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STRUCTURAL CONTROL FOR SEISMIC PROTECTION OF STRUCTURES

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ABSTRACT

Although one can do nothing about the level of seismic hazard a structure could experience, it is now well known that seismic structural response can be reduced by structural control techniques. Modern seismic response control methods can be divided into either passive or active controls. Hybrid techniques which combine the advantages of the two are also being considered. Base isolation is a well known passive control method. Other passive methods are supplementary damping or energy dissipation devices such as viscoelastic dampers, friction dampers, fluid dampers and other yielding devices. The active control methods for aerospace and electrical engineering applications, are now being considered for control of civil structures. This paper describes some latest passive and active structural control methods. Some active control methods with potential for application to civil structures are identified.

INTRODUCTION

Earthquake resistant design of structures has come a long way since early fifties when the first world conference on earthquake engineering was organized at the University of California, Berkeley. Early research efforts were mostly spent in understanding the behavior of structures subjected to earthquake induced ground motions through the application of vibration theory which at that time was commonly used in mechanical engineering applications. Several decades of research was aimed to calculate the response of structures subjected to dynamic loads, and the subject of structural dynamics was born. Methods to analyze linear and nonlinear structures for seismic inputs defined by acceleration time histories, and later by response spectra, were developed to calculate displacements, forces induced in structural members, floor accelerations and ductility demand expected to be accommodated by members and connections in nonlinear ductile structures. Structures were designed such that the calculated response quantities for a given seismic design input were within their allowable values.

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This procedure implicitly assumed that nothing much could be done to reduce a structure's response. Lately, however, this assumption is being challenged. Indeed, we can not do much about the seismic hazard inasmuch as one can not reduce the level of ground shaking expected at a site due to a fault rupture, but we can certainly device techniques to reduce the effect of a ground motion on a structure. The methods that are used to reduce the response of a structure fall in the domain of structural control.

Broadly speaking, structural control methods can be classified as passive control and active control. The methods which combine the good attributes of these two methods to achieve better performance and reliability are also being examined. They are commonly referred to as hybrid methods of structural control.

The passive methods are those in which no external force or energy is applied to effect control. The structural motion itself activates the control device or mechanism. The active control methods, on the other hand, need counteracting external forces or externally activated devices to change response. The time variation of external forces or activation of other devices needed to control the response is based of the measurements of external disturbance and /or the structural response. To measure the input and response, sensors are installed. These measurements are supplied to a computer which calculates the forces required to counteract the effect of external disturbance. The calculated forces are applied by hydraulically or electrically operated actuators.

The structures installed with these devices are also being referred to as "smart structures." This nomenclature is due to its comparison with a human body. In a smart structure, sensors installed to measure disturbance and structural response are akin to human sensors, computer calculating the counteractive forces is like a human brain and the mechanical actuators applying forces are equivalent to human muscles. Of course, human equivalents are immensely more sophisticated and complicated than those in a smart structure.

This survey paper provides an overview of various methods that are being currently considered for the purpose of structural response control. Some of these methods are in a fairly advanced stage and are, in fact, being used in actual structures. There are also some which have developed to an experimental stage in the laboratories, and yet there are others which are still in their conceptual and theoretical development stage. Because of the broadness of the topics covered here, no attempt has been made to provide either complete technical details or a comprehensive list of publications in these areas. Reference is, however, made to several outstanding review papers which usually provide comprehensive bibliographical information about the work done in some of these areas

PASSIVE STRUCTURAL CONTROL

Basically there are two approaches of passive structural control. In the first approach, ground motion input to a structure is filtered to remove the harmful harmonics which are usually the first few frequencies of the structures. In the second approach, the vibratory energy of an earthquake is dissipated at harmless locations in energy dissipation devices or in disposable elements which act as fuse. The first approach is what is commonly known as base isolation and the second approach is known as passive control through energy dissipators.

Base Isolation

Perhaps of all structural control techniques, base isolation is in its most advanced stage. The idea of base isolation for earthquakes is about eighty years old. Since 1970, it has been used in the U.S., Europe, Japan, China, Mexico and perhaps other countries. Now it is being used even to retrofit some existing buildings. A comprehensive review of the work on this topic is given by Kelly (1986a, 1986b), Buckle (1986) and Buckle and Mays (1990).

In a nutshell, the concept of base isolation is as follows. The earthquake induced ground motion usually contain high energy in a certain frequency range. For the Western United States Earthquake, this frequency range is between 1 to 10 Hz. The structures with dominant modes in this frequency range will experience large response due to resonance effect, where as those with frequencies outside this range will experience smaller response. This can be clearly seen from the average ground response spectrum in Fig. 1, which shows the response of single degree of freedom structures of different frequencies subjected to the ground motions recorded on firm sites in the western United States. The response can be significantly less if a structural frequency is much less than the predominant frequency range of the input. The base isolation devices create this condition. These devices essentially consist of relatively flexible bearing supports which can safely support the gravity load but are quite compliant in the lateral direction. Elastomeric bearings are commonly used for base isolation. They reduce the fundamental frequency of the combined structure-bearing system significantly in the lateral direction, such that only a significantly reduced energy is transmitted to the superstructure. The concept is well accepted by the profession as there are now provisions in codes for the design of base isolated structures.

Conceptually the idea is simple. However, there are several design and operational limitations involved. One can not make these bearings very flexible to avoid large deformations and thus possible instability and failure of the bearings. To avoid large deformation of these bearings, introduction of the damping mechanism to dissipate energy in the isolation bearings is also considered desirable, although the presence of damping only reduces the effectiveness of the isolation phenomenon. Damping also introduces high frequency response in the superstructure. There is also a possibility of a permanent offset remaining after an earthquake event, if no significant restoring mechanism is provided to bring the structure back to its original position. Also, base isolation can not be used for all structures in all situations. For example, it is not practical to use it with very tall buildings which are already flexible. The buildings in the range of 6 to 10 stories are good candidates. Also it can not be used for buildings on soft sites where the ground input is already filtered to posses low frequency motions.

Besides elastomeric bearings, other types of isolation bearing have also been examined. The use of simple sliding surfaces to isolate a structure has also been considered (Mostaghel and Tanbakuchi, 1983; Qamaruddin, et al, 1986; Malushte and Singh, 1989). China has some demonstration projects on this idea. The structure slides whenever the lateral force exceeds the friction force at the sliding interface. The acceleration at the base of the structure is thus limited to the coefficient of friction at the sliding interface. Thus by keeping this coefficient of friction low, the acceleration felt by the structure can be reduced. However, the friction coefficient can not be reduced arbitrarily as there is a tradeoff involved. For low coefficient of friction values, the sliding displacement of the structure will be large, requiring a correspondingly large obstruction-free clearance. Also after a large earthquake event, a large residual displacement from the original central position of the structure may be left since there is no restoring forces to bring the structure back. There are other practical problems which can effect the efficiency of sliding isolation such as cold bonding, freezing and deterioration of the sliding surfaces.

A combination of elastomeric bearing with sliding friction has also been proposed to introduce damping at the isolation interface. An example of this is the resilient-friction base isolator (R-FBI), proposed by Mostaghel and Khodaverdian (1987). It consists of a set of Teflon coated flat rings with a central rubber core. As the rubber core deforms, the rings slide against each other and dissipate energy by Coulomb friction.

Another arrangement called friction pendulum systems (FPS) utilizes gravity effect to introduce the restoring force needed to bring the structure back near to its original position (Zayas, et al, 1987)). It consists of a concave bearing surface on which an articulated friction slider operates. Fig. 2 shows a schematics of this arrangement. The radius of curvature, R, determines the sliding or isolation period of the system as $T = 2\pi\sqrt{R/g}$. The larger the radius of curvature, the larger the isolation period (or smaller frequency). However, the larger radius also means a smaller restoring force. Because of friction between the articulated slider and concave sliding surface, some earthquake energy is dissipated before it filters through the structure. The maximum acceleration of the structure at its base is also considerably reduced, thus reducing the forces, displacements and deformations in the structure.

Friction pendulum bearing systems can be placed between the basement and foundation of a structure. They can also be installed at the top or bottom of the bottom most columns of a structure where the isolation effect is desired. The freezing at the sliding surfaces may require special temperature controls. Also special materials are required to avoid deterioration of the sliding surface.

The use of rollers or ball bearings has also been advocated for base isolation, but there can be problems at the bearing surfaces due to deterioration caused by high concentrated stresses, cold welding and weather related deterioration.

Energy Dissipating Systems

Base isolation controls the response of a structure by merely shifting its frequency and not by dissipation of vibration energy. The energy dissipation mechanics in base isolation are only used to limit the deformation of the base isolating spring. The energy dissipating devices, on the other hand, can also be installed at in a structure to convert a part of the vibration energy into heat at other predecided location.

The energy balance equation in seismodynamics of a structure can be written in the following form (Akiyama, 1985; Uang and Bertero, 1988)):

$$E_i = E_k + E_s + E_d \tag{1}$$

Where E_i represents the energy input to the structure by the surrounding media. Some of this input energy gets converted into kinetic energy E_k of the structural mass, some into potential energy (strain energy) E_s stored in deformed structural elements and the remaining energy E_d gets dissipated into heat through internal damping mechanism in structural and non structural components. If a structure is expected to store more strain energy than its elastic element can accommodate, they break or yield. This breaking or yielding means some permanent damage to the overstrained elements. However, if external energy dissipation devices are installed to augment energy dissipation, then less will be available for the kinetic and strain energies in the structure thus reducing the chances of causing permanent damage to the structural elements. Various types of energy dissipation devices that are being investigated for structural applications are *viscous dampers, friction dampers, steel yielding elements* and *viscoelastic dampers.*

Viscous Dampers: In the dynamic analysis of structure, it is common to model inherent internal energy dissipation in structural and non structural elements by linear viscous dampers. It is done primarily for mathematical convenience of the analysis, and not because the damping is indeed of the viscous type. However, one can also install actual viscous dampers in which damping is provided by the passage of a viscous fluid through a constricted orifice on a piston moving in a cylinder filled with the fluid. The amount of energy dissipated depends upon the size of the hole and viscosity of the fluid. Damping force in these devices depends upon the relative velocity of the piston. These devices do not contribute to the stiffness of a structure on which they are installed. The force displacement diagram for these dampers is an ellipse for a harmonic motion, and the area of the ellipse represents the amount of energy dissipated in a cycle. Several proprietary dampers have been developed for defense applications, and their use for civilian application in structures is now being aggressively pursued. These can be installed in the cross bracings of a framed structure or in chevron-type of braces (inverted V-braces).

The methods are well developed for calculating design response of a linear structure fitted with these dampers for ground motions defined by acceleration time histories or response spectra. However, further studies on these dampers are still continuing about their optimal placement in a structure, and their use as active devices in parametric structural control.

Friction Dampers: Friction dampers are becoming quite popular for building applications. Like viscous dampers they can also be installed in cross bracing or chevron- type of braces. They consists of two friction pads which slide against each other due to earthquake induced relative motion. To invoke friction force, there must be a normal reaction on the sliding interface. These dampers do contribute to structural stiffness. The ideal force deformation diagram of this damper is a rectangle, representing the hysteresis loop. Again, the area of this hysteresis loop represents the energy dissipated by the device during a cycle of sliding. Some of the problems associated with these dampers are due to maintenance of the friction surfaces. When two materials remain in static contact for a long time under a sustained normal force, as it would normally happen between two earthquake events, they tend to cold bond or freeze and the desired level of friction coefficient can not be guaranteed. To avoid these problems, research on these dampers is being actively pursued.

The schematic of a spring loaded friction damper, designed by Sumitomo Metals of Japan (1987) is shown in Fig. 3. It consists of a cylindrical housing with wedges, friction pads and a compressed spring. The spring is pre-compressed by tightening the nut to provide a desired level of force to the wedges, which in turn provides the normal pressure on the friction pads. The rated capacity (the force required to cause slippage) of such a damper can be related to the spring load and the friction coefficients by the following simple expression (Fujita, et al 1991)

$$F = 2\mu_1 P \frac{1 - \mu_2 \tan\theta}{\mu_2 + \tan\theta} \tag{2}$$

where F = the rated capacity; μ_1 and μ_2 are the coefficients of friction, respectively , for the primary interfaces and the interface on the wedges; P = spring force; and θ = the angle which the wedge makes with the horizontal. Fig. 4 shows idealized hysteresis loops for such a friction damper. Experimentally obtained loops are also similar, and these have been shown to be quite stable under wide range of conditions. The loading and unloading lines may have some slopes because of the elasticity of connecting hardware through which the force is transmitted. In any case, the area under these loops can be quite large indicating a significant amount of energy dissipation, providing a very desirable supplemental damping.

Another type of simple friction damper, extensively tested by Popov et al (1993) and his co-workers (Grigorian et. al. 1992), consists of a slotted bolt connection. High strength bolts in the connection pass through holes slotted along the length of the member to permit sliding at a pre-calculated force. The bolts are tightened to provide a desired magnitude of normal force on the sliding surfaces. This normal force determines the force required to cause slippage. The hysteretic characteristics of these connections are similar to those shown in Fig. 4. The sliding surfaces consists of brass on steel, providing a more stable hysteresis characteristics than those provided by two similar materials. Simplicity of this connection makes it especially attractive for earthquake engineering applications.

Although the principle of operation of these dampers is quite simple, design procedures for structures provided with these requires some simplification. How to size them, best location for their installation, calculation of design response for inputs defined in terms of ground response spectra, etc. are some design issues which need further studies. It has also been observed that these dampers introduce high frequency content in the motion of floors, which may not be desirable for high frequency secondary systems supported on building floors. It is also noted that, unlike viscous dampers or viscoelastic dampers to be discussed later, these dampers are not activated by small disturbances unless the normal force is set very low.

Yielding Steel Plate Energy Dissipators: These dampers consist of several X-shaped plates (Fig. 5) assembled parallel to each other with spacer blocks. This device was originally proposed by Bechtel Power Corporation for piping supports in nuclear power plants. They are quite sturdy and resistant to environmental effects. The device can be easily installed on chevron bracings in buildings at several desired locations. When a building vibrates, the plates bend as beams with double curvature. When yielding occurs, because of the X shapes of the plates yielding spreads over the entire length rather than being confined to ends which would have been the case if uniform width plates were used. Because of this, these plates are also called uniform strength plates. These plates also provide stiffness till they yield and dissipate energy in hysteresis cycles, therefore, they are also called as Added Damping and Stiffness (ADAS) devices. The form of the hysteresis loops for different levels of yielding for these devices is shown in Fig. 6 (Namita, et al. 1991), which can be conveniently represented by Ramberg-Osgood hysteresis model in analytical investigations. The hysteretic behavior of these devices has been thoroughly examined by Hanson (1990).

As was the case with friction dampers, sizing, best location for installation, calculation of design response for input defined in terms of ground response spectra, etc. are some design issues which need to be examined for effective application of these dampers. Also, these dampers are effective in energy dissipation only for strong excitations; for low level excitations there is no additional energy dissipation unless very thin yielding plates are used.

Viscoelastic Dampers: Several buildings in the U.S. have been installed with viscoelastic dampers to reduce wind induced structural vibrations. The applicability of these dampers to mitigate earthquake effects have been investigated (Lin et. al, 1988; Chang et al, 1991). These dampers can be placed in a cross bracing or on a chevron bracing. A viscoelastic damper consists of a polymeric material sandwiched between two parts which deforms in a shearing mode, as shown in Fig. 7. The material is designed to have a large storage modulus and loss factor to achieve a high dissipation of energy per unit volume. The material properties depend upon the temperature, frequency of excitation and the level of strain. The energy is dissipated during each hysteresis cycle of deformation and gets converted into heat, causing some increase in the temperature of the material. However, this temperature has not been observed to reduce effectiveness of the material any significantly during short duration transient vibrations such as those caused by earthquake type disturbances (Chang et al, 1992). The annual and diurnal temperature changes, however, must be considered in the design of these dampers. For design, perhaps the properties corresponding to one of the two extreme temperature values can be adopted, although it is not quite clear which extreme value will lead to a conservative design decision. The low temperatures make the polymer more stiff and less dissipative and the opposite is true for high temperatures. Depending upon how much the dampers contribute to the overall stiffness, the response may increase or decrease with a change in the temperature. These design issues require further studies. Further effort is required to characterize the properties of these dampers in a simple and convenient-to-use form for design purposes.

ACTIVE STRUCTURAL CONTROL

Active structure control is a branch where the motion of a structure is actively counteracted by devices that are installed to apply external forces or which activate reactions, based on the observed response and/or external disturbance. The theoretical basis of the modern control theory were primarily developed for electrical, mechanical or aerospace applications. Since 1970, the application of the control concept to civil structures has also received increasing attention. Yao deserves the credit, and thanks, for introducing the concept to civil engineering community through his paper in 1972 (Yao, 1972). Now structural control is one of the most active research areas in civil engineering holding great promises for future applications in civil infrastructure systems. Soong (1988) and Yang and Soong (1988) provide an excellent survey of the work done in this area till 1988.

Control Algorithms

The equations of motion of a multi-degree-of-freedom structure subjected to earthquake induced ground excitation and applied with external control forces can be written in the following matrix form:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\dot{\mathbf{x}} = -\mathbf{M}\mathbf{r}\ddot{x}_g(t) + \mathbf{D}\mathbf{u}(t) \qquad (3)$$

where $\mathbf{x}$ = relative displacement vector; $\mathbf{u}(t)$ = vector of m control forces; $\ddot{x}_g(t)$ = ground acceleration; **M**, **C**, and **K**, respectively, are the mass, damping, and stiffness matrices of dimension $n \times n$; **D** is the location matrix identifying the degrees of freedom where the control actions are applied; and **r** = excitation influence vector.

In control applications, it is a standard practice to express this equation in the following state form,

$$\dot{\mathbf{z}} = \frac{d}{dt}\begin{Bmatrix}\mathbf{x}\\ \dot{\mathbf{x}}\end{Bmatrix} = \begin{bmatrix}\mathbf{0} & \mathbf{I}\\ -\mathbf{M}^{-1}k & -\mathbf{M}^{-1}\mathbf{C}\end{bmatrix}\begin{Bmatrix}\mathbf{x}\\ \dot{\mathbf{x}}\end{Bmatrix} + \begin{bmatrix}\mathbf{0}\\ \mathbf{M}^{-1}D\end{bmatrix}\mathbf{u}(t) + \begin{bmatrix}\mathbf{0}\\ -\mathbf{Mr}\end{bmatrix}\ddot{x}_g(t) \tag{4}$$

or written in standard form:

$$\dot{\mathbf{Z}} = \mathbf{AZ} + \mathbf{Bu} + \mathbf{E}\ddot{x}_g(t) \tag{5}$$

where **Z** is a 2n state vector, matrix **A** is 2n×2n, **B** is 2n×m and **E** is a 2n excitation vector.

It is desired to define the control actions **u** in some optimum fashion. For linear system, the linear optimal control theory has been most commonly used. To obtain the optimum control forces, it is common to minimize the following non-negative quadratic performance function which depends upon the state vector as well as the applied forces.

$$J = \int_0^{t_f} \left(\mathbf{Z}^{\mathrm{T}}\mathbf{QZ} + \mathbf{u}^{\mathrm{T}}\mathbf{Ru}\right) dt \tag{6}$$

The weighting matrices **Q** and **R**, respectively, must be positive semi-definite and positive definite, respectively. Using the variational formulation, the optimal solution can be defined as a linear combination of the state vector as follows:

$$\mathbf{u}(t) = -\frac{1}{2}\mathbf{R}^{-1}\mathbf{B}^{\mathrm{T}}\mathbf{PZ} \tag{7}$$

where the matrix $\mathbf{P}(t)$ is obtained as the solution of time dependent Riccati equation. It is acceptable to ignore the time dependence of the matrix, and in that case the Riccati equation can be written as follows:

$$\mathbf{PA} - \frac{1}{2}\mathbf{PBR}^{-1}\mathbf{P} + \mathbf{A}^{\mathrm{T}}\mathbf{P} + 2\mathbf{Q} = 0 \tag{8}$$

Standard computing packages are now available to solve this equation. The process of defining the control forces as described above is called the design of controllers. It is seen that control forces are linearly related to the state variables. The forces dependent upon the displacement quantities alter the stiffness and those dependent on the velocities alter the damping characteristics of the structure.

Other approaches (Meirovitch, 1980) and improvements to the above procedure such as instantaneous optimal control approach (Yang et al 1987; Soong, 1988) have also been developed to design controllers.

It is noted that to apply these control schemes, we need to know the values of the entire state vector at every instant of time. This, however, may not be practical. Therefore controllers which require the knowledge of only a few states have also been developed. Of course, such controllers can not be as effective as the controllers based on the full state feedback.

Also, it is not practical to expect that the state measurements, calculation of the control forces and their application to the structure can be carried out instantaneously. Some finite time is consumed in the measurements of response quantities and their processing to calculate the control forces. Also because of actuator dynamics, there is a finite time delay in the actual execution of the control forces. The delays, if not properly compensated in the design of a controller, will not produce desired reduction in response and in some cases it may even aggravate the situation to cause instability. Methods have now been developed to compensate for such time delays in approximate manner (Soong, 1990).

In civil structures, nonlinear behavior is implicit in many structural designs for seismic loads. Also, active structural control can be used with other protective devices such as passive control devices described earlier. Since most of these passive methods render a structure nonlinear, it is necessary to have control schemes which can be applied to nonlinear systems. Several such schemes have been proposed in the research literature recently, for example, Feng et al, (1991) and Yang et al, (1992).

One of the very promising methods applicable to linear as well as nonlinear structures is the sliding mode control or variable structure control approach, developed by Utkin (1978, 1992). An outstanding feature of this approach is its robustness. That is, the approach is quite insensitive to uncertainties of system parameters - - a very desirable feature for its application to civil structures. Its application to civil structures has been pioneered by Yang et al (1994) and Ramu et al (1994).

The underlying basis of this approach is that for every dynamic system one can define sliding surfaces on which the system is stable, and if the system is forced to remain on these surfaces it will eventually approach the zero-state. The controller design process in this approach is divided in to two independent parts: (1) definition of sliding surfaces and (2) evaluation of controller force. For m number of controllers, one needs to define exactly m sliding surfaces. They are defined as linear combinations of the state vector as:

$$\sigma = \mathbf{S}\mathbf{Z} = 0 \tag{9}$$

where the $(2n \times m)$ matrix **S** is determined as described by Utkin (1992). First the state equations of motion are rearranged such that the last m equations correspond to the degrees of freedom where the actuator forces are applied. If this rearrangement leaves the first 2n-m equations with zero actuator forces, then the equations are in the so-called regular form. However, if does not then a simple transformation of the state variables as follows will transform them in to their regular form,

$$\mathbf{Y} = \mathbf{T}\mathbf{Z} \tag{10}$$

where matrix **T** is defined in terms of the submatrices $\mathbf{B}_1$ and $\mathbf{B}_2$ of the input matrix **B** (obtained after rearrangement) as follows:

$$\mathbf{T} = \begin{bmatrix} \mathbf{I}_1 & -\mathbf{B}_1\mathbf{B}_2^{-1} \\ \mathbf{0} & \mathbf{I}_2 \end{bmatrix}. \tag{11}$$

where $\mathbf{B}_1$ and $\mathbf{B}_2$, respectively, are the (2n-m)× m upper and (m× m) lower parts of matrix **B**. It is noted that after rearrangement of the equations of motion mentioned above, matrix $\mathbf{B}_2$ becomes non-singular. Matrices $\mathbf{I}_1$ and $\mathbf{I}_2$ are identity matrices of sizes (2n-m)×(2n-m) and (m×m) respectively. Eq. 10 transforms the state equation (5) and the sliding surfaces (9), written in terms of new state variable **Y**, as follows:

$$\mathbf{Y} = \bar{\mathbf{A}}\mathbf{Y} + \bar{\mathbf{B}}\mathbf{u} \tag{12}$$

$$\sigma = \bar{\mathbf{S}}\mathbf{Y} = 0 \tag{13}$$

where now the transformed matrices $\bar{\mathbf{A}}$, $\bar{\mathbf{B}}$ and $\bar{\mathbf{S}}$ are defined as,

$$\bar{\mathbf{A}} = \mathbf{T}\ \mathbf{A}\ \mathbf{T}^{-1} = \begin{bmatrix} \bar{\mathbf{A}}_{11} & \bar{\mathbf{A}}_{12} \\ \bar{\mathbf{A}}_{21} & \bar{\mathbf{A}}_{22} \end{bmatrix} \tag{14}$$

$$\bar{\mathbf{B}} = \begin{bmatrix} 0 \\ \mathbf{B}_2 \end{bmatrix},\ \bar{\mathbf{S}} = \mathbf{S}\mathbf{T}^{-1} = \begin{bmatrix} \bar{\mathbf{S}}_1 \\ \bar{\mathbf{S}}_2 \end{bmatrix}, \tag{15}$$

It is quite appropriate and convenient to choose $\bar{\mathbf{S}}_2$ to be an identity matrix. The motion along the sliding surfaces is governed by the matrix $(\bar{\mathbf{A}}_{11} - \bar{\mathbf{A}}_{12}\bar{\mathbf{S}}_1)$. To obtain $\bar{\mathbf{S}}_1$ we can use the pole assignment method such that all the eigenvalues of this matrix will have negative real parts. This ensures the stability of sliding motion. As suggested by Utkin (1992), $\mathbf{S}_1$ can also be constructed using the linear quadratic regulator approach by minimization of a linear quadratic function. Under certain conditions the linear quadratic regulator solution will also lead to matrix $(\bar{\mathbf{A}}_{11} - \bar{\mathbf{A}}_{12}\bar{\mathbf{S}}_1)$ with all stable eigenvalues. If the dimension $2n - m$ is large, this latter procedure is more convenient than the pole assignment approach where a decision about the choice of $2n - m$ poles must be made. Once matrices $\bar{\mathbf{S}}_1$ and $\bar{\mathbf{S}}_2$ are known the original matrix **S** can be defined using the transformation matrix **T** simply as $\mathbf{S} = \bar{\mathbf{S}}\ \mathbf{T}$.

Calculation of control forces to bring the state trajectory to a sliding surface can be achieved in several ways. The use of Lyapunov function approach can also be used to ensure that the state trajectory approaches the sliding surface asymptotically as time increases, although it would never intersects the sliding surface. In an approach used by Yang et al (1994), one chooses a positive definite matrix **a** to define the control forces as

$$\mathbf{u} = -(\mathbf{SB})^{-1}\,\mathbf{SE}\ddot{x}_g - \left[(\mathbf{SB})^{-1}\,\mathbf{SA} + \mathbf{a}\mathbf{B}^T\mathbf{S}^T\mathbf{S}\right] Z \tag{16}$$

The choice of matrix **a** will of course determine how fast the trajectory will approach a sliding surface, but to satisfy the Lyapunov's stability condition any positive definite matrix can be chosen. It is convenient to choose a diagonal matrix with positive diagonal elements.

Application of Control Forces

In structural applications, the control force can be applied in several different ways. One of the most direct methods is to use diagonal tendons which can be pulled alternatively to apply forces in two reverse directions. It is most convenient to use tendons in the first story where the winch reaction is transmitted to the foundation directly.

Another way of applying force is through a tuned mass damper. Tuned mass dampers can be used as passive devices to reduce a structure's response. A tuned mass damper is usually placed on the roof of a building to primarily control the first mode which usually participates the most in a structure's response. The reaction force provided by a tuned mass damper to its support on the structure can be augmented appropriately by an external force which is applied to the mass of the damper. See Fig. 8. Such an arrangement is also called as active tuned mass damper. The magnitude and time variation of this force is determined according to an appropriate control algorithm.

One can also use a simple mass which is directly excited by an actuator without any connection to the structure through a spring. In this case the inertial reaction provides the controlling force, the magnitude and time variation of which is determined according to an appropriate control law. Control force can also be applied as time and amplitude regulated pulses created by air blast.

PRACTICAL FEASIBILITY OF ACTIVE CONTROL

There are several issues in the application of active control to civil structures subjected to extreme loads such as earthquakes. One of them is the reliability of the system. Most of the time, a control system will be idle and will be activated only when a strong disturbance is felt. What are the chances that it will work when needed is a very real issue. Also these control systems require an external source of power to operate the actuators. Will that source, when it is needed the most, be available to supply the required power? Also, the magnitude of control force and the level of power needed can be quite significant, as is observed from the following numerical example.

Numerical results were obtained for a typical 10 story structure. The ground excitation was represented by 1941 El Centro earthquake with maximum ground acceleration value of about 0.3 g. The building represents a medium size office building with about 4,00 sq. m. of area per floor. The control force was applied at the top of the structure through a tuned mass damper with a total mass of about 3% of the total building mass. The fundamental frequency of the building was 6.4 rad/ sec., or about 1.0 Hz. The modal viscous damping was assumed to be 3% of the critical. The tuned mass damper reduced the maximum displacement response to 65% and acceleration response to about 74% of the original building response with no tuned mass damper.

The response was further reduced by applying controlling force. The controlling force was calculated by the sliding mode approach. The displacement and acceleration responses were further reduced to a level of 31% and 42%, respectively, of the original building response. It demonstrates that both the tuned mass damper and active control approach can used be reduce the response. However, the maximum level of force required to be applied by the actuator was observed to be quite large – 2828 KN (about 70% of the average floor weight). Perhaps more critical is the peak power demand for this control which was observed to be 3.4 MW. It is a significant amount of power, the availability of which during an intense ground shaking like El Centro can be quite questionable. Although the power demand was high, the energy consumption was not very high compared to the energy dissipated by viscous damping which was two orders of magnitude higher. Energy flow fluctuated, implying that there is a possibility of using regenerative actuators.

PARAMETRIC-ACTIVE CONTROL

Since the level of force and power requirements to control a realistic civil structure can be significant, other novel ideas are also being examined. It is noted that the total energy spent in controlling the 10 story structure in the example problem was not really large. A significant portion of the energy spent in applying the control force was in fact recoverable. It is not surprising, especially in view of the fact that a small increase in the level of viscous damping from 2 to 5% can reduce the response significantly, although the amount of additional energy dissipated due to increased damping is not very large. It indicates that a small amount of energy dissipation can reduce the response significantly. Therefore, several different approaches which do not require large power are being considered for active control of civil structures. They do not apply counteracting forces directly, but they change the damping and stiffness parameters of the structural system ingeniously. Some of these approaches have been aimed to dynamically change the damping level whereas others are directed to change the stiffness. In optimal and sliding control approach also, the control forces continuously altered the stiffness and damping matrices, but not parametrically.

In dampers using viscous fluids, the energy dissipation can be dynamically changed by (1) altering the viscosity of the fluid and (2) altering the diameter of the orifice through which the fluid passes. Electro-rheological fluids are being considered as possible media for dampers as their viscosity can be reversibly changed almost instantaneously by application of electric field. By altering electric field according to an appropriate control algorithm, desired damping force can be obtained. The electric power required for these changes can be easily supplied by a simple battery. The damping force in a damper can also be easily and quickly changed by increasing or decreasing the size of orifice, and the power needs for such a change can be easily met by a simple battery.

The stiffness properties of a structure can also be changed appropriately to effect a desired control. For this a structure can be provided with cross braces which can be removed and attached at suitable time intervals. One way of accomplishing this is through locking and unlocking mechanisms. Another way is to open and close a fluid by- pass valve in a cylinder traversed by a piston with no orifice, as shown in Fig. 9. When the valve is open, the bracing on which this device is installed provides no resistance and thus no stiffness. However, when the valve is closed, the device contributes to stiffness. In such a case, the compressibility of the fluid should not be ignored in computing the stiffness.

The algorithms for opening and closing of the valves in the preceding stiffness regulator, or for adjusting the opening of the orifice in a fluid damper or for regulating the electric field in the electro-rheological damper, all can be developed by the sliding mode approach presented in the previous section (Yang et al , 1994).

The main advantage of these approaches is that they can be operated with a very nominal power source to introduce appropriate adjustments in the system parameters. These small changes in system parameters can bring about a significant change in structural response. These approach make use of this fact very effectively.

CONCLUDING REMARKS

Design of structures for the maximum level of demand imposed by a seismic environment is neither necessary nor desirable. The level of seismic demand can be significantly reduced by passive and active structural controls. The paper reviews a host of options that are available now in passive and active control. Passive control strategies are being already implemented in new and existing buildings and structures. The active control strategies, on the other hand, are still in their infancy. The classical method of direct intervention through application of counteractive control forces is, probably, not going to work with civil structures simply because of their large masses and stiffnesses. More innovative approaches are being sought. The parametric control methods with nominal power demands seem to provide more practical strategies for seismic structural control.

REFERENCES

1. Akiyama, H. (1985). "Earthquake-resistant limit-state design for buildings," Univ. of Tokyo Press, 1985.
2. Buckle, I. G. (1986). "Development and application of Base isolation and passive energy dissipation: A world overview." Proceedings of a Seminar and Workshop on Base Isolation and Passive Energy Dissipation, ATC-17, Applied Technology Council, Redwood City, California, pp. 153-174.
3. Buckle, I. G., and Mays, R. L., (1990). "Seismic isolation: history, application and performance - A World overview," Earthquake Spectra, 6(2), pp. 161-202.
4. Chang, K. C., Soong, T. T., Oh., S.-T., and Lai, M. L., (1991) "Seismic response of a 2/5 scale steel structure with added viscoelastic dampers," Report No. NCEER-91-0012, National Center for Earthquake Engineering Research, State University of New York, Buffalo.
5. Chang, K. C., Soong, T. T., Oh, S. T., and Lai, M. L., (1992) "Effect of ambient temperature on viscoelastically damped structure," J. of Structural Engineering, Vol. 118, No. 8, pp. 1955-1973.
6. Feng, M., Shinozuka, M. and Fujii, S. (1991), "Hybrid Isolation System Using Friction-Controllable Sliding Bearings," Dynamics and Control of Large Structures, Ed. L. Meirovitch, Virginia Polytechnic Institute and State University Press, Blacksburg, VA, pp. 207-218.
7. Fijita, K., Kukubo, E., Nakatogowa, T., Shibata, H., Kunieda, M., Hara, F., Suzuki, K., Ichihashi, I., Yoshimura, H., Zaitsu, T. and Ono, T., (1991), "Development of Friction damper as a Seismic Support for the piping system in nuclear power plants," Active & Passive Damping, PVP-Vol. 211, ASME, Pressure Vessel & Piping Conference, San Diego, California, June 23-27.
8. Grigorian, C. E., Yang, T.-S., and Popov (1992), "Slotted bolted Connections Energy dissipators," Report UCB/EERC-92/10, Earthquake Engineering Research Center, University of California, Berkeley.
9. Hanson, R. D. (1990). "Supplemental damping for improved seismic performance of buildings," ISET Annual Lecture, Bulletin, Indian Society of Earthquake Technology, Paper No. 300, Vol. 27, No. 4, pp. 1-23.
10. Kelly, J. M., (1986a), "Progress and Prospects in Seismic Base Isolation," Proceedings of a Seminar and Workshop on Base Isolation and Passive Energy Dissipation," ATC-18, Applied Technology Council, Redwood City, California, pp. 29-38.

11. Kelly, J. M., (1986b), "A Seismic base isolation: A review and bibliography," Soil Dynamics and Earthquake Engineering, 202-216.
12. Lin, R. C., Liang, Z., Soong, T. T. and Zhang, R. H., (1988), "An experimental study of seismic structural response with added viscoelastic dampers," Technical Report NCEER-88-0018, National Center for Earthquake Engineering Research, State University of New York, Buffalo.
13. Malushte, S. R. and Singh, M. P. (1989), "A Study of seismic response characteristics of structures with friction damping," J. Earthquake Engineering and Structural Dynamics, Vol. 18, pp. 767-783.
14. Meirovitch, L. and Oz, H., (1980) "Active control of structures by modal synthesis," Structural Control (Ed. H. H. Leipholz), North-Holland Publishing Company, pp. 505-521.
15. Mostaghel, N. and Tanbakuchi, J. (1983), "Response of sliding structures to earthquake support motion," Earthquake Engineering and Structural Dynamics, Vol. 11, pp. 729-748.
16. Namita, H., Hara, F., Ichihashi, I., Satoh, A., Farakawa, S.-I., Kuneida, M., Suzuki, K., Fukuda, T., Takata, K., and Kobayashi, H., (1991), "Development of the elastic-plastic damper as a seismic support for piping system in nuclear power plant," Active and Passive Damping, PVP-Vol. 211, ASME, Pressure Vessel and Piping Conference, San Diego, California, June 23-27.
17. Mostaghel, N. and Khodaverdian, M. (1987), "Dynamics of resilient-friction base isolator (R-FBI)," Earthquake Engineering and Structural Dynamics, Vol. 15, pp. 379-390.
18. Popov, E. P., Yang, T. S. and Grigorian, C. E., (1993) "New directions in structural seismic design," Earthquake Spectra, 9(4).
19. Qamaruddin, M., Arya, A. S., and Chandra, B. (1986), "Seismic response of brick buildings with sliding super structures," J. of Structural Engineering, ASCE 112, No. 3, pp. 558-572.
20. Ramu, K., Singh, M. P. and Nerves, A., (1994), "Mitigation of wind and earthquake effects on structures by sliding mode control," Proceedings of the 1st World Conference on Structural Control," Los Angeles, California, August 3-5.
21. Soong, T. T. (1988), "State-of-the-art review: Active Structural Control in Civil Engineering," J. of Eng. Struct., Vol. 10, No. 2, pp. 73-84.
22. Soong, T. T. (1990), "Active structural control: Theory and Practice," Longman Scientific & Technical, England.
23. Sumitomo, Metals, (1981), "Friction Damper for Earthquake Response Control," A pamphlet distributed by the company, 1987-12.
24. Uang, C. M. and Bertero, V. V. (1988), "Use of energy as a design criterion in earthquake resistant design," Report No. UCB/EERC-88/18, Earthquake Engineering Research Center, Univ. of California, Berkeley, November.
25. Utkin, V. I., (1978), "Sliding modes and their application in variable structural systems," MIR publishers, Moscow.
26. Utkin, V. I. (1992), "Sliding Modes in Control Optimization," Springer-Verlag, New York.
27. Yang, J. N., Akbarpour, A. (1987), "New optimal control algorithms for structural control," J. of Engineering Mechanics, ASCE, Vol. 113, No. 9, pp. 1369-1386.

28. Yang, J. N., and Soong, T. T., (1988),. "Recent advances in active control of civil engineering structures," J. of Probabilistic Engineering Mechanics, Vol. 3, No. 4.

29. Yang, J. N., Li, Z., and Vongchavalitkul, S. (1992), "A Generalization of optimal control theory: linear and nonlinear control," J. of Engineering Mechanics, ASCE, Vol. 120, No. 2, pp. 266-283.

30. Yang, J. N., Wu, J. C., Agrawal, A. K., and Li, Z., (1994), "Sliding mode Control for seismically-excited linear and nonlinear civil engineering structures," National Center for Earthquake Engineering Research, State Univ. of New York at Buffalo, Technical Report, NCEER-94-0017.

31. Yao, J. T. P. (1972), "Concept of structural control," J. of the Structural Division, ASCe, Vol. 98, No. 7, pp. 1567-1574.

32. Zayas, V. A., Low S. S. and Mahin, S. A. (1987), "The FPS Earthquake resisting system: experimental report," Report UCB/EERC-87/01, Earthquake Engineering Research Center, Univ. of California, Berkeley.

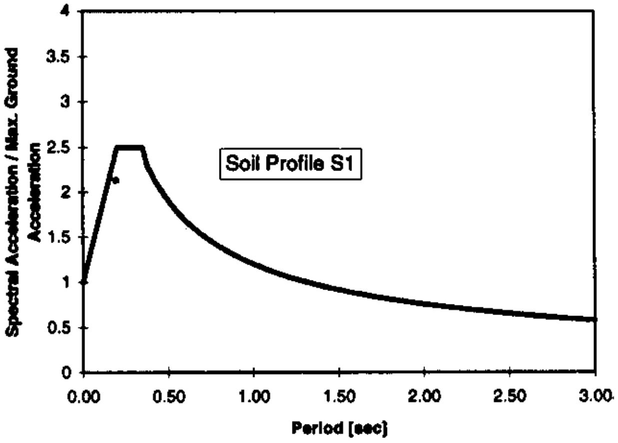

Figure 1: NEHRP Normalized Response Spectra for Rock or Stiff Soil Condition.

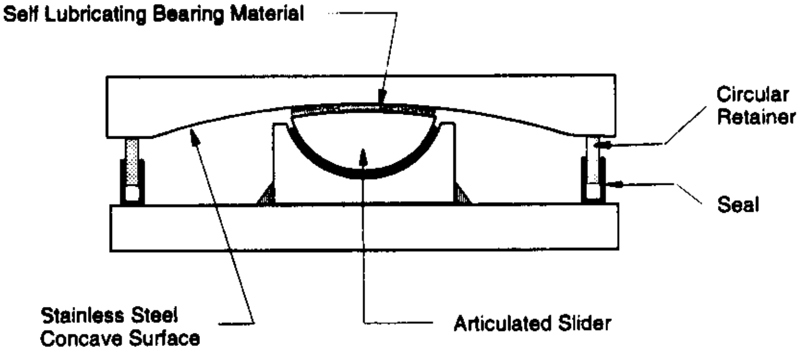

Figure 2: Cross Section of a Friction Pendulum Isolator.

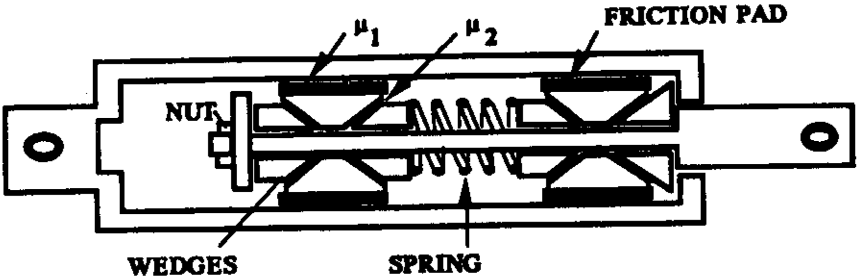

Figure 3: Spring Loaded Friction Damper.

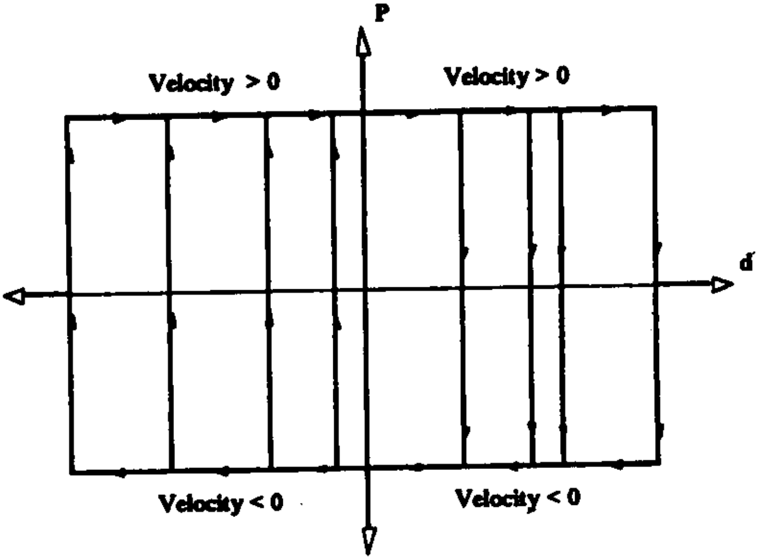

Figure 4: Idealized Hysteresis Loops of a Spring Loaded Friction Damper.

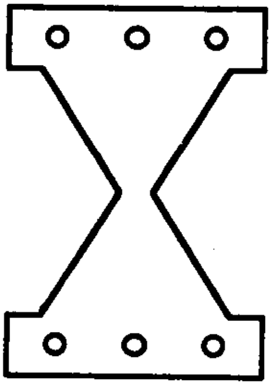

Figure 5: A Uniform Strengh Plate from ADAS Device.

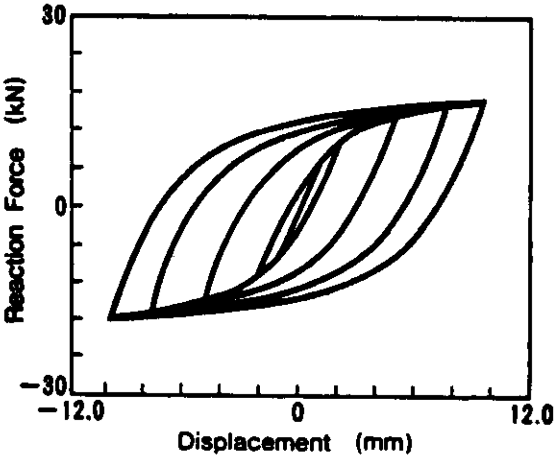

Figure 6: Hysteresis Loops of an ADAS Device.

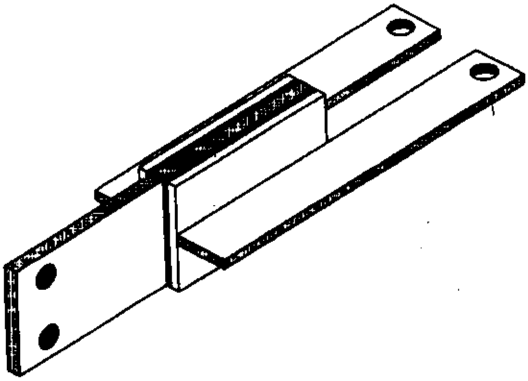

Figure 7: Schematic of a 3M Viscoelastic Damper.

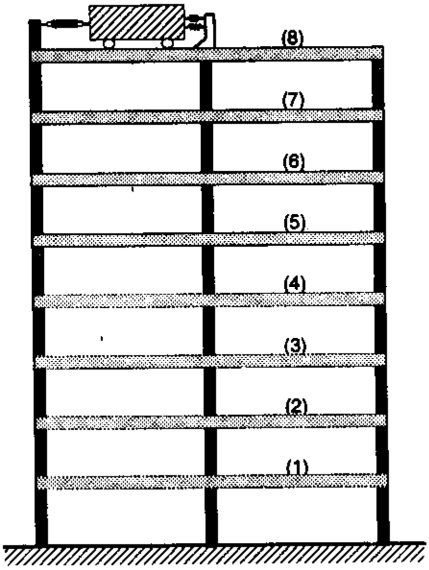

Figure 8: Multi Story Building with Tuned Mass Damper.

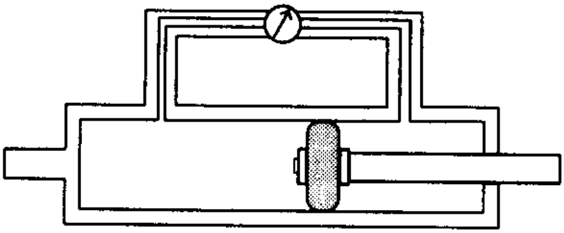

Figure 9: A Device to Regulate Stiffness in a Brace.