PARTIALLY ISOLATED STRUCTURE DYNAMICS UNDER RANDOM EXCITATION

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Abstract

This paper reports the damping augmentation technique of a building structure by implementing damping devices in such a manner that they work just like a mixer for heterodyne signal processing for a receiver. The previous studies by the authors clarified how the structure dynamics with damping devices are evaluated by means of the third order differential equation instead of the second order ordinary differential equation. The example configuration of a structure frame with damping devices along with laminated rubber bearings has been studied both analytically and experimentally. The variation of the damping coefficient shifts the frequency of the structure into the average of the two extreme cases of the structure dynamics. The natural frequency of the target structure is changed from the original structure dynamics as the damping coefficient varies from zero to infinity. The steel structure frame with nonlinear dampers is designed and fabricated for a shaking table test, which is scheduled in August, 2018. The paper will report some of the on-going results from the shaking table tests as well.

Introduction

Accumulation of the structural health monitoring data from the building frames with damping devices for the last decade in Japan triggered a crucial discussion about the performance evaluation of dampers in case of large earthquake events. Neither oil damper nor friction damper was reported to have worked well as was expected from the numerical calculation in the design phase of many projects. The author wrote a paper that explained the reason why the damping devices worked well only in calculation but seldom in application in 2004. The real dynamics of the structure system is so complicated that we could not properly express it in the second order differential equation. The third order differential equation is necessary to represent the structure dynamics in the real world. The author also demonstrated the numerical calculation based on the feedback model in the same paper which explained the physical reason why the conventional damping devices showed small performance. In addition to the theoretical study, the author proposed an innovative structure system that is the main theme of this paper. The damping devices worked together with laminated rubber bearings inside of the rigid frame under ground motion. This frame system is referred to the partial isolation in this paper. The author reports the design phase of the specimen, which is 4-story-high steel frame in *Figure 1 and Figure 2*, and also shows some of the numerical results from the proposed mathematical model based on the feedback theory.

Review of the Previous Study

The author explained the reason why damping performance is far less than expected from the numerical estimation based on the second order differential equation in 2004. The author extended the method of creating the feedback model into nonlinear version. The precise modeling of the damper dynamics clarifies why and how performance loss takes place in the real system. In fact, we could not achieve damping augmentation unless we successfully increased the natural frequency as well. Based on the second order differential equation, you can increase the damping factor independently from the natural frequency, which never happens in the real structure dynamics. Installation of damping devices into a building structure modifies both the damping factor and the natural frequency at the same time. If you would expect 5% damping factor from the target structure, you should increase its stiffness more than 20% as compared with the original structure dynamics. Under ordinary circumstances it would be impossible to achieve such a large modification of stiffness. It is true that damping augmentation is a solution for seismic protection, but the conventional method of damper installation does not work well. The author invented a new formation of damping devices along with laminated rubber bearings for the purpose of seismic protection. The research activity was supported by JST (Japan Science and Technology Agency) Grant #23560681 under the title of "The partially isolated structure dynamics" from 2011 to 2013. The author has also received a financial support from *Tokyu Construction Co., Ltd*. for the ongoing shaking table tests to verify the theoretical estimation and to demonstrate the performance of *Partial Isolation*.

Specimen of Partial Isolation

The author shows the process of specimen frame design for the purpose of explaining the concept of partial isolation of the structure. As compared with the conventional damping device installation into rigid frame, the dampers are arranged with laminated rubber bearings shown in *Figure 2*. The lateral force caused by the ground motion is transferred to the oil dampers while the vertical force is transmitted to laminated rubber bearings. Their stiffness in the vertical direction is roughly 1,000 times as large as their lateral stiffness. The damping device is a compressive buffer that generates compressive reaction only. In other words, there is no tensile reaction forces applied to the specimen frame. There are eight pieces of laminated rubber bearings, and each one of them is placed at every corner of the ground floor as well as the second floor of the specimen frame. Installation of the damper along with the laminated rubber bearing is also shown in *Photo 1* and the side view of the specimen in Y-direction is shown in *Photo 2*.

The author selected the same cross sectional shape for the beams and columns of the specimen. Every member has the same channel section that is 125 mm high and 35 mm wide, its flange is 8.0 mm thick. The yielding stress of the material is more than 240 N/mm^2 for all the members. High tension bolts (F10T, M16) are used for every connection between columns and girders. Additional solid steel weights are placed at the top, fourth, and third floor level. Each weight is 500kg and there are six of them placed at each floor. The total weight of the steel columns and beams is approximately 4,500 kg in all. It is supposed to be distributed evenly in the vertical direction for the simulation model.

The unique feature of the specimen is the combination of the damper and rubber bearing, which drastically improves the damping performance of the structure. We conducted an eigenvalue simulation in each lateral direction for the specimen without dampers. According to this real eigenvalue analysis, the first modal frequency is 4.82Hz in the X-axis, and 4.69Hz in the Y-axis. Then the dampers are replaced by simple bracing with equivalent axial stiffness. We did the same eigenvalue analysis that estimates the frequency 6.25Hz in the X-axis and 5.99Hz in the Y-axis. The equivalent axial stiffness of the dampers is supposed to be more than 17.5 KN/mm, which is the result from the ambient vibration test after the fabrication of the specimen. There is an estimation formula cited from the past in 2004, which clarified the relation between the damping performance and the stiffness augmentation. This formula is derived from the feedback control modeling under stationary random excitation process. The author published an English version of the original paper in 2010. Please refer to the past papers in the list for the derivation of the formula. The expected damping performance is shown in Table 1, where the first modal frequency change from the eigenvalue analysis is substituted into *Equation 2* in the following section.

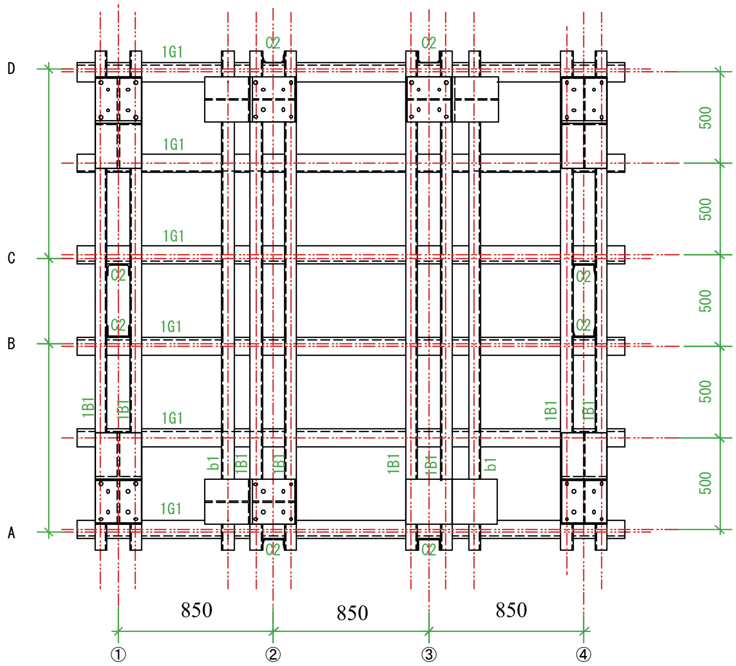


Figure 1. The ground floor plan of the specimen frame

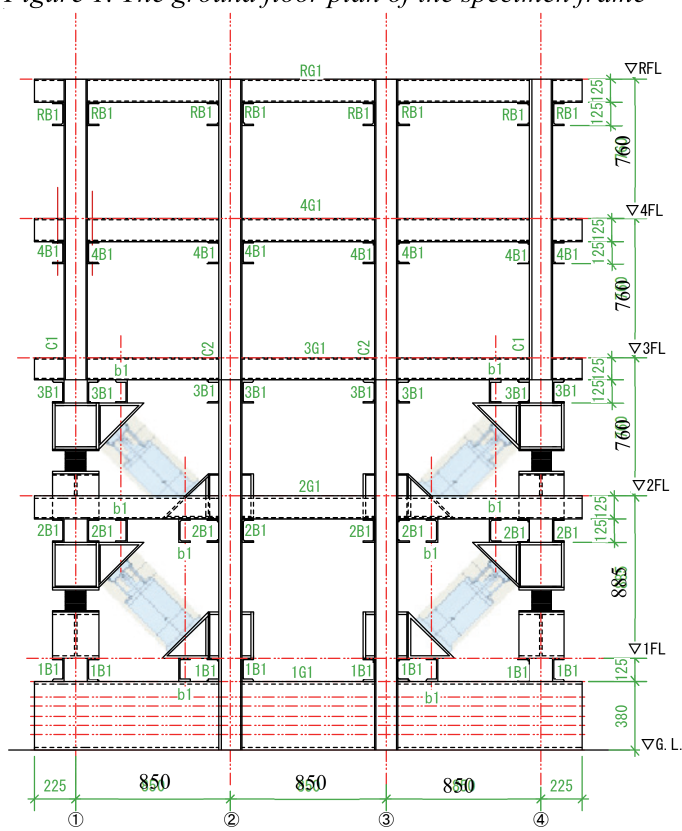


Figure 2. The Axis-A of the specimen frame

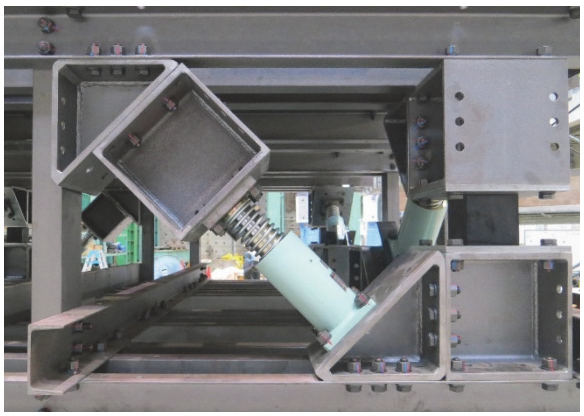


Photo 1. Installation of oil damper and laminated rubber bearing

Photo 2. The Axis-1 of the specimen frame

Table 1. Damping Performance Expected from Eigenvalue Analysis

	Original frame	*Optimum frame*	*Infinite frame*
X direction	$C_d = 0.0$	$C_{opt} = 0.50$ *KN sec/mm*	$C_d = \infty$
	ω_o =30.3 r/sec	ω_{opt} =35.1 r/sec	ω_∞ = 39.3 r/sec
	----------	$\eta_{opt} = 0.110$	$\beta = 0.682$
Y direction	$C_d = 0.0$	$C_{opt} = 0.50$ *KN sec/mm*	$C_d = \infty$
	ω_o = 29.5 r/sec	ω_{opt} =33.8 r/sec	ω_∞ = 37.6 r/sec
	----------	$\eta_{opt} = 0.105$	$\beta = 0.625$

Performance Evaluation by Eigenvalue Analysis

Damping augmentation is precisely evaluated by the eigenvalue analysis according to *Equation 2* that is referred to the paper in 2004. When the damping coefficient c_d of the frame system is zero, the first modal angular frequency of the system is ω_o. As we can recognize the difference between the system parameters shown in *Figure 3*, the left hand side picture corresponds to ω_o. As the damping coefficient c_d increases, the damping factor η becomes large and comes to the maximum value η_{opt}, which corresponds to the middle of *Figure 3*, whose damping performance is evaluated by *Equation 2*. As the damping coefficient goes to infinity, the damping performance comes down and converges to zero and the natural angular frequency converges to ω_∞. You can easily find the optimum coefficient of the dampers by comparing the angular frequencies changing from the original model to the infinity model as in *Figure 3*.

$$\text{Stiffness augmentation :}\quad \beta = \frac{{\omega_\infty}^2 - {\omega_o}^2}{{\omega_o}^2} \tag{1}$$

$$\text{Upper limit of the damping factor :}\quad \eta_{opt} = \frac{\beta}{2+\beta}\sqrt{\frac{1}{2(2+\beta)}} \tag{2}$$

$$\text{Frequency of the optimum system :}\quad \omega_{opt} = \sqrt{\frac{{\omega_\infty}^2 + {\omega_o}^2}{2}} \tag{3}$$

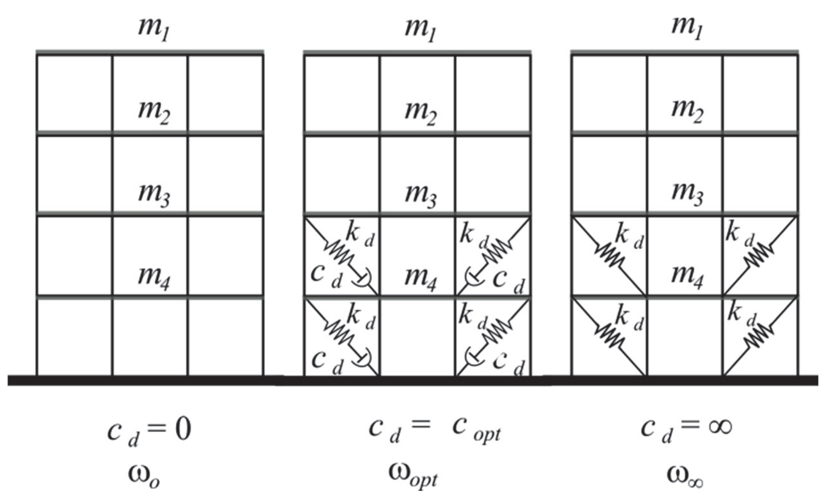


Figure 3. Performance evaluation by means of eigenvalue analysis

Feedback Control Model

The author referred to the paper published in 2004, while creating the dynamic model of the specimen structure. The response displacement of each floor point is denoted by *x1, x2, x3*, and *x4* while lateral forces acting on the floors are represented by *f1, f2, f3,* and *f4*, respectively. The reactions generated by the dampers are denoted by *u1* and *u2*, while their strokes are referred to *y1* and *y2*. These notations are shown in *Figure 3*, where the *Axis-A* of the specimen can be represented by the dynamic model that has the block diagram shown in *Figure 5,* where there are no dampers placed in the frame structure. *Equation 4* specifies the quantities of those notations as the result of finite element analysis.

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ y_1 \\ y_2 \end{bmatrix} = \begin{pmatrix} 0.361 & 0.325 & 0.284 & 0.217 & 0.0470 & 0.1600 \\ 0.325 & 0.316 & 0.282 & 0.216 & 0.0470 & 0.1590 \\ 0.284 & 0.282 & 0.272 & 0.214 & 0.0420 & 0.1580 \\ 0.217 & 0.216 & 0.214 & 0.187 & 0.0190 & 0.1320 \\ 0.047 & 0.047 & 0.042 & 0.019 & 0.0188 & 0.0147 \\ 0.160 & 0.159 & 0.158 & 0.132 & 0.0147 & 00992 \end{pmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ u_1 \\ u_2 \end{bmatrix} \tag{4}$$

[*mm/KN*]

The mass of each floor is denoted by *m1, m2, m3* and *m4* as is indicated in *Figure 4.* They are estimated and given by *Equation* 5, which represents a quarter of the whole frame system. Because there are four dampers placed in the same direction, and *u1* and *u2* represent each one of those damper reaction forces. This assumption means that each damper reaction comes from the motion of a quarter of the total weight.

$$\begin{bmatrix} m_1 \\ m_2 \\ m_3 \\ m_4 \end{bmatrix} = \begin{pmatrix} 875 \\ 1063 \\ 1063 \\ 313 \end{pmatrix} \qquad (5)$$

$[kg]$

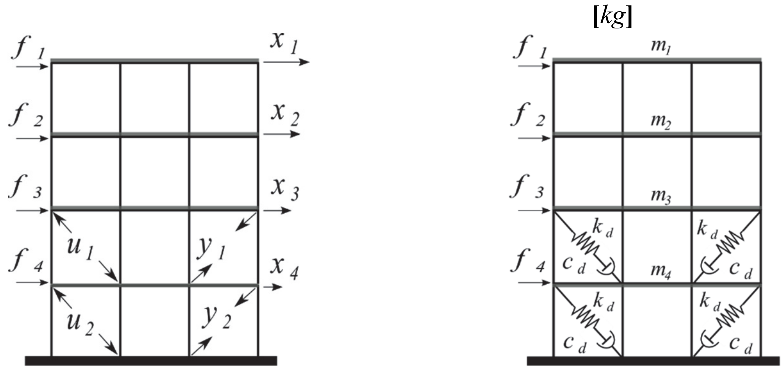


Figure 4. Interaction between Frame Deformation and Damper Reaction

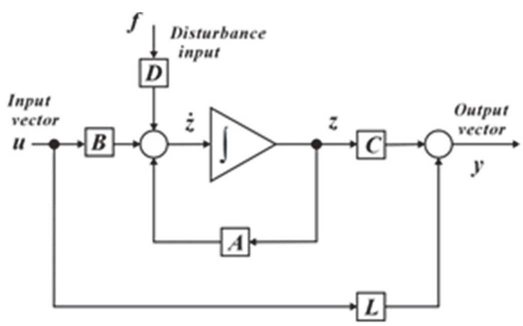


Figure 5. Block diagram of the frame dynamics without dampers

Damper Properties

The oil dampers are represented by the cascade connection of the axial stiffness and damping coefficient in *Figure 6*. The mathematical model that describes the illustration in *Figure 6* has the identical block diagram shown in *Figure 7.* The mathematical expression of the dampers is given by *Equation 6*. The axial stiffness of one damper is 17.5 *KN/mm*, which is the result of finite element analysis and the observation of the ambient vibration of the specimen frame. The optimum frequency exists in the middle of the two extreme cases ω_o and ω_∞ , the optimum damping coefficient c_{opt} is consistent with the optimum frequency so that you can find the optimum value by changing it from zero to infinity. Numerical calculation is demonstrated in the last chapter of the paper.

$$\begin{cases} \dot{v} + \omega_d v = \omega_d y \\ u = k_n v - k_n y \end{cases} \quad \text{where} \quad \omega_d = \frac{k_n}{c_d} \qquad (6)$$

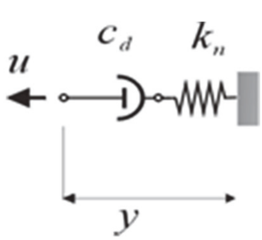


Figure 6. The oil damper model

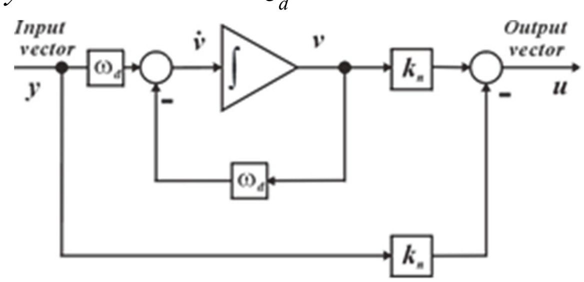
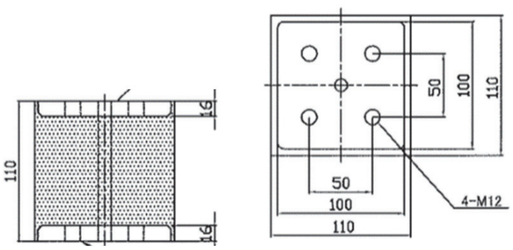


Figure 7. Block diagram of the oil dampers

Laminated Rubber Specification

The configuration of the rubber bearing is shown in *Figure 8,* where the thickness of the rubbers and the steel plates are indicated and the shear modulus of the rubber materials is roughly 0.6 N/mm^2. The static loading test was conducted to identify the lateral stiffness of the bearing. The vertical stiffness is approximately 700 *KN/mm*, which was also obtained from the loading test conducted by the manufacture. The eight pieces of the rubber bearings are tested all together for a cyclic loading test, whose result is shown in *Figure 9*. The lateral stiffness of one bearing is roughly 0.5*KN/mm.*



Side view Bottom view

Steel plate is 4.5 mm and rubber is 1.0 mm.

Figure 8. The laminated rubber bearing

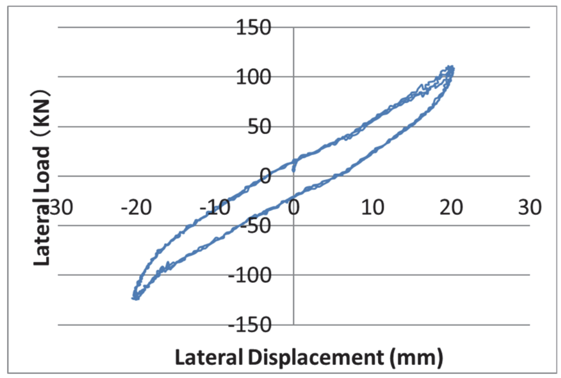


Figure 9. Lateral loading test for rubber bearings

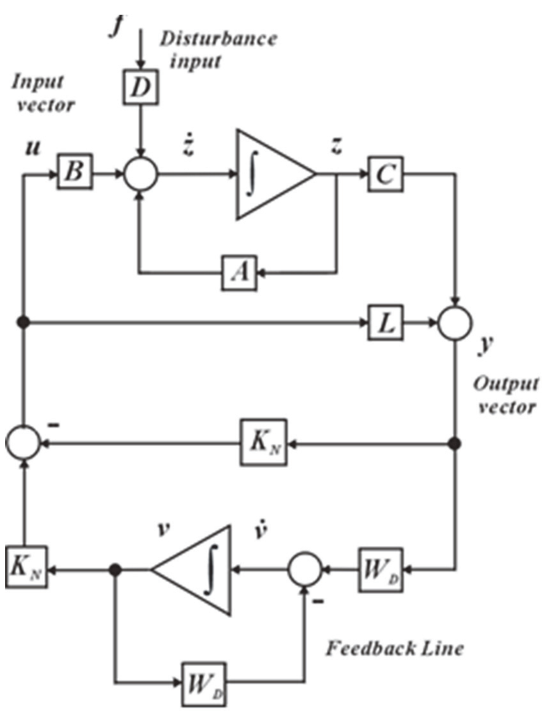


Figure 10. Block diagram of the total system

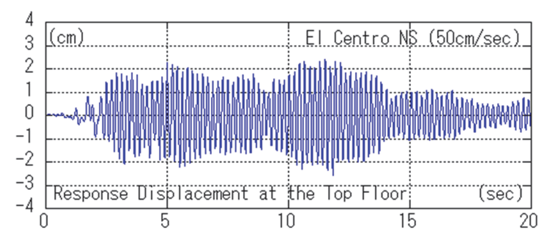


Figure 11. With damper coefficient 0.01KNsec/mm

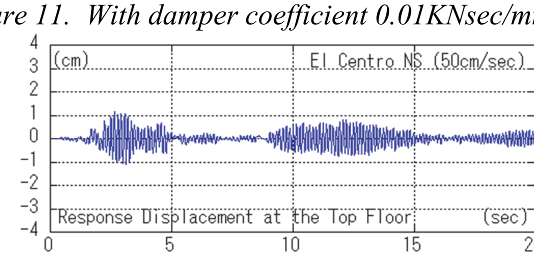


Figure 12. With damper coefficient 0.50KNsec/mm

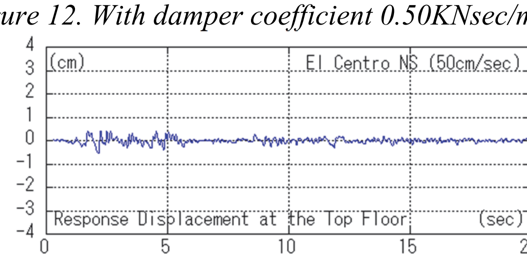


Figure 13. With damper coefficient of 100KNsec/mm

Numerical Calculation

Our goal is the reduction of response deformation of the specimen frame under large earthquakes by means of damping augmentation of the system dynamics. There are three studies conducted to identify the optimum damping coefficients to maximize damper performance. The damping coefficient is changed from virtually zero to infinity, while they are subjected to the same ground motion with the same intensity. As the damping coefficient increases from zero to optimum, the response displacement at the top floor of the specimen frame gradually decreases. We found the optimum damping coefficient is approximately 0.50*KNsec/mm* for each damper, and the time history of the displacement response is shown in *Figure 12*. The excitation data used for this simulation is El Centro NS whose maximum velocity is normalized at 50 cm/sec. The result shown in Table 1, which is eigenvalue analysis, is compatible with the dynamic simulation in the time domain.

Conclusion

The innovative structure system composed of damping devices and laminated rubber bearings is briefly reported in this paper. The currently going shaking table test and the specimen frame design is also reported.

References

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