

Review Of Algorithms For Control Systems For Civil Engineering Structures

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ABSTRACT

One of the most significant technological innovations in the structural engineering field is the practical application of active and semi-active control to civil structures. A number of structures integrating active, hybrid, and semi-active response control technologies have been constructed in Japan, China and USA. Any control system whether it is in aircraft, spaceship or building; it needs an algorithm to be run by the computer installed in the structure. A state-of-the-art review on algorithms for response-triggered structural control systems is presented. The review 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. This study focuses on the development of an active control algorithm based on several performance levels anticipated from an isolated building during different levels of ground shaking corresponding to various earthquake hazard levels. The proposed active control algorithms change the control gain depending on the level of shaking imposed on the structure. These active control systems have been evaluated using a series of analyses performed on ground motion records. Simulation results show that the newly proposed algorithms are effective in improving the structural as well as nonstructural performance of the building for selected earthquakes.

Keywords – Active Control, Algorithms, Control-theories, Structure Control-System.

I. INTRODUCTION

The most important task of civil engineering structures is to design them such that they can withstand the forces and accommodate the deformations without major damage or a collapse. The response of the system can always be limited by providing stiffer structural members but in general the system would become uneconomical. So it has been a common practice to generate more ductile designs, providing the means for adequate energy dissipation through the yielding of individual members and generation of localized plastic hinges. The occurrence of damage during a seismic event is unavoidable in this design philosophy. Further, the permanent deformations in the structure surviving the seismic events may seriously affect its service life. Recently the attention of the civil engineering community has moved on reducing forces and deformations in structures through the methods of the structural control in which information is fed into the controller which processes the measured quantities and structural properties to generate the corresponding control signal, which is then input to

the actuators which may be driven by a power source to produce the control action, as shown in Fig 1. These method of response reduction can address not only the prevention of total failure or the limitation of damages but also they can be designed to provide comfort to the occupants of the structure on the basis of mode of operation of these special devices the structural response control methods can be broadly classified as passive, active and semi-active control approaches.

A passive control system does not require an external power source for operation and utilizes the motion of the structure to develop the control forces. Control forces are developed as a function of the response of the structure at the location of the passive control system. An active control system typically requires a large power source for operation of electro-hydraulic or electro-mechanical actuators which supply control forces to the structure. Control forces are developed based on feedback from sensors that measure the excitation and/or the response of the structure. The feedback from the structural response may be measured at locations remote from the location of the active control system.

A semi-active control system requires a relatively small external power source for operation (like a battery) and utilizes the motion of the structure to develop the control forces, the magnitude of which can be adjusted by the external power source. Control forces are developed based on feedback from sensors that measure the excitation and/or the response of the structure. The feedback from the structural response may be measured at locations remote from the location of the semi-active control system. Sometimes these systems are combined to form hybrid control systems.

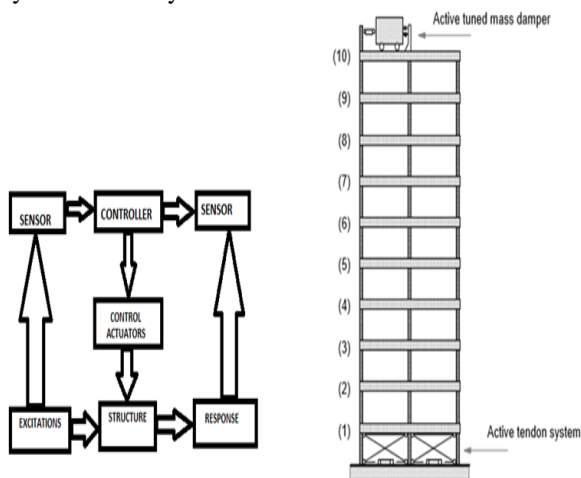


Fig 1: Control system applied on a building

Some actual applications of active control schemes for the reduction of wind-induced vibrations of tall buildings have been reported. The 11-storey building made of rigid steel frames is located at Chuo-Ku, Tokyo, with a frontage of 4 m and a total height of 33 m. Two AMDs are located at the top floor, spaced apart with masses of 4 tons and 1 ton, respectively Fig 2. The idea of providing two AMDs was to control the torsional response of the structure also. The schematic diagram of the AMD is shown 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. Sensors are placed at the basement, 6th floor, and at the 11th floor. Other example is a Duox system on ANDO Nighikicho, Tokyo. It has 14 storeys and two basement levels, and is made of rigid steel frames. Above the ground, mass of the building is 2600 tons. Two-directional simultaneous AMD is placed on the top of a TMD which is placed on the top floor as shown in Fig 3. The damping system of the TMDs consists of oil dampers. The TMD mass is 18 tons, while the AMDs have 2-ton mass, each. 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.

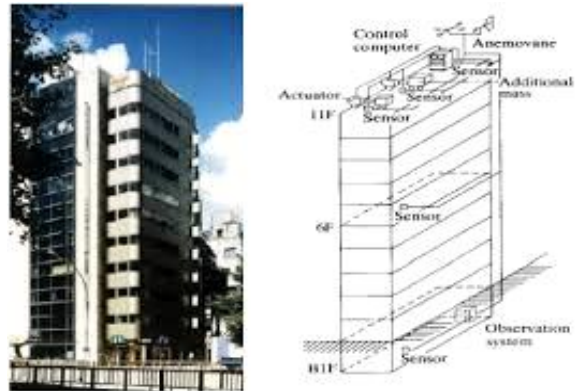


Fig 2: Building at Chuo-Ku.

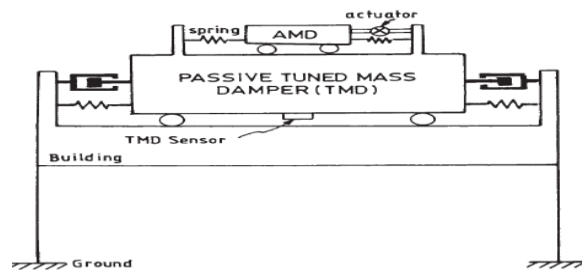


Fig 3: Duox system for ANDO building

II. CONTROL SYSTEM THEORY FOR DYNAMICS OF STRUCTURES

Most of the control theories reported in the literature are based on deterministic control system with lumped parameters and time-varying control operations. The dynamic equation of motion for all control methods is given as

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

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:

$$u(t) = K_1x(t) + C_1\dot{x}(t) + E_1f(t) \quad (2)$$

where K_1 , C_1 , and E_1 are respectively control gains which can be time-dependent. From Eqs. (1) and (2), it follows that

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

It is seen from Eq. (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 reduce the response totally. 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,

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

where, $z(t)$ is the state vector defining displacement and velocity of the structure. IN the recent years, various algorithms have been developed to process the information from ground excitation, state of the structure, as discussed below.

2.1 Linear-Quadratic 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 Liapunov's quadratic performance index J of the following form is carried out.

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

where Q and R are called 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

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

in which G is called the gain matrix. 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).

2.2 Method of Pole Assignment

Having defined $u(t)$ by Eq. (6) the control equation of motion can be written in the form:

$$\ddot{z}(t) = (A + BG) z(t) + Hf(t) \quad (7)$$

The modal damping ratios and frequencies obtained from the modified matrix $(A + BG)$ provide the dynamic characteristics of the system. The gain matrix G can be chosen such that the eigenvalues of the modified matrix take a set of prescribed values. 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. 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).

2.3 Modal Space Control Algorithm

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 Eq. (5) can be constructed, and a total performance function, ΣJ_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.

2.4 Instantaneous Control Technique

In this control algorithm, the latest values of external excitation are 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 by now. The performance function $J(t)$ is minimized subjected to the constraint given by the expression of the evolution of the state vector $z(t)$ subject to the constraint given by the expression of the evolution of the state vector $z(t)$ over the time-interval Δt . Some 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.

2.5 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).

2.6 Non-linear Control Theory

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 feedback 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), Suhardjo 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 Matrix-Riccati equation.

2.7 Generalized Feedback Control

In this control scheme, the dynamic equations of controller are also incorporated. As a result, absolute acceleration of the structure also becomes another feedback, 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).

2.8 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).

2.9 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).

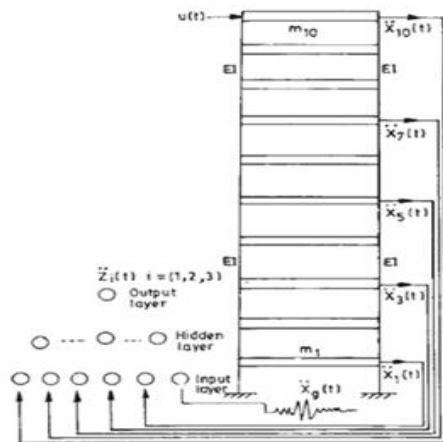


Fig 4: Active neuro fuzzy control.

2.10 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 SET 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 nonlinear 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 Fig 4. 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 behavior 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).

2.11 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:

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

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

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

$$E[u(t)u^T(t)] = KSK^T \quad (10)$$

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

III. FUTURE DIRECTIONS

Besides the availability of the advanced algorithms, there are a number of problems encountered in the practical implementation of the active control scheme. Because of these problems, active control of structures has not yet 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 modeling error, time delay, limited sensor, parameter uncertainties and system identification, reliability, cost-effectiveness and hardware requirement. These problems have gained attention of the researchers, and it is hopeful that control systems will soon be applied to a large number of structures in developing as well as developed countries.

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