Performance Evaluation of a Building Structure with Nonlinear Dampers by means of Network Sensors under Earthquake Disturbances

ISAO NISHIMURA

ABSTRACT:

The author designed and implemented a set of highly nonlinear oil dampers that connected a newly constructed gymnasium with an existing office building on the campus of Musashi Institute of Technology in Tokyo, 2003. They were designed to provide only compressive reaction to the structures and no tensile forces at all. In the design phase of the project, the author discovered that these half-effective dampers could achieve as much performance as from the fully effective linear dampers. Interaction between the structure and device dynamics was considered in the time domain analysis, which revealed that the highly nonlinear characteristics in the local members have small effect on the global dynamics of the whole system. In other words, the structure response can be simulated by a linear dynamics in spite of nonlinear damping materials. This analytical prediction caused a serious discussion among the engineers over the design issue whether to adopt the proposal or not. As a result, we made a decision to equip the structure with health monitoring system as well as nonlinear dampers. We started implementing a network sensor that was connected to the Internet after the construction project was completed. Each one of those network sensors is connected to a 16bit A/D converter and a data logger, which are then connected to the Internet by way of a gateway computer. This is the basic configuration of the separated sensor station, which forms a LAN as described above. There have been three sensor stations, which form a network and send data up to the client PC in the author's laboratory. One of the weak points associated with this type of sensor network is that we could not synchronize the timing of data acquisition of the A/D converters.

On the 23 of July 2005, we had an earthquake whose epicenter is about 50 kilometers east of Tokyo. The magnitude of the event was 6.0 and the intensity level is 5 according to JMA scale, which was for the first time in nearly 14 years in the urban area of Tokyo. We obtained a beautiful data that clearly show the linear system response with 6 % damping factor, which strongly supports the prediction and supposition of the mathematical model and the following analysis. It is also noted that we can easily identify the timing of the event because of the system linearity. This result compensates for the weakness of the sensor network configuration and shows the feasibility of this type of sensor installation. This type of sensor network has a strong advantage over the conventional system because of its flexible installation and easy expansion.

Dep. of Architecture, Faculty of Engineering, Musashi Institute of Technology
Email: inishimu@sc.musashi-tech.ac.jp

LINEAR DAMPER IN MAXWELL MODEL

Looking back over the original idea of dynamic absorber by Ormondroyd in 1928 and its optimization method by Den Hartog in 1947, we notice that the most simplified model that has the same principle in common is expressed in Maxwell Model shown in Figure 1. It is true that there is the optimum-damping coefficient c_{opt} that reduces the response of the mass to the lowest level, but the solutions are different under different types of disturbances such as harmonic, stationary random, and non-stationary disturbances. Although a countless number of studies have been reported for selecting c_{opt}, since Warburton had pointed out the effect of disturbances in 1982, the author wishes to remove it when evaluating the performance of damping devices. Therefore the closed form solution of the most desirable c_d is defined as c_{opt} that is expressed in Equation 1, where the optimum-stiffness k_{opt} associated with c_{opt} is introduced and defined as the left model in Figure 2.

As we increase the damping coefficient c_d, the frequency of the model also increases. Logically, there should be a relation between the damping augmentation and the stiffness increase. Once this relation is clarified, it is easier to extend the optimum formula into more complex structure dynamics. This is the author's motivation to introduce the optimum-stiffness k_{opt} for specifying the optimum-damping coefficient c_{opt} in Equation 1. For further discussion, additional arguments are introduced as follows: the circular frequency of the original Maxwell Model is ω_o, the circular frequency of the Maxwell Model with infinitely large damping coefficient is ω_∞, the circular frequency of the Maxwell Model with the optimum damping coefficient is ω_{opt}, the equivalent damping coefficient of the Voigt Model is c_{eq}.

$$c_{opt}\omega_o = 2k_{opt} \quad where \quad \omega_o = \sqrt{\frac{k}{m}} \quad k_{opt} = \frac{k_d}{2} \tag{1}$$

If we know k_d, the stiffness associated with the damper, it is rather easy to find k_{opt} because it should be half of k_d. Therefore we can predict the optimum-frequency ω_{opt} by Equation 2. The task left over is how to evaluate the performance of the optimum Maxwell Model in Figure 2. The pole locations of the equivalent Voigt Model are selected to the corresponding Maxwell Model's pole locations. As a result of this replacement, we have obtained Equation 3.

$$\omega_{opt} = \sqrt{\frac{\omega_o^{\,2} + \omega_\infty^{\,2}}{2}} \tag{2}$$

$$c_{eq} = 2m\omega_{opt}\eta_{eq} \quad where \quad \eta_{eq} = \frac{\beta}{2+\beta}\sqrt{\frac{1}{2(2+\beta)}} \quad \beta = \frac{\omega_\infty^{\,2} - \omega_o^{\,2}}{\omega_o^{\,2}} = \frac{k_d}{k} \tag{3}$$

NONLINEAR COMPRESSIVE DAMPER IN 2-MASS SYSTEM

The idea of connecting two adjacent building structures by means of damping devices with a purpose of reducing their response motions at a time can be long traced back to Kunieda, who extended the principle of P-Q lock point method from dynamic absorber into another configuration of structure system. There is the optimal damping factor c_{opt} that achieves the best performance of the damping device in the 2-mass system in Figure 3, just like Maxwell Model in Figure 1. Suppose that we are interested in the major structure, which is denoted as system-1 in Figure 3, the original system circular frequency ω_o in Equation 1 should be replaced by ω_1. The original discussion based on this supposition is to be referred to Nishimura, who compared the stationary random responses of Maxwell model and Voigt model under white noise excitation. Then the validity of Equation 1 is numerically investigated in the time domain under several different non-stationary random disturbances. As the result of these previous studies, k_{opt} in Figure 4 was defined in the same manner in Figure 2 and related with the optimum damping coefficient in Equation 1. The linearity of the damper is one of the key suppositions for the above analysis. It, however, is not relevant to the final performance evaluation index in Equation 3, which only contains stiffness parameter β. It can be naturally conceived that the nonlinearity of damping coefficient should have nothing to do with the performance in terms of η_{eq} in Equation 3. One extreme example of this inference is the replacement of linear damper by compressive nonlinear damper in Figure 4. A compressive damper has a highly nonlinear characteristic that yields no tensile force and works only when compressive reaction is action on it. A numerical analysis is carried out to show an example of this replacement in prior to actual design phase of the Gymnasium project (See Figure 5, and 6.).

The parameters in models of Figure 4 are given in Table 1, where the optimum parameters of the linear model are also given. The time histories of the response displacement of system-1 of linear and non-linear models under El Centro (NS) earthquake ground motion are shown respectively in Figure 5 and 6, from which we notice little difference between the two models. This analytical prediction is later proved to be true by comparing the observed earthquake data with linear analytical simulations.

APPLICATION PROJECT

Brief introduction of the application project is given in this section. The area and weight of the gymnasium and the annex office building are shown in Table 2, in which the results of the eigen value analysis based on the FEM model are also shown. As a result of FEM frame analysis, we came to know that the annex structure is as stiff as the gymnasium entrance frame in E-W direction. The mathematical model for dynamic study in the previous section is based on those data. There are enough shear walls arranged in the N-S direction in the main building structure, on the other hand the 3rd floor is supported by rather slender columns without major shear walls in the E-W direction. The horizontal forces in E-W direction should be transferred to the annex office building when earthquakes happen. We decided to use oil dampers to connect two building structures in E-W direction because of this reason.

We used a simple model in Figure 4 for designing the damper specification. Even though a better performance is roughly expected, yet careful selection of damping coefficient is still the key factor for achieving the best performance of the devices. According to the preliminary study, the appropriate compressive damping coefficient for one device should be around 15 KN sec/mm, which is certified in the factory test before installation (See Figure 7, 8 and Photo 1.). The compressive damper characteristic is clearly seen in Figure 8. For small level of cyclic loading, the damping coefficient is adjusted smaller than 15 KN sec/mm.

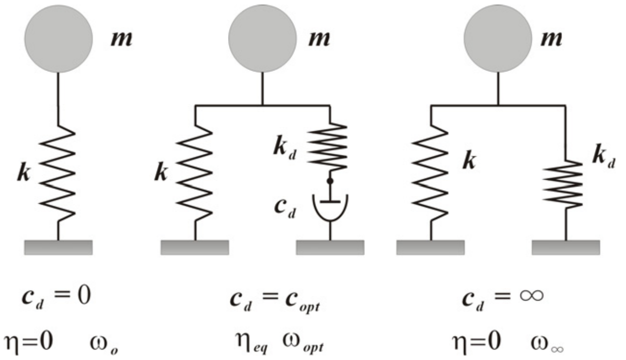


Figure 1. Optimum Damping Coefficient for Maxwell Model

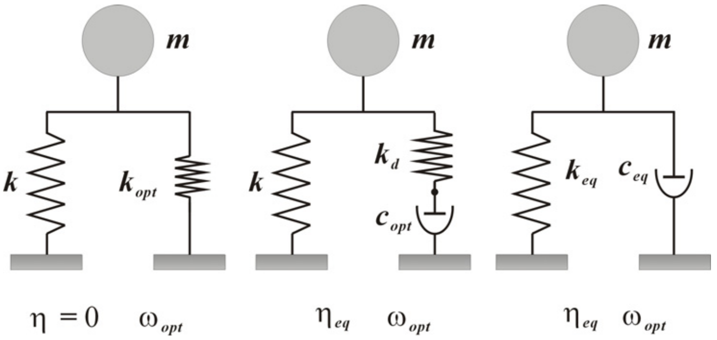


Figure 2. Optimum Maxwell Model and the Equivalent Voigt Model

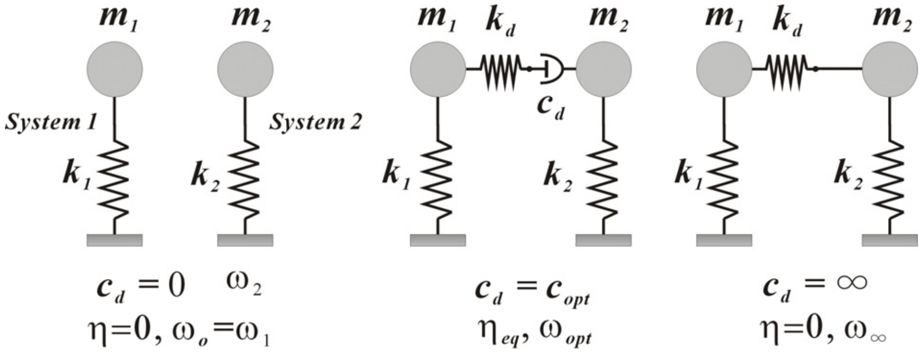


Figure 3. Optimum Damping Factor for 2-Mass System (System 1 is considered.)

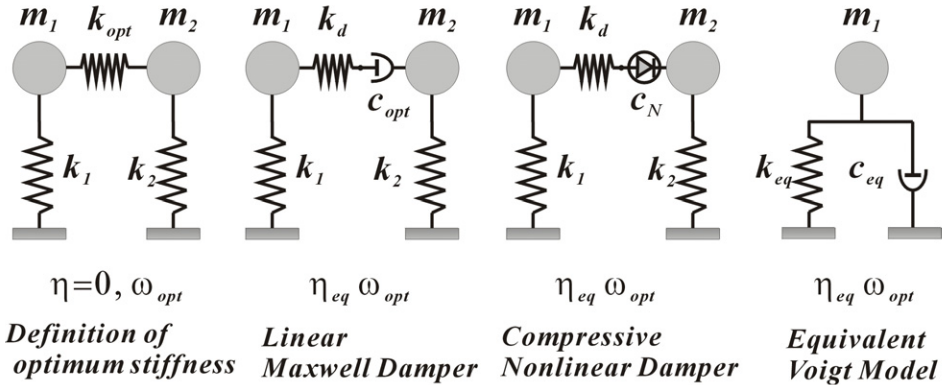


Figure 4. Linear Optimum / Nonlinear Optimum / Equivalent Voigt Model

Table 1. Parameters of Linear Connection Damper and Compressive Damper

System 1	$\boldsymbol{\omega}_1 = \boldsymbol{\omega}_o = 25.2$ rad/sec; $\boldsymbol{k}_1 = 3000$ KN/mm; $\boldsymbol{m}_1 = 4.7 \times 10^6$ kg
System 2	$\boldsymbol{\omega}_2 = 70.0$ rad/sec; $\boldsymbol{k}_2 = 3000$ KN/mm; $\boldsymbol{m}_2 = 6.0 \times 10^5$ kg
Damper parameters	$\boldsymbol{k}_d = 800$ KN/mm; $\boldsymbol{\omega}_\infty = 28.2$rad/s; $\boldsymbol{\omega}_{opt}$. $= 26.7$ rad/s; $\boldsymbol{k}_{opt} =$
Linear Damper	$\boldsymbol{c}_{opt} = 32.0$ KN sec/mm; $\eta_{eq} = 0.055$
Compressive Damper	$\boldsymbol{c}_N = 60$ KN sec/mm (For compression only.); $\boldsymbol{k}_d = 800$ KN/mm

Table 2. Basic Dynamic Properties of Gymnasium and Office Building

Gymnasium Properties (Preliminary Study)	4th FL. 104.9m^2, 3rd FL. 1732.9 m^2 2nd FL. 2725.8m^2, 1st FL. 2633.3 m^2	Effective mass at 3rd FL. $\boldsymbol{m}_1 = 4.7 \times 10^6$ kg Frequency $\omega_1 = 25.2$ rad/sec
Office Properties (Preliminary Study)	3rd FL. 430.9 m^2, 2nd FL. 518.3 m^2 1st FL. 518.3 m^2	Effective mass at 3rd FL. $\boldsymbol{m}_2 = 6.0 \times 10^5$ kg Frequency $\omega_2 = 70.0$ rad/sec
Damper Specification	Damper stiffness 200KN/mm per one damper. Damping coefficient 15 KN sec/mm per one damper.	

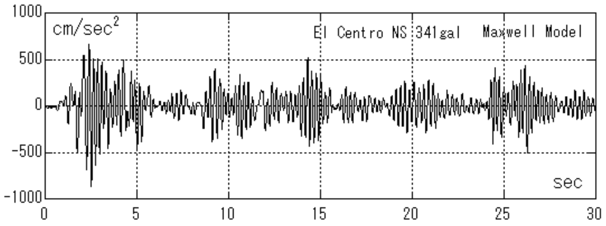


Figure 5. Linear Maxwell Damper

Photo 1. Damper Installation (3rd FL)

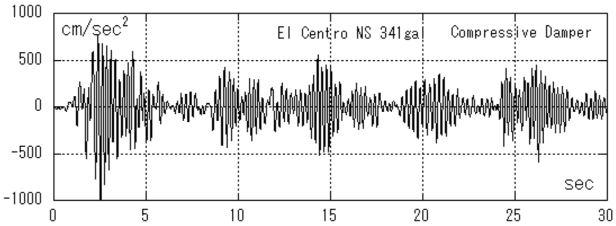


Figure 6.Compressive Nonlinear Damper

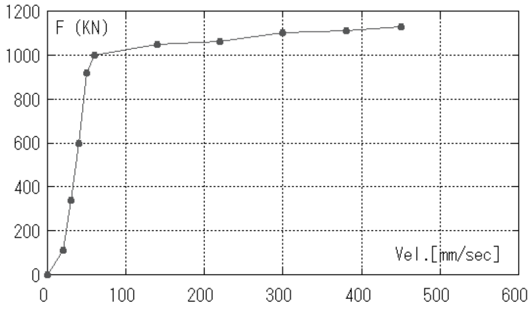


Figure 7.Test Results of Damper Coefficient

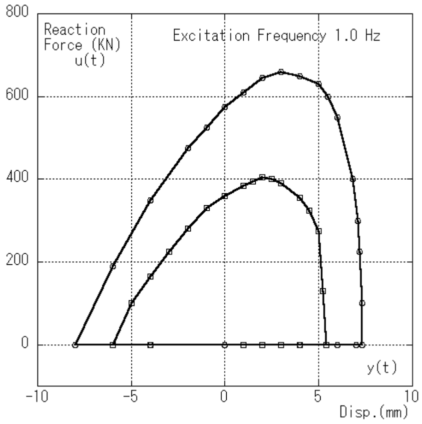
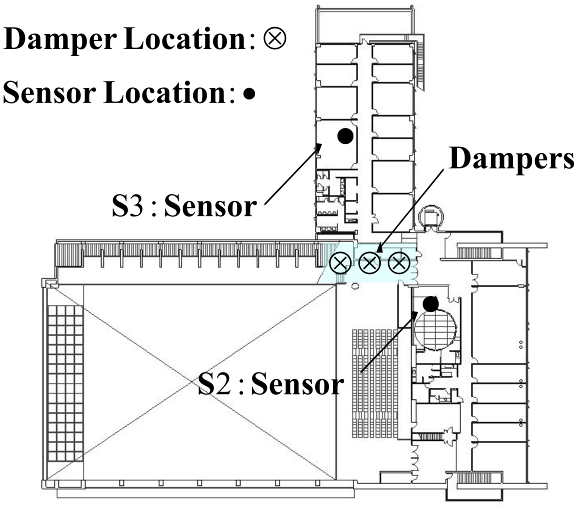
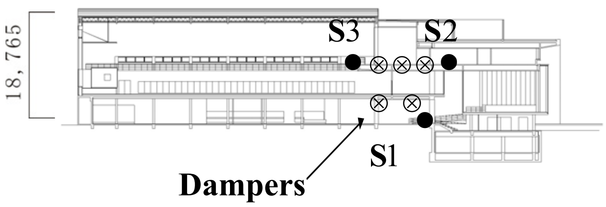


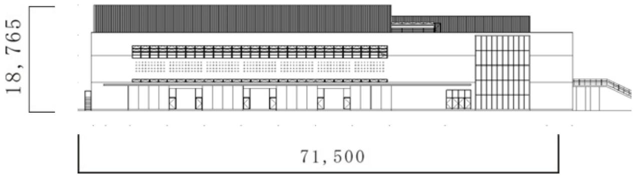
Figure 8. Cyclic Loading Test Results



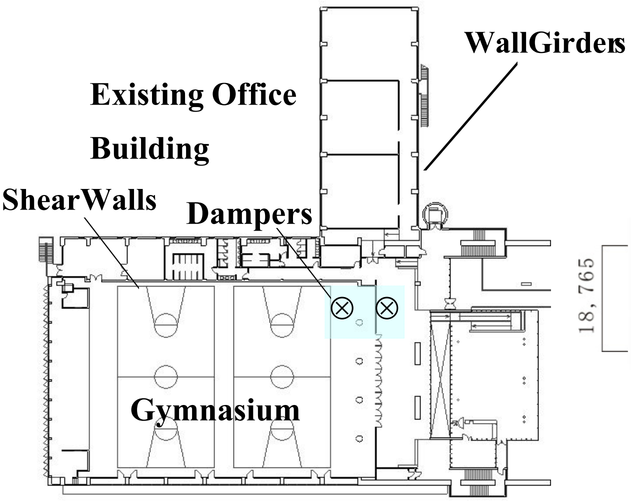
3rd Floor Plan



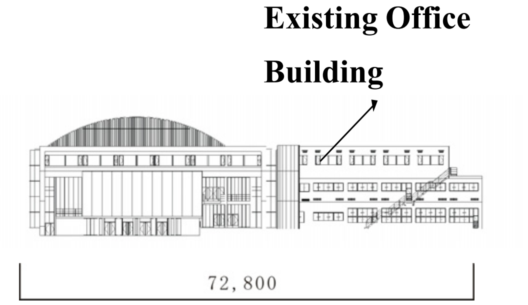
North-South Section



East Side Elevation



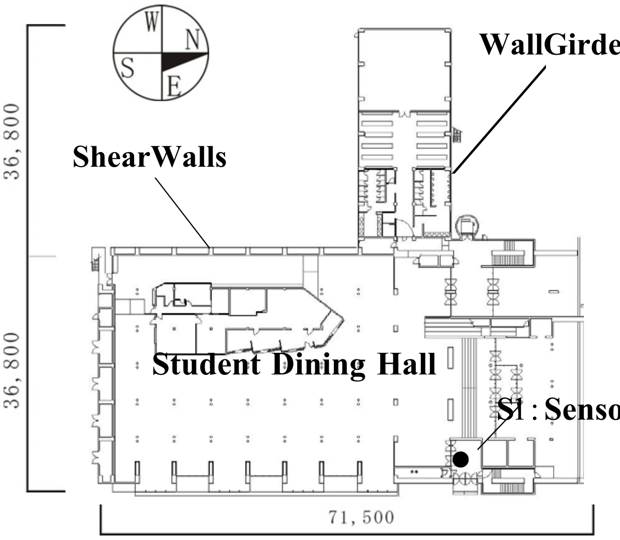
2nd Floor Plan



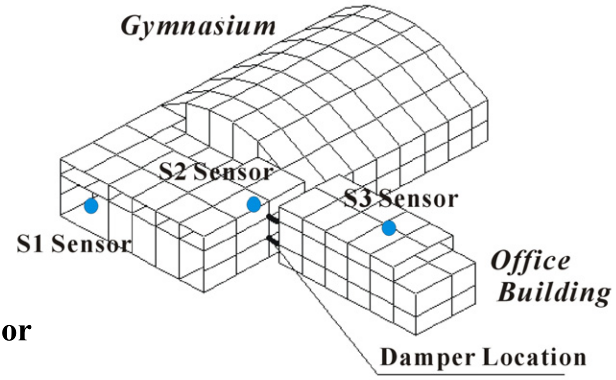
North Side Elevation

(Entrance Side View)

unit: [mm]



1st Floor Plan



FEM Model for Eigen Value Analysis

Skeleton View of the Gymnasium Frames

Figure 9. Sensor Locations and Damper Locations

DATA ACQUISITION SYSTEM

The purpose of the structure health monitoring that the author adopted for this project is to evaluate the performance of building structures with compressive dampers. Special attention is paid to non-linearity of the damping devices, because preliminary study showed that local non-linearity would disappear naturally but change the global dynamics in an average sense. It is extremely difficult even impossible to identify the mathematical model that could explain cause and effect, but it would be much easier to create a mathematical model which would explain the observed phenomena. Both of them have clearly different objectives and purposes. In this project, the author started observing the earthquake response dynamics of the structure to create a model to explain the phenomena not the cause-and-effect. The local area network sensor system is shown in Figure 11. It is composed of two accelerometers, 16-bit A/D converter with data logger PC, and another PC that works as a gateway computer with global IP address. There are three Local Area Network sensor systems (LAN) working individually so that none of them are synchronized and each one of them starts data acquisition according to its own trigger level (See S1, S2 and S3 in Figure 9.). There is a remote PC that is connected to each LAN by way of Internet (See Figure 10.). It works as a control center for down loading the data from each LAN.

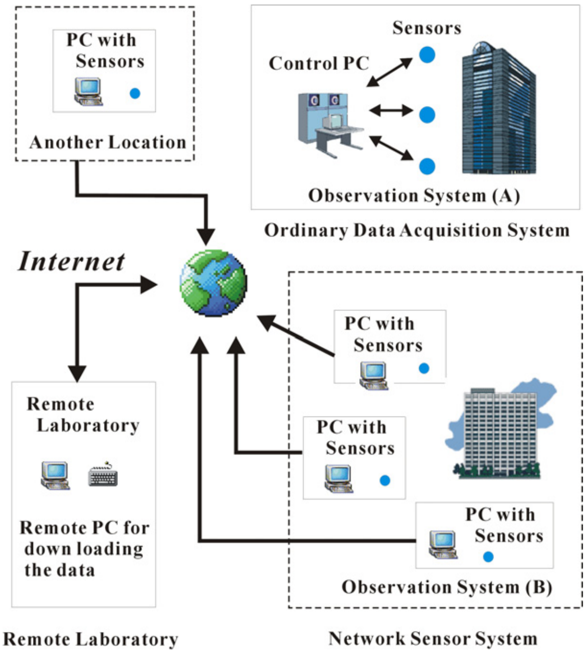


Figure 10. Global Network Sensor System

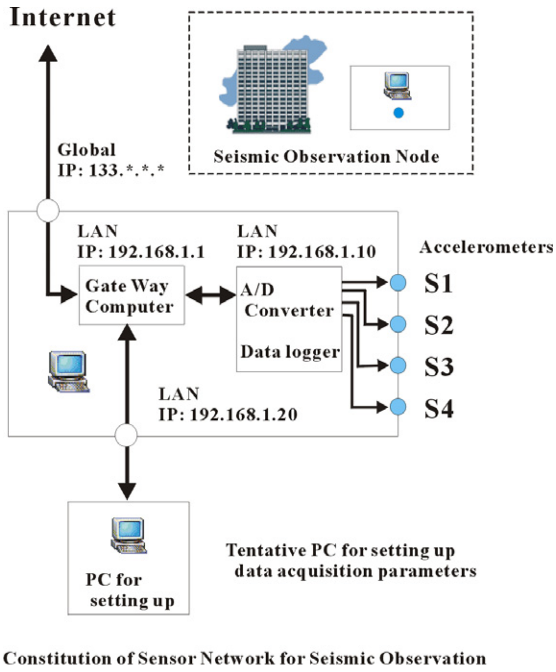


Figure 11. Local Network Sensor System

EARTHQUAKE RECORD OF 23 JULY AND 16 AUGUST IN 2005

There have been two noticeable events since the author's laboratory started observation using the network sensors. One of them occurred on 23 July 2005, whose epicenter is located about 50km east of Tokyo, and recorded magnitude 6.0 and intensity 5 according to JMA scale. The other one occurred about 300km away from Tokyo on 16 August 2005 with magnitude 7.2 and intensity 4. The observed acceleration data on the ground floor are shown in Figure 16, and 17, respectively. The acquired response acceleration histories at 3rd floor are shown in Figure 12 and 13, respectively. There are also shown transfer functions of 3rd floor from ground floor for each event. Even though the intensity levels are different, there is noticed little difference between the two transfer functions (See Figure 18.). Using the observed ground data and a simple Voigt Model shown in Figure 19, we can simulate the 3rd floor acceleration responses shown in Figure 14 and 15. As is mentioned previously, this mathematical model is created to explain the phenomena, or equivalently there is about 6% damping augmentation achieved and 1st modal frequency is about 4.25Hz. In spite of the damper's non-linearity, the global dynamics can be simulated in a linear model. Judging from the data, we could safely believe this supposition and use this simple evaluation method to estimate the damper performance for more complex building structures.

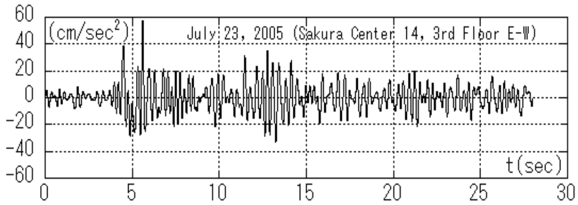


Figure 12. Observed Acc. on the 3rd FL

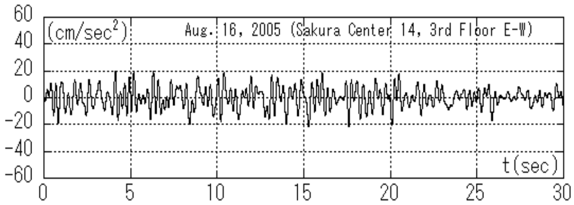


Figure 13. Observed Acc. on the 3rd FL

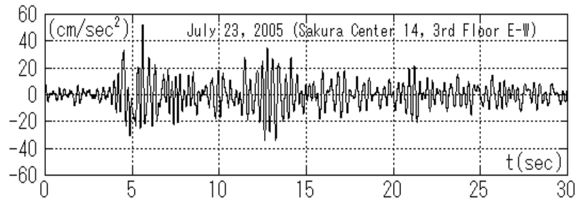


Figure 14. Simulated Acc. on the 3rd FL

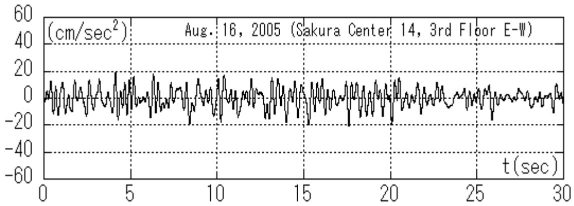


Figure 15. Simulated Acc. on the 3rd FL

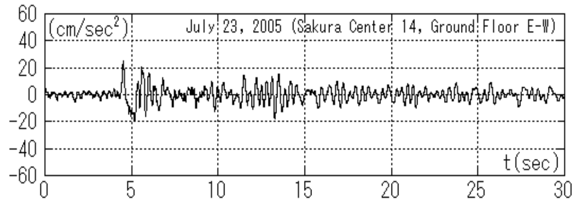


Figure 16. Observed Acc. on the 1st FL
Data recorded on July 23, 2005 (E-W)

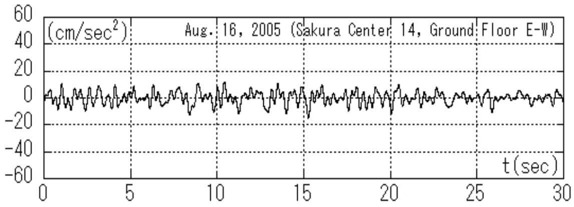
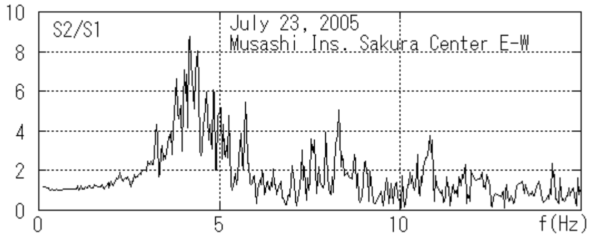
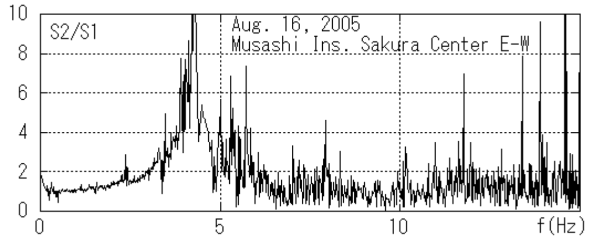


Figure 17. Observed Acc. on the1st FL
Data recorded on August 16, 2005 (E-W)



Data of July 23, 2005



Data of August 16, 2005

Figure 18. Transfer Function (E-W direction) of 3rd FL(S2)/Ground FL(S1)

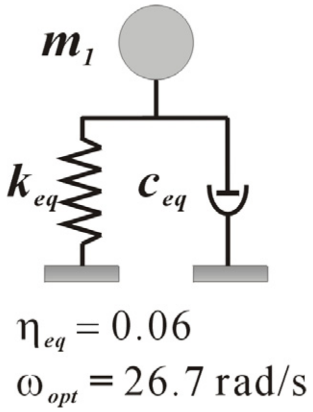


Figure 19. The Equivalent Voigt Model for Evaluating the Damping Performance

CONCLUSIONS

The performance of compressive dampers installed in a building structure is studied by acceleration data that were obtained by using network sensors connected each other by way of internet. The expected damping augmentation is certainly observed and verified by comparing the analytical simulation and the response acceleration record.

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