NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
State University of New York at Buffalo

ACTIVE STRUCTURAL CONTROL IN CIVIL ENGINEERING

by

T.T. Soong
Department of Civil Engineering
State University of New York at Buffalo
Buffalo, NY 14260

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NOTICE

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1 Professor, Dept. of Civil Engineering, State University of New York at Buffalo

NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
State University of New York at Buffalo
Red Jacket Quadrangle, Buffalo, NY 14261

ABSTRACT

The objective of this paper is to provide a state-of-the-art assessment of active control research as applied to civil engineering structures. An attempt is made to present it with less specialized research content suitable for a more general readership. Recent activities in control algorithm development, control system design and practical aspects of their applications are summarized followed by a discussion on possible future directions.

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SECTION 1
INTRODUCTION

In structural engineering, "active structural control" has become known as an area of research in which the motion of a structure is controlled or modified by means of the action of a control system through some external energy supply. There are a number of motivating factors for conducting this research. They include the following:

a. With the trend toward taller, longer and more flexible structures, undesirable vibrational levels could be reached under large environmental loads such as strong wind, large waves and strong earthquakes, thus adversely affecting human comfort and even structural safety. The application of active control is one of the options in safeguarding such structures against excessive vibrations. In fact, "super-tall" buildings with up to 500 stories are being considered as possibilities in the near future [96, 97], for which control systems, either active or passive, may become an integral part.

b. Active or hybrid active-passive systems can be attractive candidates for retrofitting or strengthening existing structures against, for example, earthquake hazards. Current passive means of using interior shear walls or base isolation systems are structurally invasive. Active systems, on the other hand, can be more effective and can be incorporated into an existing structure with less interference. In a report prepared for the National Research Council addressing research issues based on lessons learned from the 1985 Mexico earthquake [71], research on retrofit of buildings using devices which "might increase damping or modify the natural period" is recommended. This objective can be easily achieved using active or active-passive systems.

c. Civil Engineering structures are not designed to withstand all possible external loads. However, extraordinary loading episodes do occur, resulting in structural damage or failure. Active control in this context can mean a last resort attempt to save a structure which, without it, would not be able to survive. This extra protection is particularly attractive when one considers the high cost of some recent large structures such as deep-water offshore platforms, not even mentioning lives that might perish otherwise. The same is true for structures which serve critical functions, for which "failure" is synonymous with "disaster".

d. Some structures house valuable and sensitive equipment or secondary systems. Their operating safety is of paramount importance. Active control can thus be applied at the substructure level to insure proper operating conditions for secondary systems.

e. Passive control devices such as base isolation systems, viscoelastic dampers and tuned mass dampers, have been installed in some existing structures, resulting in improved structural performance. Passive devices, however, have inherent limitations. Consider, for example, the tuned mass damper system installed in the Citicorp Center, New York [72, 98, 103]. Since it is tuned to the first modal frequency of the structure, it is basically designed to reduce only the first mode vibration. An active mass damper, on the other hand, can be effective over a much wider frequency range. Hence, the study of active structural control is a logical extension of the passive control technology.

f. Finally, the idea of active control itself is not only attractive, but potentially revolutionary, since it elevates structural concepts from a static and passive level to one of dynamicism and adaptability. One can envision future structures having two types of load resisting members: the traditional passive members that are designed to support basic design loads, and active members whose function is to augment the structure's capability in resisting extraordinary loads. Their integration in an optimal fashion can conceivably result in better utilization of material and lower cost [25, 94, 95].

Thus motivated, there has been a flurry of research activities in the area of active control of civil engineering structures over the last 20 years. In this paper, an attempt is made to assess the present state of knowledge in this research area and possible future directions.

It should be mentioned that the basic concepts of active control are not new; they have been the staple of electrical and control engineering for many decades. And they have been applied successfully in a variety of disciplines such as aerospace engineering and mechanical engineering. More recently, motion control of large space structures has also been a subject of intensive research. However, active control of civil engineering structures, as indicated above, has a more recent origin. While much of the theoretical basis is rooted in modern control theory, as we shall see, its application to civil engineering structures is unique in many ways and presents a host of new challenges.

SECTION 2
ACTIVE CONTROL SYSTEM AND CONTROLLED STRUCTURAL BEHAVIOR

Early notions of an actively-controlled structure are contained in [121-123] in which Zuk advances the notion of "kinetic structures". Zuk makes the distinction between active controls which are designed to reduce structural motion and those which generate structural motion. The kinetic structures described by Zuk belong to the latter. Conceptually, Zuk visualizes all manners of buildings as being able to change form, shape, and configuration in order to make themselves adaptable to ever changing forces and functional usages. For example, buildings could be compactly prepackaged in a factory, and conveniently transported to the site. At the site, it would be energized, causing it to self-deploy or erect itself by means of control systems. Similarly, one can envision structures which are self-collapsing, reversible, or are able to change shape, or control enclosed space through structural manipulation by means of control devices.

All the work reported here, however, belongs to the first category, namely, controls designed to reduce structural motion. According to Zuk [121-123], the earliest attempts in this direction were made in the 1960's when Eugene Freyssinet proposed in 1960 to use prestressing tendons as control devices to stabilize tall structures. Independently, Lev Zetlin in 1965 conceived the idea of designing tall buildings, whereby cables are fixed to the structural frame and attached to hydraulic jacks at the base. Sensors are used to detect movement at the top of the structure and to signal a control device which, in turn, directs the action of the jacks. Unfortunately, neither structure was built. Other early attempts include that of Nordell [70], who suggested the use of active systems which can be activated to provide increased strength to a structure prior to any "exceptional" overloading.

A systematic assault on active control research did not begin until 1972, when Yao laid down a more rigorous control-theory based concept of structural control [117]. In [117], an excessive-response triggered structural control system is suggested as an alternative approach to addressing the safety problem in structural engineering.

As described in Yao [117] and in most of the subsequent publications, an active structural control system has the basic configuration as shown schematically in Fig. 2-1. It consists of:

a. Sensors located about the structure to measure either external excitations, or structural response variables, or both.

b. Devices to process the measured information and to compute necessary control forces needed based on a given control algorithm.

c. Actuators, usually powered by external energy sources, to produce the required forces.

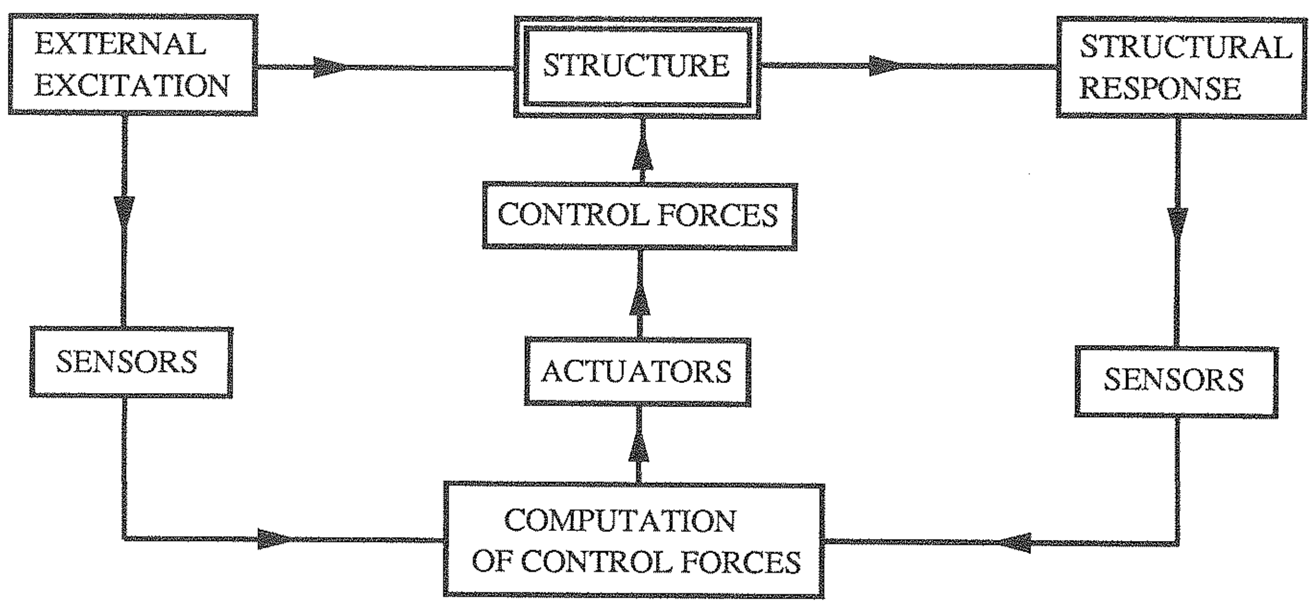

FIGURE 2-1 Schematic Diagram of Active Control

When only the structural response variables are measured, the control configuration is referred to as closed-loop control since the structural response is continually monitored and this information is used to make continual corrections to the applied control forces. An open-looped control results when the control forces are regulated only by the measured excitations. In the case where the information on both the response quantities and excitation are utilized for control design, the term open-closed loop control is used in the literature.

To see the effect of applying such control forces to a structure under ideal conditions, consider a building structure modeled by an n-degree-of-freedom lumped mass-spring-dashpot system. The matrix equation of motion of the structural system can be written as

$$M\ddot{\underset{\sim}{x}}(t) + C\dot{\underset{\sim}{x}}(t) + K\underset{\sim}{x}(t) = D\underset{\sim}{u}(t) + E\underset{\sim}{f}(t) \qquad (2\text{-}1)$$

where:

M = n x n mass matrix
C = n x n damping matrix
K = n x n stiffness matrix
$\underset{\sim}{x}(t)$ = n-dimensional displacement vector
$\underset{\sim}{f}(t)$ = applied load or external excitation
$\underset{\sim}{u}(t)$ = applied control force vector
D = n x m matrix defining the location of the control force vector
E = n x r matrix defining the location of the excitation

Suppose that the open-closed loop configuration is used in which the control force $\underset{\sim}{u}(t)$ is designed to be a linear function of the measured displacement vector $\underset{\sim}{x}(t)$. the velocity vector $\dot{\underset{\sim}{x}}(t)$ and the excitation $\underset{\sim}{f}(t)$. The control force vector takes the form

$$\underset{\sim}{u}(t) = K_1\,\underset{\sim}{x}(t) + C_1\,\dot{\underset{\sim}{x}}(t) + E_1\,\underset{\sim}{f}(t) \qquad (2\text{-}2)$$

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

The substitution of eq. (2-2) into eq. (2-1) yields

$$M\ddot{\underset{\sim}{x}}(t) + (C - DC_1)\,\dot{\underset{\sim}{x}}(t) + (K - DK_1)\,\underset{\sim}{x}(t) = (E + DE_1)\,\underset{\sim}{f}(t) \qquad (2\text{-}3)$$

Comparing eq. (2-3) with eq. (2-1) in the absence of control, it is seen that the effect of open-closed loop control is to modify the structural parameters (stiffness and damping) so that it can respond more favorably to the external excitation. The effect of the open-loop component is a modification (reduction or total elimination) of the excitation or the input. The choice of the control gain matrices K_1, C_1 and E_1 depends on the control algorithm selected.

SECTION 3
CONTROL ALGORITHMS

Research efforts in active structural control have focused on a variety of control algorithms based on different control design criteria. Some are considered classical as they are direct applications of modern control theory. Some, however, are specifically proposed for civil engineering structural control applications due to the fact that, as mentioned earlier, they give rise to some unique control problems.

To facilitate discussions, let us again use eq. (2-1) to represent the structure under consideration which, using the state-space representation, can be written in the form

$$\dot{\underset{\sim}{z}}(t) = A\underset{\sim}{z}(t) + B\underset{\sim}{u}(t) + H\underset{\sim}{f}(t) \tag{3-1}$$

where:

$$\underset{\sim}{z}(t) = \begin{bmatrix} \underset{\sim}{x}(t) \\ \dot{\underset{\sim}{x}}(t) \end{bmatrix} \tag{3-2}$$

is the 2n-dimensional state vector,

$$A = \begin{bmatrix} O & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \tag{3-3}$$

is the 2n x 2n system matrix, and

$$B = \begin{bmatrix} O \\ M^{-1}D \end{bmatrix} \text{ and } H = \begin{bmatrix} I \\ M^{-1}E \end{bmatrix} \tag{3-4}$$

are location matrices specifying, respectively, the locations of controllers and external excitations in the state space. In eqs. (3-3) and (3-4), 0 and I denote, respectively, the null matrix and the identity matrix of appropriate dimensions.

3.1 Optimal Linear Control

A classical result, it provides a solution for control design based on the minimization of a quadratic performance index J of the form

$$J = \int_{o}^{t_f} \left[\underset{\sim}{z}^T(t)\, Q\underset{\sim}{z}(t) + \underset{\sim}{u}^T(t) R\underset{\sim}{u}(t) \right] dt \tag{3-5}$$

In the above, the superscript T indicates vector or matrix transpose, the time interval $[o,t_f]$ is defined to be longer than that of the external excitation, Q is a 2n x 2n positive semi-definite matrix, and R is an m x m positive definite matrix. The matrices Q and R are referred to as weighting matrices, whose magnitudes are assigned according to the relative importance attached to the state variables and to the control forces in the minimization procedure. The assignment of large values to the elements of Q indicates that response reduction is given priority over the control forces required. The opposite is true when the elements of R are large in comparison with those of Q. Hence, by varying the relative magnitudes of Q and R, one can synthesize the controllers to achieve a proper trade off between control effectiveness and control energy consumption.

Under linear closed-loop control, it can be shown that the required control vector is given by [24]

$$\underset{\sim}{u}(t) = -\frac{1}{2} R^{-1} B^T P(t) \underset{\sim}{z}(t) \tag{3-6}$$

where the superscript -1 represents matrix inverse. The matrix P(t) is symmetric and positive definite satisfying the Riccati matrix equation of the form

$$\dot{P}(t) + P(t)A - \frac{1}{2} P(t)BR^{-1}P(t) + A^T P(t) + 2Q = 0, \quad P(t_f) = 0 \tag{3-7}$$

For many structural problems, however, it has been found that P(t) remains constant over a large portion of the time interval $[0,t_f]$, dropping rapidly to zero near t_f [113, 114]. Hence, P(t) can often be approximated by a constant matrix and the control gain, defined as the coefficient of $\underset{\sim}{z}(t)$ in eq. (3-6), is a constant. Since all the parameters of the Riccati equation are presumably known, the matrix P(t) can be determined off-line, and the only on-line computation required during control execution involves matrix multiplication as indicated by eq. (3-6).

The mechanics of implementing optimal linear closed-loop control is relatively straightforward, and it has been studied extensively in the context of active control of civil engineering structures [6 ,7, 27, 28, 30, 31, 91, 105]. Depending on the choice of the weighting matrices, various levels of control effectiveness can be achieved. While linear control laws can also be derived for open-loop and open-closed loop control schemes, closed-loop control results are widely used since, as the control forces are continuously corrected and modified by the instantaneous structural response, the control algorithm is less sensitive to uncertainties and inaccuracies in the mathematical model used for a structure and its parameters.

It has been pointed out that, since the external excitation is ignored or set to zero in the derivation of the Riccati equation, the control law given by eq. (3-6) is not truly optimum [113, 114]. By including the excitation term in the Riccati equation, however, its solution then requires a priori knowledge of the loading history. This is generally not possible for excitations such as earthquakes, wind forces, wave load, etc., encountered in structural engineering. New control algorithms which circumvent this difficulty have been proposed, and some of them will be discussed in the latter part of this section.

3.2 Pole Assignment

Consider the state-space equation (3-1). The system matrix A defines the open-loop system dynamics and its eigenvalues provide modal damping and frequency characteristics. Let the control force be determined by closed-loop feedback, i.e.,

$$\underset{\sim}{u}(t) = G\underset{\sim}{z}(t) \tag{3-8}$$

where G is a constant control gain matrix. The closed-loop system thus takes the form

$$\dot{\underset{\sim}{z}}(t) = (A + BG)\,\underset{\sim}{z}(t) + H\underset{\sim}{f}(t) \tag{3-9}$$

in which the system matrix becomes A+BG. As has been observed in Sec. 2, this modification of the system matrix through active control alters, in part, modal damping ratios and frequencies. This is reflected by the fact that the eigenvalues of A+BG, denoted by η_j, j = 1, 2,...,2n, are generally different from those of A.

Since η_j, j = 1, 2,...,2n, defines the controlled system behavior, a feasible control strategy is to choose the control gain G in such a way that the η_j's take a set of values prescribed by the designer. Control algorithms developed based on this procedure are generally referred to as pole assignment techniques. Successful application of these algorithms thus requires judicious placement of the closed-loop eigenvalues on the part of the designer as well as a good understanding of the uncontrolled structural modal behavior.

Pole assignment algorithms have been studied extensively in the general control literature [73]. Its application to the study of civil engineering structural control has been fruitful when only few vibrational modes contribute significantly to the structural response [2, 53]. In these cases, attention needs only to be paid to these selected modes and a more clear choice of the closed-loop eigenvalues can be made. Additionally, the method of pole assignment offers a convenient base for comparison when, for example, relative merits of various control implementation devices are evaluated [14].

It is noted that pole assignment leads to feasible as opposed to optimal control. However, the solution for the control gain G based on prescribed eigenvalues is in general not unique [73]. Hence, some optimality criteria can be incorporated into a pole assignment algorithm.

Let us also remark that the term "modal control" has been used to mean pole assignment in the control literature [73]. This terminology, however, causes some confusion in the area of structural control since modal control here generally implies a wider class of control algorithms involving control design in the modal space. One of these modal-domain control algorithms is described below.

3.3 Independent Modal Space Control (IMSC)

As the name implies, control system design based on IMSC takes place in the modal space. Assuming that a structure possesses normal modes, it is well known that the equation of motion of an n-degree-of-freedom structural system can be decomposed into a system of n decoupled single-degree-of-freedom systems in the modal coordinates. Using again the state space equation (3-1) and defining the modal transformation

$$\underset{\sim}{z}(t) = T\underset{\sim}{y}(t) \tag{3-10}$$

where T is the modal matrix in the state-space form, one obtains a system of two-dimensional modal state-space equations in the form

$$\dot{\underset{\sim}{y}}_j(t) = A_j \underset{\sim}{y}_j(t) + B_j \underset{\sim}{u}_j(t) + H_j \underset{\sim}{f}_j(t), \quad j = 1,2,...,n \tag{3-11}$$

where the subscript j is used to indicate quantities in the jth mode.

Equation (3-11) has the appearance of a set of traditional decoupled modal equations except for the fact that they are in general coupled through the modal control forces $\underset{\sim}{u}_j(t)$, since each $\underset{\sim}{u}_j(t)$ usually depends on all the modal state vectors. If, however, each $\underset{\sim}{u}_j(t)$ is designed to depend on $\underset{\sim}{y}_j(t)$ alone. e.g.,

$$\underset{\sim}{u}_j(t) = G\underset{\sim}{y}_j(t) \tag{3-12}$$

eqs. (3-11) then becomes mutually independent, thus permitting independent control design of n second-order systems. Control algorithms based on this design procedure have been referred to as control by modal synthesis [59] or, more commonly, independent modal space control [60 - 67]. The procedure essentially shifts the problem of control design from a coupled 2n-order structural system to n second-order systems, a considerably simpler problem with substantial savings in computational efforts. It is particularly attractive when only a few critical nodes must be controlled.

The modal control forces $\underset{\sim}{u}_j(t)$ can be determined by using the method of pole assignment or, if optimal control is desired, they can be determined by minimizing a quadratic performance index J of the form

$$J = \sum_{j=1}^{p} J_j \tag{3-13}$$

where p is the number of controlled modes and J_j are the modal performance indices taking, for example, the form

$$J_j = \int_0^{t_f} \left[\underset{\sim}{y}_j^T(t) Q_j \underset{\sim}{y}_j(t) + \underset{\sim}{u}_j^T(t) R_j \underset{\sim}{u}_j(t) \right] dt \tag{3-14}$$

Upon determination of the modal control forces. the physical controller forces can be synthesized subsequently via a linear transformation involving the modal participation matrices.

Independent modal space control has been analyzed for a number of control design problems involving civil engineering structures [59, 63, 65, 66]. Its optimality, however, requires that the number of controllers be at least equal to the number of controlled modes.

3.4 Instantaneous Optimal Control

It has been mentioned in Sec. 3.1 that the classical optimal closed-loop control is not truly optimum because the excitation term is ignored in the derivation of the Riccati matrix P(t). Recognizing the fact that, at any particular time t, the knowledge of the external excitation may be available up to that time instant t, this knowledge can be utilized in arriving at improved control algorithms.

One of such attempts makes use of a time-dependent performance index J(t) defined by [113, 114]

$$J(t) = \underset{\sim}{z}^T(t) Q \underset{\sim}{z}(t) + \underset{\sim}{u}^T(t) R \underset{\sim}{u}(t) \tag{3-15}$$

Optimal control laws are derived by minimizing J(t) at every time instant t for all $0 \le t \le t_f$. Hence, these control laws are referred to as instantaneous optimal control algorithms [113, 114].

The starting point of the derivation of instantaneous optimal control algorithms is to consider the evolution of the state vector z(t) over a small time interval Δt. It can be obtained from eq. (3-1) as

$$z(t) = T\,D(t - \Delta t) + \frac{\Delta t}{2}\,[B u(t) + H f(t)] \tag{3-16}$$

where:

$$D(t - \Delta t) = e^{\Lambda \Delta t} T^{-1} \left\{ z(t - \Delta t) + \frac{\Delta t}{2} \left[B u(t - \Delta t) + H f(t - \Delta t) \right] \right\} \tag{3-17}$$

In the above, Λ is the 2n x 2n diagonal matrix consisting of complex eigenvalues $\lambda_j (j = 1....,2n)$ of the system matrix A, and T is the 2n x 2n modal matrix of corresponding eigenvectors.

The minimization of J(t) in eq. (3-15) subject to constraint (3-16) leads to, in the case of instantaneous optimal closed-loop control,

$$u(t) = -\frac{\Delta t}{2} R^{-1} B^T Q z(t) \tag{3-18}$$

and the response state vector z(t) is obtained from eqs. (3-16) and (3-18) as

$$z(t) = \left[I + \left(\frac{\Delta t}{2}\right)^2 B R^{-1} B^T Q \right]^{-1} \left[T D(t - \Delta t) + \frac{\Delta t}{2} H f(t) \right] \tag{3-19}$$

Open-loop and open-closed loop control laws can be similarly obtained [113, 114].

Some evaluation of these instantaneous optimal control algorithms has been recently carried out, both analytically and experimentally, for structures subject to earthquake-type excitations [51, 113, 114]. Again, depending on the choice of the weighting matrices Q and R, various levels of control effectiveness can be achieved. Since more information is utilized, they, in theory, outperform classical optimal control algorithms. Furthermore, classical optimal control algorithms require the solution of the Riccati equation (3-7), which can be cumbersome for a structure with many degrees of freedom.

3.5 Bounded State Control

In general, the purpose of active control is served when a set of structural response variables are maintained within an allowable region determined by the requirements of structural safety and human comfort. Under safety considerations, relative displacements at selected locations of the structure are of central concern and, for human comfort, the absolute accelerations. Thus, active control algorithms designed to limit the state variables within prescribed bounds, or bounded state control, is of practical importance when applied to civil engineering structures.

All pulse control strategies proposed in the literature fall into this category [54-56, 68, 74, 75, 77-79, 99, 100]. The basic idea behind pulse control is that a train of force pulses properly applied to a structural system can produce a response matching that produced by a continuous loading of arbitrary nature within specified error bounds. The objective of pulse control design advanced in [54-56, 99, 100] is to destroy the gradual rhythmic build-up of the structural response in the case of resonance by means of short-interval high-energy pulses. A continuous monitoring of the system state variables is required. To conserve energy, control is activated only when some prespecified threshold has been exceeded. In [55, 99, 100], the pulse magnitudes are determined analytically so as to minimize a non-negative cost function. The control procedure proposed in [54, 56] consists of application of pulses every time a zero crossing of the response variable is detected. The magnitudes of the pulses are functions of the instantaneous velocities.

In [74, 75, 77-79], the pulse control design is anticipatory, namely, pulses are applied a short time interval prior to an anticipated threshold crossing. These algorithms require state prediction but cover the case of non-resonant as well as resonant response.

Generally speaking, pulse control procedures are relatively simple to implement; they require less on-line computational efforts when compared with other modern control techniques. They are also suited for treatment of inelastic structures. Another advantage has to do with possible savings of control energy required. In the pulse control mode, since small vibrational levels are tolerated, control forces need to be applied only when necessary and a relatively small amount of energy may be sufficient for periodic corrective actions.

Another approach to bounded state control is discussed in [43, 44] using linear state feedback laws such as that given in eq. (3-8). Based on an extension of the Lyapunov function methods, it follows, in a sense, the pole assignment concept to achieve bounded state control. This approach does require that the external excitation remains within a closed bounded region.

3.6 Other Control Algorithms

Not included in the discussions above are a wide variety of suboptimal or ad hoc control techniques, most of which are tailored to specific structural environments or specific sensor-controller specifications. More recent work includes discussions on predictive control [80, 81] and fuzzy control [119-120] as possible control philosophies. Simultaneous control and structural parameter optimization is another topic receiving increasing attention at present [25, 29, 94, 95].

SECTION 4
PRACTICAL CONSIDERATIONS

While most of the references cited in Sec. 3 give encouraging results, it is important to recognize that they are largely based on idealized system descriptions under ideal conditions. In terms of real-time applications, it has been pointed out that a number of important problems must be addressed from a practical standpoint [32, 119]. The importance of taking these practical considerations into account in the algorithm development has been stressed and some of these issues are briefly described below.

Modeling Errors and Spillover Effects. Civil engineering structures are distributed-parameter continuous systems. With a very few exceptions [46, 48]. analytical and simulation control results obtained to date are based on greatly simplified structural models. In fact, as indicated in Fig. 4-1, a two-stage model reduction procedure is generally carried out whereby the distributed-parameter system is first reduced to a many-degrees-of-freedom system discretized in space, which we shall refer to as a full order system (FOS); it is then further reduced to a discrete-parameter system with a small number of degrees of freedom, referred to here as the reduced-order system (ROS). As shown in Fig. 4-1, control design is generally carried out based on the reduced-order system, necessitated by practical limitations as well as computational considerations.

When an ROS-based control design is synthesized and applied to a real structure, inevitable errors such as control and observation spillovers and possible instability are introduced [19-21, 32, 36, 47, 67, 89, 91, 101, 110, 111]. Various methods of spillover compensation have been proposed but their practicality has yet to be demonstrated.

Time Delay. In treating ideal systems, the assumption is made that all operations in the control loop as shown in Fig. 2-1 can be performed instantaneously. In reality, however, time has to be consumed in processing measured information, in performing on-line computation, and in executing the control forces as required. Thus, time delay causes unsynchronized application of the control forces and this unsynchronization not only can render the control ineffective, but may also cause instability in the system. The importance of time delay compensation in structural control has been demonstrated in the laboratory [30, 31, 51, 57] and several compensation methods have been proposed. These include modification of the control gain by performing a phase shift of the measured state variables in the modal domain [30, 31, 51] and methods of updating the measured quantities kinematically or dynamically [13, 57].

Limited Sensors and Controllers. Consider, for example, optimal linear control as described in Sec. 3.1. It is seen from eq. (3-6) that the knowledge of full state vector z(t) is generally required, i.e., 2n sensors are needed. Practical considerations, however, preclude the availability of such a complete set of information. Hence, output feedback is more realistic than state feedback.

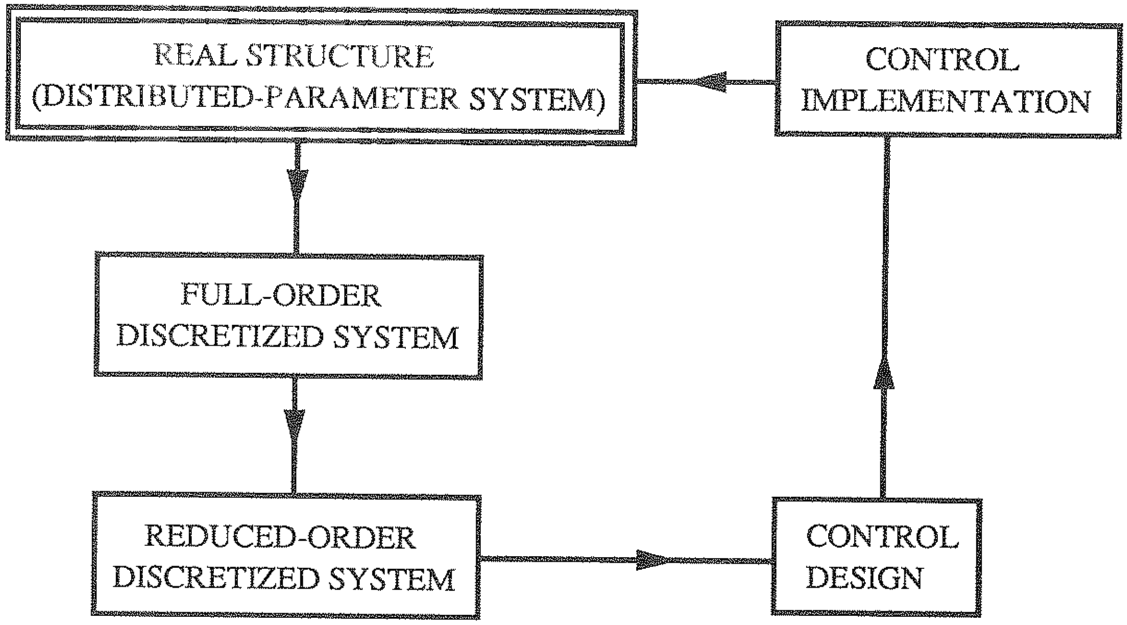

FIGURE 4-1 Model Reduction and Control Design

In other words, the vector quantity representing the measurements is proportional to the state vector but whose dimension is smaller than that of the state vector. While output feedback problems have been extensively treated in the control literature, they do give rise to added complications in control implementation. Recently, output feedback supplemented by observers has been examined in the context of structural control [4, 32, 36, 91].

For the same practical reasons, implementable control schemes also require that as few controllers as possible be used. While controllability conditions can generally be met, the physical placement and distribution of controllers over a continuous structure is not a trivial problem.

Finally, optimization of sensor and controller locations is important in structural control from the standpoint of economy and external energy savings. Furthermore, control results can be sensitive to their locations. Some attempts have been made in addressing this question [26, 89] but it remains to be largely an unsolved problem.

Parameter Uncertainties and System Identification. Parameter uncertainties are another major concern. More recent work has begun to address the problem of control sensitivity to structural parametric uncertainties [116, 120], which depends on the control algorithm, locations of sensors and controllers, load history, and the control device used in a given situation. The attendant problem of system identification in conjunction with on-line active control has also received some attention [118, 119].

It is also noted that structures under strong environmental loads are expected to undergo nonlinear and time-dependent degrading behavior. Thus, time-varying parameter values can occur and on-line identification and control becomes a real issue under these conditions.

Discrete-time Control. An important consideration in real-time control implementation is the discrete-time nature in the application of a control algorithm. Strictly speaking, continuous-time control algorithms such as those developed in Sec. 3 can only be executed in discrete time since a digital computer is usually used for on-line computation and control execution. Digital computers are better suited for real-time control because of their flexibility, reliability and speed. As a consequence, output measurements are digitized as feedback signals and control forces are applied in the form of piecewise step functions through the use of A/D converters. Hence, they are not continuous functions as called for when using continuous-time control algorithms.

With this in mind, discrete-time formulation of active structural control has been a topic of some recent publications [32, 80, 81], some of which include the discussion of time delay compensation and the use of observers in the case of output feedback.

Reliability. While reliability is of central importance in all areas of system analysis, design and synthesis, it takes on an added dimension of complexity, both technologically and psychologically, when an active control system is relied upon to insure safety of a structure. First of all, when active control is only used to counter large environmental forces, it is likely that the control system will be infrequently activated. The reliability of a system operating largely in a standby mode and the related problems of maintenance and performance qualification become an important issue. Furthermore, active systems rely on external power sources which, in turn, rely on all the support utility systems. These systems, unfortunately, are most vulnerable at the precise moment when they are most needed. The scope of the reliability problem is thus considerably enlarged if all possible ramifications are considered [22].

Not to be minimized is the psychological side of the reliability problem. There may exist a significant psychological barrier on the part of the occupants of a structure in accepting the idea of an actively controlled structure, leading to perhaps perceived reliability-related concerns.

Other Considerations. In addition, eventual implementability of an active control system will depend on the solution or resolution of a number of key problems dealing with hardware development and its cost-effectiveness when compared with other means of structural control. Active control requires the generation of large control forces, for which a new generation of actuators and control systems will be required. Furthermore, appropriate control devices must be developed not only based on technological considerations, but also on economic, aesthetic. and structural integration grounds. Above all, cost-effectiveness must be carefully assessed for various specific structural applications.

SECTION 5
CONTROL MECHANISMS AND EXPERIMENTAL STUDIES

In order to perform feasibility studies and to carry out control experiments in the laboratory, investigations on active structural control have focused on several control mechanisms as described below. They may well be forerunners of active control devices to be applied to full-scale structures in the near future.

Tendon Control. Active control using structural tendons, proposed as early as 1960 by Freyssinet, has been one of the most studied mechanisms both on paper and in the laboratory. The system generally consists of a set of prestressed tendons connected to a structure whose tensions are controlled by electrohydraulic servomechanisms. One of the reasons for favoring such a control mechanism has to do with the fact that tendons are already existing members of many structures. Thus, active tendon control could make use of existing tendons and thus minimize extensive additions or modifications of an as-built structure. This is attractive, for example, in the case of retrofitting or strengthening an existing structure. Another attractive feature is that active tendons can operate in the pulsed mode as well as in the continuous-time mode. Thus, active tendon control can accommodate both continuous-time and pulse control algorithms.

Active tendon control has been studied analytically in connection with control of slender structures [82, 106], tall buildings [9, 14, 31, 37, 85, 86, 109, 111, 112], cable-stayed bridges [107, 108] and offshore structures [74, 77, 78]. Early experiments involving the use of tendons were performed on a series of small-scale structural models [83], which included a simple cantilever beam, a king-post truss and a free-standing column while control devices varied from tendon control with manual operation to tendon control with servovalve-controlled actuators. Actuator dynamics and placement of sensors and controllers were studied. The influence of time delay was demonstrated by varying the phase of the feedback control force [83].

In [23, 24], active deformation control of a 10-meter girder was developed analytically and experimentally. Pneumatic cushions were supported on steel cables which were connected to both ends of the girder. Pneumatic pressures in the cushions were adjusted according to the deflection of the girder until cable forces counteracted the sum of dead weight and live load.

More recently. a comprehensive experimental study of tendon control was carried out using a carefully calibrated structural model under seismic-type loading supplied by a shaking table [30, 31, 51, 93]. The model structure was a three-story steel frame, which was made to behave dynamically similar to a prototype structure by means of artificial mass simulation. The control forces were supplied by a servo-controlled hydraulic actuator through a system of tendons attached to the first floor of the structural model.

The control algorithms tested in this series of experiments included the classical optimal closed-loop control and the instantaneous optimal control algorithms described in Sec. 3. In addition, the effects of time delay, control and observation spillovers, and modeling errors were carefully examined. Experimental results compared favorably with analytical results obtained under the same conditions, and they show that the motion of all three floors can be effectively controlled using a single actuator when control design is carefully carried out by taking into account the above-mentioned practical considerations.

Active Tuned Mass Dampers. The study of this control mechanism was in part motivated by the fact that tuned mass dampers for motion control of tall buildings, operating in a passive mode, are already in existence [58, 72, 98]. It is thus natural to ask what additional benefits can be derived when they function according to active control principles. Indeed, a series of feasibility studies of active and semi-active tuned mass dampers have been made along these lines [11, 28, 35, 52] and they show, as expected, enhanced effectiveness for tall buildings under either strong earthquakes or severe wind loads. Comparative studies have also been carried out concerning relative merits associated with active tuned mass dampers and active tendons for specific applications [14, 37, 84, 86, 102, 109].

Recently, experimental studies of active tuned mass damper systems have been carried out in the laboratory using scaled-down building models [41, 42]. In [42], an active mass damper was placed on the top of a four-story model frame whose motion was a function of the measured state variables following the optimal closed-loop control algorithm. The model structure was placed on a shaking table which provided simulated earthquake-type base motion. Preliminary results show significant reduction of vibration levels of the structure. In the case of [41], the active control system employed was termed an "active mass driver" which acted directly as an external energy supply instrument to suppress the structural vibration. The active mass driver was placed on top of a three-story steel frame which, in turn, was bolted to a shaking table. Shaking table test results showed that the control effect was extended to all floors.

Pulse Generators. Gas pulse generators, producing pulsed forces generated by the release of air jets, have been proposed for implementation of pulse control algorithms [56, 68]. The applications of such control devices to a six-story scaled-down structural model were performed recently [68]. Discussions on some of the recently developed cold-gas generators having potential structural control applications can be found in [17, 18].

Semi-active auxiliary mass dampers have also been suggested as an alternate pulse-control mechanism [33]. Hence, instead of using cold-air jets or other mass ejection techniques to provide directly the required control forces, control objectives are accomplished through internal momentum transfer between the structure and the auxiliary masses. An on-line control procedure is used to optimize the parameters of the auxiliary mass dampers located about the structure.

Aerodynamic Appendages. The use of aerodynamic appendages as an active control device to reduce wind-induced motion of tall buildings was first proposed in [39, 40]. Its main attractive feature is that the control designer is able to exploit the energy in the wind to control the structure, which is being excited by the same wind. Thus, it eliminates the need for an external energy supply to produce the necessary control force; the only power required is that needed to operate the appendage positioning mechanism.

Additional analytical studies of aerodynamic appendages using optimal control algorithms were carried out [12, 27] as well as a wind-tunnel experimental study [90]. The experiment was conducted using a scaled-down model of a tall structure. A small metal appendage, situated at the top, was controlled by means of a solenoid activated by the sign of structural velocity as sensed by a linear differential transformer. The results obtained give a good indication of the efficiency that can be expected.

More recent publications related to appendages include a comparative study of appendages, active mass dampers and active tendons for wind-excited tall building control [14], a more detailed design study [15], and a discussion on their aesthetic aspects when appendages are deployed in an urban setting [92].

Other Control Mechanisms. Other methods of control that have been proposed include the use of a gyroscope for reducing wind-induced vibration of a suspension bridge [69] and the use of actively controlled air chambers for controlling wave-induced motion of an off-shore platform [88]. In [88], an open-bottom structural model floating in a water-filled tank was used to simulate the response of a floating platform under wave loads. The air pressure in the air chamber trapped between the water and the platform was actively servo-controlled to reduce the structural response under simple harmonic waves. Experiments gave encouraging results in correcting the heave motion of the platform.

Finally, the combined use of two active control systems and hybrid active-passive systems have also been suggested for some specific structural applications [14, 16, 38, 79].

SECTION 6
POSSIBLE FUTURE DIRECTIONS AND CONCLUDING REMARKS

On the basis of the analytical and experimental results obtained to date, it appears evident that active structural control holds great promise as a concept for civil engineering applications. Faced with future trends in structural design and with increasingly stringent structural performance criteria, active control is an eminently logical alternative in insuring structural integrity and serviceability to traditional static methods of over-conservative design. As seen from this overview, past work has progressed to a stage where a good understanding has been gained as to how active control systems for civil engineering structures can perform under realistic conditions. Technically, active systems are within the scope of becoming a reality.

There are other good signs. First, it is encouraging to see that interest in active control research has expanded beyond narrow academic circles. At present, consulting and design professionals [102] as well as construction industries [41, 42] have taken active interest. On another front, it is important to note that the development of active control technology must go hand in hand with advances in other allied areas such as computers, electronics, measurement techniques, instrumentation, materials research, etc. Current rapid progress in all these areas can only enhance the development of active structural control. Moreover, it reflects favorably on the all-important cost factor.

While much has been accomplished, it is also clear that a number of serious obstacles remain and they must be overcome before implementability of the active control concept can be realistically assessed. As outlined below, these obstacles dictate in a significant way possible future research directions.

a. Since the concept of an active-controlled structure is a significant departure from traditional structural concepts, real obstacles exist with respect to its acceptance by the civil engineering and construction professions at large. This is particularly true when structural safety is to rely upon an active control system. Thus, in order to gain a first level of acceptance, it appears prudent to consider, as short-term control objectives, comfort control or last resort protection measures for critical structures.

b. As demanded by reliability, cost and hardware development, applicable active control systems must be simple. Simple control concepts using a minimum number of actuators and sensors may well deserve more attention in the near future. Simple control, of course, does not mean simple problems. Since civil engineering structures are complex systems, this inherent incompatibility gives rise to a number of concerns such as those discussed in Sec. 4.

c. The experimental studies carried out to date have been severely limited in size and scope.

Further experimental verification must be considered as the single most important task to be undertaken. More laboratory tests need to be performed using larger multi-degree-of-freedom structural models with multiple controllers. These tests need to be followed by full-scale testing either in the laboratory or in the field.

d. The important questions of hardware development, reliability and cost effectiveness must be addressed. However, to find answers to these questions are more long-term tasks since they will depend on control strategies, specific structural applications, hardware details and a variety of other issues, many of which, as suggested above, need to be better understood and further developed.

SECTION 7
REFERENCES

1. Abdel-Rohman, M., and Leipholz, H.H.E., "Active Control of Flexible Structures," ASCE J. Struc. Div., 104, 1251-1266, 1978.

2. Abdel-Rohman, M., and Leipholz, H.H.E., "Structural Control by Pole Assignment Method," ASCE J. Eng. Mech. Div., 104, 1157-1175, 1978.

3. Abdel-Rohman, M., and Leipholz, H.H.E, "A General Approach to Active Structural Control," ASCE J. Eng. Mech. Div., 105, 1007-1023, 1979. Also in [45], pp. 1-28.

4. Abdel-Rohman, M., Leipholz, H.H.E., and Quintana, V.H., "Design of Reduced-Order Observers for Structural Control Systems," in [45], pp. 57-78.

5. Abdel-Rohman, M., Quintana, V.H., and Leipholz. H.H.E., "Optimal Control of Civil Engineering Structures," ASCE J. Eng. Mech., 106, 57-73, 1980.

6. Abdel-Rohman, M., and Leipholz, H.H.E., "Automatic Active Control of Structures," ASCE J. Stru. Div., 106, 663-677, 1980. Also in [45], 29-55.

7. Abdel-Rohman, M., and Leipholz, H.H.E., "Stochastic Control of Structures," ASCE J. Stru. Div., 107, 1313-1325, 1981.

8. Abdel-Rohman, M., "Active Control of Large Structures," ASCE J. Eng. Mech. Div., 108, 719-731, 1982.

9. Abdel-Rohman, M., and Leipholz, H.H.E.. "Active Control of Tall Buildings," ASCE J. Stru. Eng., 109, 628-645, 1983.

10. Abdel-Rohman, M., and Leipholz, H.H.E., "Optimal Feedback Control of Elastic Distributed-Parameter Structures," J. Comp. Stru., 19, 801-805, 1984.

11. Abdel-Rohman, M., "Effectiveness of Active TMD for Building Control," Trans. Can. Soc. Mech. Eng., 8, 179-184, 1984.

12. Abdel-Rohman, M.. "Optimal Control of Tall Buildings by Appendages," ASCE J. Struc. Eng., 110, 937-946, 1984.

13. Abdel-Rohman, M., "Structural Control Considering Time Delay Effect," Trans. Can. Soc. Mech. Eng., 9, 224-227, 1985.

14. Abdel-Rohman, M., "Feasibility of Active Control of Tall Buildings Against Wind," ASCE J. Struc. Eng., 113, 349-362, 1987.

15. Abdel-Rohman, M., and Al-Zanaidi, M., Design of Appendages for Tall Building Control," ASCE J. Struc. Eng., 113, 397-408, 1987.

16. Abdel-Rohman, M., and Nayfeh, A.H., "Active Control of Nonlinear Oscillations in Bridges," ASCE J. Eng. Mech., 113, 335-348, 1987.

17. Agababian Assoc., Validation of Pulse Techniques for the Simulation of Earthquake Motions in Civil Structures, AA Rept. No. R-7824-5489, El Segondo, CA, 1984.

18. Agababian Assoc., Induced Earthquake Motion in Civil Structures by Pulse Methods, AA Rept. No. R-8428-5764, El Segondo, CA, 1984.

19. Balas, M., "Feedback Control of Flexible Systems," IEEE Trans. Aut. Contr., AC-23, 673-679, 1978.

20. Balas, M., "Active Control of Flexible Systems," J. Optim. Th. Appl., 24, 415-436, 1978.

21. Balas, M., "Active Control of Large Engineering Structures: A Naive Approach," in [45], pp. 107-125.

22. Basharkhah. M.A., and Yao, J.T.P., "Reliability Aspects of Structural Control." Civil Eng. Syst., 1, 224-229, 1984.

23. Bouten, H., and Meyr, H., "Control Design for ADC Girder," in [50], pp. 199-214.

24. Bryson, A.E., Jr., and Ho, Y.C., Applied Optimal Control, Wiley, New York, 1975.

25. Cha, J.Z., Pitarresi, J.M., and Soong. T.T., "Optimal Design Procedures for Active Structures," ASCE J. Stru. Eng., submitted.

26. Chang, M.I.J., and Soong. T.T., "Optimal Control Placement in Modal Control of Complex Systems," J. Math. Analy. Appl., 75, 340-358, 1980.

27. Chang, J.C.H., and Soong. T.T., "The Use of Aerodynamic Appendages for Tall Building Control," in [45], pp. 199-210.

28. Chang, J.C.H., and Soong, T.T., "Structural Control Using Active Tuned Mass Dampers, ASCE J. Eng. Mech. Div. 106, 1091-1098, 1980.

29. Cheng, F.Y., and Pantelides, C.P., "Optimal Control of Seismic Structures," in Dynamic Response of Structures, (G.C. Hart and R.B. Nelson, eds.), ASCE, New York, 764-771, 1986.

30. Chung, L.L., Reinhorn, A.M., and Soong, T.T., "An Experimental Study of Active Structural Control," in Dynamic Response of Structures, (G.C. Hart and R.B. Nelson, eds.), ASCE, New York, 795-802, 1986.

31. Chung, L.L., Reinhorn. A.M., and Soong, T.T., "Experiments on Active Control of Seismic Structures," ASCE J. Eng. Mech., in print.

32. Chung, L.L., and Soong. T.T., "Practical Considerations in Discrete Time Structural Control," Proc. ASME Vibrations Conference, Boston, MA. 1987.

33. Dehghamyar, T.J., Masri, S.F., Miller, R.K., and Caughey, T.K., "On-line Parameter Control of Nonlinear Flexible Structures, in [50], pp. 141-159.

34. Domke, H., "Survey, Advantage and Restraints of ADC in Civil Engineering," in [50], pp. 172-184.

35. Hrovat, D., Barak, P., and Robins, M., "Semi-Active vs. Passive or Active Tuned Mass Dampers for Structural Control," ASCE J. Eng. Mech., 109, 691-701, 1983.

36. Ibidapo-Obe, O., "Active Control Performance Enhancement for Reduced Order Models of Large Scale Systems," in [50], 318-328.

37. Juang, J.N., Sae-Ung, S., and Yang, J.N., "Active Control of Large Building Structures," in [45], 663-676.

38. Kelly, J.M., Leitmann, G., and Soldatos, A.G., "Robust Control of Base-Isolated Structures Under Earthquake Excitations," J. Optim. Th. Appl., 53, 159-180, 1987.

39. Klein, R E., Cusano, C., and Slukel, J.V., "Investigation of a Method to Stabilize Wind Induced Oscillations in Large Structures, Paper No. 72-WA/AUT-11, 1972 ASME Annual Meeting, New York, 1972.

40. Klein, R E., and Salhi, H., "Time Optimal Control of Wind Induced Structural Vibrations Using Active Appendages," in [45], pp. 415-430.

41. Kobori, T., Kanayama, H., and Kamagata, S., "Dynamic Intelligent Building as Active Seismic Response Controlled Structure," Proc. Annual Meeting Arch. Inst. Japan, Tokyo, 1987, submitted.

42. Kuroiwa, H., and Aizawa, S., Private Communication, May, 1987.

43. Lee, S.K., and Kozin, F., "Bounded State Control of Structures with Uncertain Parameters," in Dynamic Response of Structures, (GC Hart and R.B. Nelson, eds.), ASCE, New York, 788-794, 1986.

44. Lee, S.K., and Kozin, F., "Bounded State Control of Linear Structures," in [50], pp. 387-407.

45. Leipholz, H.H.E., (ed.), Structural Control, North-Holland, Amsterdam. 1980; Proc. First Intern. IUTAM Symp. on Structural Control, University of Waterloo, Waterloo, Canada, June 4-7, 1979.

46. Leipholz, H.H.E., "Distributed Control of Elastic Plates," Mech. Res. Comm., 9, 133-136, 1982.

47. Leipholz, H.H.E., "On the Spillover Effect in the Control of Continuous Elastic Systems," Mech. Res. Comm., 11, 217-226, 1984.

48. Leipholz, H.H.E, "Control of Continuous Structural Systems," Preprint 84-007, ASCE Convention, Atlanta, GA, 1984.

49. Leipholz, H.H.E., and Abdel-Rohman, M., Control of Structures, Martinus Nijhoff, Amsterdam, 1986.

50. Leipholz, H.H.E., (ed.) Structural Control, Martinus Nijhoff, Amsterdam. 1987; Proc. Second Intern. Symp. on Structural Control, University of Waterloo, Waterloo, Canada, July 15-17, 1985.

51. Lin, R.C., Soong, T.T., and Reinhorn, A.M., "Active Stochastic Control of Seismic Structures," Proc. US-Japan Joint Seminars on Stochastic Structural Mechanics, Boca Raton, FL, 1987.

52. Lund, R.A., "Active Damping of Large Structures in Winds," in [45], pp. 459-470.

53. Martin, C.R., and Soong, T.T., "Modal Control of Multistory Structures," ASCE J. Eng. Mech. Div., 102, 613-623, 1976.

54. Masri, S.F., Bekey, G.A., and Udwadia, F.E., "On-line Pulse Control of Tall Buildings," in [45], pp. 471-492.

55. Masri, S.F., Bekey, G.A., and Caughey, T.K., "Optimal Pulse Control of Flexible Structures," ASME J. Appl. Mech., 48, 619-626, 1981.

56. Masri, S.F., Bekey, G.A., and Caughey, T.K., "On-line Control of Nonlinear Flexible Structures," ASME J. Appl. Mech., 49, 877-884, 1982.

57. McGreevy, S., Soong, T.T., and Reinhorn, A.M., "Experimental Study of Time Delay Compensation in Active Structural Control," ASME J. Dyna. Syst. Meas. Contr., submitted.

58. McNamara, R.J., "Tuned Mass Damper for Buildings," ASCE J. Stru. Div., 103, 1785-1798, 1977.

59. Meirovitch, L., and Oz, H., "Active Control of Structures by Modal Synthesis," in [45], pp. 505-521.

60. Meirovitch, L., and Oz, H., "Modal Space Control of Distributed Gyroscopic Systems, J. Guid. Contr. Dyna., 3, 140-150, 1980.

61. Meirovitch. L. and Baruh. H. "Control of Self-Adjoint Distributed Parameter Systems," J. Guid. Contr. Dyna., 5, 60-66, 1982.

62. Meirovitch, L. and Baruh, H., "Robustness of the Independent Modal Space Control Method," J. Guid. Contr. Dyna., 6, 20-25, 1983.

63. Meirovitch, L. and Silverberg, L.M., "Control of Structures Subjected to Seismic Excitations," ASCE J. Eng. Mech, 109, 604-618, 1983.

64. Meirovitch, L., and Silverberg, L.M., "Globally Optimal Control of Self-Adjoint Distributed Systems," Optim. Contr. Appl. Meth., 4, 365-386, 1983.

65. Meirovitch, L., "Control of Structures Subjected to Seismic Excitation," ASCE J. Eng. Mech., 109, 604-618, 1983.

66. Meirovitch, L., and Ghosh, D., "Control of Flutters in Bridges," ASCE J. Eng. Mech., 113, 720-736, 1987. Also in [50], pp. 458-472.

67. Meirovitch, L., "Some Problems Associated with the Control of Distributed Structures," J. Optim. Th. Appl., 54, 1-22, 1987.

68. Miller, R K., Masri, S.F., Dehghanyar. T.J., and Caughey, T.K., "Active Vibration Control of Large Civil Structures," ASCE J. Eng. Mech., in print.

69. Murata, M., and Ito, N., "Suppression of Wind-Induced Vibration of a Suspension Bridge by Means of a Gyroscope," Proc. Int. Conf. Wind Effects on Bldg. Struct., Tokyo, 1971, pp. 1057-1066.

70. Nordell, W.J., Active Systems for Elastic-Resistant Structure, Tech. Rept. R-611, Naval Civil Engineering Laboratory, Port Hueneme, CA, 1969.

71. NRC Committee on Earthquake Engineering, Research Agenda: Learning from the 19 September 1985 Mexico Earthquake, National Research Council, Washington, D.C., 1986.

72. Petersen, N.R., "Design of Large Scale Tuned Mass Dampers," in [45], pp. 581-596.

73. Porter, B., and Crossley, T.R., Modal Control: Theory and Applications, Taylor and Francis, London, 1972.

74. Prucz, Z., and Soong, T.T., "On Reliability and Active Control of Tension Leg Platforms," in Recent Advances in Engineering Mechanics and Their Impact on Civil Engineering Practice (W.F. Chen and A.D.M. Lewis, eds.), 2, 903-906, 1983.

75. Prucz, Z., Soong. T.T., and Reinhorn, A.M., "An Analysis of Pulse Control for Simple Mechanical Systems," ASME J. Dyna. Syst. Meas. Contr., 107, 123-131, 1985.

76. Reinhorn, A.M., and Manolis, G.D., "Current State of Knowledge on Structural Control," Shock Vib. Digest, 17, 35-41, 1985.

77. Reinhorn, A.M., Soong, T.T. and Manolis, G.D., "Disaster Prevention of Deep Water Offshore Structures by Means of Active Control." Proc. ASME Fifth Int. OMAE Conf., Tokyo, Japan, 39-44, 1986.

78. Reinhorn, A.M., Manolis, G.D., and Wen, C.Y., "Active Control of Inelastic Structures," ASCE J. Eng. Mech., 113, 315-333, 1987. Also in [50], 564-579.

79. Reinhorn, A.M., Soong, T.T., and Wen, C.Y., "Base Isolated Structures With Active Control," Proc. ASME PVD Conf., San Diego, CA, 1987.

80. Rodellar, J., Barbat, A.H., and Martin-Sanchez, J.M., "Predictive Control of Structures," ASCE J. Eng. Mech., 113, 797-812, 1987. Also in [50], 580-593.

81. Rodellar, J., Chung, L.L., Soong, T.T., and Reinhorn, A.M., "Experimental Digital Predictive Control of Structures," Proc. 1987 ASME Vibrations Conference, Boston, 1987.

82. Roorda, J., "Tendon Control in Tall Structures," ASCE J. Stru. Div., 101, 505-521, 1975.

83. Roorda, J., "Experiments in Feedback Control of Structures," in [45], pp. 629-661.

84. Sae-Ung, S., and Yao, J.T.P., "Active Control of Building Structures," ASCE J. Eng. Mech. Div., 104, 335-350, 1978.

85. Samali, B., Yang, J.N., and Yeh, C.T., "Control of Coupled Lateral-Torsional Motion of Wind-Excited Buildings," ASCE J. Eng. Mech. 111, 77-796, 1985.

86. Samali, B., Yang, J.N., and Liu, S.C., "Control of Lateral-Torsional Motion of Buildings Under Seismic Load," ASCE J. Stru. Eng., 111, 2165-2180, 1985.

87. Samali, B., Yang, J.N. and Yeh, C.T., "Active Tendon Control System for Wind-Excited Tall Buildings," in [50], pp. 612-630.

88. Sirlin, S., Paliou, C., Longman, R.W., Shinozuka, M., and Samara, E., "Active Control of Floating Structures," ASCE J. Eng. Mech., 112, 947-965, 1986. Also in [50], pp. 651-668.

89. Soong, T.T., and Chang, M.I.J., "On Optimal Control Configuration in Theory of Modal Control," in [45], pp. 723-738.

90. Soong, T.T., and Skinner, G.T., "Experimental Study of Active Structural Control," ASCE J. Eng. Mech. Div., 107, 1057-1068, 1981.

91. Soong, T.T., and Chang, J.C.H., "Active Vibration Control of Large Flexible Structures," Shock Vib. Bull., 52, part IV, 47-54, 1982.

92. Soong, T.T., Bilgutay, A., Schmitz, G., and Ben-Arroyo, A.F., "Aesthetics of Tall Structures with Aerodynamic Appendages," in Tall Buildings (S.D. Ramaswamy and C.T. Tam, eds.), TBRC, 37-41, 1984.

93. Soong, T.T., Reinhorn, A.M., and Yang, J.N., "A Standardized Model for Structural Control Experiments and Some Experimental Results," in [50], pp. 669-693.

94. Soong, T.T., and Pitarresi, J.M., "On Optimal Design of Active Structures," in Computer Applications in Structural Engineering, (D.R. Jenkins, ed.), ASCE, 1987, pp. 579-591.

95. Soong, T.T., and Manolis, G.D., "On Active Structures," ASCE J. Stru. Eng., 113, 2290-2301, 1987.

96. "Supertall Structures, the Sky's the Limit," Eng. News Record, November, 1983.

97. Tucker, J.B., "Superskyscrapers: Aiming for 200 Stories," High Tech., 5, 50-63, 1985.

98. "Tuned Mass Damper Steady Sway of Skyscraper in Wind," Eng. News Record, August, 1977, pp. 28-29.

99. Udwadia, F.E., and Tabaie, S., "Pulse Control of a Single-Degree-of-Freedom System," ASCE J. Eng. Mech. Div., 107, 997-1010, 1981.

100. Udwadia, F.E., and Tabaie, S., "Pulse Control of Structural and Mechanical Systems," ASCE J. Eng. Mech. Div., 107, 1011-1028, 1981.

101. Vilnay, O., "Design of Modal Control of Structures," ASCE J. Eng. Mech. Div., 107, 907-916, 1981.

102. Wiesner, K.B., "The Role of Damping Systems," Proc. 3rd Int. Conf. Tall Bldg., Chicago, 1986.

103. Wiesner, K.B., "Tuned Mass Dampers to Reduce Building Wind Motion," Preprint 3510, ASCE Convention, Boston, 1979.

104. Wolf, J.P., and Madden, P.M., "An Assessment of the Application of Active Control to Reduce the Seismic Response of Nuclear Power Plants," Nucl. Eng. Desion., 6, 383-397, 1981.

105. Yang, J.N., "Application of Optimal Control Theory to Civil Engineering Structures," ASCE J. Eng. Mech., 101, 818-838, 1975.

106. Yang, J.N., and Giannopoulos, F., "Active Tendon Control of Structures," ASCE J. Eng. Mech. Div., 104, 551-568, 1978.

107. Yang, J.N., and Giannopoulos, F., "Active Control and Stability of Cable-Stayed Bridge," ASCE J. Eng. Mech. Div., 105, 677-694, 1979.

108. Yang, J.N. and Giannopoulos, F., "Active Control of Two-Cable-Stayed Bridge," ASCE J. Eng. Mech. Div., 105, 795-810, 1979.

109. Yang, J.N., "Control of Tall Buildings Under Earthquake Excitations," ASCE J. Eng. Mech. Div., 108, 50-68, 1982.

110. Yang, J.N., and Lin, M.J., "Optimal Critical-Mode Control of Building Under Seismic Loads," ASCE J. Eng. Mech. Div., 108, 1167-1185, 1982.

111. Yang, J.N., and Lin, M.J., "Building Critical-Mode Control: Nonstationary Earthquakes," ASCE J. Eng. Mech. Div., 109, 1375-1389, 1983.

112. Yang, J.N., and Samali, B., "Control of Tall Buildings in Along-Wind Motion," ASCE J. Stru. Div., 109, 50-68, 1983.

113. Yang, J.N., Akbarpour, A., and Ghaemmaghami, P., "New Optimal Control Algorithms for Structural Control," ASCE J. Eng. Mech., 113, 1369-1386, 1987.

114. Yang, J.N. Akbarpour, A., and Ghaemmaghami, P., "Optimal Control Algorithms for Earthquake-Excited Buildings," in [50], 748-761.

115. Yang. J.N., and Soong, T.T., "Recent Advances in Active Control of Civil Engineering Structures," J. Prob. Eng. Mech., in print.

116. Yang, J.N., and Akbarpour, A., "Effect of System Uncertainty on Active Structural Control," Proc. ASCE 6th Structural Congress, Orlando, FL, 1987.

117. Yao, J.T.P., "Concept of Structural Control," ASCE J. Stru. Div., 98, 1567-1574, 1972.

118. Yao, J.T.P., "Identification and Control of Structural Damage," Solid Mech. Archives, 5, 325-345, 1980. Also in [45], pp. 757-777.

119. Yao, J.T.P., and Abdel-Rohman, M., "Research Topics for Practical Implementation of Structural Control," in [50], 762-767.

120. Yao, J.T.P., "Uncertainties in Structural Control," Proc. ASME Vibrations Conference, Boston, MA, 1987.

121. Zuk, W., "Kinetic Structures," Civil Engineering, 39, No. 12, 62-64, 1968.

122. Zuk, W., and Clark, R.H., Kinetic Architecture, Van Norstrand Reinhold, New York, 1970.

123. Zuk, W., "The Past and Future of Active Structural Control Systems," in [45], pp. 779-794.

National Center for Earthquake Engineering Research
State University of New York at Buffalo