STRUCTURAL SEMI-ACTIVE CONTROL DEVICE

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SUMMARY

Methods for vibration reduction of structures under dynamic excitations such as wind and earthquake were generally classified into active control and passive control. Both methods have their specific application field and limitations. Recently, especially after Kobe Earthquake 1995, researchers gradually doubt about the feasibility of these methods by strong earthquakes. Engineers and researchers intend to find more efficient and more reliable methods for vibration reduction under strong seismic excitations. Methods such as hybrid control and semi-active control are developed and have directed researcher's attention to development of control apparatus. One semi-active control apparatus that is invented and constructed by the author will be presented in this report. Moreover, some numerical results are used to examine the feasibility of this control system.

The semi-active control apparatus, which is introduced in this report, includes active joints and stiffeners. Active joints are particularly connectors that can release the restraint in one of two specific directions. The stiffeners are same as common stiffener improving the lateral stiffness of structures such as shear wall, bracing and prestressed tendon. They are fixed connected to the structure at one side, and indirectly connected via active joints to the structure at the other side. The stiffeners have the function to store the control energy by vibration of structures. The stiffeners in cooperation with active joints will dissipate a large amount of mechanical energy of seismic excited structures, even though the stiffener is elastically deformed. The most noticeable feature of this system is that there is no external energy required. Structural vibration under strong earthquake will be evidently and reliably reduced. The functional principle and construction of active joint are in detail introduced at first part of the text. An experimental result of small model and some numerical analysis will be used to show the efficiency of the new system. The results conclude that this semi-active control system will reduce more than 70% of maximal deflection without disadvantage to induce.

INTRODUCTION

Engineers have learned by catastrophic earthquake experiences, that the safety of structures is usually not guaranteed under economic consideration. For the sake improving the seismic resistant capacity of structures, the strength of structural members or the stiffness of structure will be improved. But unfortunately, this attempt is not always successful and usually uneconomical. Moreover, the performance design requires in many cases reduction of displacement and/or acceleration response under specific earthquake magnitude. Seismic resistant design, which generally enhances the structural ductility, can merely improve the structural safety but can't reduce the seismic response. Modern technologies were developed in recent years. They improve the structural safety by means of reducing response.

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Technologies attempt to reduce the response of structures under dynamic excitations are generally classified into active control [Leipholz et al 1986, Soong 1990] and passive control [Aguirre et al. 1992, Xia 1992] method. Both methods have their specific application field and limitations. Recently, especially after Kobe Earthquake 1995, researchers gradually doubt about the feasibility of these methods by strong earthquakes. Engineers and researchers intend to find more efficient and more reliable methods for vibration reduction under strong seismic excitations. Methods such as hybrid control and semi-active control [Kurino et al. 1998] are developed and have directed researcher's attention to the development of control apparatus. The most important features of semi-active control method are high reduction effect and minimal demand on control energy. Due to low energy demand, the semi-active controls are absolutely stable, which is generally a problem of active controls.

A semi-active control apparatus designed by the author [Shih 1997] will be introduced in this paper. Key advance of the new proposed control method consists in the development of active joints, which are practically connectors that can release the restraint between main structure and stiffeners in one of two specific directions. By utilizing the active joints, the sign of inner stress of stiffeners can be changed without striking requirement on external energy supply. The directions of resultants of stiffeners act on structure are then reversed, and it is possible, that the resultants always oppose against the motion of the structure. Mechanical energy of structure is dissipated, even though the stiffeners deform elastically.

FUNDAMENTAL PRINCLPLE

Stiffeners such as bracing and shear walls are believed to be available for dissipating structural mechanical energy only when they practice plastic deformations or viscose effect is present. Elastic deformed member are generally acknowledged to be incapable of energy dissipation. This viewpoint was not always correct. We can use the relation between work, force and displacement to declare it.

Basic equation indicates the relation of work; force and displacement vector takes the form:

$$dW_s = \vec{F}_s \cdot d\vec{x} \tag{1}$$

In equation (a) dW_s is not real differential of work but the work done by a constant force by infinitesimal motion of structure. Vector $\vec{F}_s$ is the resultant vector of stiffener acting on main structure and $d\vec{x}$ is the infinitesimal displacement vector of point subjected to force $\vec{F}_s$. Divide both side of equation (1) by infinitesimal time interval dt, we obtain the following equations:

$$\frac{dW_s}{dt} = \vec{F}_s \cdot \frac{d\vec{x}}{dt} \qquad \text{or} \tag{2}$$

$$\dot{W}_s = \vec{F}_s \cdot \dot{\vec{x}}\,. \tag{3}$$

It is clear from equation (3) that the change rate of work depends on magnitude of vectors $\vec{F}_s$ and $\dot{\vec{x}}$, and also on the angle between these two vectors. In case, that the force $\vec{F}_s$ and velocity $\dot{\vec{x}}$ are collinear, stiffener can perform negative work, if the force acts opposite to the motion of structure. In general case that stiffeners always connect with main structure, there is a fixed relation between the vector $\vec{F}_s$ and $\vec{x}$. The change rate of work done by elastic stiffener is negative when magnitude of displacement increases, but is positive when magnitude of displacement decreases. Total work done by stiffener in every half cycle of oscillation is zero. This is the reason why elastic deformed stiffener can't dissipate energy.

On the contrary, elastic deformed stiffener can perform energy dissipation if the stiffener is not fixed connected to main structure. In case, that stiffener is decoupled at on end, the stiffener vibrates freely after the decoupling in natural frequency of stiffener. The interaction force between stiffener and structure suddenly becomes zero. This state holds until the stiffener is again coupled with the structure. If the stiffener is coupled again before the free vibration stops, an interaction force exists between stiffener and structure. The magnitude lies between zero and the magnitude before decoupling, and the direction can be either opposite or identical to the original one, depends on deformation state of the stiffener. Because we can always select a reaction force opposing to the motion of structure, negative change rate of work can be guaranteed. This feature makes it possible that the elastic deformed stiffeners are also capable of energy dissipation. Energy dissipation by means of decoupling and re-coupling action in sequence is the basic principle of this new proposed control method. An apparatus that make it possible will be presented in next section.

ACTIVE JOINT

To perform the required function above, active joint, that connects the stiffener and main structure, must act fast and precisely. Relative to re-coupling, the fast and precise decoupling is relative simple to achieve. The major difficulty consists in the accurate re-coupling action. According to the illustration in last section, the optimal instant of re-coupling is that moment about half natural period of the stiffener after the decoupling, since the maximal negative change rate of work can be achieved at this moment. This time interval is usually less than 0.002 seconds. No literature describes an apparatus that is enough precise to do it.

Figure 1 shows an active joint proposed by the author. The active joint consists essentially of two single-directional connectors. Both connectors allow relative motion between stiffener and main structure in one specific direction (left or right). In case that the hydraulic mechanism for decoupling is still, the stiffener and structure are practice coupled together, and relative motion in both directions is prevented. If the hydraulic cylinder acts on one connector (say the right one), relative motion in direction left is free, while the relative motion in the other direction remains prevented. This property results in automatic re-coupling at the optimal instant. It is also to emphasize that the force necessary to release the one-side connector is little. The operation of the active joint requires only tiny energy.

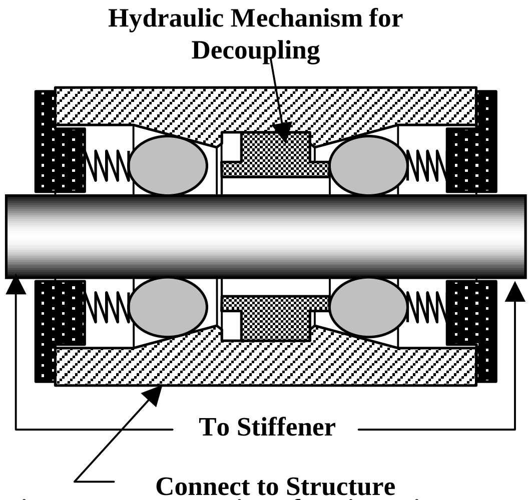

Figure 1: Construction of Active Joint

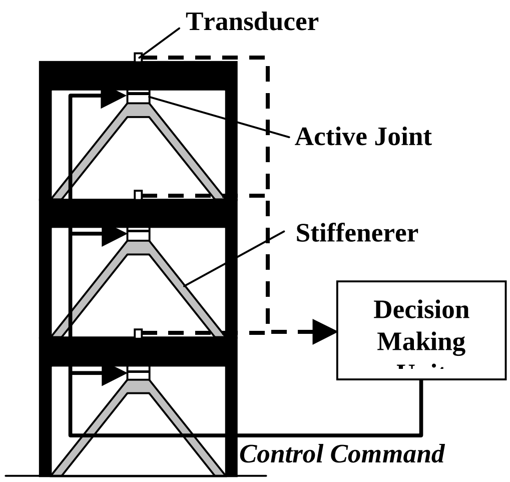

Figure 2: Setup of Semi-Active Control System with Active Joints

Figure 2 shows the setup of semi-active control system with active joints. Transducers are needed for every active joint to detect the direction of motion at related story. When the direction of motion changes, the Decision Making Unit sends a control signal to the associate active joint. The interaction force between stiffener and main structure is then reversed.

Figure 3 shows the typical time history of interaction force F_s . In this figure, it is found that the magnitude after decoupling and re-coupling action reduces some. This is a result of friction and damping effect in active joint and stiffener. The reasonable ratio between these two magnitude lies between 0.7 and 0.95, which depend on the natural frequency of stiffener and quality of active joint. The ratio is called restoring-coefficient (denoted by α) and defined as following equation.

$$\alpha = \frac{\left|\vec{F}_{s,1}\right|}{\left|\vec{F}_{s,0}\right|} \tag{4}$$

Where $\left|\vec{F}_{s,0}\right|$ and $\left|\vec{F}_{s,1}\right|$ are magnitudes of reaction force before and after control actions, respectively.

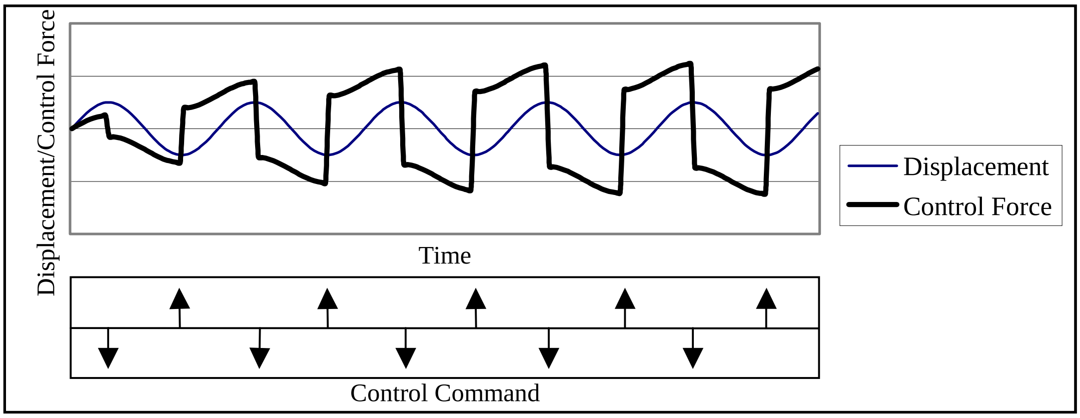

Figure 3: Typical Time History of Control Force and Control Command

EXPERIMENTAL STUDIES

Experiments on scaled down single degree of freedom model were performed for the purpose verifying the vibration reduction effect of the control system with active joints. Three groups of experiments were proceeded, they are: Group I, free vibration tests; Group II, harmonic excited vibration tests at resonant frequency; group III, excited vibration tests. The response histories will avail against qualitative verification of control effect. To keep the identity of the dynamical properties of controlled and uncontrolled systems, same stiffeners were used in all tests. The system parameters for all experiment models are shown in Table 1.

Table 1: System parameters of experiment models

Model	Mass (kg)	Structural Stiffness(N/m)	Stiffener Stiffness(N/M)	Structural Damping Ratio(%)	Active Joint present	Restoring-Coefficient (α)
Without Control	81.86	2720	843	1.5	NO	-
With Control	81.86	2720	843	1.5	YES	0.68

As indicated in Table 1, the ratio of stiffener's stiffness to total stiffness is 0.23. Relative to the ratio of common passive systems such as ADAS system, this value is very little [Xia 1992]. The major advantage of this feature is that the natural frequency of controlled system will not be apparently increased, so that the acceleration response will also be reduced.

The restoring-coefficient was estimated by experimental data prior to the tests. Because of large influence of friction effect on small model, this value is little. Although the condition impairs the control effect, the time histories of displacement response indicate a noticable reduction effect.

Result of Free Vibration Tests

Response time histories are shown in Figure 4. Results of free vibration tests indicate a rapid elimination of vibration. Essential displacement disappears in about one oscillation. The tiny vibration after first period cannot be eliminated from control system, because the remaining interaction force between stiffener and main structure cannot overcome the friction in active joint.

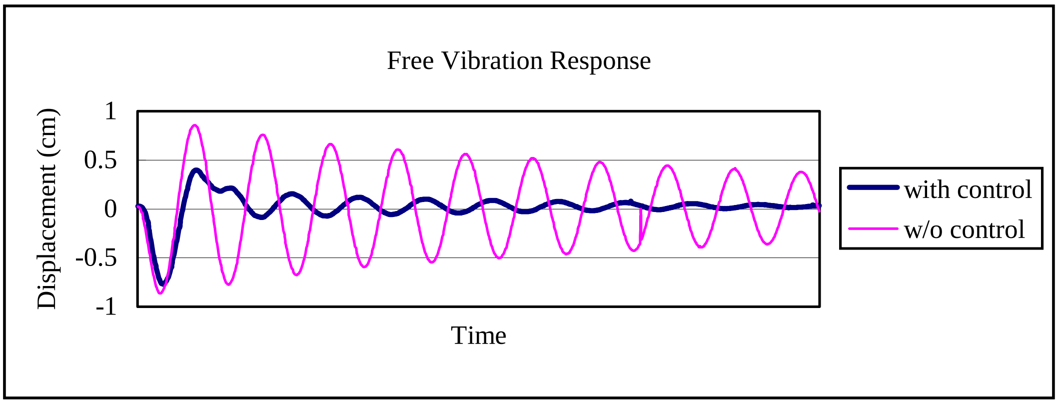

Figure 4: Response time history of free vibrations

Harmonic excited vibration tests

In these tests, structures were excited by harmonic loading with the natural frequency of structures (1.05Hz). Results were shown in Figure 5. The response of system with control is as expected lower than that without control. An equivalent damping ratio of 25% can be concluded from the time history in Fig. 5.

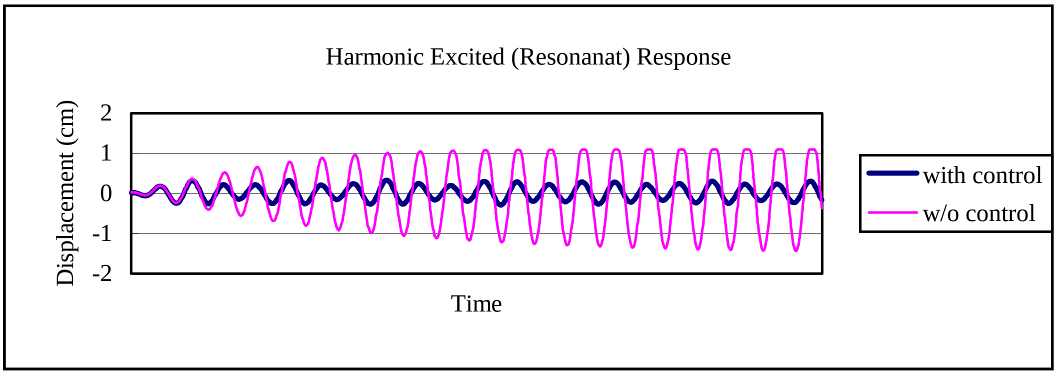

Figure 5: Displacement response under harmonic (resonant) excitation

Seismic excited vibration tests

Record of ground motion of earthquake EL Centro in 1940 was scaled down and simulated to excite the models. Both controlled and uncontrolled response time histories are shown in Figure 6. It can be concluded from the time history that the maximum displacement of system with control equals about 50% of system without control. Main reason for the poor reduction effect is the low restoring coefficient. As mentioned earlier, the influence of friction is serious for small model. Experiments on larger models will be performed in this year.

The fact that there is no evident change in natural frequency is also worthy to emphasize, besides the reduction of displacement. The acceleration response is also reduced under this condition. It is reasonable that the maximal displacement occurred when the essential ground motion arrives. This can be a key point to improve the control method. This problem could be overcome by means of prestressing the stiffeners prior to the earthquake. An even better control effect is expected.

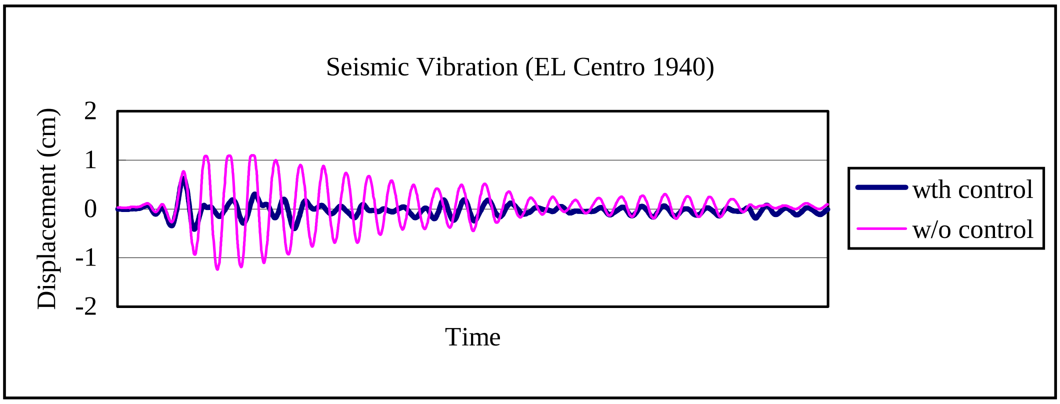

Figure 6: Displacement response under seismic excitation (EL Centro1940)

CONCLUSION

A semi-active control device, namely active joint, was presented. The active joint consists merely of elementary machine elements. A high reliable control is achieved, because no precise control is needed for the proposed control method. Results of numerical studies in another work of the author [Shih 1996] indicate following important conclusions:

1. 80% of maximal displacement can be reduced by use of active joints.
2. A high equivalent damping ratio of 40% can be achieved.
3. The control effect will only slightly affect by malfunction of several active joints.

Further experimental studies on larger models are planned and will be performed at National Center of Research on Earthquake Engineering (Taiwan) at the end of this year. Effects of friction and control algorithm will be studied.

REFERENCE

Aguirre, M., Sánchez, A.R. (1992), "Structural Seismic Damper", *ASCE, Journal of Structural Engineering, Vol. 108, No. 5*.

Kurino, H. and Kobori, T. (1998), "Semi-Active Structural Response Control by Optimizing the Force-deformation Loop of Variable Damper", *Second World Conference on Structural Control, Kyoto.*

Leipholz, H.H.E., Abdel-Rohman, M. (1986), *Control of Structures*, Martinus Nijhoff Publishers.

Shih, M.-H. (1996), *Eine active Regelung zur Schwingungsreduzierung von Bauwerken unter seismischen Beanspruchungen*, Dissertation, RWTH Aachen, Germany.

Shih, M.-H. (1997), "Active Control Apparatus and Method for Vibration Reduction", American Patent, Application No. 08/916.951.

Soong, T. T. (1990), *Active Structural Control - Theory and Practice,* Longman, London and Wiley, NewYork.

Xia, C., Hanson, R.D. (1992), "Influence of ADAS Element Parameters on Building Seismic Response", *ASCE, Journal of Structural Engineering", Vol. 118, No. 7, July.*