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EXPERIMENTAL STUDY OF ACTIVE CONTROL SYSTEM FOR COUPLED STRUCTURES

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ABSTRACT

This paper proposes a new type of smart structural system which consists of active control devices coupling two structures. By controlling the devices as if they have a variable stiffness or a variable damping, we can make the two structures to keep away from the predominant period of earthquake. One of the authors has proved two theorems concerning the inverse problem of natural period. If we use these theorems, control values can be calculated easily with conventional computers.
The control effects of the several kinds of algorithms are investigated by numerical simulations and experimental methods. The control algorithms that are examined in this paper are as follows.

Method 1: Quasi-damping system given by restoring force control
Method 2: Quasi-damping system given by relative velocity control
Method 3: Negative stiffness control
Method 4: Optimal stiffness control

Where the Method 3 is a new originated control technique.

As concluding remarks, it appeared that the proposed active coupling control system is useful enough, and shows considerably good reduction of vibrations by Method-1 to Method-3. However, with Method-4, the reduction was not enough. This may be caused by computing time.

1. INTRODUCTION

There are many reports regarding the active control system to reduce the vibration of single building which enhances the structural resistance and habitability. There are many cases where adjacent buildings having different shape and structure style are built, such as twin buildings and nuclear reactor facilities. The vibration of two neighboring buildings can be effectively reduced if both buildings are coupled with the joining member having actuator and the quasi-stiffness and quasi-damping are given. We have performed the numerical analysis so as to check the validity of building control system by coupling two buildings, developed the experiment equipment, andperformed experiment. This report discusses the algorithm of control by coupling two buildings, the result of analysis, and the result of experiment. The experiment equipment which we used is shown below.

2. CONTROL ALGORITHM

The active control system for coupled building structures is a method to control vibration by coupling two adjacent buildings with the joining member provided with actuator and giving a force to both buildings by actively shrinking and stretching the joining member. Various control algorithms are applicable for coupled building structures. Of all four methods mentioned below, we have preferred the method 3 (control with negative stiffness) which was expected to give the best effect by numerical analysis. However, at first we have adopted the method 1 and method 2 for the model experiment since they have the more simple algorithm. We discuss also a new method, namely the quasi-optimum control method (method 4). Below are shown applicable 4 methods.

Method 1
The restoring force is set according to the displacement between buildings, and a control force corresponding to it is given. The relation between restoring force and displacement is assumed to be expressed as parallelogram (Fig. 1). This allows us to take into consideration quasi-damping effect additionally. The control is effected by stretching or shrinking the joining member only when the sign of interbuilding velocity changes.

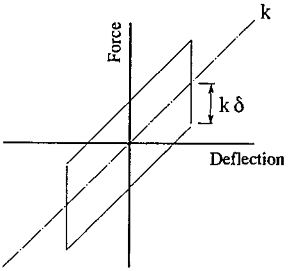


Fig. 1 Properties of control force (Method 1)

Method 2
Damping which is proportional to interbuilding velocity is given as a control force. The interbuilding displacement is read with specific intervals, velocity is calculated, control force corresponding to it is calculated, and the control force is given to control by stretching or shrinking the joining member.

Method 3
In the case when a three-floor building model and a two-floor building model are coupled with each other by connecting their 2nd floors as shown in Fig. 2, the relation between additional stiffness (k) of joining member and natural period is expressed as shown in Fig. 3 [1]. As is evident from the figure, if the additional stiffness of joining member is positive, the period of all orders becomes shorter, but if it is negative, the period of all orders becomes longer. The period at negative stiffness changes more remarkably than at positive stiffness. This control is designed so that the natural period of whole system (coupled buildings) is extended by giving the negative quasi-stiffness to the joiningmember, and deviated from the predominant period of earthquake vibration to maintain the non-resonance state.

Let us assume that δ and kq are interbuilding deformation and negative stiffness given to the joining member, respectively. If a force of kq.δ occurs, the member acts as if it has a stiffness of kq. Assuming that k is intrinsic stiffness of joining member, we get the force k.δ caused by the deformation δ. Assuming that L is stretch and shrinkage of actuator, we can get the negative stiffness, using the following formula (see Fig. 4).

$$L = -kq.\delta/k + \delta$$

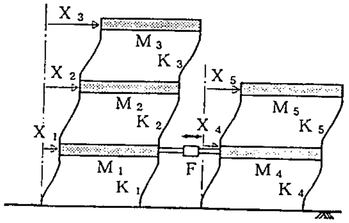


Fig. 2 Analysis model

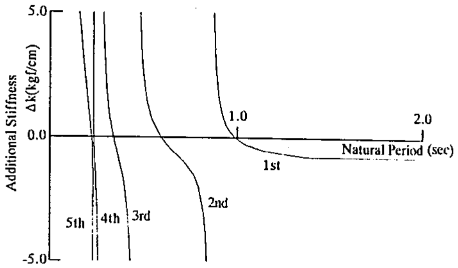


Fig. 3 Relation between natural period and additional stiffness

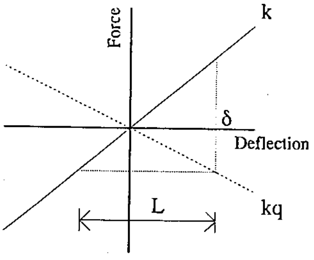


Fig. 4 Stiffness of joining member

Method 4
Let us assume that the movement of actuator can be given arbitrarily on the n-th stage. The energy of the next step (kinetic energy and potential energy) is calculated with respect to each movement from the quantity of current step (displacement, velocity, acceleration, etc.), minimum movement shift is found, and the actuator is moved to control. Since this method needs longer measurement time and calculation time at each step, the real experiment data are not available.

3. RESULT OF ANALYSIS

The object of active control is adjacent 3-floor building and 2-floor building whose 2nd floors are coupled to each other. Figure 2 shows the analysis model. The specification of building conforms to the experiment model. The Newmark's β method ($\beta = 1/4$) was used for time history analysis which was performed with 0.01 second intervals. The result of analysis for El Centro 1940 NS input is shown for each control method.

Method 1

Figure 5 shows the relation between response acceleration (rms) of top of each building and motor movement δ. The theoretical values show that the response value reduces as the motor movement increases. If the time lag resulting from calculation of control force and measurement of interbuilding displacement in experiment and the limit of motor movement within unit time are taken into consideration, it becomes impossible to get the experimental control effect identical with the theoretical one when the movement increases, and response does not reduce. The response value, as shown in Fig. 1, is minimum near $\delta = 0.8$. Hence, in the experiment $\delta = 0.8$ is set.

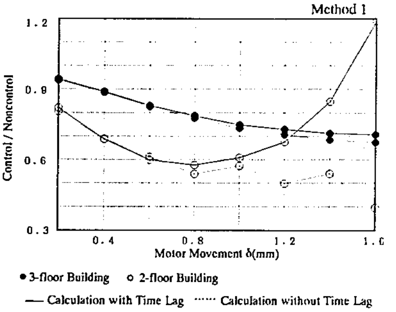


Fig. 5 Relation between response value and motor movement

Method 2

Figure 6 shows the relation between response displacement (rms) of top of each building and the coefficient C at different interbuilding velocity. The theoretical data indicate that the response value reduces as the coefficient increases. If the time lag and motor movement limit are taken into consideration, the control force identical with the theoretical one cannot be given if the coefficient is increased as in case of method 1, so that the response cannot be reduced. It appears minimum near C = 0.03. In the experiment, C = 0.03 was adopted.

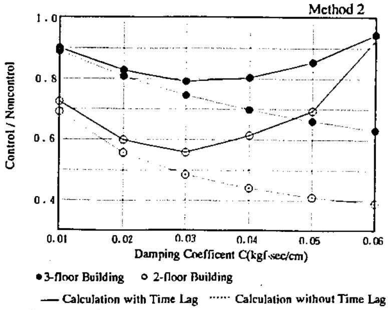


Fig. 6 Relation between response value and damping coefficient

Method 3

Figure 7 shows the relation between response displacement (max. rms) of top of each building and negative stiffness Kq. With this model, the response value is lowest near Kq = - 0.5 to -1.0 (kgf/cm). In our experiment Kq = -0.9 (kgf/cm) was set.

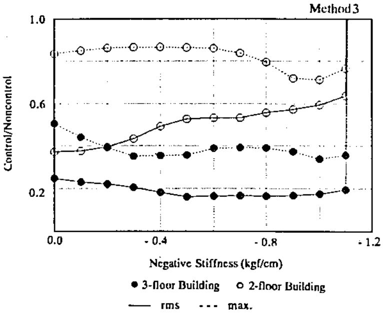


Fig. 7 Relation between response value and negative stiffness

Method 4

Figure 8 shows the time history in the example of analysis by this method and the result of analysis where control was not applied. The response was reduced in the whole duration.

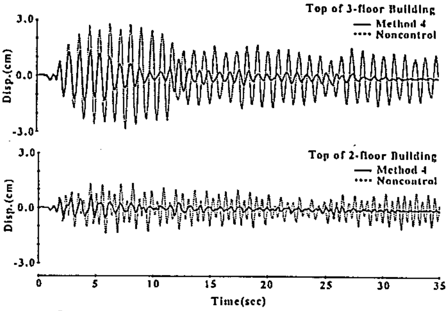


Fig. 8 Displacement response waveforms depending on El Centro NS input (Method 4)

4. EXPERIMENT EQUIPMENT

Figure 9 shows the control system of experiment equipment. This equipment is a variation of the equipment shown in Reference [2] which has been modified for twobuildings. The building models are 3-floor building and 2-floor building. The same floors of these buildings can be coupled with the aid of spring. Table 1 shows the specification of building models. Table 2 shows the natural period of each uncoupled building and the natural period of coupled buildings (the 2nd floors were coupled to each other). The spring end of 2-floor building is connected to the stepping motor of rack and pinion mechanism fixed on the floor. If the motor is rotated, the rack moves horizontally, and the control force is given to the building by stretching or shrinking the spring. The control procedure is as follows. The relative displacement of both buildings is detected by the laser sensor, it is input into the computer (NEC PC9801DA with math coprocessor) through the AD converter board, and the control force is determined according to the obtained information. Then, pulse is generated by using the pulse control module, and the motor at the end of spring is driven to give the control force. Pulse is given with specific time intervals in the pediestrial mode. The control program language is BASIC.

Both buildings are laid on the common ground table which can be moved on the rails of base with the aid of stepping motor having ball screw. This enables the excitation data, such as earthquake wave and sine wave, to be input. The stands installed on the base are provided outside the both buildings to install the sensor.

Table 1. Building specification

Weight of each floor (kgf)		Stiffness of each story (kgf/cm)	
3-floor building	2-floor building	3-floor building	2-floor building
Roof 9.97	Roof 8.38	3rd story 2.7	2nd story 2.7
3rd floor 10.63	2nd floor 8.54	2nd story 2.3	1st story 2.4
2nd floor 10.75		1st story 2.0	
Stiffness of joining spring (kgf/cm) Method 1 and 2 = 0.946 Noncontrol and Method 3 = 2.63		Building primary damping: 0.3%	

Table 2. Natural period (unit : sec)

	First	Second	Third
3-floor building	0.99	0.33	0.22
2-floor building	0.59	0.21	-
Coupled building	0.91	0.53	0.31

5. RESULT OF EXPERIMENT

5.1 Free vibration

Figure 10 shows the relative displacement waveform with respect to the ground table of top of 3-floor building used for free vibration experiment where forced displacement was given to the top of 3-floor building. It has been revealed that although the equivalent damping in noncontrol state which was determined from this waveform is about 0.3% the method 1 gives about 1.6%, and method 2 gives about 0.9%, namely 5 times and 3 times higher than in noncontrol state. With the method 3, the amplitude reduces remarkably, and the damping increases notably (15.0%).

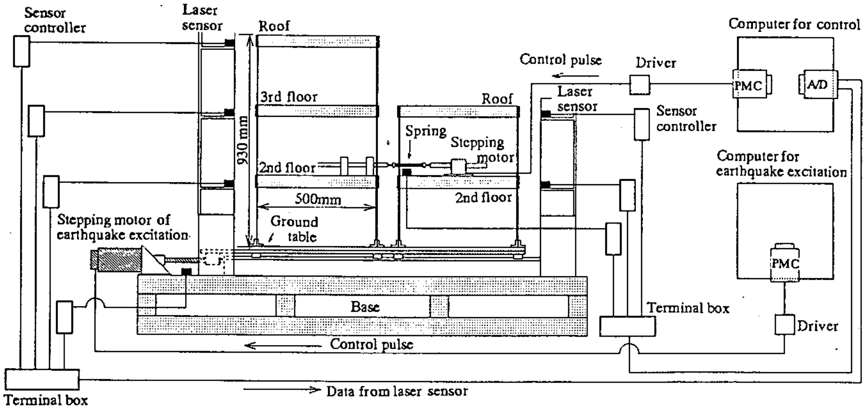


Fig. 9 Control system

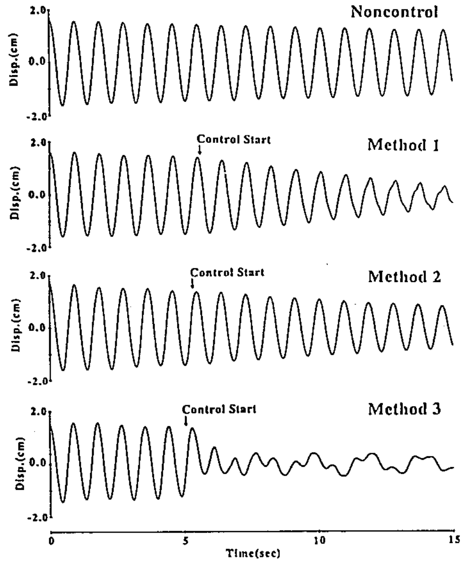


Fig.10 Free vibration displacment waveforms of top of 3-floor building

Figure 11 shows the relation between the interbuilding displacement of each control method and spring reaction. With the method 1, an insignificant thinning is observed near maximum displacement due to insignificant delay of beginning of motor movement but the shape is nearly as expected. The figure of method 3 shows that the curve representing interbuilding displacement vs. spring reaction slopes down, thereby indicating the negative stiffness. Figure 12 shows the running spectrum of responce waveform which was observed at the top of 3-floor building by applying the method 3. This evidences that the spectrum amplitude at the predominant frequency(A) of building reduces gradually after the control is started, and that the first(B) and the second(C) frequencies of coupled building which has negative stiffness appear as expected.

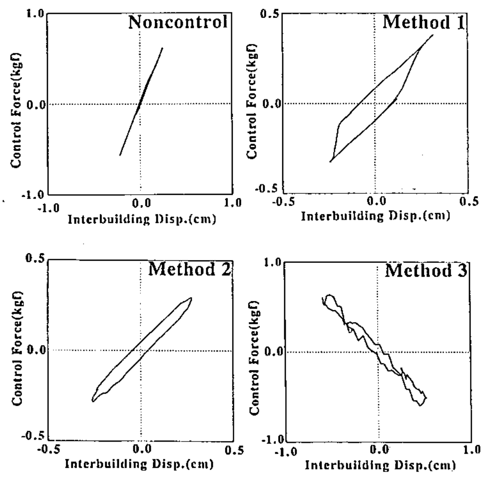


Fig. 11 Relation between interbuilding displacement and control force

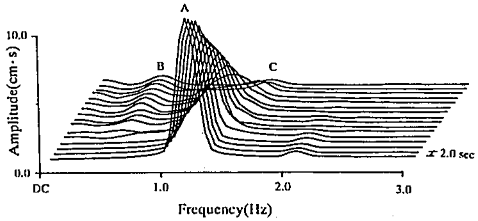


Fig. 12 Running spectrum of top of 3-floor building (Method 3)

5.2 Resonance curves

Figure 13 shows the resonance curves representing the control state of method 3 giving the best effect and the noncontrol state. In the figure the black circles represent the experiment data whereas the solid line indicate the analytical data. If the control is applied, the

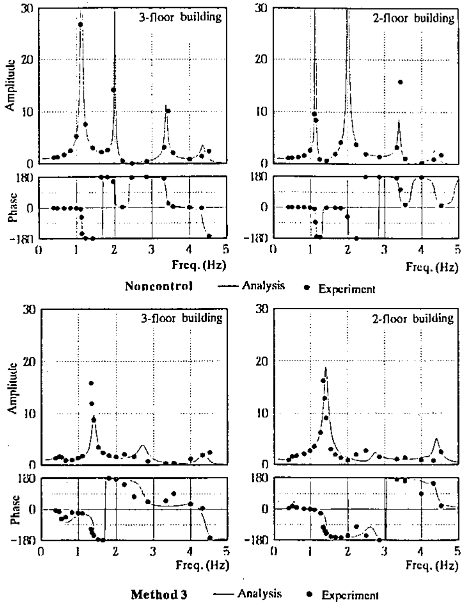


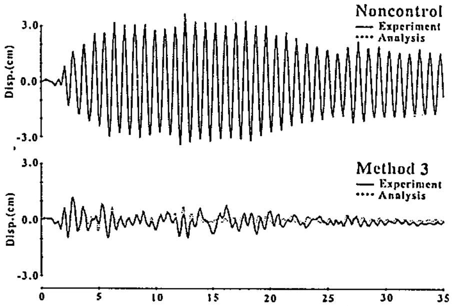
Fig. 13 Resonance curves

period increases, so that the first frequency appears near 0.5 Hz. The response coefficient reduces due to apparent damping caused by time lag. In both cases, namely in control state and noncontrol state, the analytical data well match with experimental data. The value of peak in this state is fairly smaller than in noncontrol state.

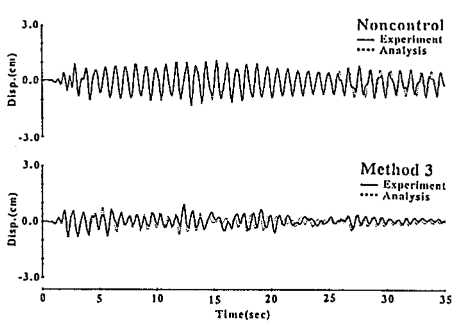
5.3 Earthquake excitation

Below is discussed the result of experiment using by method 3.

Figure 14 shows the displacement waveforms of building tops depending on earthquake excitation. Figure 14 (a) shows the displacement waveformsof 3-floor building top where Figure 14 (b) shows the displacement waveforms of 2-floor building top. The solid line indicates the result of experiment whereas the broken line indicates the result of analysis. Table 3 shows the value of maximum and rms of response displacement of top of each building. The earthquake wave is given by multiplying the displacement amplitude of El Centro 1940 NS by 0.1. Excepting the first several response waves,the amplitude reduces remarkably as a whole. The value of rms of 3-floor building and 2-floor building reduced about to 1/5 and 1/2,respectively.



(a) Top of 3-floor Building



(b) Top of 2-floor Building

Fig. 14 Displacement response waveforms depending on El Centro NS input

Table 3. Value of rms and maximum of response displacement depending on EL Centrol NS input

Experiment	Top of 3-floor Building		Top of 2-floor Building	
	max. (cm)	rms (cm)	max. (cm)	rms (cm)
Noncontrol	3.72	1.70	1.27	0.52
Method 3	1.23	0.31	0.93	0.26

6. CONCLUSION

The authors reported the analysis with 4 different algorithms and result of experiment of the active control system for coupled structures. The result of experiment revealed that each control method gives the control effect and that the method 3 (control with negative stiffness) gives the best effect. Our experiment was conducted at constant negative stiffness (-0.9 kg/cm). Our intention is to keep the non-resonance state of coupled structures which is realized by deviating the period of building from the predominant period of earthquake by changing the negative stiffness with the lapse of time. The authors are planning to continue the experiment of method 4. The authors will make a proofing model building having a height of about 3 meter to examine the active control effect in consideration of real earthquake.

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