, results of the push-pull switch pairs were discussed. The excitations were sweep sines. The purpose of these tests was to examine the results of push-pull type RSPM actions with both L_1 and L_2 commands. These two local loops were basic feedback modifications. During the tests, different values of stiffness connecting to the functional switches were used to seek the optimal vibration reduction. Results were compared with those obtained from theoretical analyses.

First, the functional switches were used to deliver 50% of the total stiffness of the original test structure. Figures 5-6 and 5-7 show the peak values of the relative displacement between the ground level and the roof level with constant acceleration inputs. The input levels were 0.1g (figure 5-6), and 0.15g (figure 5-7). In figure 5-6, two cases were compared: 1) the structure with two push-pull type RSPM functional switches; and 2) the structure with two rigid bracings whose stiffness was the same as that of the switches in the "on" position. In figure 5-7, three cases were compared: 1) the structure with two push-pull type RSPM switches; 2) the structure with number 2 switch working normally and number 1 switch fixed at the "on" position; and 3) the structure with number 1 switch working normally and number 2 switch fixed at the "on" position.

Table 5-VI lists the values of the equivalent damping, maximum deformation, maximum base shear and the percentage reduction of the RSPM scheme of figure 5-6.

Table 5-VI Sweep Sine Test with Double Switches, Input Level 0.1g

	Rigid Bracing	Functional Switches	
		Experimental	Theoretical
Damping ratio (%)	8.1	35.2	38.0
Maximum deformation (mm)	27.2	6.2	6.0
RSPM reduction (%)	77.3		
Maximum base shear (lbs)	507.8	127.0	
RSPM reduction (%)	77.0		

Table 5-VII lists the values of the equivalent damping and maximum deformation of the three cases shown in figure 5-7.

Table 5-VII Sweep Sine Test with Double Switches, Input Level 0.15g

	Switch # 1 fixed	Switch # 2 fixed	Push-pull
Damping ratio (%)	32.2	30.0	35.4
Maximum deformation (mm)	14.1	11.4	11.1

As the next step, the functional switches were commanded to deliver 75% of the total stiffness of the original test structure. Figure 5-8 shows the peak values of the relative displacement between the ground and the roof with constant acceleration inputs. The input level was 0.1g. This time, five cases were compared: 1) the structure with two push-pull type RSPM functional switches; 2) the structure with two viscous dampers with the RSPM switches set in the "damp" position; 3) the structure with fixed high stiffness; 4) the structure with number 1 switch working normally and number 2 switch fixed at the "on" position; and 5) the structure with number 2 switch working normally and number 1 switch fixed at the "on" position.

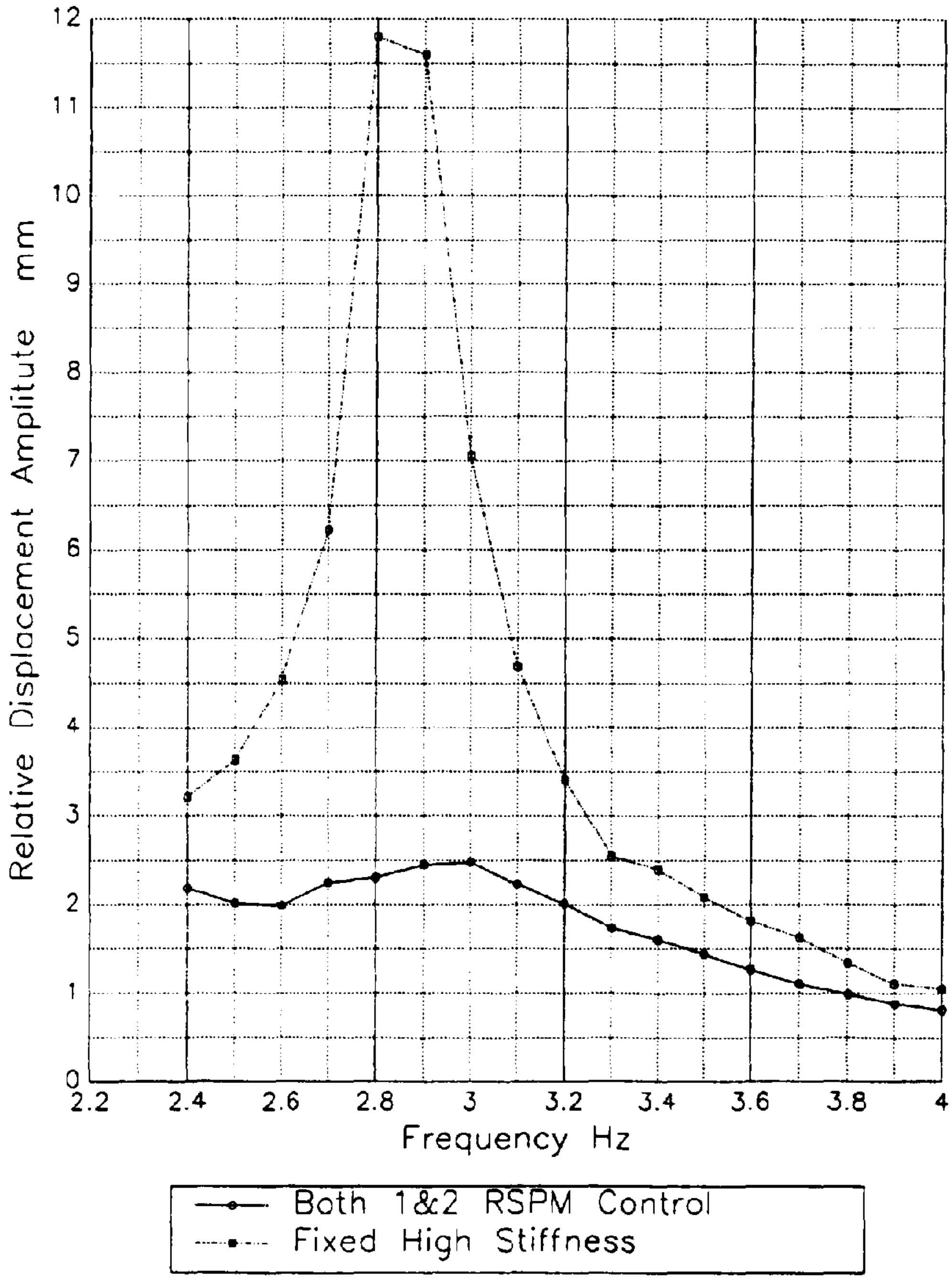

FIGURE 5-6 Peak Values of Relative Displacement Between Ground and Roof (0.1g Input)

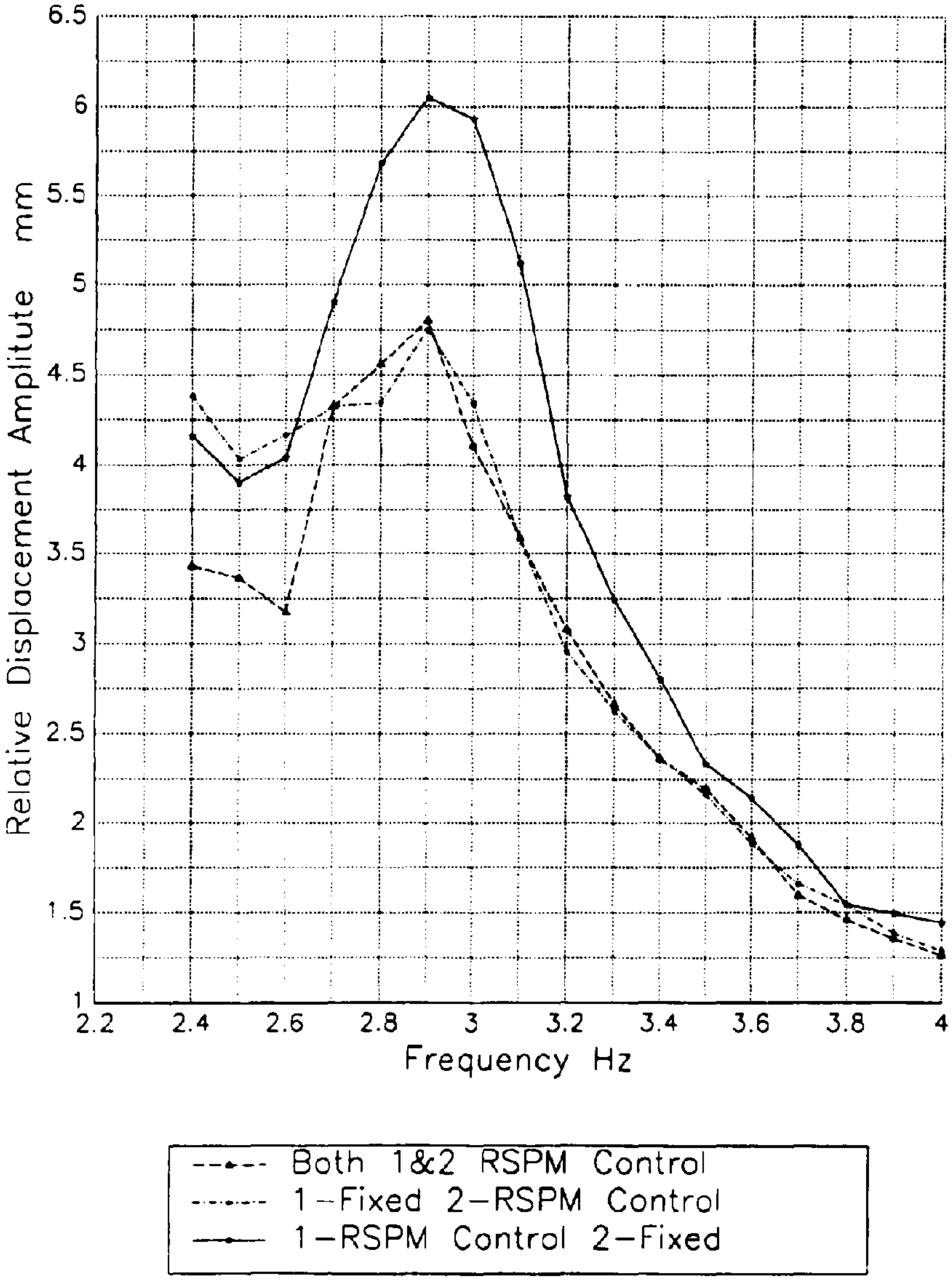

FIGURE 5-7 Peak Values of Relative Displacement Between Ground and Roof (0.15g Input)

Table 5-VIII lists the values of the equivalent damping, maximum deformation, and the percentage reduction of the RSPM of the five cases shown in figure 5-8.

Table 5-VIII Sweep Sine Test with Double Switches, 75% Total Stiffness of Original Structure

	Dampers	Functional Switches		Both Switches	Switch #1	Switch #2
		Experimental	Theoretical	Fixed	RSPM	RSPM
Damping ratio (%)	17.8	35.2	38.0	8.0	22.4	24.0
Maximum deformation (mm)	14.7	3.2	3.1	10.2	6.8	5.7
RSPM reduction (%)	77.1					

These test results illustrate that the push-pull type functional switches associated with L_1 and L_2 loop modifications work well. The level of vibration reduction was large. Even when compared to the use of passive dampers (17% damping ratio), the level of vibration reduction through RSPM was significant.

As a brief review of the effects of equivalent damping, figure 5-9 presents a comparison of the displacements of Structure 1 with RSPM, with increased stiffness and damping, respectively. It can be seen that Structure 1 with RSPM has an equivalent damping close to 70%.

5.4 Single Direction Earthquake Input for Structure 1 with RSPM

In this section, the results of the response of the RSPM system using earthquake ground motion records (El Centro 1940 and Northridge 1994 (see Goltz, 1994)) as excitation input was presented. The test conditions, amplitudes and time duration of the records were modified for convenience according to the similitude law.

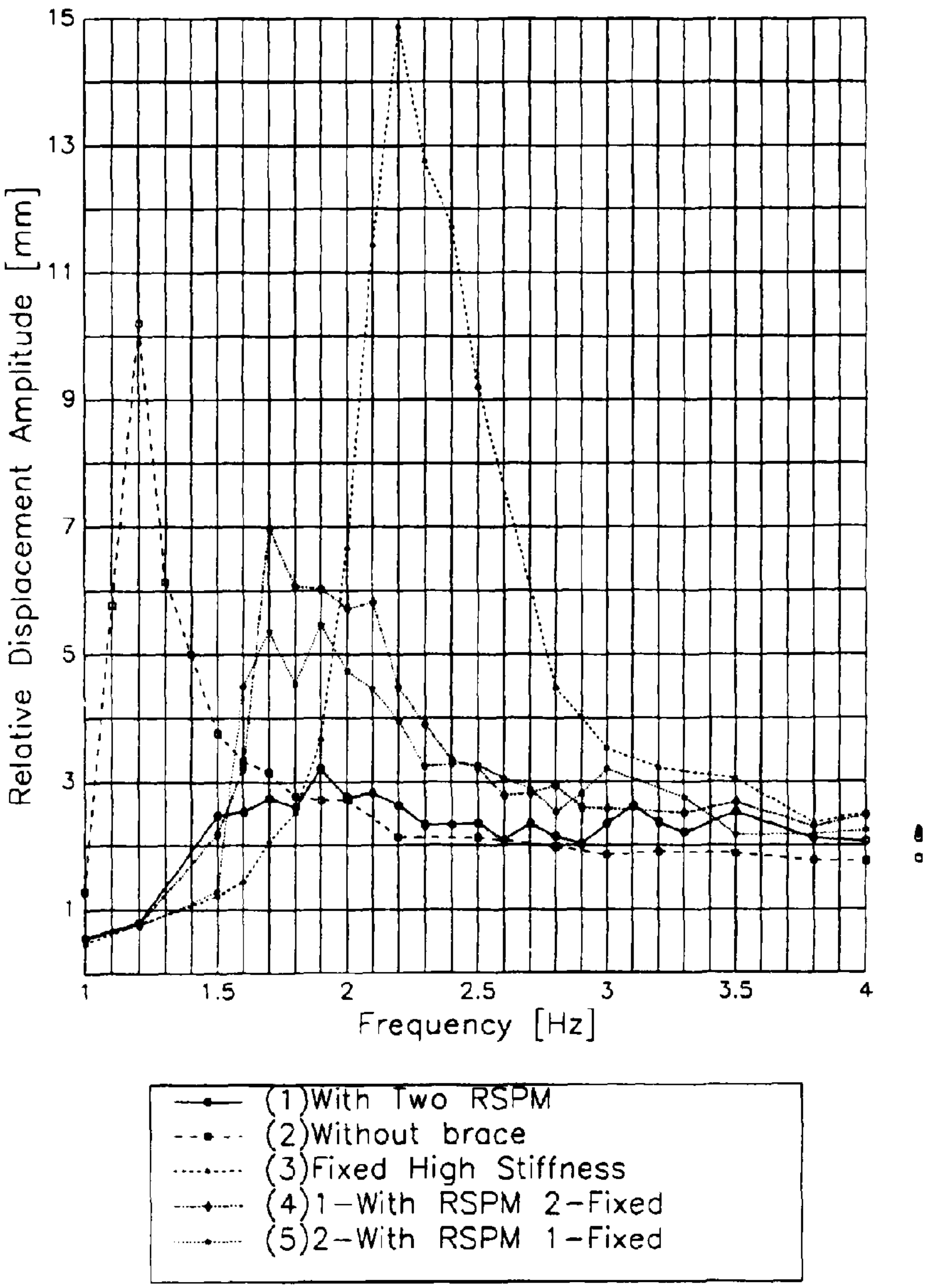

FIGURE 5-8 Comparison of Frequency Responses Between Five Tests

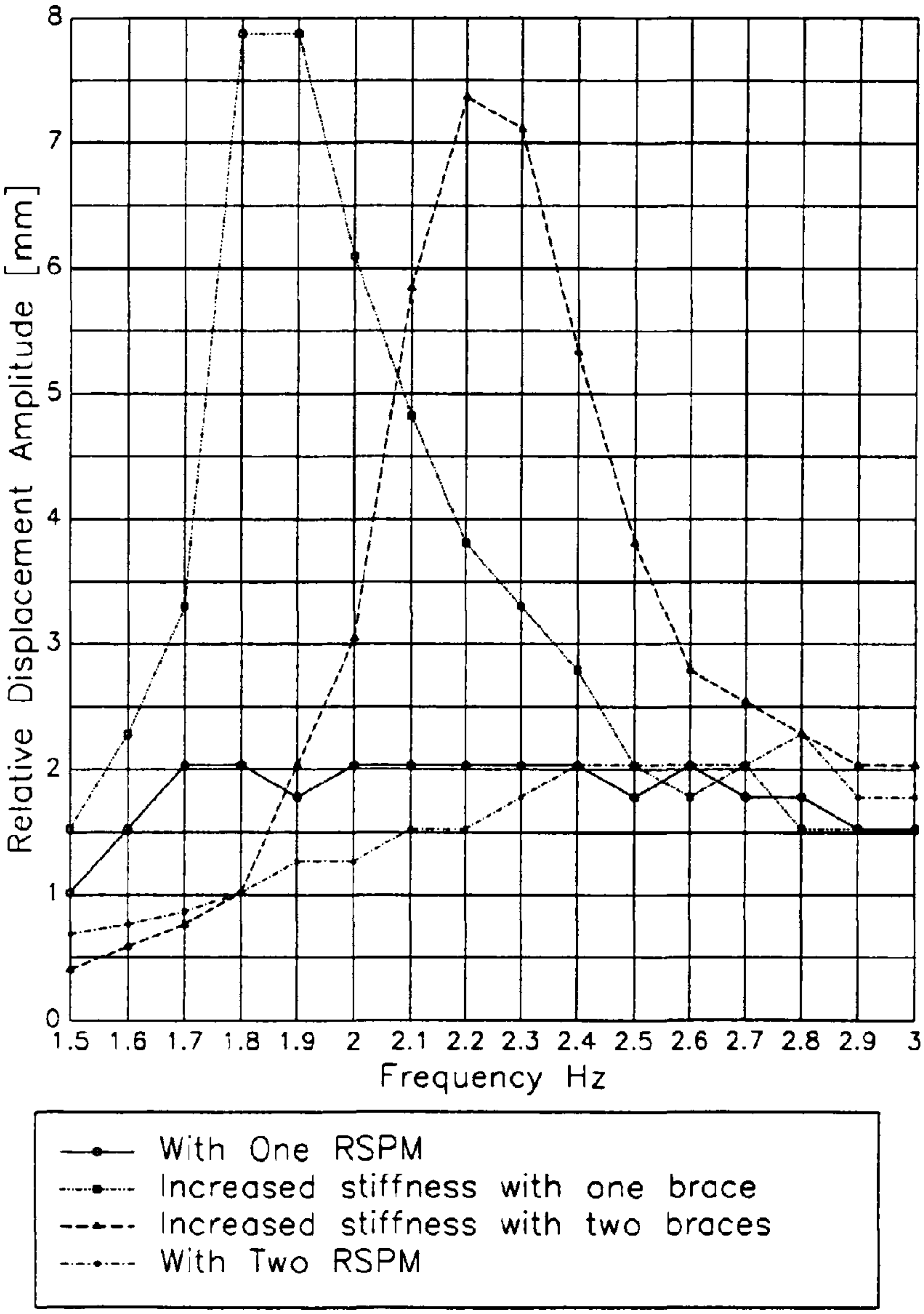

FIGURE 5-9 Comparison of Frequency Responses Between RSPM and Conventional Methods

Figure 5-10 shows the response time history of the system with two push-pull type RSPM functional switches and the response time history of the same structural set up with the switches set at the "on" position, both under the El Centro earthquake excitation. Figure 5-11 shows the same configurations, both under Northridge earthquake excitation. In these cases, the damping ratio of the structure was about 8% and the stiffness was about 50% higher than that of the original test structure. The response time history of the structure with the switches set at the "damp" position all the time was also studied. In this case, the stiffness was about the same as that of the original structure, but the damping ratio was about 17%. The two cases allow comparison of vibration reduction capability of the RSPM system with the typical "high stiffness" approach and the passive damping control method. It was observed that the structure with high damping exhibits a higher response than that with a high stiffness. Therefore, for comparisons between RSPM controlled and uncontrolled cases, only the "high" stiffnesses were used. In figure 5-10, the input level was reduced to 0.3 g from the original 0.4 g of the El Centro record, because the input level of the original ground motion was too high which may introduce yielding to the test structure without innervating actions. In figure 5-11, the input level was also reduced to 0.4 g.

The RSPM scheme achieved about a 50% reduction over the structure with high stiffness and more than 70% reduction over the structure with higher damping. The total reduction was consistent with the results of the sweep sine tests.

Vibration reduction through RSPM begins at the start of the structural responses to the earthquake. The first peak of the time history was being reduced more than 50%. This can be seen by comparing the responses shown in figures 5-10 and 5-11. In many typical control methods, it is difficult to reduce the first few peaks of the time history, unless a combination of devices were used (Pong et al., 1994). In general, most vibration control schemes using energy dissipation methods become effective after a given time period has elapsed and sufficient energy has been accumulated in the system. The ability to reduce the first few peaks of the time history was an important performance indicator of a vibration control approach. This conclusion can be

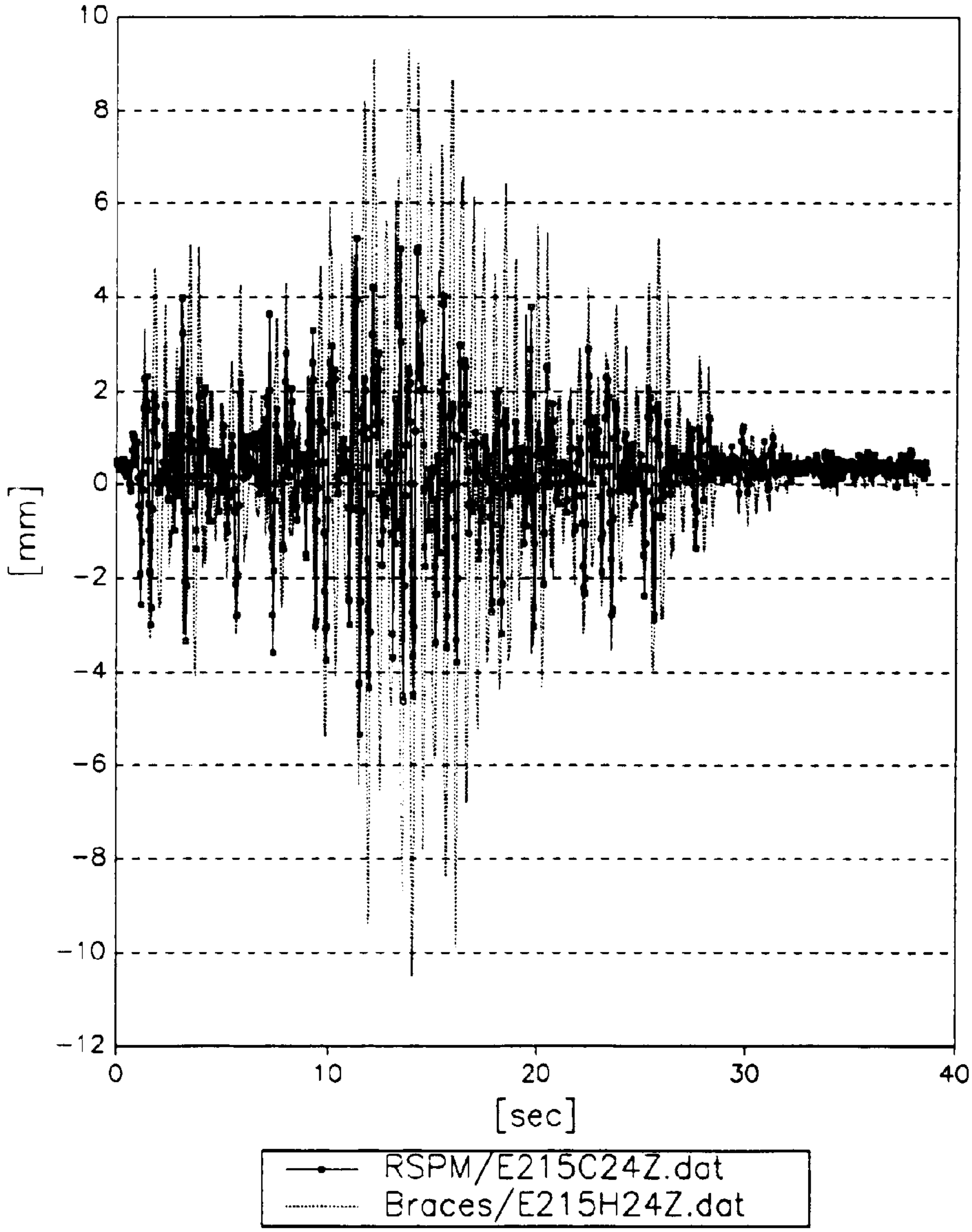

FIGURE 5-10 Comparison of Responses Under El Centro Earthquake (1940)

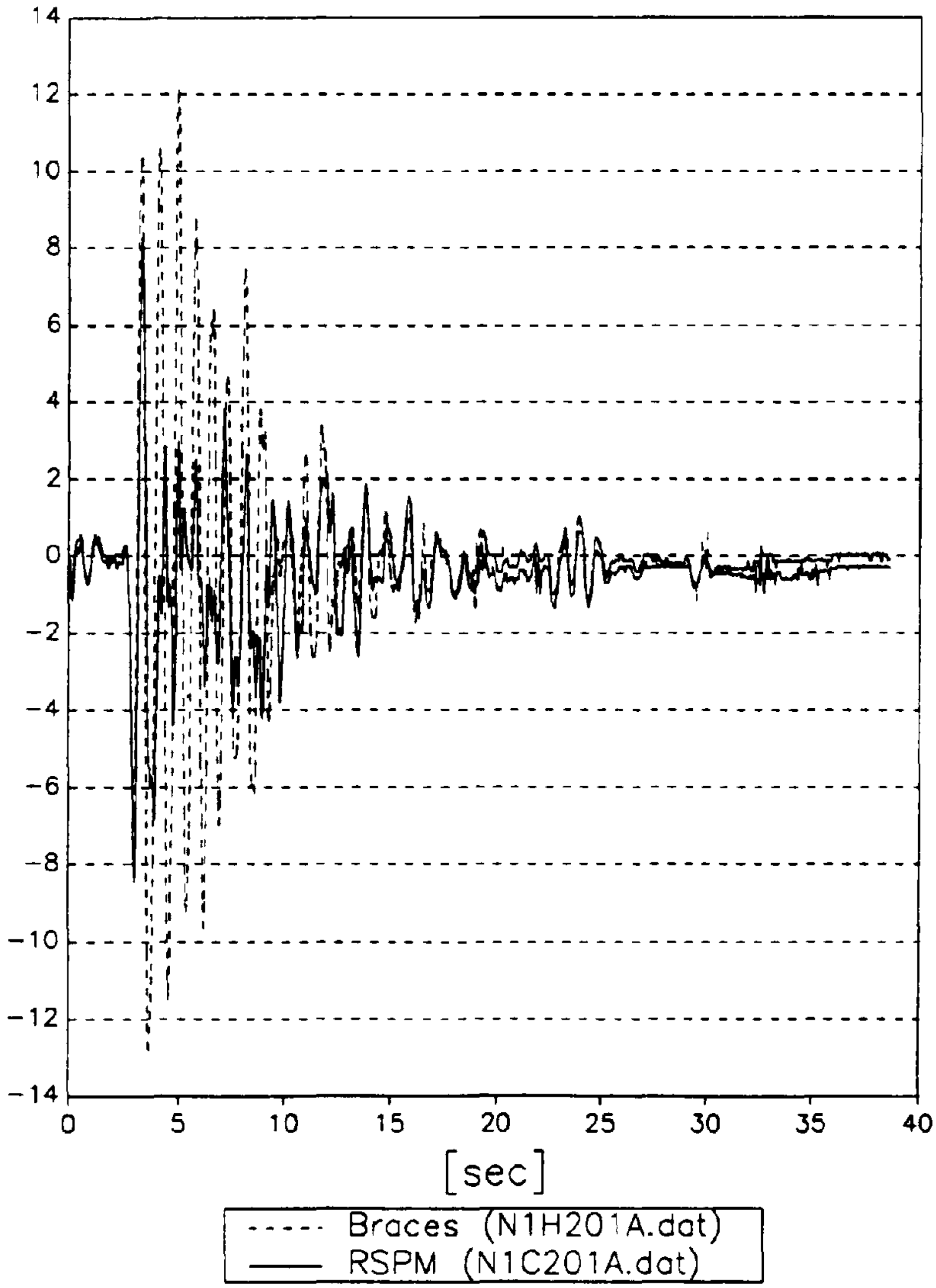

FIGURE 5-11 Comparison of Responses Under Northridge Earthquake (1994)

clearly realized in computer simulations, and has recently been verified through earthquake ground motion tests.

It may be noted that the response of the test structure with high damping was larger than with high stiffness, mostly because the major frequency components of both the El Centro and the Northridge earthquakes were lower than the natural frequency of the test structure. Passive damping control was not effective in these cases.

Table 5-IX summarizes the maximum responses and base shears, the high stiffness and high damping cases compared with the responses of RSPM.

Table 5-IX Single Direction Earthquake Input

	RSPM	High Stiffness	High Damping
Max. displacement (mm)	4.96	9.91	21.22
RSPM reduction (%)		50.0	85.0
Max. base shear (lbs)	241.0	529.0	472.0
RSPM reduction (%)		54.4	49.1

Table 5-IX shows that, with the RSPM, the base shear can also be significantly reduced. Figures 5-12 through 5-15 show the base shear time histories of the test structure with high stiffness and with RSPM, respectively. It can be seen that the reduction of the base shear of the test structure with RSPM vs. that with high stiffness was about 50%. It should be noted that the base shear time histories of the test structure with high damping were larger than with high stiffness. These results coincide with the comparisons of displacements.

5.5 Multi-Direction Earthquake Input for Structure 1 with RSPM

There were two specific reasons to use multi-directional earthquake ground motions in the RSPM scheme. First, the ground motions of earthquake are in fact more or less multi-directional, although research has been sparse in this area. The dynamic behavior of a structure when subjected to different types of input, (single direction and multi-direction), can be quite different. In order to observe these phenomena and verify the computer simulated results of multi-directional excitations, a two direction shaking table was used to conduct the experiments.

Secondly, RSPM uses a feedback scheme. That is, the system only reacts when certain signals are picked up by the sensors. In practice, virtually any sensors will have transverse sensitivity. In other words, they may pick up signals perpendicular to the axis of the functional switch which can mislead the switch into reacting incorrectly. Algorithms associated with RSPM that do not consider this "cross effect" may fail to reduce vibration. Therefore, it was necessary to examine the sensitivity of the RSPM scheme by using multi-directional ground motions.

Because of the limitation of the instrumentation capacity, output of the earthquake records and the response data could not be handled simultaneously. Thus, no time history was recorded in these preliminary tests. However, comparisons were observed between the single input and the multiple inputs by using the oscilloscope. A 14% reduction of the efficiency was observed when multiple input was used. In these cases, the total reduction was about 43% when compared with the results of high stiffness and about 70% total reduction when compared with the results of high damping. The base shear can also be reduced by about 40% or more.

Table 5-X summarizes the maximum responses and base shears of the test structure with RSPM, high damping and high stiffness schemes.

Table 5-X Multi-Direction Earthquake Input

	RSPM	High Stiffness	High Damping
Max. displacement (mm)	5.68	9.93	18.97
RSPM reduction (%)		43.0	70.3
Max. base shear (lbs)	254.0	481.0	509.0
RSPM reduction (%)		47.2	50.0

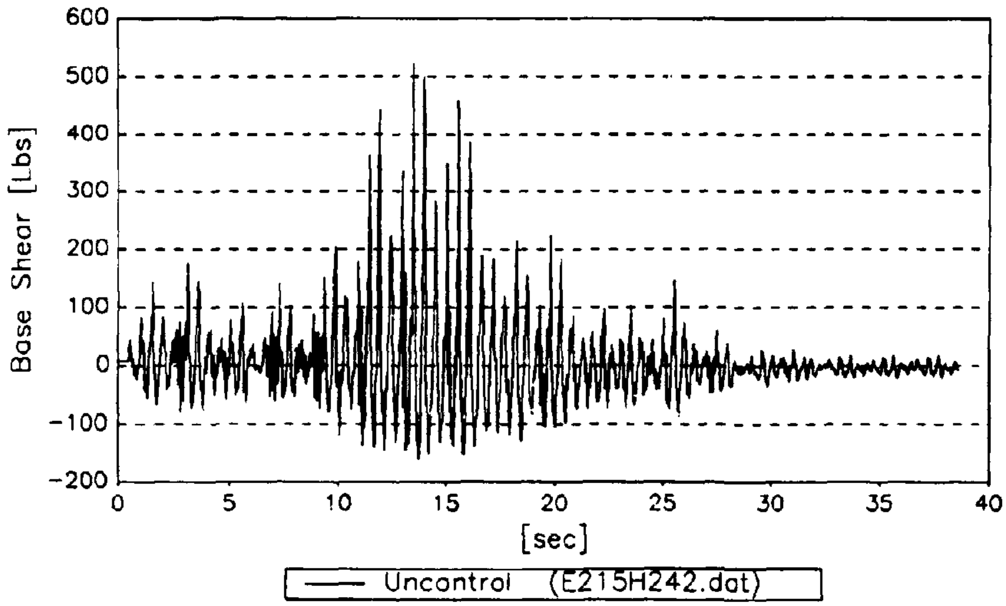

FIGURE 5-12 Base Shear of Structure without RSPM, Under El Centro Earthquake

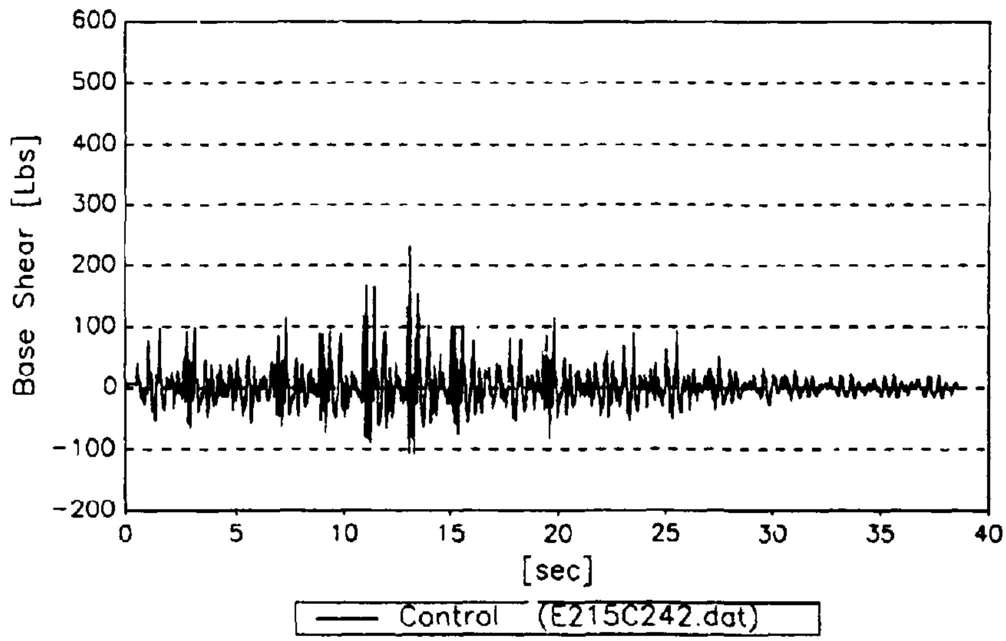

FIGURE 5-13 Base Shear of Structure with RSPM, Under El Centro Earthquake

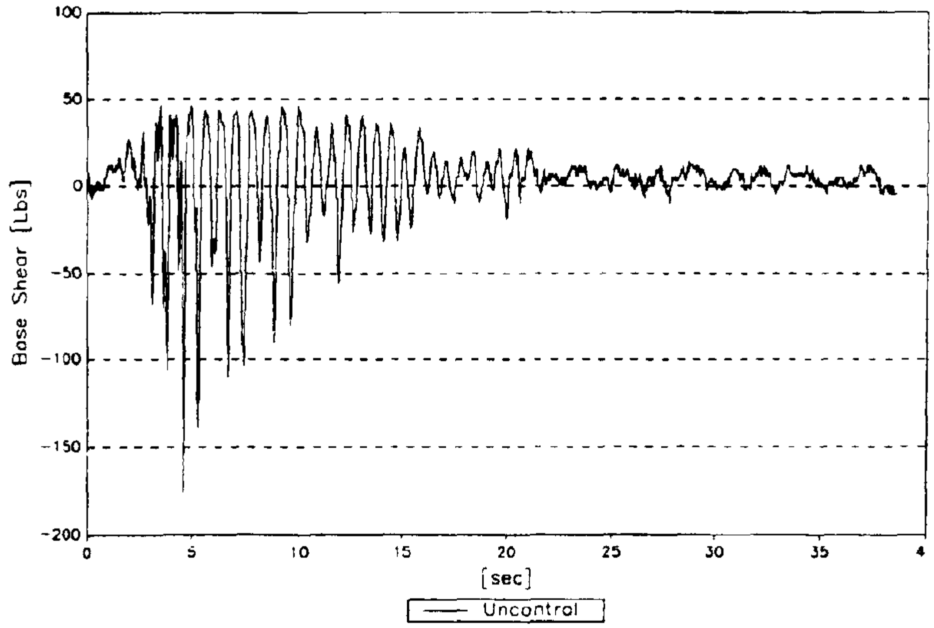

FIGURE 5-14 Base Shear of Structure without RSPM, Under Northridge Earthquake

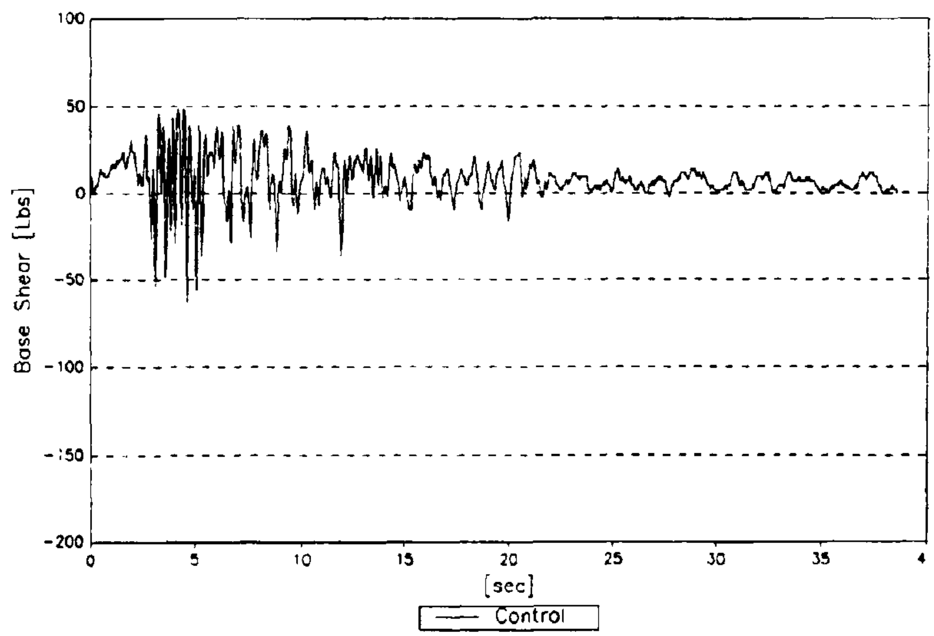

FIGURE 5-15 Base Shear of Structure with RSPM, Under Northridge Earthquake

Table 5-X shows that multi-directional input affects vibration reduction. This can be compensated for by the L_3 loop modification, which was not implemented in the pilot experimental program.

5.6 Single- and Multi-Direction Earthquake Inputs for Structure 2 with RSPM

In July 1994, Structure 2 (see figure 5-2 (b)) was prepared to experimentally verify vibration reduction through RSPM on MDOF structures. This structure was also used to develop the proposed hierarchical modification loops. Although further studies are still being performed, pilot tests have shown good agreement between theoretical analysis and experimental data.

SECTION 6
SUMMARY

For a number of years, the authors have been interested in learning from the "self-adjusting" abilities of living system and in applying such principles to the design and construction of man-made systems. The rapid advances in the development of sensors, computer logic and hardware, and control processes and devices in recent years have made it possible to advance the concept of "innervated structures" as a class of intelligent structures through real-time structural parameter modifications. This report presents some preliminary theoretical development, based on a very much simplified biomechanical control concept, as substantiated by a pilot experimental program on structural vibration reduction due to earthquake ground motion. RSPM is equally applicable to other time-dependent loading conditions.

Traditional seismic-resistant design of structures has evolved from the viewpoint of modified static stiffness. In past decades, ductility was regarded as the important issue in structural design against earthquakes. In recent years, vibration control technologies developed by the aerospace and mechanical engineering professions have become a subject of study by structural engineers to reduce vibration to protect against strong earthquake ground motions.

There are several fundamental issues facing the structural engineering community in the development of structural control. Most of all, major civil engineering structures are MDOF systems. Technologies developed under the assumptions of SDOF systems (found in many mechanical systems) and proportionally damped systems do not necessarily apply to generally damped systems. Most structural control technologies currently under development must sooner or later address some fundamental questions concerning the dynamics of MDOF systems. One of the key questions is the behavior of MDOF systems with enhanced damping. Today, it is still not known whether increasing the damping is always beneficial to a MDOF structure. The concept and principle of an innervated structure is established based on certain biomechanical behaviors of living systems (e.g. human body motion control). The innervating actions are the modification of structural parameters (mass, damping and stiffness) by a hierarchical algorithm in real-time, through equilibrium considerations of all energy quantities (both conservative and dissipated) of an MDOF system. This approach is developed by the authors in an earlier study on the subject of complex energy and structural damping (Liang and Lee, 1991d).

The first basic component of an innervated structure is a special sensory system. Otherwise, the structure is totally passive. The second basic component of an innervated structure is the algorithm to executive real-time structural parameter modifications. The key issue here is to modify the parameters of the structures themselves to limit the vibration levels within certain bounds. The third basic component of an innervated structure is the functional switch. They provide the self-adjusting ability of the structure without relying on large external forces required by actuators used in conventional active control schemes.

In this report, all three basic components are introduced. The details of the sensory system will be reported separately. They are described in a fashion to invite discussion and wider participation by researchers. The field of developing innervated structures will continue indefinitely as more and more is understood with respect to human locomotion and skeleton control.

In order to show the unique features of RSPM, a comparison of RSPM with other existing technologies in earthquake engineering was made. The latter include 1) structures with energy absorbing means (EAM); 2) tuned mass dampers (TMD); and 3) active control (AC). Comparison with and discussion of base isolation will be dealt with in a separate publication.

1.) Among EAM, TMD and AC, TMD is usually used for slim-shaped buildings and yields the minimum vibration reduction. An example is used to compare regular TMD and RSPM-TMD. An airport control tower is to be equipped with a TMD to reduce vibrations excited by both winds and earthquakes. With 17 kps added mass, the maximum damping ratio with TMD design is calculated to be 6%, (original damping ratio of the tower is 3%). A less than 15% vibration reduction can be achieved by such a design. Whereas an RSPM added TMD system can have more than 11% damping ratio and more than 35% vibration reduction, with the same added mass. The TMD method is sensitive to design and construction errors. A 5% change in damping and/or stiffness for added mass can decrease the net damping ratio increase from 3% down to 1%. Whereas more than 20% changes in the above-mentioned parameters will only affect the vibration reduction from 35% down to 30%.

TMD adds an additional mass, and is connected to the main structure through dampers and springs as traditionally defined dynamic absorbers; RSPM-TMD employs virtually the same setup of regular TMD except functional switches are used to replace the regular dampers. Since the basic setups and construction for both methods are the same, the estimate cost of RSPM-TMD is the added cost of the functional switch. Compared to the performance and total cost of the airport control tower, the performance/cost ratio of RSPM-TMD is significantly higher.

2.) Typically, AC adopts linear control theory and reduces vibration responses by delivering counter forces which are, in general, either proportional to feedback velocity or displacement. The former is equivalent to increasing damping forces and the latter is equivalent to increasing the spring force that is comparatively much larger than damping forces. Because of the limitation of large-powered actuators, the feedback force of AC is often proportional to velocity, ie. it is actually the damping force.

EAM uses various added dampers to absorb vibration energy, thus increasing the effective damping forces. In this sense, typical EAM and AC actually employ the same methodology of increasing damping forces. However, due to difficulties such as feedback time delay, etc., the counter force applied by AC cannot be 100% effective at really damping forces. A 70% effectiveness is currently the cap to reduce the effectiveness of AC. Thus, despite theoretical advantages, AC in practice does not provide better results than that of EAM. Among all EAM devices, the fluid damper, providing added viscous damping to structures, has shown the best reduction both theoretically and experimentally with virtually the same cost as the others. Therefore, the fluid damper as a representative EAM is used to compare with RSPM.

3.) In general, for all EAM devices as well as RSPM, the dampers and/or functional switches must be mounted on certain supporting members that have limited stiffness. Such a stiffness is denoted by S and the lateral stiffness of the original structure is denoted by K. For a viable design with reasonable costs, S should not be too much larger than K. For a simple SDOF structure with fluid damper, roughly a 10% damping requires S > 0.5 K. A 20% damping requires S > 1.5 K. A 30% damping requires S > 2 K. Note that when S = 2 K and if the supporting member is used to increase the lateral stiffness, the entire structure can have three times stiffness than the original structure, which is believed to already have more than two times vibration reduction. As a comparison, the structure with a 30% damping ratio may not have such a large reduction. Therefore, 30% damping provided by fluid dampers may be considered to be a practical cap.

Denote the possible peak response by X_m.

$$X_m = 1/(2\,\xi_{eq}\,K_{eq})$$

Here ξ_{eq} is the equivalent damping ratio and K_{eq} is the equivalent stiffness.

For the case of fluid damper, the maximum value of ξ_{eq}, as mentioned above, is taken as 30% and K_{eq} =K.

Therefore

$$X_{m,\,\text{fluid damper}} > 1.5 / K \tag{6.1}$$

Note that, for a VE damper with a narrow operating frequency range,

$$X_{m,\,VE\,damper} > 1.7\,/\,K \tag{6.2}$$

For RSPM, ξ_{eq} can achieve as high as 60%. When choosing S = K, and for $K_{eq} = 2$ K, $\xi_{eq} = 50\%$, we have

$$X_{m,\,RSPM} = 1/(2 \times 0.5 \times 2\,K) = 0.5\,/\,K \tag{6.3}$$

Comparing Equation (6.1) and (6.2), the peak response of RSPM can be three times smaller than that of a fluid damper.

Note that, in this case, RSPM only requires S = K. And, RSPM requires the supporting member to have the stiffness in only one direction (tension) whereas the fluid damper must have the supporting member to provide stiffness in both directions (tension-compression). This fact also has cost implications

In random excitations, such as earthquake ground motions and winds, the peak response of a structure is less than $1/(2\ \xi_{eq}\ K_{eq})$ and in terms of equivalent damping and stiffness, RSPM will only have two times smaller peak response compared to that of the fluid damper. However, EAMs, including fluid dampers, cannot select optimal mass, damping and stiffness as RSPM does and therefore cannot avoid "narrow-band-resonance." Thus, the input energy of RSPM can be smaller than that of EAMs.

The above brief comparisons suggest that RSPM is not only a promising technology itself, but also has the ability to improve the performance of other passive vibration control and energy absorbing technologies. In addition, RSPM helps to better define a new direction of research in the pursuit of developing innervated structures.

SECTION 7
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