FUTURE DIRECTIONS IN STRUCTURAL CONTROL

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ABSTRACT :

This paper focuses on the application of active, hybrid, and semi-active structural control systems to buildings. With the installation of an active mass driver system in the kyobashi Seiwa Building in Tokyo in 1989, Professor Kobori and his associates launched the active control movement. While there has been steady progress in Japan in terms of implementation of structural control devices in structures, this has not been the case in other countries. Based on what has been accomplished since 1989 and on personal experiences, personal views are presented in this paper concerning outlook of active structural control and pressing issues that must be addressed in order to further advance the concept of structural control as a cornerstone in modern structural engineering.

KEYWORDS: Structural Control, Integrated Design, Structural Optimization

I. INTRODUCTION

Over the last 30 years, great strides have been made in advancing the theory and practice of active structural control technology, which includes semi-active and hybrid systems. However, as one surveys current activities in research and application, it is clear that this entire area is still evolving and much of its application potentials still need to be identified and realized. It thus deserves stepped-up research efforts and further development. Several of these focus research areas are summarized below. Due to space limitations, this paper will focus only on one of these areas, namely, integrated design of control/structural systems.

Implementation targeted research. While significant improvement has been made in theoretical development, the gap between theory and implementation remains large. The whole implementation process which requires integration of results from diverse interdisciplinary research efforts has not been well addressed. Important research issues that need to be addressed include fail safe measures, software-hardware integration, more efficient and robust sensing and actuation mechanisms, new materials, and standardization of the design and implementation process.

Research for focused application opportunities. It is important to identify application areas in which active control technology uniquely qualifies. One such opportunity is clearly in the direction of mitigation of higher level hazards. In the context of earthquake and wind engineering, active control systems remain to be one of only a few alternatives for structural protection under extraordinary loads.

Since active control systems can potentially achieve higher levels of structural integrity and safety under adverse loads, they are particularly attractive when applied to critical facilities and their contents where higher performance levels are required. These facilities include hospitals, emergency command centers, police and fire stations, and possibly embassies (against blast loads).

Integrated control/structural systems. Much of structural control research and applications have been concerned with structures equipped with control devices in order to enhance structural performance under adverse loads. In most cases, the structure and the control system are individually designed and optimized. On the other hand, an exciting consequence of structural control research is that it also opens the door to new possibilities in structural forms and configurations, and this can only be achieved through integrated design of structures with control elements as an integral part.

This paper will highlight the third area. An optimization procedure for producing integrated control/structural system is developed. A simple steel portal frame is used to show the procedure in detail.

II. INTEGRATED DESIGN

In recent years, several approaches have been proposed for integrated design of structure/control systems in aerospace and civil engineering structures. For civil engineering structures, for example, a variational approach has produced good results [1-2]. However, due to complex nature of the resulting equations, the optimization problem is usually nonconvex. Therefore, numerical techniques are usually required to obtain a solution

Redesign approach: The optimization problem becomes easier when the design procedure is divided into two steps. In control of buildings, the structure is traditionally designed first and then the controller. The proposed method reverses the procedure by designing the structure after the controller is given. The fundamental idea of redesign was proposed by Smith *et al.* [3]. In this section, the idea of redesign is incorporated into the integrated design of civil engineering structural/control systems. The procedure is summarized in the following steps:

First Step. The desired structure is chosen and it is assumed fixed while the controller is designed in order to satisfy a given performance requirement (e.g., drift, absolute acceleration, base shear, etc.) of the initial structure. The dynamic response of the initial structure in this step is called "Target Response".

Second Step. The structure and the controller are designed co-operatively to achieve a common goal (the target dynamic response of the first step). This structure redesign is accomplished to reduce (minimize) the amount of active control power needed to achieve the "Target Response". In other words, the structure is redesigned for better controllability. These two steps can be better understood by considering relationship between spectral acceleration and spectral displacement (S_a-S_d) in structural design. In Figure 1 is shown a typical (S_a-S_d) spectrum for several damping levels. $S_d(T_0, \beta_0)$ and $S_a(T_0, \beta_0)$ are the spectral coordinates of the original structure with period T_0 and damping β_0. In *Step 1*, the structure at point 1 is made lighter by reducing its stiffness and it moves to point 2 in Figure 1. Then a controller is applied to bring back the structure to the initial target response at point 3. In *Step 2*, the structure is redesigned in order to achieve the same performance, but with less amount of active control forces or damping. During the redesign, mass, stiffness and damping are modified in order to achieve this goal, reaching finally point 4 in Figure 1. At the end of this step, the building will maintain the same performance, but with less amount of control forces. The integrated redesign procedure is formulated in the following for the case when the building is assumed linear for simplicity.

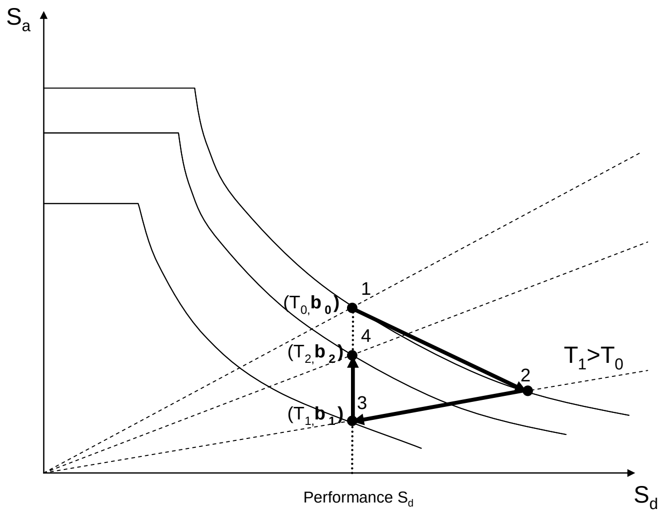

Figure 1 Redesign procedure in S_d-S_a plane

Following Smith *et al.* [3], consider a multi-degree-of-freedom linear building structure subjected to an external excitation. The equation of motion with active control force is given by

$$\mathbf{M}\ddot{\mathbf{x}}(t)+\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{K}\mathbf{x}(t)=\mathbf{H}\mathbf{u}(t)+\boldsymbol{\eta}w(t). \tag{1}$$

where $\mathbf{x}$(t) is the displacement vector, **M, C** and **K** are, respectively, the mass, inherent damping and stiffness matrices; $\mathbf{u}$(t) is the active control force vector; **H** is the location matrix for the active control forces; $\boldsymbol{\eta}$ is the excitation influence matrix; $\mathbf{T_s}$ is the location matrix of the restoring forces and w(t) is the external excitation. In the state space, Equation (1) becomes:

$$\dot{\mathbf{z}}(t)=\mathbf{A}\mathbf{z}(t)+\mathbf{B}\mathbf{u}(t)+\mathbf{e}(t). \tag{2}$$

where

$$\mathbf{z}(t)=\begin{bmatrix}\mathbf{x}(t)\\ \dot{\mathbf{x}}(t)\end{bmatrix},\quad \mathbf{e}(t)=\begin{bmatrix}\mathbf{0}\\ \mathbf{M}^{-1}\boldsymbol{\eta}\end{bmatrix}w(t),\quad \mathbf{A}=\begin{bmatrix}\mathbf{0} & \mathbf{I}\\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C}\end{bmatrix},\quad \mathbf{B}=\begin{bmatrix}\mathbf{0}\\ \mathbf{M}^{-1}\mathbf{H}\end{bmatrix}. \tag{3}$$

Step 1. A control law is employed such that the structural system has acceptable performance such as satisfaction of certain constraints on the dynamic response. Many methods are available. Using a linear control law, for example $\mathbf{u}(t)$ can be expressed as

$$\mathbf{u}(t)=\mathbf{G}\mathbf{z}(t). \tag{4}$$

where $\mathbf{G}$ is the gain matrix.

Step 2. Following *Step1*, the redesign concept is to change the mass, stiffness, damping matrices, respectively, by $\Delta\mathbf{M}$, $\Delta\mathbf{K}$ and $\Delta\mathbf{C}$, and to determine the control force $\mathbf{u}$ so that the new system becomes

$$(\mathbf{M}+\Delta\mathbf{M})\ddot{\mathbf{x}}(t)+(\mathbf{C}+\Delta\mathbf{C})\dot{\mathbf{x}}(t)+(\mathbf{K}+\Delta\mathbf{K})\mathbf{x}(t)=\mathbf{H}\mathbf{u}_a(t)+\boldsymbol{\eta}w(t). \tag{5}$$

where

$$\mathbf{u}_a(t)=\mathbf{G}_a\mathbf{z}(t). \tag{6}$$

where $\mathbf{G_a}$ is the active part of the controller after redesign. The main idea is to separate the control law, Equation (4), into a passive part which is implemented into the physical system by redesign, and an active part which constitutes the remaining active control law required after structure redesign. Therefore, the control law is written in the following form

$$\mathbf{H}\mathbf{u}(t)=\mathbf{H}\mathbf{G}\mathbf{z}(t)=\mathbf{H}\mathbf{G}_a\begin{bmatrix}\mathbf{x}(t)\\ \dot{\mathbf{x}}(t)\end{bmatrix}-\Delta\mathbf{M}\ddot{\mathbf{x}}(t)-\Delta\mathbf{C}\dot{\mathbf{x}}(t)-\Delta\mathbf{K}\mathbf{x}(t). \tag{7}$$

and the closed-loop system after redesign is

$$(\mathbf{M}+\Delta\mathbf{M})\ddot{\mathbf{x}}(t)+(\mathbf{C}+\Delta\mathbf{C})\dot{\mathbf{x}}(t)+(\mathbf{K}+\Delta\mathbf{K})\mathbf{x}(t)=\mathbf{H}\mathbf{G}_a\mathbf{z}(t)+\boldsymbol{\eta}w(t). \tag{8}$$

where $\mathbf{u_a}$(t), which is given by Equation (6), is the active part of the controller and $\Delta\mathbf{M}\ddot{\mathbf{x}}(t)+\Delta\mathbf{C}\dot{\mathbf{x}}(t)+\Delta\mathbf{K}\mathbf{x}(t)$ is the passive part. The objective of the redesign is to find the passive control ($\Delta\mathbf{M}$, $\Delta\mathbf{K}$, $\Delta\mathbf{C}$) in order to minimize the control power needed to satisfy Equation (7) for any given $\mathbf{G}$. Note that the closed-loop system response before and after redesign remains unchanged; therefore, all the designed closed-loop system properties remain unchanged.

Let $\mathbf{B_k}$, $\mathbf{B_c}$ and $\mathbf{B_m}$ be the stiffness, damping and mass connectivity matrices of the structural system. The changes in the structural parameters can be expressed in the form

$$\begin{aligned}\Delta\mathbf{K} &= \mathbf{B_k G_k B_k^T} \\ \Delta\mathbf{C} &= \mathbf{B_c G_c B_c^T} \quad . \\ \Delta\mathbf{M} &= \mathbf{B_m G_m B_m^T}\end{aligned} \tag{9}$$

where

$$\begin{aligned}\mathbf{G_k} &= diag\left(\ldots,\Delta k_i,\ldots\right) \\ \mathbf{G_c} &= diag\left(\ldots,\Delta c_i,\ldots\right) \; . \\ \mathbf{G_m} &= diag\left(\ldots,\Delta m_i,\ldots\right)\end{aligned} \tag{10}$$

This gives the following presentation for the desired control law

$$\mathbf{HG}\begin{bmatrix}\mathbf{x}(t)\\ \dot{\mathbf{x}}(t)\end{bmatrix} = \mathbf{HG}_a\begin{bmatrix}\mathbf{x}(t)\\ \dot{\mathbf{x}}(t)\end{bmatrix} - \begin{bmatrix}\Delta\mathbf{K} & \Delta\mathbf{C}\end{bmatrix}\begin{bmatrix}\mathbf{x}(t)\\ \dot{\mathbf{x}}(t)\end{bmatrix} - \Delta\mathbf{M}\ddot{\mathbf{x}}(t). \tag{11}$$

Substituting the solution of $\ddot{\mathbf{x}}(t)$ from Equation (1), it yields

$$\mathbf{HGz}(t) = \mathbf{H}\left(\mathbf{G}_{active} + \mathbf{G}_{passive}\right)\mathbf{z}(t). \tag{12}$$

where

$$\mathbf{G}_{active} = \mathbf{G}_a . \tag{13}$$

$$\mathbf{G}_{passive} = -\mathbf{I_0 B_p G_p B_p^T L}. \tag{14}$$

with

$$\mathbf{B_p} = \begin{bmatrix} B_k & 0 & 0 \\ 0 & B_c & 0 \\ 0 & 0 & B_m \end{bmatrix},\ \mathbf{G_p} = \begin{bmatrix} G_k & 0 & 0 \\ 0 & G_c & 0 \\ 0 & 0 & G_m \end{bmatrix},\ \mathbf{I_0} = \begin{bmatrix} I & I & I \end{bmatrix},.\ \mathbf{L} = \begin{bmatrix} I \\ \mathbf{M}^{-1}\left(\mathbf{HG} - \begin{bmatrix}\mathbf{K} & \mathbf{C}\end{bmatrix}\right) \end{bmatrix}$$

An approach to solving numerically the constrained optimization problem is to use the "*Exterior penalty function method*" that is part of the Sequential Unconstrained Minimization Techniques (SUMT), because it requires the solution of several unconstrained minimization problems.

III. NUMERICAL EXAMPLE

Consider a 2-D moment resisting one-story and one-bay steel frame (Figure 2). The frame consists of two columns (W14×257 and W14×311) and one beam (W33×118). The columns are 345 MPA (50ksi) steel and the beam is 248 MPA (36ksi). The bay width L is 9.15m (30ft) and the height h is 3.96m (13 ft). The frame is subjected to a zero-mean white noise stationary horizontal base acceleration with peak ground acceleration of 0.25 g. The mass is M=159.450 kN sec^2/m, the stiffness is K=76987.117 kN/m and the damping coefficient is C= 140.147 kN sec/m that is determined assuming

Rayleigh damping equal to 2%.

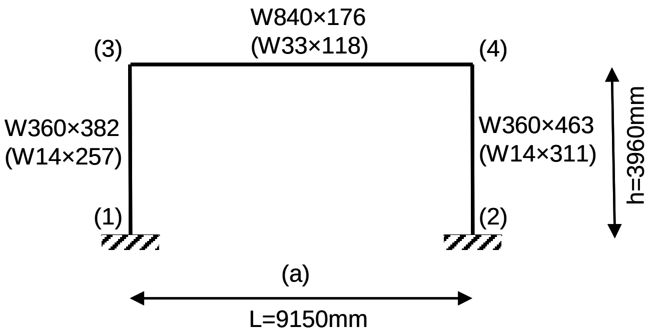

Figure 2. SDOF steel frame under white noise excitation

The period of the uncontrolled frame is T_0 =0.28 sec. The required lateral stiffness Ks necessary for supporting the gravity loads is

$$K_s = 0.18K\ . \tag{14}$$

The frame has been designed in order to limit the drift to 0.5% (x_{lim}=1.98cm). Following *Step 1*, consider now a possible reduction of K by introducing a diagonal active brace member while maintaining the original performance level (0.5% drift). Mass will be changed accordingly while damping reduces according to Rayleigh damping constraint. For the active structure, the equation of motion can be written as

$$M_a\ddot{x}(t)+C_a\dot{x}(t)+K_a x(t)=Hu(t)+\eta w(t). \tag{15}$$

where K_a is the achievable stiffness in the columns of the active structure and $u(t)$ is the control force in the active brace, which can be determined by using a control algorithm such as LQR. In this example, a reduction of stiffness of 60% is selected in order to satisfy the same performance level of 0.5% drift with a maximum active control force of 94.86 kN.

Many combinations are possible in determining the section properties of the columns and the beam for which it is possible to obtain a stiffness reduction of about 60%. In this example, the two columns are substituted by two W14×99 sections (Figure 3). Using this selection, it is possible to obtain a reduction of stiffness of 61.8% and the new updated stiffness is

$$K_a = 29401.127\ \text{kN/m}. \tag{16}$$

The initial structural steel mass of the frame is

$$M_{S0} = 10924\ \text{lb=4959.5kg}. \tag{17}$$

With added active brace, the structural steel mass is

$$M_S = 6114\ \text{lb=2775.7kg}.$$

Consequently, the structural steel weight is reduced by 44% by adding an active brace with a maximum control force of 94.86 kN. Table 1 gives the maximum drift and absolute acceleration response for the initial structure and the redesigned structure with the active brace installed. Table 1 also shows that it is possible to obtain a reduction of structural steel mass without modifying the performance of the structure.

Table 1 Maximum response for white noise with pga of 0.25g

Uncontrolled			U_{max}=94.86kN		
(1)	(2)	(3)	(4)	(5)	(6)
Drift x_i [%]	$\ddot{x}_a$ [m/sec^2]	M_{S0} [kg]	Drift x_i [%]	$\ddot{x}_a$ [m/sec^2]	M_S [kg]
0.49	11.15	4959.5	0.50	5.81	2775.7

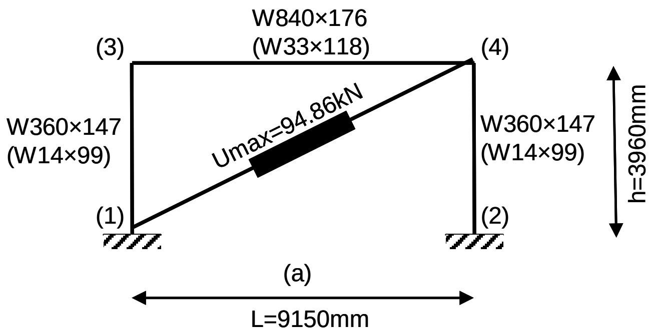

Figure 3 Steel portal frame with active brace

Step 2 of the redesign procedure can now be carried out by minimizing control power while keeping drift at 0.5%. By imposing a lower bound for the lateral stiffness equal to K_s in Equation (14) and assuming a lower bound for the mass at 75% of the initial value, the optimal structural parameters and the associated control force are given in Table 2. The percentage reduction of mass is -25%, stiffness is -62.3% and damping is -39.5%.

Table 2 Optimal structural parameters after redesign for white noise with pga of 0.25g

M	K	C
kg	kN/m	kN sec/m
159450	76987.1	140.1

M_{opt}	K_{opt}	C_{opt}	U_{opt}
kg	kN/m	kN sec/m	kN
119587	29010.1	59.930	92.434

It is shown that a substantially lighter structure can be designed to achieve a specified performance objective when an active brace is integrated into the structure in an optimal fashion.

III. CONCLUSIONS

A redesign approach has been outlined in this paper to determine the optimal control/structural system such that an optimal structural configuration can be achieved while satisfying a specified performance objective. It is shown that, using the two-step redesign approach, an efficient solution procedure can be developed. While a simple one-story one-bay structure is used as a numerical example, the redesign approach is equally efficient in dealing with multi-degree-of-freedom linear and nonlinear structural systems.

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