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Shaking table tests of bending-shear vibration model with magneto-rheological fluid damper

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ABSTRACT

This paper discusses seismic response control of high-rise building utilizing magneto-rheological fluid damper (MR damper). For high-rise building, bending displacement of whole system due to column elongation cannot be neglected. To simulate the behavior of a high-rise building during an earthquake, one-mass system consisting of a cantilever column and a spring to limit the top rotation has been prepared for this feasible study. A MR damper has been set into the vertical direction to control rotational motions of the system. The MR damper can change damping force according to exciting current. ON/OFF control method for input current is investigated in this study. Through shaking table tests, it is cleared that proposed control method can effectively reduce the acceleration response of high-rise system.

1. INTRODUCTION

For many high-rise building, vibration control methods such as TMD(Tuned Mass Damper), AMD (Active Mass Damper) and HMD (Hybrid Mass Damper) that uses devices setup on top of buildings are already employed. Most of those systems are expected to work for habitability in case of winds and in case of aftershocks. These control systems designed for seismic response are still few. During earthquake, high-rise buildings show not only shear deflection which occurs in inter-story must be taken into account, also the flexural deformation which is caused by column elongation must be considered. Thus, some proposals of energy dissipation technique based on a flexural deformation are suggested. Y.Shinozaki (2008) developed response control system with intensive energy absorption devices. In this technique, vibration control system is divided into bearing material for vertical response and energy dissipation part. Most of all of the seismic response energy can be absorbed by energy dissipation device. Y.Omika (2004) proposed the flexural deformation response control system. A

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horizontal force caused by earthquake or winds is resisted by the core wall which is located at the center of the plan. The horizontal behavior excites the rotational motion of top beam. A viscous damper is set in vertical direction of top beam. The force of viscous damper is expected to reduce rotational response of top beam.

On the other hand, a semi-active control system, which controls structural characteristics according to vibration condition is proposed in a base isolation system and a vibration control system. A Magneto-rheological fluid (MR) damper is used as variable damper. MR damper can change its viscous characteristics by magnetizing. A exciting coil adopted in MR damper performs its viscous characteristics to change by exciting currents. Example of study on semi-active vibration control by MR damper installed in base-isolated layer has been reported. H.Kanno et al (2008) has studied semi-active control by MR damper, and suggested a simple control method due to response displacement of inter-story level of structure. The complex model as optimal control and robust control is difficult to adopt in buildings that shows non-linear characteristic. Independent dispersion system is desired at the point of view of fail-safe is needed. The simple control for reduction of response acceleration and its effectiveness of damper support members are already verified in those studies.

This paper proposed the semi-active control based on the flexible deformation of high-rise building. Bending shear model with one mass system that shows vibration characteristic of high-rise building is prepared for this paper. The scaled MR damper is set in vertical directions of this model. Shaking table tests are performed as a feasible study. ON/OFF control algorithm that switched by response velocity and displacement is adopted, and the reduction of response acceleration is discussed.

2. OUTLINES OF BENDING SHEAR MODEL

Bending shear model, which shows a behavior of bending vibration of a high-rise building is shown in Fig.1. A cantilever is a principal member for the model. A limit spring restricts rotational movement of the top of the model.

A configuration of bending shear model that produced in this study is shown in Fig.2. The height of the model is 687mm, and flexible length of cantilever element is 600mm. A flat steel slab installed on top position is 300mm wide and 500mm long. The flat steel slab is regarded as a mass of 28.8kg. Both of the limit spring and the MR damper are installed in a vertical direction connecting by bearings. The supporting member of MR damper has 10mm thickness which is enough stiff compared with the limit spring. The cantilever is made of phosphor bronze, which size is 120mm wide and 5mm thick. The limit spring is made of steel which size is 30mm wide and 2.3mm thick. From material tests, modulus of longitudinal elasticity of the phosphor is 5.8×10^4N/mm^2, bending stiffness of limit spring is 11.0N/mm.

Fig.3 shows schematic of the MR damper, which has 0.2kN on capacity and 42mm stroke. Specifications of MR damper are shown in Table 1. As a hydraulic oil, MRF-132DG developed by Load Corporation is used. The flow path is designed by by-pass system, which separates magnetic choke from pressure chamber. The width of orifice is 3mm, length is 46mm. A detached exciting coil is attached around orifice.

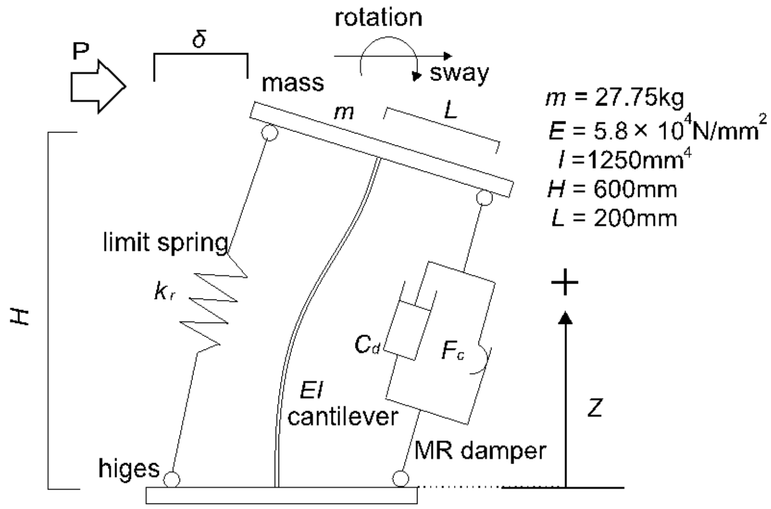


Fig. 1 schematic diagram of bending shear vibration system

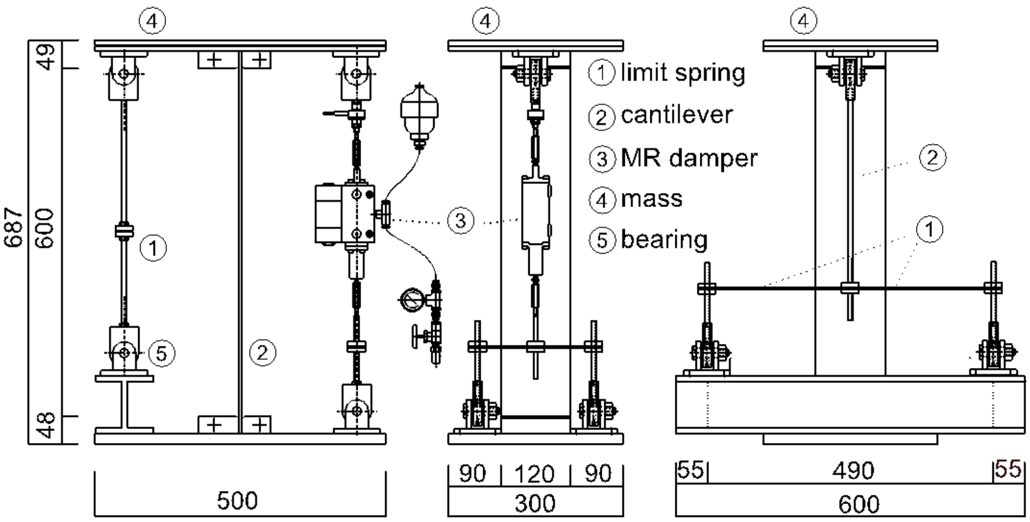


Fig. 2 configuration of tested bending shear vibration model with MR damper

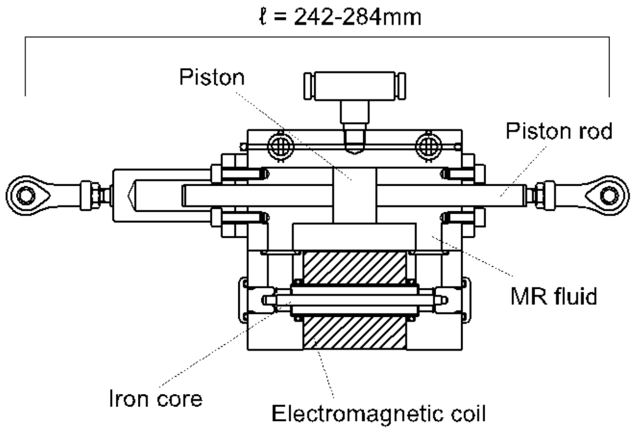


Fig. 3 schematic of 0.2kN MR damper

Table 1 specifications of the MR damper

Maximum force		0.2kN
Stroke		42mm（±21mm）
Cylinder bore		30mm
Piston rod dia.		14mm
Bypass orifice	Outer dia.	13mm
	Inner dia.	7mm
	Orifice width	3mm
	Orifice length	46mm
MR fluid		MRF-132
Electromagnet	Coil	Φ0.35/2PEW 860T
	Resistance	13Ω

Through a performance tests, relationships between damper force and displacement when inputted velocity of 10cm/s sinusoidal waves are shown in Fig.4, and relationships between damper force and velocity when inputted triangle waves which have 10mm amplitude(5steps from 1cm/s to 10cm/s of peak velocity) are shown in Fig.5. Variable damper force becomes 2.5 times larger than the force with free field when 1.0A constant currents are applied. When 2.0A constant currents are employed this force becomes 3.2 times longer than the force without magnetic field. Because the relationship between damper force and velocity shows almost linear, it suggests that MR damper has property of Bingham characteristics.

To examine numerical analysis of bending shear model, bottom of cantilever is $z = 0$ and an upper of vertical direction axis z is defined that positive as shown in Fig.1. The range is $0 \leq z \leq H$. An equation of moment when horizontal force P is acted to the model is given by

$$M(z) = P(H - z) - k_r L^2 \theta_T \quad (1)$$

A relationship between a horizontal force P and a horizontal displacement δ is given by

$$P = \frac{12EI}{PH^3}\left(\frac{\gamma + 1}{\gamma + 4}\right)\delta \quad (2)$$

Where E is modulus of longitudinal elasticity of cantilever, I is second moment of area. γ is the ratio bending stiffness of limit spring to cantilever as given by

$$\gamma = \frac{k_r L^2 H}{EI} \quad (3)$$

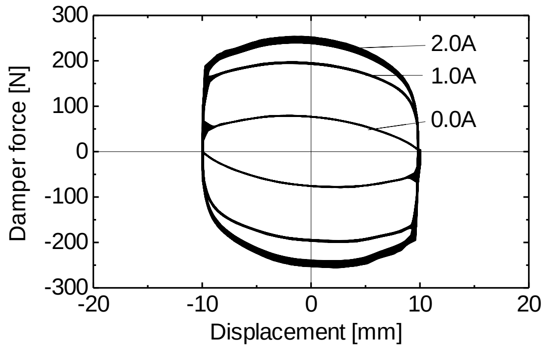


Fig. 4 displacement – damper force hysteresis loop

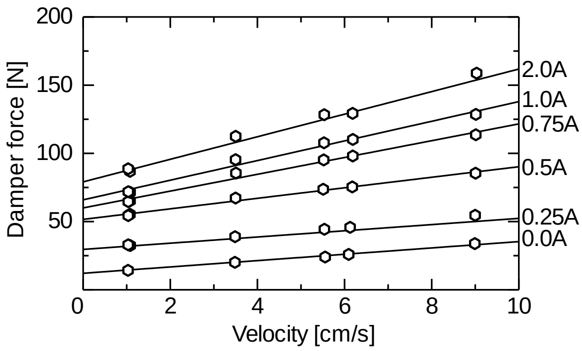


Fig. 5 velocity – damper force relationship

A Bingham models which is parallel connection of a friction element and a viscous element is regarded as numerical model which simulates MR damper characteristic. Relationship between friction force (F_c) and exciting currents (I_c) is shown in Fig.6. Relationship between viscous coefficient (C_d) and I_c is shown in Fig.7. Those relationships as a function of exciting currents are modeled by

$$F_c = 79.7(1 - e^{-I_c}) + 14.7 \tag{4}$$

$$C_d = 8.2(1 - e^{-I_c}) + 1.6 \tag{5}$$

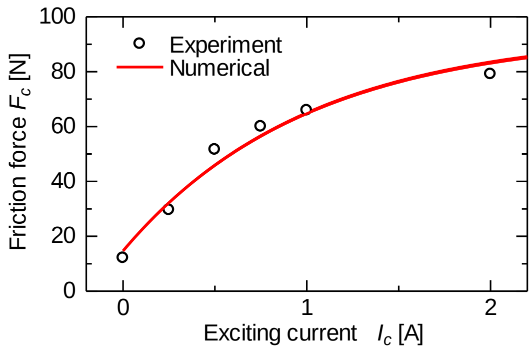


Fig. 6 exciting currents – friction force F_c relationship

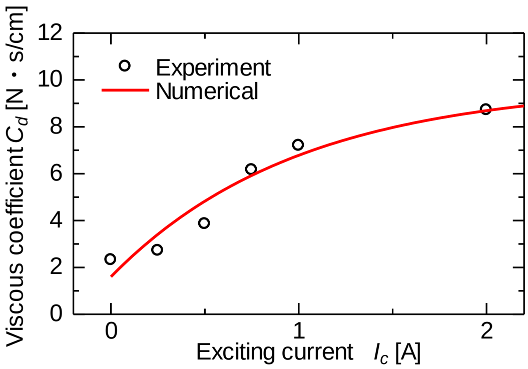


Fig. 7 exciting currents – viscous coefficient C_d relationship

A transfer function obtained from inputted swept wave is examined to evaluate vibration characteristics. Acceleration amplitude of logarithmic swept wave is constant (30cm/s^2), and with a frequency range from 0.5Hz to 5.0Hz. A photograph of the model set up on a shaking table is shown in Fig.8. Transfer functions of the system without damper (w/o), with damper but without excitation current (free field) and damper with a constant excitation current of 2.0A are shown in Fig.9. Predominant frequencies of transfer functions are 1.45Hz (w/o), 1.52Hz (free field), and 2.52Hz (2.0A constant currents). These show that natural period of the system is shortened by the force of MR damper. Amplification ratio in the case of 2.0A inputted is larger than in the case of free field. During 2.0A excited, damping force of MR damper is too large for the bending shear model to occur bending deflection. Thus, MR damper limit top rotational motion, natural period of the vibration system is shorter than free field. Therefore, amplification ratio is larger than free field.

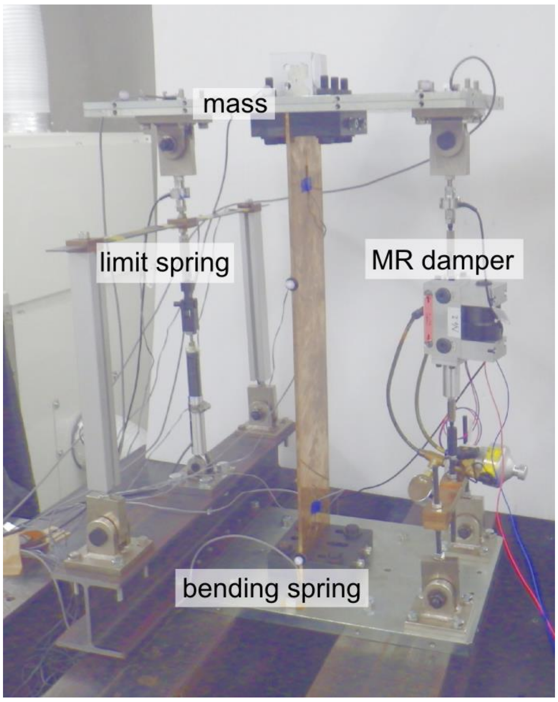


Fig. 8 general view of the bending shear model

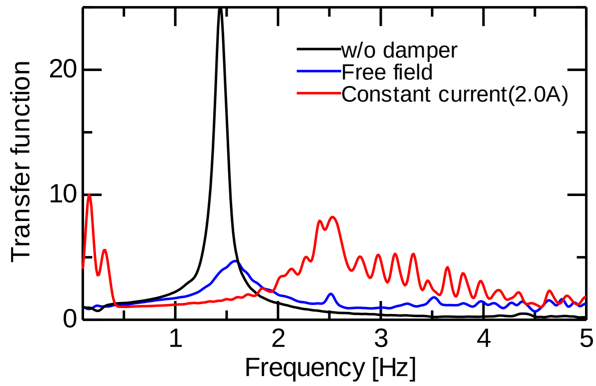


Fig. 9 transfer function of system by inputting swept sine wave

3. SEISMIC RESPONSE CONTROL EXPERIMENT

Through shaking table tests, seismic response reduction by the MR damper is examined. In ON/OFF control, exciting currents is switched free field (OFF) or 2.0A constant currents (ON) is adopted. The method of switching exciting currents is determined by response velocity and displacement. MR damper switched ON (2.0A) when the sign of response velocity and displacement are different. MR damper switched OFF when the sign of those are same. In the relationship between damper force and displacement as shown in Fig.10, exciting currents turned ON when the relationship is in 2nd and 4th quadrant, and turned OFF when the relationship is in 1st and 3rd quadrant. This control method is not cause of shortened natural period of the system and suppresses the increase of response acceleration.

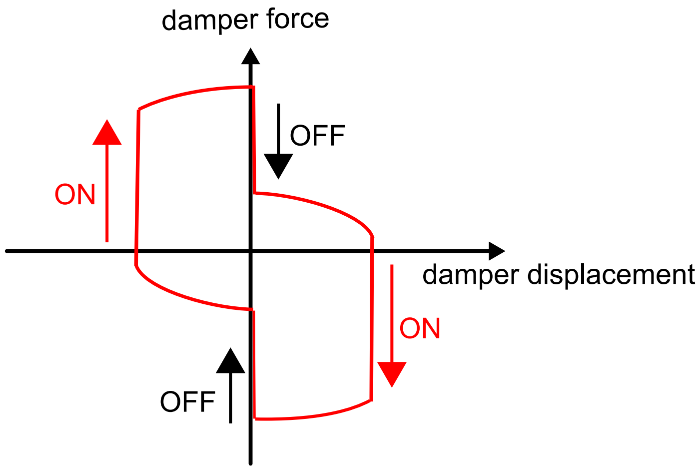


Fig. 10 designed hysteresis loop of MR damper
under proposed ON/OFF control

A diagram of control system is shown in Fig.11. Computer installed AD/DA board which is used for control scheme. A feedback signal of main structure is only horizontal displacement. Switching ON/OFF control is determined by sign of velocity get from time derivative of horizontal displacement. Control signal, which is used a voltage considering the electrical resistance of MR damper, is 7 times larger through the amplifier. Horizontal displacement is measured at sampling frequency of 1kHz, and the control is performed at 100Hz.

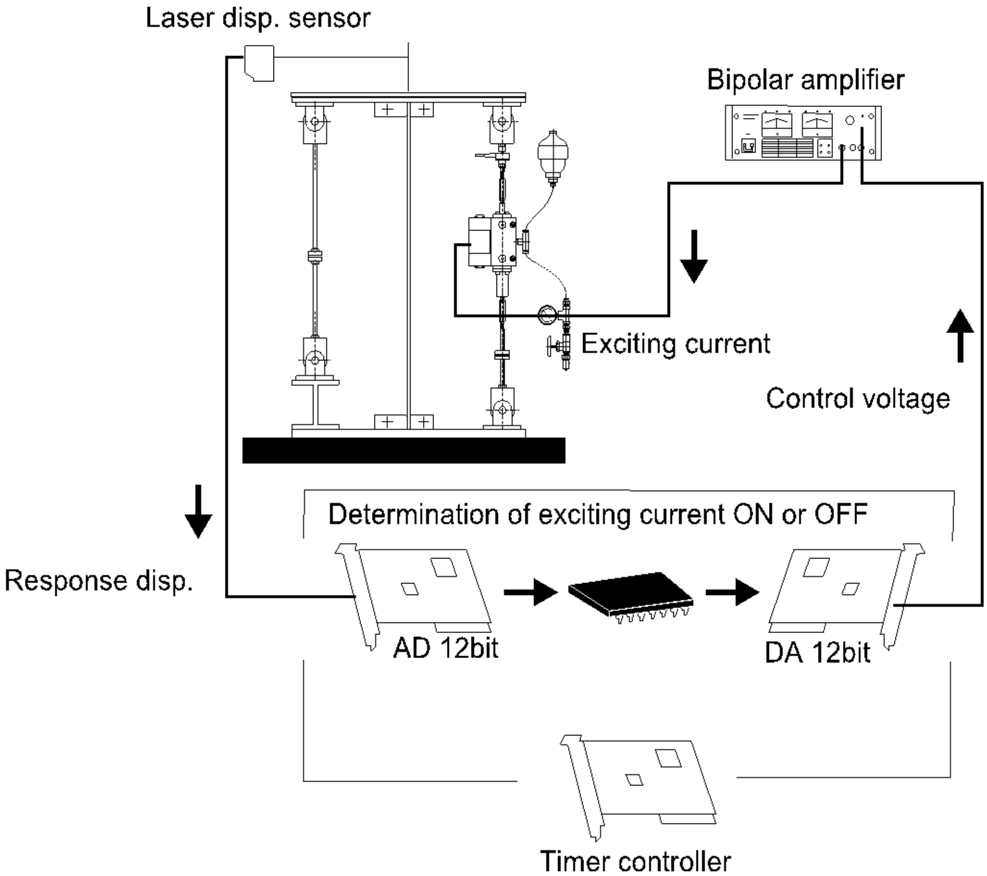
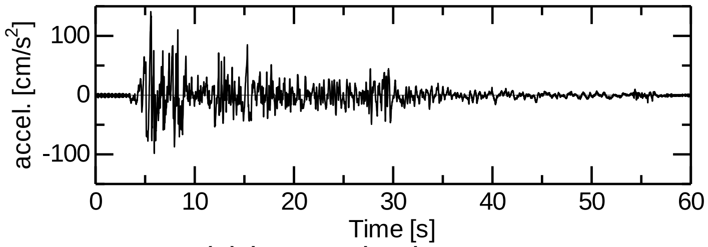


Fig. 11 schematic diagram of the control system

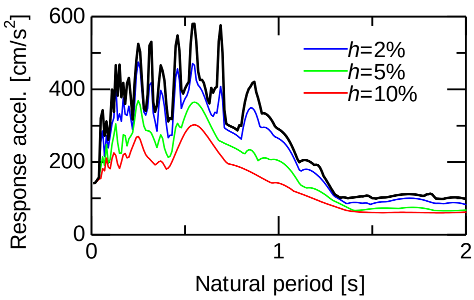
Input wave used in the shaking table tests is observed ground motion record of El Centro (1940) NS scaled 40% amplitude of original wave. Time history of acceleration and acceleration response spectrum are shown in Fig.12. High pass filter of 0.5Hz is used in order to adopt the actuator specifications of shaking table.

Seismic response of free field, 2.0A constant currents, and ON/OFF control is compared in shaking table tests. Time history of response acceleration is shown in Fig.13. Maximum and RMS values is shown in Table 2. ON/OFF control decreases the maximum response well around 6s. In the case of 2.0A constant currents, slightly larger response vibration continues under short period after the maximum response. On the other hand, the effect of damping is shown in early state after the maximum response in the case of ON/OFF control. As shown in Table 2, reduction of maximum displacement in ON/OFF control is slightly larger compared with 2.0A constant currents. However, it is confirmed that reduction of maximum acceleration is effective compared with 2.0A constant currents. It shows that ON/OFF control has high efficacy to reduce RMS values of response acceleration that mean average response during earthquake.

A reduction effectiveness of shear force is examined. In this paper, shear force is



(a) input seismic wave



(b) response spectrum

Fig. 12 input seismic wave and response spectrum

evaluated by using response strain, which acquired from strain gages set on flexible area of cantilever. Both of strain data of top and bottom are shown in Table 3 when bottom of cantilever strain reaches maximum value. It is speculated that ratio of flexural height is about 0.67 because strain ratio of top to bottom is about 2:1 under free field. On the other hand, the strain ratio in case of 2.0A constant currents is about 6:5. Therefore ratio of height of inflection point is 0.55 in this case. Deformation mode in the case of 2.0A exciting currents is different from free field. The strain ratio in ON/OFF control shows that the deformation mode under ON/OFF control becomes as same as the mode of free field. Its occurred by switching OFF when the sign of response displacement is turned across zero. When the strain difference of vertical end is attributed to shear force, of which free field is the largest among 3 cases because maximum response displacement is the largest. In the case of 2.0A constant currents, though maximum response displacement is smallest among these cases, the maximum strain is largest. It suggests that ON/OFF control can suppress the strain of cantilever and the shear force of main frame.

Table 2 maximum and RMS values of experimental results

	Maximum		RMS	
	Accel. (cm/s^2)	Disp. (mm)	Accel. (cm/s^2)	Disp. (mm)
Free field	332.5	28.6	35.0	3.2
Constant current	188.4	10.5	43.8	2.0
ON/OFF control	175.9	15.9	24.6	1.8

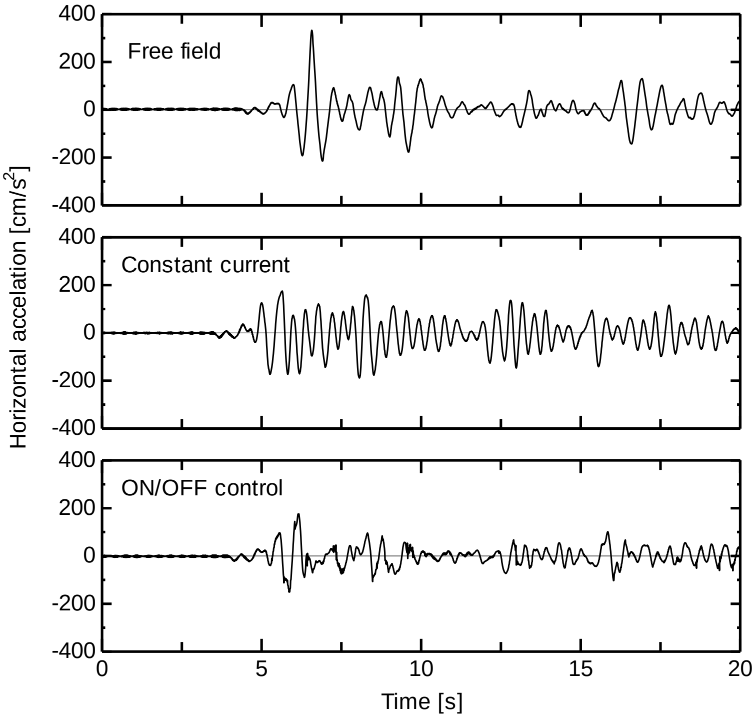


Fig. 13 time history of response acceleration

Table 3 maximum strain values of bending spring

	Top	Bottom	|Top – Bottom|
Free field	537μ	-1168μ	1705μ
Constant current	-508μ	633μ	1141μ
ON/OFF control	310μ	-680μ	990μ

The relationships between displacement and damper force or inertia force are shown in Fig.14. Inertia force of system is calculated from horizontal acceleration multiplied by mass. Hysteresis loop of ON/OFF control (relationships between damper force and displacement) shows that proposed control can draw intended hysteresis, however signal of switch control have a slight error. This is due to using horizontal displacement for the control. The problem of this system is to regard phase delay of horizontal displacement compared to MR damper displacement. A detailed examination is necessary to improve the control system. According to the relationship between inertia force and displacement, ON/OFF control performs that the peak of inertia force is smallest among these cases (free field and 2.0A exciting currents). It suggests that high efficacy reducing response acceleration corresponds to proposed control method.

In comparison with secant stiffness which connects maximum points, 2.0A constant currents (5.8N/mm) shows about 2 times higher than the case of free field (2.9N/mm). Secant stiffness in ON/OFF control is barely changed from free field. From the above condition, vibration under ON/OFF control shows same behavior with under free field. Therefore, ON/OFF control is able to have same response reduction with 2.0A constant currents.

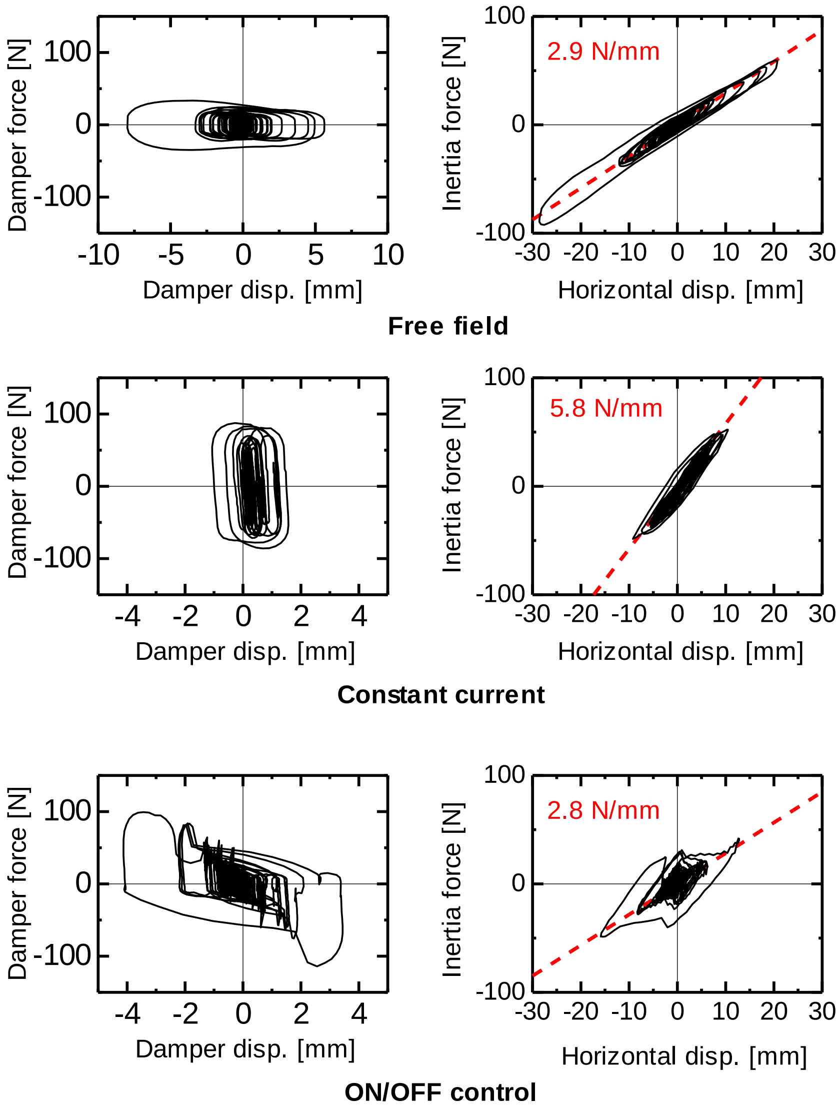


Fig. 14 comparison of hysteresis loop

4. EXAMINATIOIN OF MR DAMPER FORCE IN NUMERICAL ANALYSIS

Numerical analysis is examined in order to confirm the response reduction of ON/OFF control. Numerical model is one mass system considering top rotational motion. Damping factor of MR damper and restoring force of limit spring are considered as rotational mechanic parameter. Damping ratio of main frame is regarded as 1%. Friction force of the system, which effects on significantly its behavior during small response, is also considered. Averaged acceleration integration method with time step of 1/10000s is used for numerical analysis. Comparison of experimental results with numerical analysis results is shown in Fig. 15. In analytical results under ON/OFF control, high frequency of acceleration response is slightly remarkable, however numerical result shows well experiments. Overall, to examine the optimum force of MR damper for the response reduction, performance of MR damper is evaluated by the relationship between F_c and C_d shows linear characteristics as shown in Fig.16.

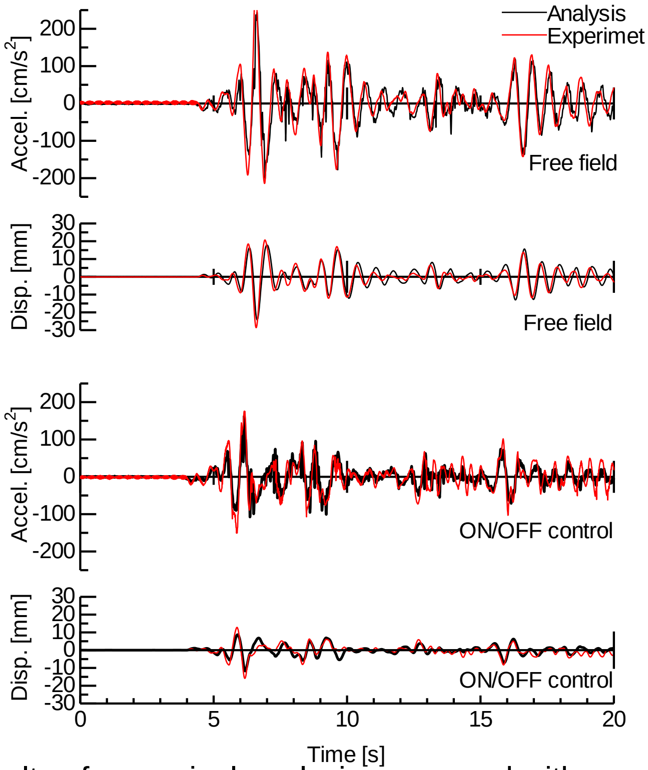


Fig. 15 results of numerical analysis compared with experiments

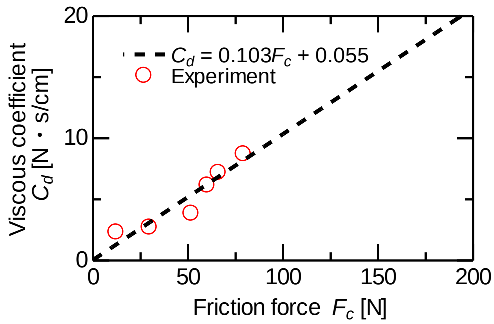


Fig. 16 relationship between viscosity and friction of MR damper

Input wave is the horizontal acceleration record on the shaking table. The range of MR damper force (F_c) used in the analysis is from 0N to 200N. Taken as reference the maximum response in case of free field, responses of 2.0A constant currents and ON/OFF control are normalized to obtain reduction ratios to confirm the performance of control. Performance curves of reduction ratios are shown in Fig.17. A vertical axis shows reduction ratio of acceleration, and a horizontal axis shows reduction ratio of displacement.

Under ON/OFF control, maximum response has a tendency to reduce response by increasing F_c. Both of ratio of acceleration and displacement have a tendency to be bottoming out from F_c = 140N. More response reduction is expected by improving performance of actual MR damper because F_c of experimental data is merely 80N. Both of decrease of acceleration and displacement under constant currents are max at F_c = 63N. However, more than F_c = 63N, maximum response increases certainly. It's caused

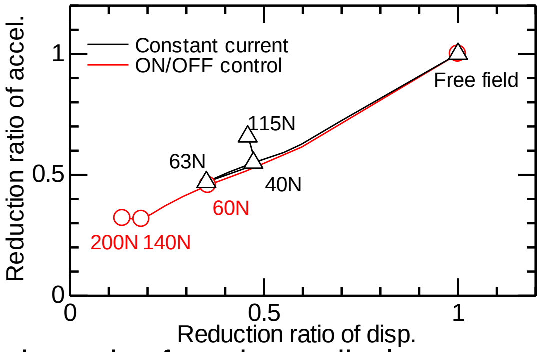


Fig. 17 reduction ratio of maximum displacement and acceleration

by the shortening rotational periods by MR damper force. Transfer function of the system is examined by inputting swept wave whose range of frequency is from 0.1Hz to 3.0Hz. Input level of swept wave is set as 70cm/s^2, in which an effective level of inputted seismic wave (Fig.12) is taken into account. Transfer function under constant currents is shown in Fig.18, and transfer function under ON/OFF control is shown in Fig.19. In transfer function under ON/OFF control shows that change of dominant frequency is rarely appeared and response ratio becomes small by increasing MR damper force. It suggests that the performance of damping increase. On the other hand, dominant frequency of constant currents becomes high by increasing MR damper force. The trend of decreasing performance of damping at F_c = 115N is confirmed. This result is the same with experimental results. This is not caused by the random characteristic of earthquake. However, more detailed analysis is necessary because input level and control force have significant influences on dominant frequency.

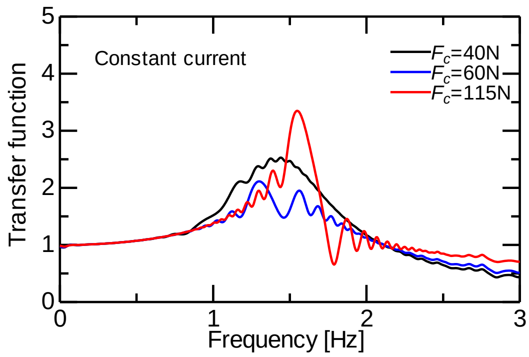


Fig. 18 transfer function under constant exciting currents

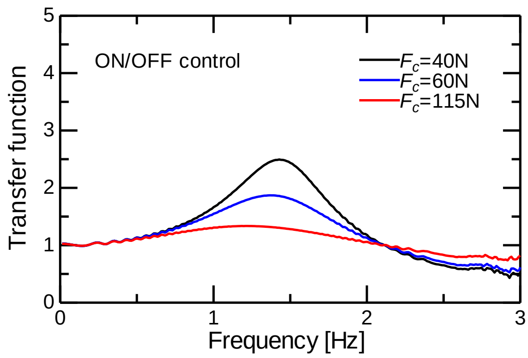


Fig. 19 transfer function under ON/OFF control

5. CONCLUSION

The bending shear model to simulate the vibration properties of high-rise buildings was proposed and subjected to shaking table tests to discuss its seismic response when vibration control system is installed on it. A simple control method of switch ON/OFF of the force in a MR damper performs to reduce the shear force and the acceleration response in the investigated model.

Although the proposed ON/OFF control method presents similar response characteristics with the case of free field for MR damper, the response reduction effects are equivalent to the case where continued maximum damping force is used.

It is expected that proposed control method would be a useful technique to control vibration of high-rise buildings where bending deformation is dominant.

ACKNOWLEDGEMENT

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