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HIGH PRESSURE SERVO-MECHANISM STRUCTURAL CONTROL SYSTEM

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ABSTRACT

Structural control systems in civil engineering are critically reviewed with their advantages and disadvantages in practical applications. Most of the control systems, including base isolation passive control systems and tendon active control systems, aim to reduce the responses of the structures so as to increase the safety of the flexible structures. In order to have a more reliable and economical control system, high-pressure servo-mechanism control system is proposed. By means of the tighten tendon, structural sidesway can be sensed by the mechanism and high pressure be guided into the actuator (high pressure cylinder) and provides control forces which will be applied to the frame in the direction of reducing the sidesway.

KEYWORDS: structural control, high pressure servo-mechanism, flexible structures

INTRODUCTION

Application of the active control concept to civil engineering type of structures was firstly proposed by Yao [1]. In addition to the base isolation or stiffen tendon control algorithms, many algorithms were introduced for the control of civil engineering type of structures, such us the optimal control algorithms [2,3], pole assignment method [4], and modal control theory [5,6], etc.. Modal control theory is properly applied to the control of highrise buildings [7,8]. Meirovitch and Silverberg proposed independent modal control with reduced order and analyzed the dynamic behavior of an undamped multi-degree of freedom structure subjected to earthquake excitation [9]. Pu and Hsu applied the method to a structure with viscous damping to find the increments of modal stiffness and damping for each mode using optimal feedback control [10]. Most of these efforts generated good results. Some of the experimental work have performed and demonstrated very good results [11]. In general, both for passive control system or active control system posses their own properties, advantages and disadvantages. Ignore the advantages, the disadvantages for the passive and active control systems can be mentioned as follows:

Disadvantages of the passive control systems:

* Potential limited: The control potential is limited because the capacity is set for a certain limit in the design and construction stage. The control function can not be adjusted timely.
* Over turning moment for highrise building: In general, base isolation passive control system is efficient to low structures. As it is applied to highrise building, the over turning moment can not be avoided usually.

Disadvantages of the active control systems:

* Relative complex: Some of the auxiliary equipment such as computers, actuators, sensors,..., etc. are needed.
* Time delay problem: Still try to solve to ensure the control forces can apply at the instant exactly needed.
* Computation error: Feed back calculation has to maintained in normal state otherwise the biased control force will ruin the control results.
* Nonlinear response:Efficient control rely on top-grade dynamic analyses. So far most of the active controlled structures are considered as linearly responded structures. That means the structure has not gone into plastic range. It is no doubt that the response must be nonlinear as the structure is excited into failure stage.
* Reliability: Switch must be always on and all the computer program, electric circuit, ..., etc. must always under normal service state. The normal state is doubt to maintain as the building subjected by severe loading such as earthquake loads. Thinking that how can we maintain the electric circuit in sound condition for the building installed by active control system while the power system in the whole city is down.

In order to improve the control system, the high pressure servo-mechanism is recommended to avoid the previous mentioned disadvantage. Figure 1 shows the proposed control system. The proposed high pressure servo-mechanism is able to induce huge control force only by igniting a small displacement. Furthermore, no electric circuit system or computing system is required. The mentioned properties happen to meet the needs for the civil structures which possesses big mass, big volume and usually small displacement. Building under control is simulated by shear beam model and theoretically the proposed servo-mechanism can be installed at all or some of the selected floors to reduce the relative horizontal displacement of the adjacent floors. Mathematical model is derived according to a multi-story structure controlled by the proposed high pressure servo-mechanism. Three types of control algorithms are derived and proposed according to different applied function of the control force. Examples of a simple portal frame controlled by the servo-mechanism is analyzed.

In addition, the control effect is verified by the experimental work. The upper cylinder of the mechanism acted as a sensor to sense the relative displacement of the floors and the high pressure is guided into the proper chamber of the lower cylinder. Control force is then induced and applied to the structures by the tendon. It is easy to show that the control force applied to the structure is always in the opposite direction to the structural displacement. That means the system is essentially a displacement control device.

MATHEMATICAL CONTROL MODEL

Multi-story building which is going to be controlled is modelled as shear building. Horizontal displacement, velocity and acceleration of each floor are considered as the primary responses. The equation of motion can be formulated as

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=[D]\{U\}+[E]\{P\} \tag{1}$$

where $[M]_{n\times n}$, $[C]_{n\times n}$, and $[K]_{n\times n}$ stand for mass matrix, damping coefficient matrix, and stiffness matrix, respectively; $\{P\}_m$ and $\{U\}_m$ stand for external excitation and control force matrix; $[E]_{n\times m}$

and $[D]_{n \times m}$ stand for the matrix related to the location of the external excitation and control forces; $\{\ddot{X}\}_n$, $\{\dot{X}\}_n$ and $\{X\}_n$ are column matrices standing for acceleration, velocity and displacement of the shear beam building.

Three different types of the control algorithms are derived as follows:

(1) Type I:

Once there is relative displacement existed between degrees of freedom, relative sidesway displacement between floors, the high pressure servo-mechanism ignited and induce control force applied to the structure by tendon. The control force is opposite to the relative displacement to reduce the displacement. The control force can be calculated according to the following formula:

$$U_j(t) = -P_j(t)A_j \mathrm{Sgn}(X_j(t) - X_{j-1}(t)) \cdot H(|X_j(t) - X_{j-1}(t)| - d) \qquad j = 2,\ 3, \ldots\ldots, n \tag{2}$$

where

$U_j(t)$ and $U_{j+1}(t)$ stand for the control force applied to the jth and (j+1)th floor, respectively;
$P_j(t)$ stands for the pressure input to the servo-mechanism installed at the jth floor;
A_j stands for the area of the piston in the lower chamber of the servo-mechanism;

$$\mathrm{Sgn}(\delta) = \begin{cases} +1 & \text{when} \quad \delta > 0 \\ -1 & \text{when} \quad \delta < 0 \end{cases}$$

$H(\cdot)$ stands for the unit step function; d is the buffer gap which is equal to the half of the amount of piston width subtracted by pressure tube diameter.

The final control force applied to the jth floor is equal to

$$\tilde{U}_j(t) = U_j(t) - U_{j+1}(t) \tag{3}$$

If the high pressure supplied by the servo-mechanism at the jth floor is a constant P_j, substituting $P_j(t) = P_j$, we obtain

$$U_j(t) = -P_j A_j \mathrm{Sgn}(X_j(t) - X_{j-1}(t)) \cdot H(|X_j(t) - X_{j-1}(t)| - d) \tag{4}$$

(2) Type II:

According to the direction of the relative displacement and relative velocity of the floors to decide whether the control forces are applied or not. The control force applied to the jth floor can be formulated as

$$U_j(t) = -P_j A_j H(|X_j(t) - X_{j-1}(t)| - d) \cdot I \tag{5}$$

where I is a decision index equal to

$$I = \text{Sgn}(X_j(t) - X_{j-1}(t)) \cdot H((X_j(t) - X_{j-1}(t)) \cdot (V_j(t) - V_{j-1}(t))) \tag{6}$$

and $V_j(t)$ is the velocity of the jth floor.

According to the formula, decision index would equal to zero, imply that the control force equal zero, as the direction of relative displacement ($X_j(t)$- $X_{j-1}(t)$) is opposite to the direction of relative velocity ($V_j(t)$- $V_{j-1}(t)$).

(3) Type III:

The application of control force is also decided according to the direction of the relative displacement and the direction of relative velocity. The function of control force is formulated as

$$U_j(t) = -P_j A_j H(|X_j(t) - X_{j-1}(t)| - d) \cdot I_1 I_2 \tag{7}$$

where I_1 and I_2 are decision index equal to:

$$I_1 = \text{Sgn}((X_j(t) - X_{j-1}(t)) \cdot (V_j(t) - V_{j-1}(t))) \tag{8}$$

$$I_2 = \text{Sgn}(X_j(t) - X_{j-1}(t)) \tag{9}$$

It reveals that $I_1 = 1$ when relative displacement and relative velocity are in the same direction, meanwhile, control force applied in a direction opposite to the relative displacement; and $I_2 = -1$ when relative displacement and relative velocity are in opposite direction, meanwhile, control force applied in the same direction as the relative displacement.

EXAMPLES

The formulas displayed in the last section are used to analyze a simple portal frame with servo-mechanism control installation. The mass, damping coefficient, and stiffness of the frames are assumed to be M = 300 ton (lumped mass), ξ = 0.02 and K = 3.4 $\times 10^7$ N/m. Earthquake acceleration spectrum of 1940 El Centro N-S are considered as the external excitation. In case of high pressure inlet is closed and the piston is locked, the effect of the system is nothing but a stiffened structure by tendon reinforced. As the piston is free to move, the tendon fail to afford any contribution. In case of high pressure inlet is opened, the system afford a semi-active control effect to the structure. The structure is assumed to vibrate in elastic behavior during excitation and control process.

Figure 2 shows the relationship between the maximum relative displacement and the control force as the buffer gap equals to zero. It shows that no matter how much the control force is, there exist positive control effect for type II and type III system while there is positive control effect for type I system only in some certain limitation. Figure 3 gives an example of the time history of the control results for the three types control algorithms. It is understandable that the structure swing back and forth, control force acted when the structure swing back to its normal position giving negative effect to the structure. That is why type I system basically gives nothing help to the structure on the view point of the structural control.

EXPERIMENTAL WORK

To check the feasibility of the structural control by high pressure servo-mechanism, an experimental work is performed by shaking table test. The proposed servo-mechanism is installed in a simple portal frame as the picture shown in Fig. 4. The 1 m × 1 m portal frame is composed by a steel boxed beam and flexible columns combined by steel blades. Each column is assembled by 1 to 4 steel blades with size of 100 cm × 10 cm × 0.07 cm. The lateral stiffness of the frame can be adjusted by changing the number of the steel blades.

Series of tests with various lateral stiffness, various magnitude of seismic spectrum, various control pressures are performed. One of typical test results is demonstrated in Fig. 5. It shows that the relative displacement between floor and the base is controlled quite well. However, once the response exceeded some kind of limit, the control system failed to assure the convergence result. One of the divergent example is shown in Fig. 6(a).

The divergent result echoes the theoretical analysis of the type I control system which is formulated in equation (2). The mechanism is then improved in order to meet the requirement of the type II control algorithm. Most of the test results are then quite well under control. One of the typical controlled results is shown in Fig. 6(b) by the relative displacement time history.

On the purpose of having an simple mechanism, that is no electrical circuit is composed in. The mechanism of type III control system has not been successfully designed. However, type II control system leads satisfied results.

CONCLUSION

1. High pressure servo-mechanism structural control system is proposed in different types. The analysis work show type II and type III give positive control results while type I gives unstable control results.
2. Buffer gap is necessary to avoid unstable phenomena. Theoretically, there is proportional relationship between control pressure and buffer gap to obtain better control results.
3. The speed of pressure input and output has not considered herein. Instantaneous pressure input and output is assumed in the example analyzed. In fact, the effect due to the pressure input and output equivalent to the effect due to buffer gaps. This effect probably is the primary factor to cause the experimental work of type I device giving positive control results.
4. Factors involved in this issue are still complex and various. For example, the variation of pressure, the speed of pressure input and output, problem of compressibility, magnitude of buffer gaps, shape and size of pressure inlet and outlet, ..., etc.. All of the above mentioned variables would change the dynamic property of the system. It is worthwhile to do further research to obtain better results.
5. Type II control device is obviously better than type I control device both in theoretical and experimental work.
6. Both theoretical and experimental analyses verified the proposed high pressure servo-mechanism would be one of feasible structural control tool in civil engineering structures. It is worthwhile to

emphasize that the proposed control system does not need to install fancy auxiliary equipment such as computers nor complex electric circuit is needed. That makes the feasibility of the system to be much higher than some other active control systems.

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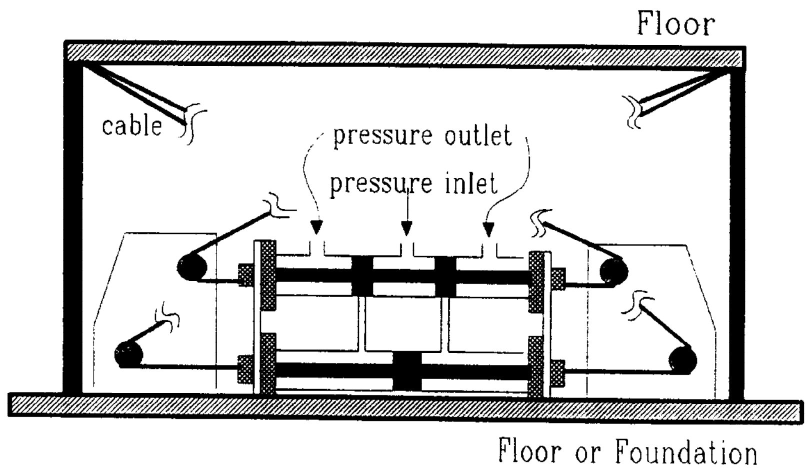

Fig. 1 The high pressure servo-mechanism device for structural control.

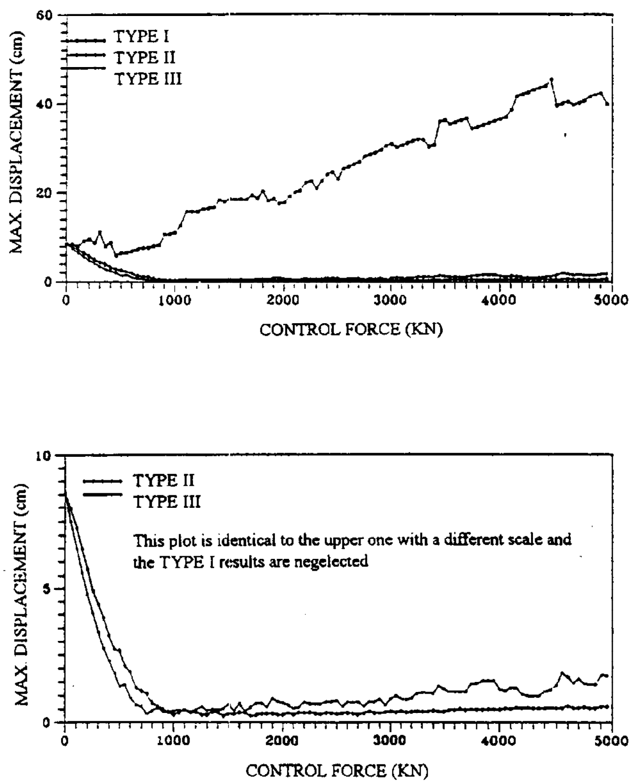

Fig. 2 The displacement vs. control force for the three types of control mechanism.

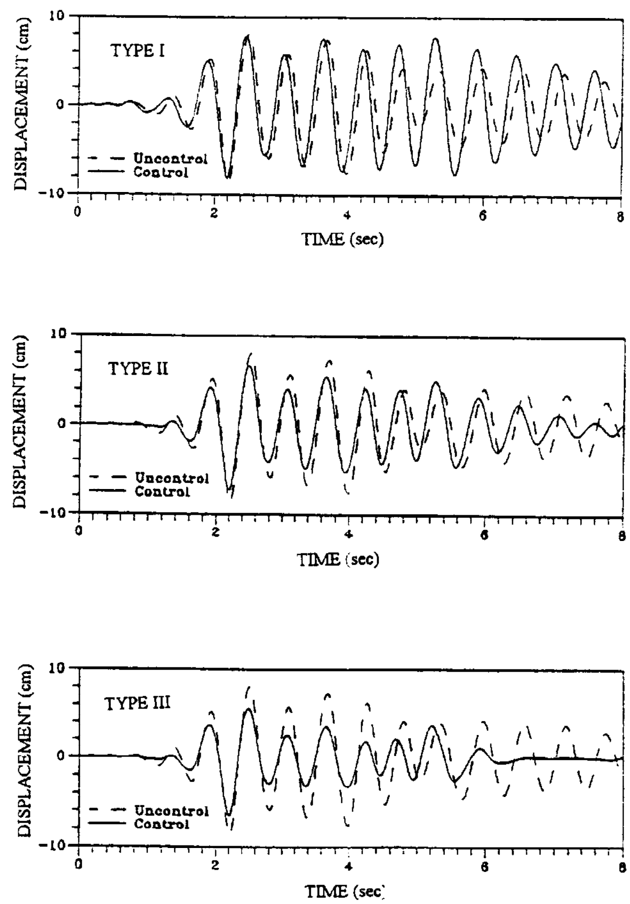

Fig. 3 The time history of displacement of the three types of control mechanism.

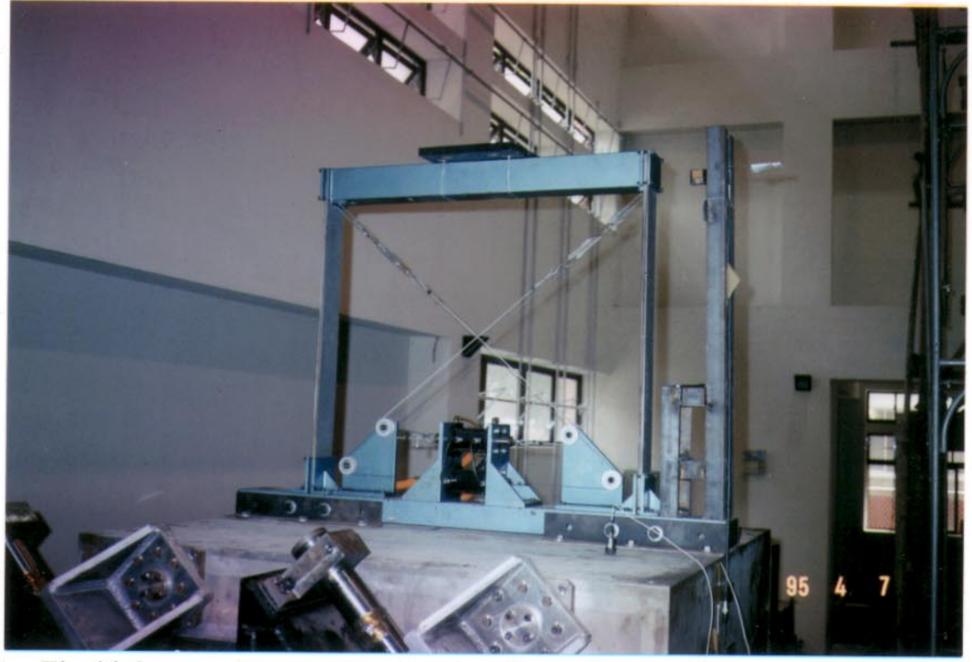

Fig. 4 The high pressure servo-mechanism device mounted on a portal frame in the experimental work.

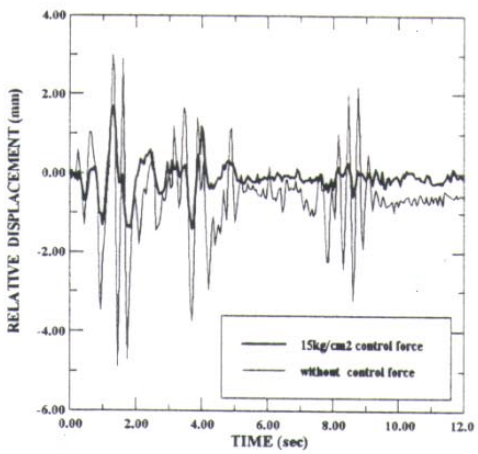

Fig. 5 The experimental results of applying control and of without control force.

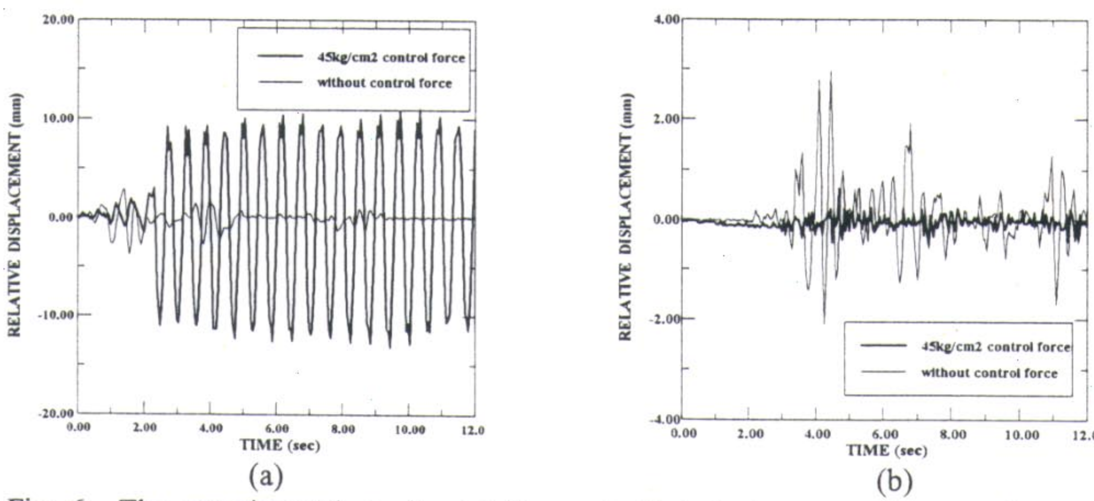

Fig. 6 The experimental results. (a) the controlled displacements became divergent when a certain limit was exceeded. (b) the phenomenum of divergent displacements vanished when a type II control was used.