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A STATE-OF-THE-ART REVIEW ON ACTIVE CONTROL OF STRUCTURES

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ABSTRACT

An updated state-of-the-art review on response-triggered structural control system is presented. The review mainly focuses on the active control of structures for earthquake excitations, and covers theoretical backgrounds of different active control schemes, important parametric observations on active structural control, limitations and difficulties of their practical implementation, and brief descriptions of three actively controlled tall buildings in Japan. A brief introduction of more promising semi-active control of structures is also presented.

KEYWORDS: Active Control, Earthquake Excitation, Tall Buildings, Semi-Active Control

INTRODUCTION

For the last thirty years or so, the reduction of structural response caused by dynamic effects has become a subject of intensive research. Many structural control concepts have been evolved for this purpose, and quite a few of them have been implemented in practice. There are a number of motivating factors for conducting this research. They include: (i) reduction of undesirable vibrational levels of flexible structures due to unexpected large environmental loads; (ii) retrofitting existing structures against environmental hazards; (iii) protecting seismic equipments and important secondary systems; and finally, (iv) providing new concepts of design of structures against environmental loading. Broadly speaking, structural control methods can be classified as passive and active control methods. The passive control method is activated by the structural motion. No external force or energy is applied to effect the control. On the other hand, active control method is effected by externally activated device, to change the response. The activation of external force is based on the measurement of external disturbance and/or structural response. Sensors are employed for the measurement purposes, and with the help of computers, the digital signal activates (converted to analog signal) the required external force. A combination of these two methods of structural control has been used to evolve hybrid control methods, for realizing stringent control requirements. In recent years, a class of active control systems, for which the external energy requirements are orders of magnitude smaller than a typical active control system, have been evolved. They are known as semi-active control systems, in which the control action is produced by the movement of the structure but is regulated by an external source of energy.

There are a number of mechanisms by which the structural control action is achieved. For example, in the category of passive control base isolation devices, visco-elastic dampers, tuned mass dampers, liquid-column dampers, liquid-mass dampers, metallic yield dampers, and friction dampers have been proposed. Out of these, base isolation devices have been widely implemented in practice. In active control, active mass/tuned mass dampers (ATMD), active tendon systems, actuators/controllers have been used. Out of these, active mass/tuned mass dampers have been implemented for the response reduction of tall buildings in controlling wind-induced vibrations. In hybrid control, the concepts using base isolation and ATMD, and visco-elastic dampers and ATMD have been proposed. In semi-active control, electro-rheological/magneto-rheological dampers, fluid viscous dampers, and tuned mass dampers are being investigated. Some of the control mechanisms, which are widely reported in the literature, are shown in Figures 1-10.

There are a few state-of-the-art papers on structural control, which provide a good overview of different structural control strategies developed and implemented in practice. They include state-of-the-art review on base isolation of structures by Kelly (1986) and by Jangid and Datta (1995). On active structural control, two state-of-the-art papers by Soong (Soong, 1988, 1996) provide an excellent overview of different active structural control systems developed till 1990. A relatively recent comprehensive review on structural control is presented by Housner et al. (1997), and a state-of-the-art review on semi-active control is recently presented by Symans and Constantinou (1999). Herein, an updated brief state-of-the-art review on response-triggered structural control system is presented. The review mainly focuses on the active control of structures under earthquake excitations. The review covers: (i) different types of active control methods and their theoretical backgrounds; (ii) important observations from the parametric studies conducted on various control strategies; (iii) limitations of active control system and practical difficulties in its implementation; (iv) a brief review of more promising semi-active control method; and finally, (v) a brief outline of a few active control strategies implemented in practice.
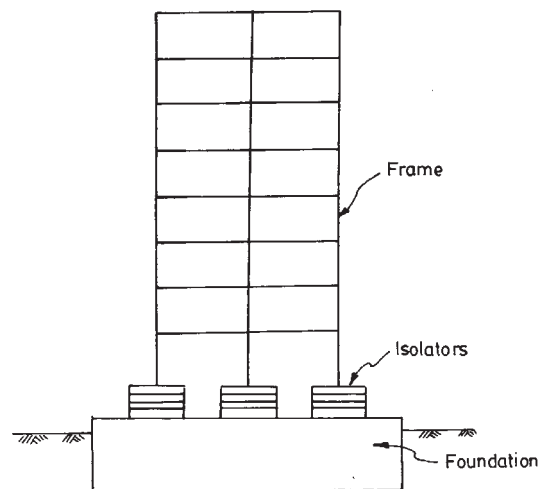

Fig. 1   Schematic view of base-isolated frame
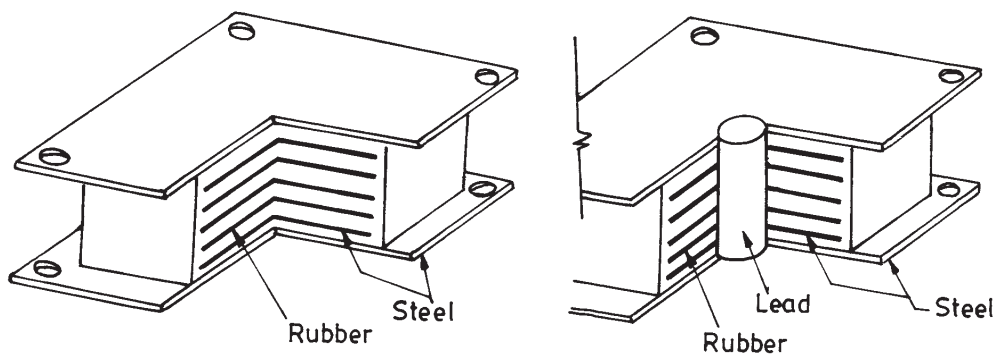

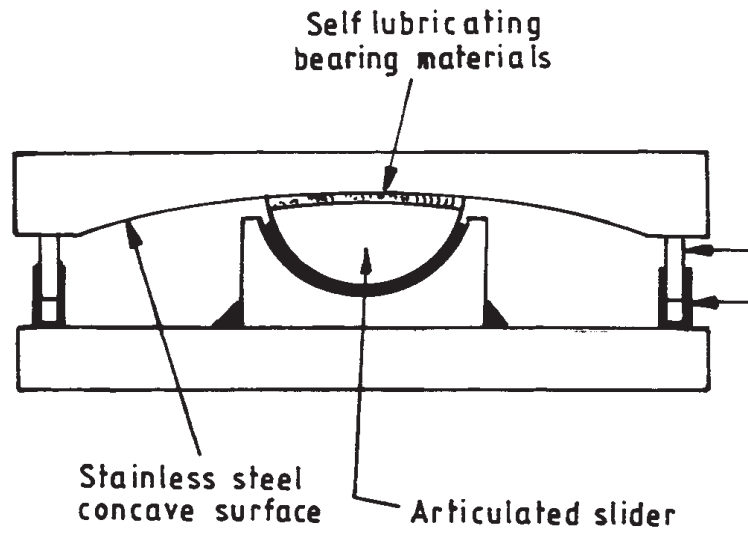Fig. 2   Laminated rubber bearing base isolators

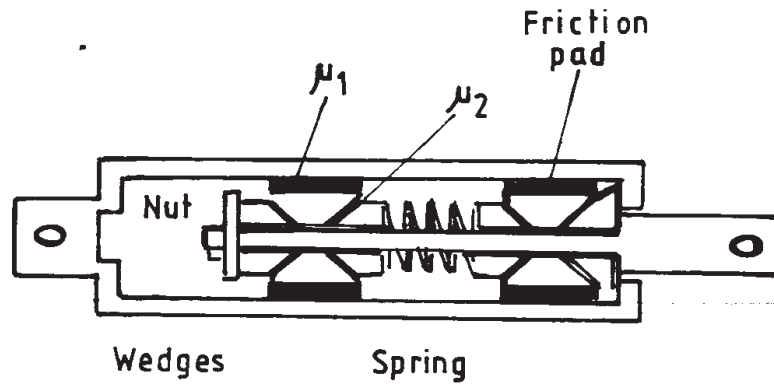Fig. 3   Friction pendulum base isolators

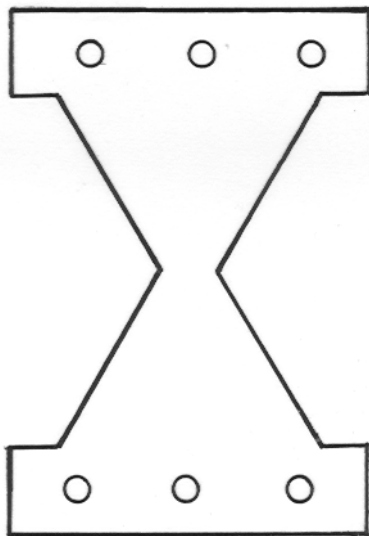Fig. 4   Friction isolation device

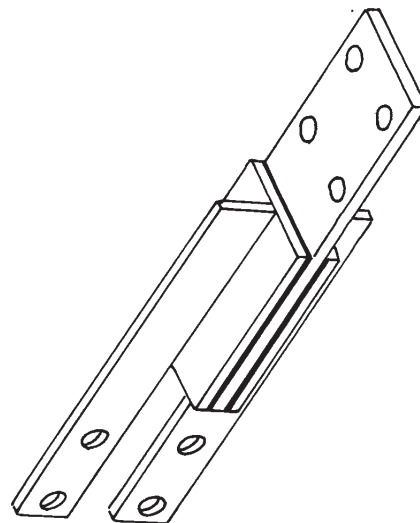Fig. 5   Yielding steel energy absorbing device

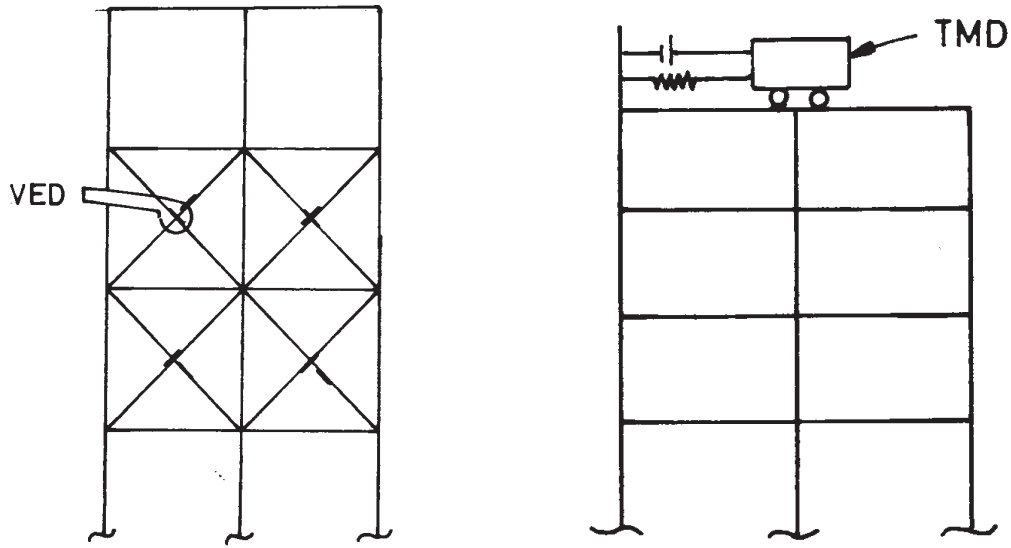Fig. 6   Viscoelastic damping device
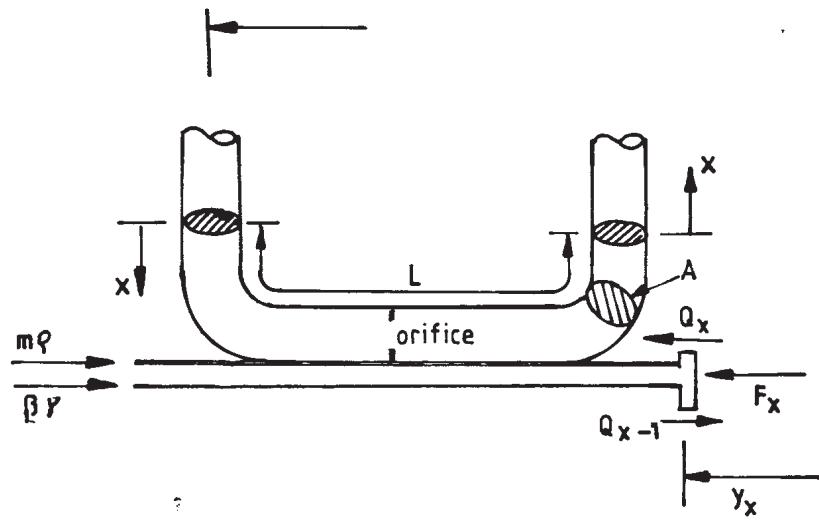
Fig. 7   Tuned mass damper

Fig. 8   Tuned liquid column damper

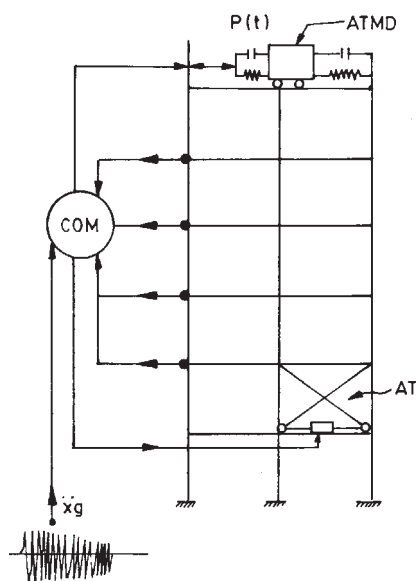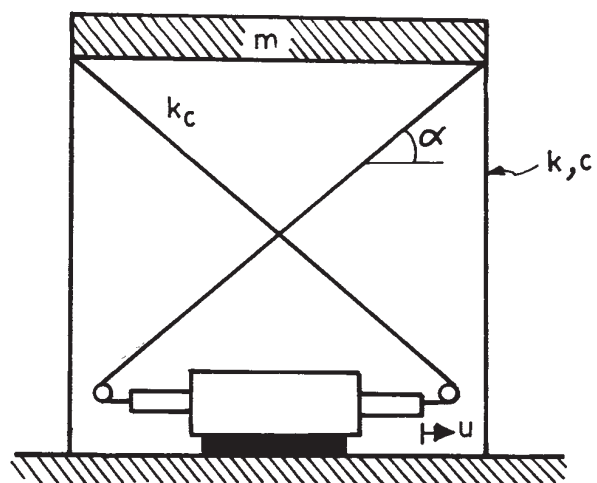Fig. 9   Active control strategies

Fig. 10   Active tendon scheme

DIFFERENT TYPES OF ACTIVE CONTROL

The early notion of actively controlled structures was presented by Zuk (1968). He distinguished between the active control, which is designed to reduce structural motion and that which generates structural motion. Kinetic structures which control enclosed space through structural manipulation belong to the second category. Earliest works on active structural control include prestressed tendon to stabilize tall structures, control of tall buildings by cables attached to jacks (Soong, 1988), and use of active systems which can provide increased strength to the structure to counter exceptional over-loading (Nordel, 1969). According to Soong (1988), Yao put forward the theory of formal active structural control which became the subject of intensive research subsequently.

Most of the control concepts have feed-back structure as shown in Figure 11. Actuators in the figure are powered by external energy sources to produce the required control force. Based on the control strategy, active control can be classified as: open loop control system (when the left side loop of Figure 11 is operative); close loop control (when the right side loop of Figure 11 is operative); and open–close loop control (when the both loops of Figure 11 are operative). An adaptive control system is a variation of open-close loop control with a controller which can adjust parameters of the system. The adaptive systems are generally used to control structures whose parameters are unknown and are based on tracking error between the measured response and the observed response. A learning control system is one which has an ability to learn and can switch over from open loop control system to close loop control system depending upon the requirements.
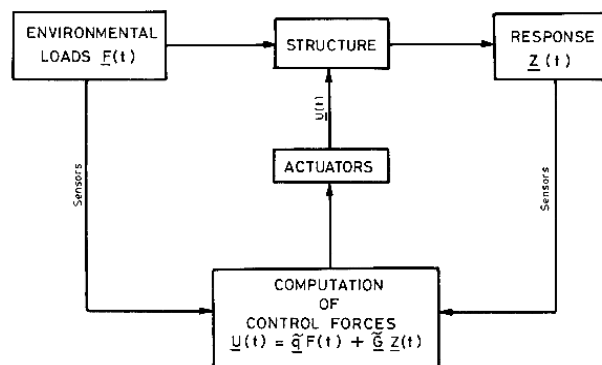

Fig. 11   Feed-back control schemes

Based on mathematical modeling, the active control of structures can be classified as: (i) linear control in which all mathematical equations and operations are linear; (ii) non-linear control in which these operations are non-linear; (iii) time-varying control in which the control functions and parameters change with time; (iv) discrete time control system in which the control parameters vary at discrete time intervals; (v) lumped parameter control system in which the control parameters are lumped; (vi) distributed control parameter system in which the parameters are function of space; (vii) deterministic control system in which all mathematical operations are deterministic; and finally, (viii) stochastic control system in which mathematical equations and operations are stochastic.

CONTROL THEORIES

Most of the control theories reported in the literature are based on deterministic control system with lumped parameters and time-varying control operations. Some of the widely reported structural control methods (algorithms) are briefly presented below.

The mathematical equation of motion for all control methods has the following structure:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = Du(t) + Ef(t) \qquad (1)$$

where M, C, K are mass, damping and stiffness matrices; $x(t)$ is the displacement vector; $f(t)$ is the excitation due to ground motion; D is the location matrix of control force; E is the location matrix for the excitation forces; and $u(t)$ is the control force vector. The control force vector has the following approximate form:

$$u(t) = K_1 x(t) + C_1 \dot{x}(t) + E_1 f(t) \tag{2}$$

where K_1, C_1, and E_1 are respectively control gains which can be time-dependent.

From Equations (1) and (2), it follows that

$$M\ddot{x}(t) + (C - DC_1)\dot{x}(t) + (K - DK_1)x(t) = (E + DE_1)f(t) \tag{3}$$

It is seen from Equation (3) that the effect of structural control is to mathematically modify the damping, the stiffness and the excitation, in such a way that the response of the system is controlled. The matrices K_1, C_1, and E_1 are called gain matrices, and can be obtained in such a way that the response, in principle, can be totally eliminated. However, in real practice, it is not possible to totally eliminate the response. Different degrees of control of response are achieved by deriving the control gain matrices K_1, C_1, and E_1. Derivation of these matrices depends on the control algorithms selected. In general, the control algorithms have some objective functions to be minimized. Accordingly, the gain matrices are derived. Different control algorithms differ in respect of finding these gain matrices or finding the control force vector, keeping in view an objective function that reduces the structural response. The solution of the control problem and the development of control algorithm are obtained by writing the control equation of motion in state space of the form:

$$\dot{z}(t) = Az(t) + Bu(t) + Hf(t) \tag{4}$$

in which $z(t)$ is the state vector.

1. Linear Optimal Control

The most popular control algorithm is based on linear optimal control theory which has closed loop structure. In this algorithm, minimization of a quadratic performance index J of the following form is carried out:

$$J = \int_0^{t_f} [z^T(t)Qz(t) + u^T(t)Ru(t)]dt \tag{5}$$

in which Q and R are referred to as weighting matrices, and t_f is the time duration over which the control force operates. The minimization problem requires the solution of a Riccati matrix equation, leading to the control force vector given as

$$u(t) = -\frac{1}{2}R^{-1}B^T P(t)z(t) = Gz(t) \tag{6}$$

in which G is called the gain matrix.

The minimization procedure does not take into account the external excitation, as it is not known *a priori*. Therefore, this control algorithm is not truly optimum. In fact, many of the control algorithms are not truly optimal in this sense. The optimal linear control can be given an open-close loop structure by incorporating the measured excitation feed-back. Many studies have been carried out on linear optimal control, such as those by Yang (1975), Abdel-Rohman and Leipholz (1983), Chang and Soong (1980), Chung et al. (1988), Soong (1992), and Sarbjeet and Datta (1998).

2. Pole Assignment Technique

With u defined by Equation (6), the control equation of motion can be written in the form,

$$\ddot{Z}(t) = (A + BG)Z(t) + Hf(t) \tag{7}$$

The modal damping ratios and frequencies obtained from the modified matrix $(A + BG)$ provide the dynamic characteristics of the dynamic system. The gain matrix G can be chosen such that the eigenvalues of the modified matrix take a set of values prescribed by the designer. Generally, the eigenvalues corresponding to the first few modes are considered. Therefore, the control scheme is useful for structures having first few modes as the predominant modes of vibration. Further, the control scheme is not an optimal control scheme, but it provides a feasible/desirable controlled response. There have been

a few works in this area, like those reported by Abdel-Rohman and Leipholz (1978), Martin and Soong (1976), and Abdel-Rohman and Nayfeh (1987).

3. Independent Modal Space Control

In this control scheme, the state space equation is written in modal co-ordinates by defining a modal control force $u_j(t)$ and modal load $f_i(t)$. The equation of motion becomes decoupled, if it is assumed that the modal control force $u_j(t)$ depends only on the modal co-ordinate $y_j(t)$. A modal quadratic performance function J_j of the form of Equation (5) can be constructed, and a total performance function $J = \sum J_j$ (Meirovitch and Oz, 1980; Meirovitch and Baruh, 1983; Meirovitch and Ghosh, 1987) is minimized to obtain the modal control force. Meirovitch and a few other researchers investigated the effectiveness of modal space control.

4. Instantaneous Optimal Control

In the instantaneous optimal control, the knowledge of external excitation up to the current time is utilized in obtaining the improved control algorithm which makes use of the time-dependent performance function $J(t)$. The optimal control force is derived by minimizing $J(t)$ at any instant of time, t. The formulation of the problem is based on writing the state vector $z(t)$ in terms of the state vector and excitation at previous time step, which are supposed to be known. The performance function $J(t)$ is minimized subject to the constraint given by the expression of the evolution of the state vector $Z(t)$ over the time-interval Δt. Some of the interesting works on instantaneous control include those by Abdel-Rohman and Leipholz (1979), and Yang et al. (1987). The minimization of the cost function is carried out over the time interval.

5. Bounded State Control

In bounded state control, the control force is applied to keep response within an allowable range. All pulse control strategies in the literature fall into this category. The basic idea of pulse control is to apply a train of force pulses to produce responses matching that produced by a continuous loading of arbitrary nature. It is meant to destroy gradual rhythmic building up of the structural response in the case of resonance. The pulse magnitudes are determined analytically so as to minimize non-negative cost function of linear quadratic regulator form. The minimization of the cost function is carried out over the inter-pulse spacing. They may be applied every time, a zero crossing of the response variable is detected. A continuous monitoring of the system state variable is required in this control scheme. The advantages of the bounded state control are its applicability for inelastic structures and its energy saving. The bounded state control was studied by Abdel-Rohman et al. (1993), Udwadia and Tabai (1981a, 1981b), Masri et al. (1981a, 1981b), Prucz et al. (1985), and by Reinhorn et al. (1987).

6. Non-linear Control

In non-linear control, a higher order performance function is minimized, such that the control force becomes a non-linear function of the state variable. The idea behind determining a non-linear control strategy is to obtain a better control of response, with relatively less control force. Wu et al. (1995) developed a non-linear control strategy in the line of LQR problem by using the solution of Riccati equation. The control force was expressed in a convenient form by using a weighted non-linearity feed-back parameter. By setting this parameter to zero, the control force becomes same as that of the LQR problem. Other works on non-linear active control include those of Shefer and Beakwell (1987), Suhardijo et al. (1992a), and Wu et al. (1995). Another type of non-linear control scheme is addressed in the literature for response reduction of non-linear structures. The stiffness and damping non-linearities can be included in this algorithm, and the non-linear equation of motion can be solved in time domain, with a control force derived as a non-linear function of state variable. The minimization of the non-linear performance function is achieved through the solution of Riccati equation.

7. Generalized Feed-Back Control

In this control scheme, the dynamic equations of controller are also incorporated. As a result, absolute acceleration of the structure also becomes another feed-back, apart from the displacement and velocity of the structure. The modified LQR performance function contains the acceleration feed-back vector, and therefore, the control force becomes a function of structural displacement, velocity and acceleration. Studies on active control with acceleration feed-back have been reported by Yang et al. (1991, 1994), Suhardjo et al. (1992b), Spencer et al. (1993), Rofooei and Tadjbakhsh (1993), Dyke et al. (1996a), and by Suneja and Datta (1998).

8. Sliding Mode Control (SMC)

Sliding mode control scheme was first developed by Utkin (1978). In the sliding mode control, a sliding surface is generated consisting of a linear combination of state variables. The sliding surface is defined such that the motion of the structure, i.e. structural response, is stable on this surface. The sliding surface is obtained by minimizing a performance function of LQR type, and thus by requiring the solution of Riccati equation. Controllers are designed such that they drive the response trajectory on to the sliding surface. This is accomplished by the Liapunov stability criterion (since the motion of the sliding surface is always stable). From this condition, the control force is estimated. A possible continuous controller which allows the response trajectory to move on to the sliding surface (even if the sliding surface is discontinuous) is obtained by allowing sliding margin. An improvement over the sliding mode control is achieved by designing a controller which provides control force based on linear feed-back system and non-linear feed-back of the state vector. The non-linear feed-back is introduced to take into consideration the uncertainties arising from the excitation. The purpose is to make the control strategy robust against all kinds of uncertainties in the system. Some of the important studies on sliding mode control include those by Yang et al. (1994), Singh and Matheu (1997), Adhikari and Yamaguchi (1997), and by Sarbjeet and Datta (2000).

9. Time Delay Compensation

The aforementioned control algorithms are based on the instantaneous effect, i.e. it is assumed that there exists no time delay between the response measurement and the control action. In reality, this is never achieved, and there always exists a time delay between the two. It is somewhat difficult to include the time delay effect in the control scheme and to define control force in terms of delayed state vector. The introduction of time delay parameter makes the system of equations as parametered differential equations and nonlinear. As a consequence, the stability analysis of the system becomes important. In fact, the time delay effect, if not properly compensated, may cause instability of the system. The importance of time delay compensation in structural control has been demonstrated in laboratory (Chung et al., 1988, 1995; McGreevy et al., 1988), and several compensation methods have been proposed (Hammerstrom and Gros, 1980; Abdel-Rohman, 1985; Soliman and Roy, 1992). These include modification of control gain by performing a phase shift of measured state variables in the modal domain and by methods updating the measured quantities dynamically. Some of the important works on the time delay effect were presented by Abdel-Rohman (1985, 1987, 1993), Jun-Ping and Kelly (1991), Jun-Ping and Deh-Shiu (1988), Yang et al. (1990), and by Chung et al. (1995).

10. Active Control Using Neural Network and Fuzzy Logic

In recent years, there has been growing application of the neural network and the theory of fuzzy logic, for controlling the structural response due to dynamic excitation. The main objective of applying this concept for structural control is to obviate the need for developing a control algorithm analytically. However, in some cases, the neural network or fuzzy logic is used, keeping in view the minimization of some objective function, which tends to reduce the structural response. These control strategies do not strictly optimally control the structural response. They are better in terms of practical applications, and are more versatile.

In the active control of structures using neural network, neural nets tend to provide control forces, which would reduce the response of the structure when subjected to unknown future earthquakes. Various types of neuro-controllers have been reported in the literature (Ghaboussi and Joghataei, 1995; Chen et al., 1995; Bani-Hani and Ghaboussi, 1998; Rao and Datta, 1998). A neuro-controller is trained with the help of a trained emulator network. The purpose of emulator network is to aid the learning of the neuro-

controller in establishing the desired relation between the immediate past history of the response of the structure and the adjusted control signals of the actuator. Emulator network is essentially used to determine the error at the output of the neuro-controller, which is minimized during the training of the neuro-controller network. Further, emulator network helps in averaging out the error developed due to the time delay effect. Once the neuro-controller is trained by using the emulator network, it can be independently used for controlling the response of the structure. The neuro-controller is trained via the minimization of certain criterion. Chen et al. (1995) described a criterion in which the instantaneous error function is taken as the summation of errors between the actual and desired responses. Ghaboussi and Joghataie (1995) considered the criterion to be the average of an expected response for the future time steps to be zero. Kim et al. (2000) used the minimization of the cost function (of closed loop control scheme, LQR) as the criterion for training. This control scheme was used to control both linear and non-linear structures.

Rao and Datta (1998) developed a control scheme by using a single neural network, for a predetermined response reduction of the single mode control of building frames. This control scheme explicitly takes into account the time delay effect in the training of the neural network. This concept was further extended to the multi-mode response of building frames in which the use of emulator network was dispensed with. The method first predicts the modal response of the structure, and then obtains the required control force to be applied to the structure. A typical neural net-based control scheme is shown in Figure 12.

In recent years, fuzzy control theory has drawn considerable interest of researchers for active and semi-active control of structures subjected to earthquake excitations. The advantage of this approach is its inherent robustness and its ability to handle the non-linear behaviour of the structure. Moreover, the computations for driving the controller are quite simple, and can be easily implemented into a fuzzy chip. In the fuzzy control, the control equation of motion is generally solved by using the MATLAB environment with the help of Simulink and Fuzzy tool boxes. Different types of fuzzy rule bases are used to map control forces according to the levels of the structural responses. The rule bases can be constructed by considering feed-back as: (i) only velocity, (ii) velocity and displacement, and (iii) velocity, acceleration, and displacement. Generally, maximum bounds on the control forces/damping coefficients for active/semi-active control schemes are prescribed. Fuzzy control does not provide an optimal control, but has more flexibility compared to the classical control theories. Different applications of fuzzy control theory for active and semi-active control of different types of structures include those by Symans and Kelly (1999), Battaini et al. (1998), Tani et al. (1998), Kurata et al. (1999).
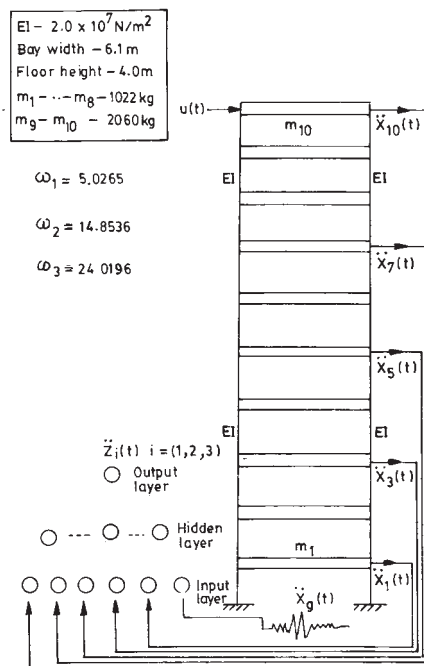

Fig. 12   Active neuro-control strategy

11. Other Types of Control Strategies

In line with the concept of active/semi-active control, a few other types of control strategy have been investigated, namely hybrid control, adaptive control, and stochastic control. Hybrid control is a combination of passive control and active control. Various combinations of passive and active systems have been attempted, such as base isolation and actuators, ATMD, visco-elastic dampers and actuators, etc. Hybrid control is preferred when more stringent control of one or more response quantities is desired. It is governed by a control algorithm in which the dynamic characteristics of structural system include those of passive control devices. Formulation of active control problem remains the same, except that the structural system becomes non-classically damped.

An adaptive controller is a controller with adjustable parameters, incorporating a mechanism for adjusting these parameters. Adaptive control is generally used to control structures whose parameters are unknown or uncertain. It consists of choice of the controlled structure, choice of a performance function, online evaluation of the performance with respect to some desired behaviour, and online adjustment of the control parameters, to bring the performance closer to the desired behaviour. The adaptive control methods are generally divided into direct and indirect methods. Indirect methods have been experimented, and have been used by considering the direct model.

The structure to be controlled is represented by

$$\dot{X}(t) = A_s X_s(t) + B_s u_s(t) \tag{8}$$

$$Y_s(t) = C_s X_s(t) - \text{observer} \tag{9}$$

Here, Y_s is the response of adaptive control.

The reference model has the similar structure, and has response with suffix *m*. The adaptive controller is based on tracking the error, $e(t) = Y_m(t) - Y_s(t)$. Both feed-forward and feed-back control are possible by the least mean-square algorithm.

Stochastic active control becomes necessary when (i) uncertainty exists in both inherent nature of the structure and exogenous forces that it sees, (ii) structures are with infinite degrees of freedom, and are not completely observable from sensors located, and (iii) sensors are also contaminated with noise. Responses are modeled as random processes, and may have non-linear transfer relationships with the input. Determination of control force requires minimization of the expected values of the cost function. The problem is mathematically tractable for white noise type of disturbance by using stochastic dynamic programming. Another variation of stochastic control consists of covariance control, such that the state feed-back gain *K* is determined such that

$$E\left[u(t)u^T(t)\right] = KSK^T \tag{10}$$

in which S is the covariance matrix of the stationary state.

SOME IMPORTANT RESULTS OF THE PARAMETRIC STUDY

Different numerical studies on the active control of buildings led to a number of interesting conclusions which are useful for the analysis, design and implementation of the active control scheme for building structures. Some of the important ones are summarized below.

It is observed that the controller placed at higher floors requires a smaller control force to achieve a large reduction in the response, while a controller on the first floor requires a larger control force (Yang, 1975).

The tendon control system, when applied to a building subjected to self-excited wind forces, provides more efficient control, for both deflection and acceleration of building, than a tuned mass damper control, on account of supplying large control force (Abdel-Rohman and Leipholz, 1983). However, it is observed by Singh and Matheu (1997) that the magnitude of actuator force required in the tendon control of building for seismic forces is much larger than that required in ATMD. Further, for ATMD control, the tuning frequencies for which the maximum reduction in response takes place, are different for different control strategies. It is observed that the maximum reduction in response does not necessarily take place at a tuning frequency equal to the structure's first natural frequency (Sarbjeet and Datta, 1998). It is also shown that the application of SMC for a building with ATMD may lead to large responses in the building

due to the interaction effect (Adhikari and Yamaguchi, 1997). As far as the control design with incomplete measured data is concerned, it is seen that the control performance is best when the sensor and the actuator are located at the top floor (Yang, 1975).

Yang et al. (1987) showed that the instantaneous optimal control algorithms are more effective than the Riccati closed loop control. However, there is a considerable improvement in results, when acceleration-velocity feed-back is used in Riccati closed loop control (Rufooei and Tadjbakhsh, 1993).The bounded force control (Abdel-Rohman et al., 1993) composed of rectangular and pulse-like force is found to be more efficient than the linearly varying control force, as produced by linear control (Riccati closed loop control). Further, it is observed that the performance of the non-linear control method is better than that of the linear control method (Yang et al., 1994). In the non-linear control method, significant reduction in the acceleration of the structure can be achieved with the control force even smaller than 1% of the weight of the structure (Suhardjo et al., 1992a). It is generally observed that the performance of SMC is found to be remarkable (Adhikari and Yamaguchi, 1997).

It is shown that the time-delay in control schemes causes unsynchronization which not only can render the control ineffective, but may also cause instability in the system. Yang et al. (1990) found that instantaneous optimal open-closed algorithm is most sensitive and critical to a system time-delay. It is shown that the adverse effects of time delay were alleviated by taking into account the actuator dynamics in the optimization process, and in particular, the acceleration response had been reduced significantly (Yang et al., 1994). For the building equipped with a hybrid control system (with base isolation), the main advantage of such a controller is its ability to increase the percentage of reduction for the peak response of rubber bearings with the increase of the earthquake intensity. Further, non-linear control method is more effective for the hybrid control (Yang et al., 1994, 1996).

Most of the conventional control schemes for civil engineering structures with fixed-base assumption are valid only for a particular range of shear wave velocity. Below such range, soil-structure interaction effect must be included in the control scheme (Yang et al., 1996).

SEMI-ACTIVE CONTROL

It originates from the passive control system, modified to allow the adjustment of mechanical properties based on feed-back from the excitation or the measured response. As an active control system, it monitors the feed-back measurement, and generates appropriate command signal. As a passive control system, control forces are developed as a result of the motion of the structure. Control forces primarily act to oppose the motion, and are developed through appropriate control algorithms. Semi-active control generally requires small amount of external power for the operation (of the order of few Watts in comparison to tens of kilo-Watts). Different types of semi-active control devices include:

(i)   **Stiffness control devices -** These devices are utilized to modify the stiffness, and hence, the natural frequency of the system. This establishes a new resonant condition during earthquakes. The devices used are stiffness bracings, which are engaged or released so as to include or not to include the additional stiffness in the system, and operate generally through fluid control within tubes by valves (Yang et al., 1996; Nagarajaiah, 1997; He et al., 2001).

(ii) **Electro-rheological dampers/magneto-rheological dampers -** They consist of a hydraulic cylinder containing micron-size dielectric particles suspended within a fluid. In the presence of current, particles polarize and offer an increased resistance to flow (a change from viscous fluid to yielding solid within milli-seconds). The magneto-rheological dampers are magnetic analogues of electro-rheological dampers, and have electro-magnets located within the piston head which generate the magnetic field (Ehrgott and Masri, 1992, 1993; Spencer et al., 1996; Dyke et al., 1996b, 1997).

(iii) **Friction control devices -** They are energy dissipators within the lateral bracing of a structure, or are as components within the sliding isolation system. The coefficient of friction of sliding is controlled by the modulation of fluid pressure in a pneumatic pressure (Akbay and Aktan, 1991; Feng, 1993).

(iv) **Fluid viscous devices -** They consist of a hydraulic cylinder, with a piston dividing it into two sides. The cycling piston forces oil through an orifice, creating the output force. The output force is modulated by an external control valve which connects two sides of the cylinder (Sack et al., 1994; Symans and Constantinou, 1997).

(v) TMDs and TLDs - The dynamic characteristics of the TMDs are controlled by the external current. In the TLDs, the length of the hydraulic tanks is modified by adjusting the rotation of the rotatable buffles in the tank, and thus, the sloshing frequencies of the fluid are changed.

In general, the equation of motion for the semi-active control of structure takes the form

$$M\ddot{X}+(C+C_v)\dot{X}+(K+K_v)X=-M_r I \ddot{X}_g \qquad (11)$$

in which C_v and K_v are variables. These can take positive discrete values (within specified bounds), and depend on the state. Most of the algorithms and control for semi-active control are studied for the variable damping. Different control algorithms developed for the variable dampers include: (i) Lyapunov stability approach, (ii) decentralized bang-bang control, (iii) clipped optimal control, (iv) modulated homogeneous friction control, and (v) Riccati matrix solution technique. Recently, Ni et al. (2002) developed semi-active vibration control by using neural network. Fuzzy control has also been used for the semi-active variable devices (Sun and Goto, 1994). The semi-active control of structures includes applications on building frames and bridges. An excellent state-of-the-art review on semi-active control system has been given by Symans (1999).

PROBLEMS OF REAL TIME APPLICATION

A number of problems are encountered in the practical implementation of the active control scheme. Because of these problems, active control of structures has not been widely applied. Apart from the availability of large power sources for the implementation of control schemes, there are some other real time application problems. They include:

(i) Modeling error - Modeling of the actual structure with limited degrees of freedom is the source of this error. The control algorithm based on the idealized model, many a times, cannot effectively control the actual structure.

(ii) Time delay - There exists a time lag between sensing the response and applying the control force. As a result, unsynchronized application of force may result, and may cause ineffective control and instability.

(iii) Limited sensor and controller - It is not practically possible to apply sensors at all points, required to obtain all response quantities of interest as feed-back. Therefore, the question of optimization of the sensors and controllers needs attention. Further, the use of an observer for constructing a state vector from the limited measurements, may reduce the effectiveness of the control schemes.

(iv) Parameter uncertainties and system identification - These uncertainties include uncertainties in the structural strength, non-linear excursions, and problems of online identification and time-dependent degradation. These may result in the loss of the effectiveness of the control schemes.

(v) Discrete time control - In practice, real time control is implemented, whereas an algorithm provides the continuous time control.

(vi) Reliability - The reliability of an active control scheme is debated because of its infrequent activation, maintenance, availability of power source at the time of episode, and psychological barrier on the part of occupants.

(vii) Cost-effectiveness and hardware requirement - They become the most practical consideration for the implementation of control schemes.

ACTUAL APPLICATIONS OF ACTIVE CONTROL

Some actual applications of active control schemes for the reduction of wind-induced vibrations of tall buildings have been reported. These control schemes have also been found to control the seismic response of buildings to moderate earthquakes. Salient features of three such applications on tall buildings are presented below:

(i) AMD on Kyobashi Seiwa Building - The building is located at Chuo-Ku, Tokyo, with a frontage of 4 m and a total height of 33 m. The building has 11 floors, and is made of rigid steel frames. Two AMDs are located at the top floor, spaced apart. First AMD has a mass of 4 ton, and second one has a mass of 1 ton. The idea of providing two AMDs was to control the torsional response of the structure also. The schematic diagram of the AMD is shown in Figure 13. A hydraulic pump of 22 kW is used

to actuate the masses. Sensors are placed at the basement, 6th floor, and at the 11th floor. The computer is provided on the top floor itself. This is the world's first AMD installed on a building.
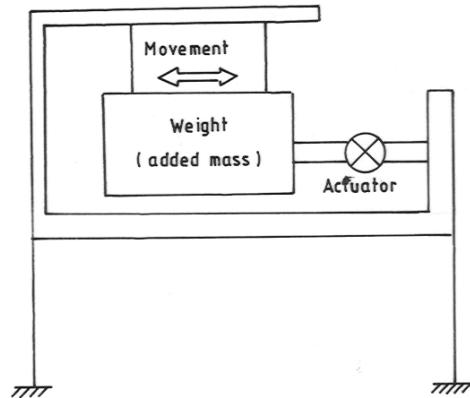

Fig. 13 Active control with AMD system

(ii) Duox on ANDO Nighikicho - It is located in Chiyoda–Ku, Tokyo. It has 14 storeys and two basement levels, and is made of rigid steel frames. Above the ground, weight of the building is 2600 t-f. Two-directional simultaneous AMD is placed on the top of a TMD which is placed on the top floor. The damping system of the TMDs consists of oil dampers. The TMD weight is 18 t-f, while the AMDs have 2 t-f weight each. The schematic diagram of the Duox system is shown in Figure 14. The Duox system operates on the principle that if the active control system fails, the TMD will provide at least the minimum control of response.
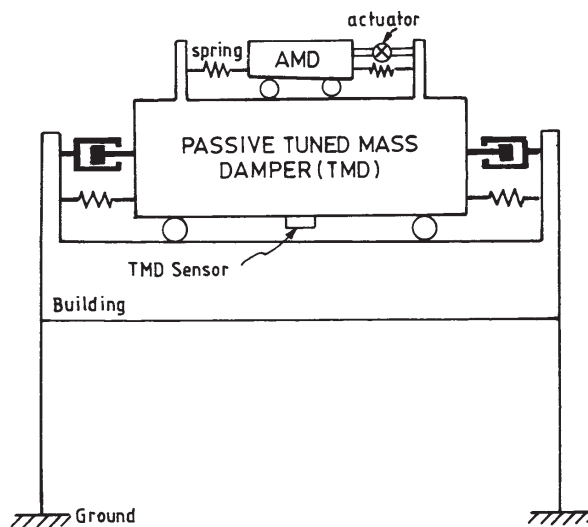

Fig. 14 Active control with Duox system

(iii) Trigon on Shinjuku Tower - It is located in Shinjuku–Ku, Tokyo, with a floor area of 264,100 m^2. The structure is made of steel and partially reinforced concrete frames. It is a 52-storeyed plus 5-basement structure, with a above-ground weight of 130,000 t-f. Three control devices are installed in the form of roller pendulum mass on the 36th floor. The control masses are 110 t each. Maximum stroke of the pendulum is 110 cm. Period adjusted is 3.7258 s, and the motor capacity to drive the pendulum is 75 kW. The schematic diagram of the roller pendulum is shown in Figure 15.
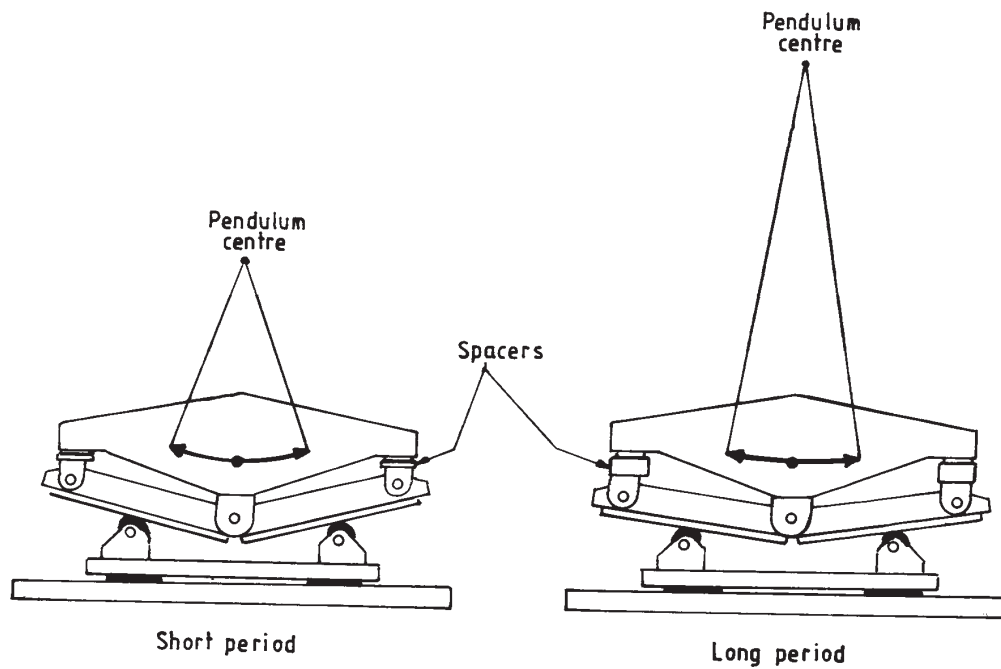
Fig. 15   Active control with Trigon (roller pendulum system)

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