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Bidirectional Connected Control Method Applied to an Experimental Structural Model Split into Four Substructures

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Abstract. Connected Control Method (CCM) is a well-known mechanism in the field of civil structural vibration control that utilizes mutual reaction forces between plural buildings connected by dampers as damping force. However, the fact that CCM requires at least two buildings to obtain reaction force prevents CCM from further development. In this paper, a novel idea to apply CCM onto a single building by splitting the building into four substructures is presented. An experimental model structure split into four is built and CCM is applied by using four magnetic dampers. Experimental analysis is carried out and basic performance and effectiveness of the presented idea is confirmed.

1. Introduction

Vibration suppression has been one of the biggest issues in civil structure, especially in the area possessing frequent earthquakes and typhoons such as Japan. Many mechanisms have been presented and applied to civil structures to reduce vibrations. Mass dampers and base isolators are the typical.

So-called "Mass damper" utilizes resonance to absorb vibration energy of the objective structure [1]. Attaching relatively small vibratory system made of auxiliary masses, springs (or other restoring mechanism such as pendulum) and dampers to the objective structure and tuning its natural frequency close to that of the objective structure, it possesses resonance with the structure. Then vibration energy of the objective structure is transferred to the attached vibratory system and is absorbed by the dampers. "Mass damper" is so simple that it can easily be equipped to civil structures, while its vibration suppression performance is governed by the mass ratio – weight of the auxiliary mass versus weight of the objective structure. Therefore, as the applicable mass ratio remains relatively low, so the reachable vibration suppression performance also remains low. Such situation is common on bigger or taller structures such as high-rise buildings.

Base isolation is another common mechanism for civil structures subjected to earthquake excitations [2]. By supporting entire structure by using bearable flexible mechanism such as rubber bearings, the natural frequency of the supported structure is dramatically dropped so that the resonance with earthquake excitation can mostly be avoided. Against to the wind excitations, however, the base-isolator hardly possess vibration suppression effect. Therefore base-isolation is not so suitable to high-rise buildings subjected to wind excitations.

Inter-story dampers are widely applied for recently-built buildings in Japan. This method is essentially simple – just put dampers between vertically adjoining floors. Its effectiveness for relatively low buildings is already confirmed, while its effectiveness for high-rise buildings is deteriorated. It is because bending vibration becomes dominant in high-rise buildings and inter-story dampers are only effective against shear vibrations.

To sum up these methods, it is difficult to reduce structural vibration of high-rise buildings subjected to wind and earthquake excitations. Therefore, authors focus on another method named "Connected control mechanism."

Connected control mechanism (CCM) is a well-known mechanism in the field of civil structural vibration control that utilizes mutual reaction forces between plural buildings connected by dampers as damping force [3]. As the difference in natural frequencies among buildings increases, so the damping effect is also increased.

CCM is already put into practical use in Japan. "Triton Square" is a complex of three high-rise buildings connected by two elastic viaducts. The effectiveness of CCM for life-size buildings are proved by this application [4]. Due to the restriction that CCM requires at least two buildings to obtain reaction force, however, further application of CCM has not been carried out yet.

To overcome this restriction and develop CCM, a novel idea to apply CCM onto a single building is presented. First, splitting the building into four substructures that possess the same height and the same number of floors but different natural frequencies (or construct the building as an aggregate of four such substructures). To form single building, the floors of the four substructures in the same height would be coupled via elastic joints such as sliding couplers or expansion joints. Putting dampers in the joints (namely between substructures), the aggregate, four substructures coupled with dampers, forms a single building equipped with CCM.

In this study, an experimental model structure split into four is built and CCM is applied by using four magnetic dampers to realize the presented idea. The model is set on a shaking table and subjected to excitations. Experimental analysis by impulse or shaking table excitation using seismic wave records is carried out and basic performance and effectiveness of the presented novel CCM is investigated.

2. Experimental Model Structures and Magnetic Dampers

As described, an experimental model structure made of four substructures are built that possess the same height and the same number of floors but different natural frequencies. In this study, two types of substructures are made and arranged in chequered pattern so that substructures possessing the same natural frequencies never be located side by side. Putting four dampers between substructures to form square, the four substructures forms single building equipped with CCM (see section *3.4*).

2.1. Experimental Model Structures

Figure 1 and 2 show the schematic design of the two types of experimental substructures. They are almost identical except the diameter of the vertical columns to change the natural frequencies.

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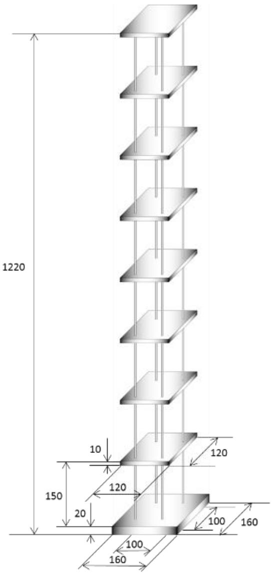


Fig.1 Schematic design of St.A

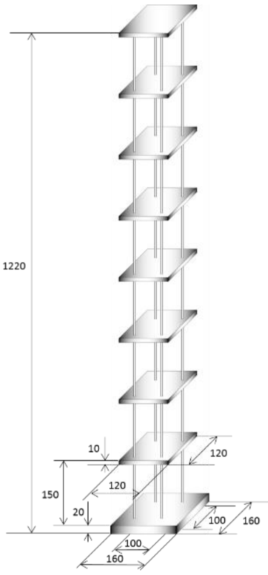


Fig.2 Schematic design of St.B

The diameter is 4 mm in the substructure A (St.A) shown in Fig.1, while it is 5 mm in the substructure B (St.B) shown in Fig.2. According to this difference, the natural frequencies of two substructures also differ. The natural frequencies of the first mode of two substructures are shown in Table 1.

Table.1 Natural frequencies of two substructures

	1st bending mode
St.A	7.85[Hz]
St.B	10.96[Hz]

Four substructures, namely St.A, St.A', St.B and St.B', are built and arranged in chequered pattern. Figure 3 shows the outlook of the arranged substructures.

Fig.3 Arranged four substructures

2.2 Magnetic Dampers

To obtain damping, eight magnetic dampers [5] are produced (two for each four couplings). Figure 4 and 5 shows the outlook of a magnet and a copper plate composing a magnetic damper, respectively. The design and parameters of the damper would be shown in the section *3.3* later.

Fig. 4 Magnet for damper

Fig.5 Copper plate for damper

3. Modelling Structures and Design of Magnetic Dampers

3.1 1-Degree-Of-Freedom Models of Substructures.

Prior to modeling and design dampers for CCM, the equivalent model of the structure is identified. First, modal analysis of the structures are carried out to identify the equivalent mass and stiffness. Figure 6 shows an example of modal shapes of St.A.

1st mode (1st bending) **2nd mode (1st torsion)** **3rd mode (2nd bending)**

Fig.6 Vibration modal shapes of St.A

In this study, the main target of the vibration suppression is the first mode. According to Reduced-order physical modeling method [6], 1-degree-of-freedom model denoting the first mode can be obtained. The identified parameters of the substructures are shown in Table 2.

Table.2 Equivalent mass of model and Equivalent stiffness of model

	Equivalent mass[kg]	Equivalent stiffness[N/m]
St.A	2.198	5347
St.B	2.213	10495

3.2 Optimal Damping Based on Fixed Point Theory

Dynamical model of CCM can be described as a simple two mass-spring system connected by a coupling damper. Figure 7 shows a schematic view of the CCM model. “m_1” and “m_2” denote the equivalent masses of the substructures, “k_1” and “k_2” denote the equivalent stiffness and “c” denotes the damping of CCM, respectively. The entire structure is subjected to ground excitation displacement u.

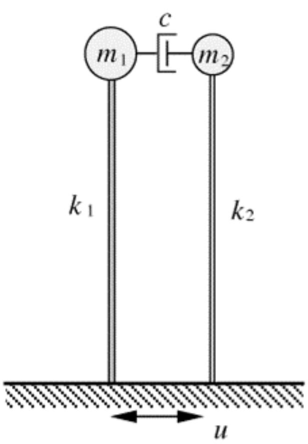


Fig.7 Reduced order vibration model and dynamics model

The optimal tuning theory for CCM is already presented according to so-called “fixed point theory.” The optimal damping coefficient is derived according to the theory [1]. The optimal damping ratio is derived as ζ=0.104 that means the optimal damping coefficient is 31.9 [Ns/m]. Figure 8 shows the computational frequency transfer functions of each substructures connected dampers with zero, the optimal or the infinite damping. The effectiveness of the optimal tuning theory is clearly shown.

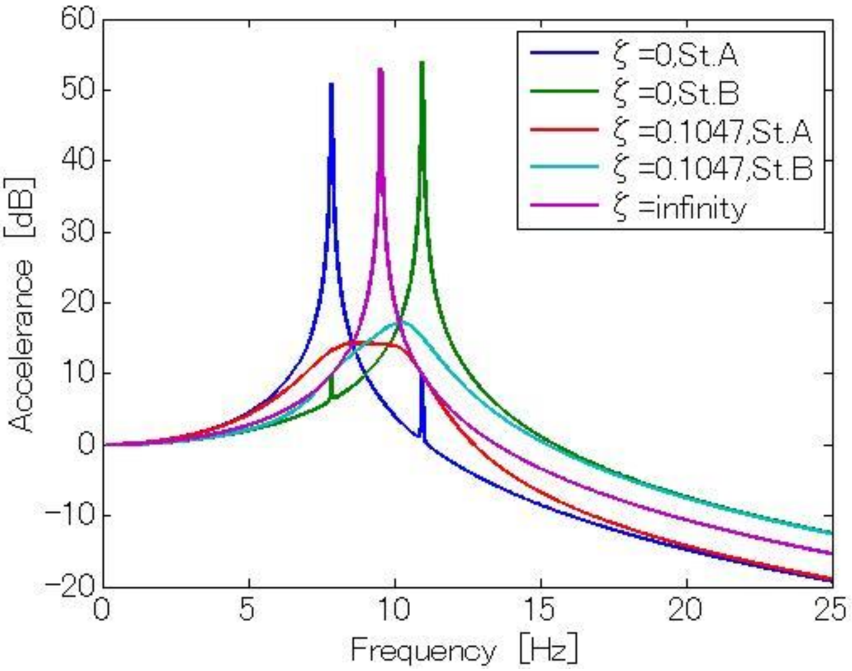


Fig.8 Frequency responses of substructures coupled by dampers

3.3 Design of Magnetic Dampers

Magnetic dampers utilizes electromagnetic induction when conductor such as copper plate goes across magnetic field. The theory of magnetic damper is already presented by Seto [3]. According to the theory, the damping coefficient can be obtained as

$$c = K\frac{atB^2}{\rho} \qquad (1)$$

where K denotes constant, *a* and *t* denotes the area and the thickness of the conductor in the magnetic field , *B* denotes the density of magnetic flux and ρ denotes the specific resistance of the conductor, respectively. The parameters of the magnets and the conductor (see section 2.2) are as follows:

$$K\text{=}0.5[\text{-}],\ a = 9.0\times10^{-4}\ [m^2],\ t = 2\times10^{-3}\ [m],\ B\text{=}0.460[T],\ \rho = 1.68\times10^{-8}\ [\Omega m]$$

The obtained damping coefficient is c=11.3 [Ns/m]. Therefore two dampers are equipped for each coupling. This means the equivalent damping coefficient for each coupling is c=22.6 [Ns/m], below the optimal damping c=31.9 [Ns/m]. This gap is caused by the experimental restriction on available copper plate. Thicker copper plate would be introduced in the near future.

3.4 Setup of Substructures and Magnetic Dampers

Figure 9 shows the schematic arrangement of substructures and magnetic dampers, while Figure 10 shows an outlook of the experimental structures with eight magnetic dampers, respectively.

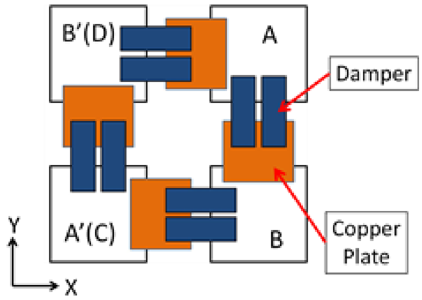


Fig.9 Arrangement of substructures and magnetic dampers

Fig.10 Outlook of four substructures with eight dampers

4. Experimental Evaluation

The performance of the presented bidirectional CCM applied to the experimental structure with four substructures is explored by experimental analysis. Frequency transfer functions are measured by using impulse excitation onto the top of the structure, while time response against seismic excitation are measured through shaking table test using seismic wave record.

4.1 Frequency Transfer Functions

Using an impulse hammer, an FFT analyzer and an acceleration pickup, frequency transfer functions are measured. The pickup is located at the top of the roof of a substructure and impulse excitation is added onto the roof.

Figure 11 shows examples of the measured frequency transfer functions. Due to transverse-torsional coupling, the influence of torsional mode also appears when dampers are mounted. Even though the coupled substructures possess significant damping that confirms the effectiveness of CCM clearly.

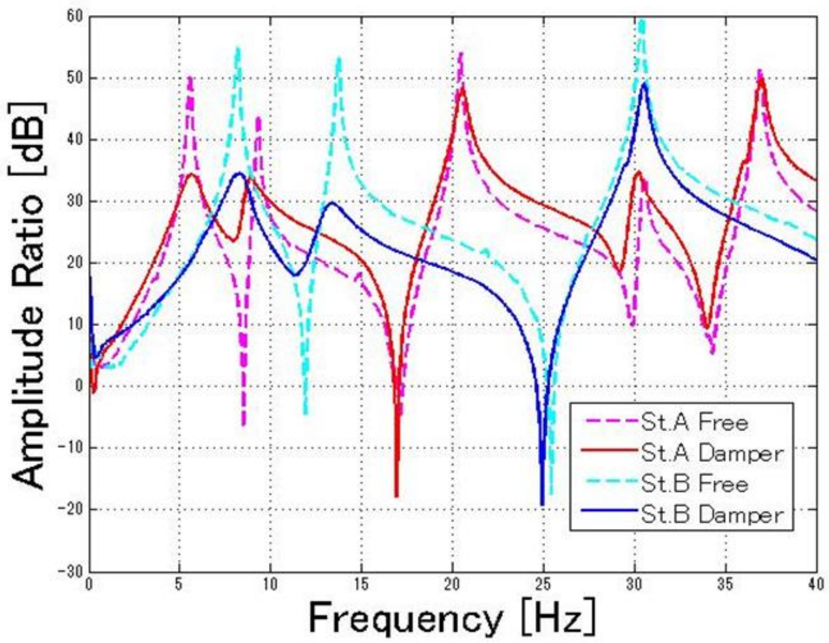
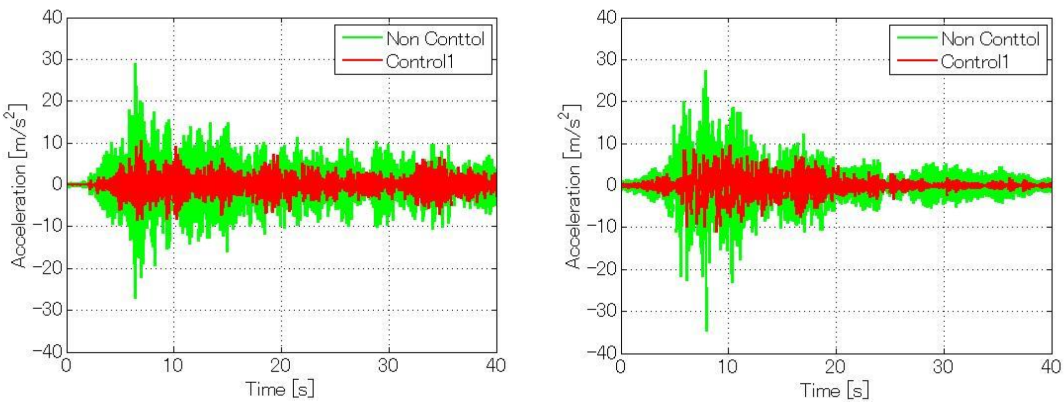


Fig.11 Transfer function (Substructure A, X direction)

4.2 Shaking Tests Using Earthquake Excitation Wave Records

Putting entire system onto a shaking table, shaking tests are carried out using seismic wave records. In this research, El-Centro and Kobe seismic acceleration records are adopted. As the experimental system is fragile and its natural frequencies are far higher than the superior frequencies of the excitation records, time- and amplitude- scaling is applied so that the superior frequencies of the records would corresponds to those of the target substructures while the amplitude of the records become one-tenth of the original.

Figure 12 shows examples of the measured time histories of the Y-direction acceleration of St.A at the roof. Peak accelerations are well suppressed by applying CCM. Besides, the peak acceleration responses of St.A and St.B in X or Y direction subjected to El Centro or Kobe earthquake wave record excitations are classified in Table 3. It is clearly shown that significant damping effect is achieved by applying CCM.



(a) El Centro (b) Kobe

Fig.12 Acceleration responses of St. A at the roof floor subjected to earthquake excitation

Table.3 Peak roof accelerations

	El Centro scaled to St.A	El Centro scaled to St.B	Kobe scaled to St.A	Kobe scaled to St.B
	[m/s^2]			
St.A X w/o CCM	23.900	21.509	28.923	37.625
St.A X CCM	11.459	15.125	17.389	19.987
St.A Y w/o CCM	28.986	23.188	34.684	33.249
St.A Y CCM	10.708	8.707	10.218	14.770
St.B X w/o CCM	12.777	12.009	15.001	18.986
St.B X CCM	9.298	9.090	12.121	12.942
St.B Y w/o CCM	28.628	21.163	21.311	30.452
St.B Y CCM	9.446	9.216	12.805	13.186

5. Concluding Remarks

In this paper, a novel idea to apply CCM onto a single building is presented. An experimental model structure split into four is built and CCM is applied by using four magnetic dampers to realize the presented idea. Modeling and design of the system are carried out according to procedures shown in previous studies. The experimental model is set on a shaking table and subjected to excitations. Experimental analysis by impulse or shaking table excitation using seismic wave records is carried out. Results of these tests showed significant effect of CCM that supports the effectiveness of the presented novel CCM.

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