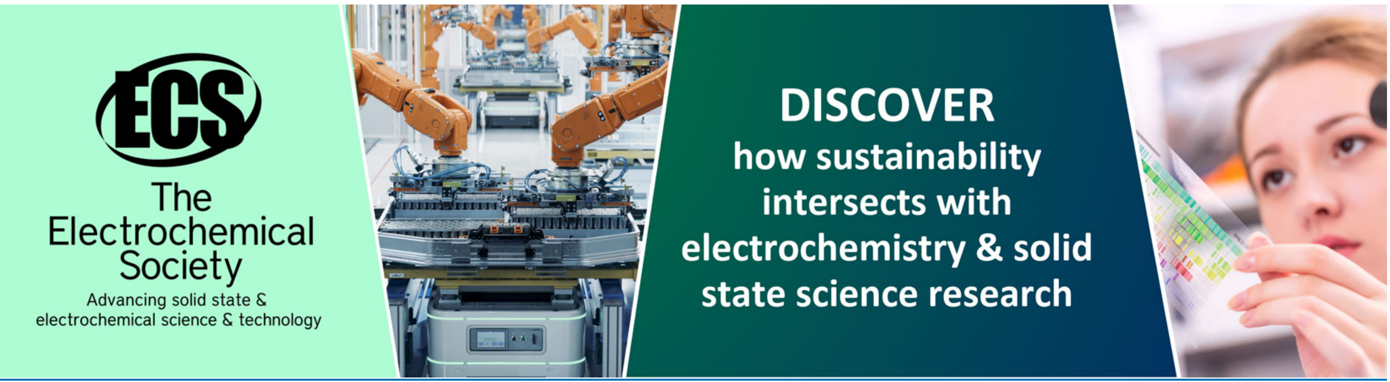
Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Vibration Control by a Shear Type Semi-active Damper Using Magnetorheological Grease

To cite this article: Toshihiko Shiraishi and Hirotaka Misaki 2016 *J. Phys.: Conf. Ser.* **744** 012012



Vibration Control by a Shear Type Semi-active Damper Using Magnetorheological Grease

Toshihiko Shiraishi, Hirotaka Misaki

Grad. Sch. of Environment and Information Sciences, Yokohama National University, 79-7 Tokiwadai, Hodogaya-ku, Yokohama 240-8501 Japan

E-mail: shira@ynu.ac.jp

Abstract. This paper describes semi-active vibration control by a controllable damper with high reliability and wide dynamic range using magnetorheological (MR) grease. Some types of cylindrical controllable dampers based on pressure difference between chambers in the dampers using "MR fluid", whose rheological properties can be varied by applying a magnetic field, have been reported as a semi-active device. However, there are some challenging issues of them. One is to improve dispersion stability. The particles dispersed in MR fluid would make sedimentation after a period. Another is to expand dynamic range. Since cylindrical dampers require sealing elements because of pressure difference in the dampers, the dynamic range between the maximum and minimum damping force according to a magnetic field is reduced. In this study, a controllable damper using the MR effect was proposed and its performance was experimentally verified to improve the dispersion stability by using "MR grease", which includes grease as the carrier of magnetic particles, and to expand the dynamic range by adopting a shear type structure not requiring sealing elements. Furthermore, semi-active vibration control experiments by the MR grease damper using a simple algorithm based on the skyhook damper scheme were conducted and its performance was investigated.

1. Introduction

Magnetorheological (MR) fluid is a type of controllable fluid whose rheological properties can be varied by applying a magnetic field. It is basically composed of micron-sized magnetic particles dispersed in carrier fluid such as mineral or silicone oil [1]. When a magnetic field is applied, the dispersed magnetic particles form chain-like structures called "cluster" along the magnetic circuit. It is considered that they prevent the movement of fluid and generate the yield shear stress. Due to its rapid response, low energy requirement, and wide dynamic range, MR fluid has attracted much attention and a variety of applications such as controllable dampers, clutches, and brakes have been developed [2]. Especially, controllable dampers using MR fluid have been actively studied due to its high potential in semi-active control applications.

Some types of cylindrical controllable dampers based on pressure difference between chambers in the dampers using MR fluid have been reported as a semi-active device. However, there are some challenging issues of cylindrical MR fluid dampers. One is to improve dispersion stability. The particles dispersed in MR fluid would precipitate and make sedimentation after a period due to density difference between the particles and the carrier fluid. When sedimentation is formed, it is difficult to re-disperse the particles and it would degrade the performance. In order to improve dispersion stability, MR grease, which includes grease as the carrier of magnetic particles, was developed [3]. Three dimensional network structure in grease might hold dispersed particles and sedimentation of particles is drastically reduced. Another challenging issue is to expand the dynamic range. Cylindrical dampers require sealing elements because of pressure difference between chambers in the dampers. Since there is sliding friction in the sealing elements, the damping force without a magnetic field increases and the dynamic range between the maximum and minimum damping force according to the strength of a magnetic field is reduced not making the best use of MR effect.

In this study, MR grease was applied to a shear type damper and its performance was experimentally verified. Furthermore, the MR grease damper was installed in a one degree-of-freedom model structure and its effectiveness as a semi-active damper was investigated by the vibration control experiments under sine excitation and pseudo-random excitation using a simple algorithm based on the skyhook damper scheme.

2. Magnetorheological grease

Grease is a solid or semi-solid lubricant composed of base oil, solid thickener, and additives [4, 5]. Internal thickener basically forms a three-dimensional fibrous structure and it is presumed that grease becomes solid because the base oil is maintained between these structures [6]. We used grease including the three-dimensional fibrous structure of thickener to stabilize the dispersion of magnetic particles instead of carrier fluid in MR fluid and developed “MR grease”. It was considered that magnetic particles dispersed in grease might be held by this fibrous structure and no or little sedimentation was produced in MR grease.

Figure 1 shows photographs of appearance of a commercial MR fluid and the developed MR grease composed of mineral oil, 1 wt% lithium soap thickener, and 75 wt% carbonyl iron particles when they were left in static state for 30 days. MR fluid was separated into two layers and its supernatant was observed. On the other hand, there was no apparent change in the MR grease. It is clear that the dispersion stability was improved by using grease as a carrier of magnetic particles.

3. Shear type magnetorheological grease damper

3.1. Structure

Figure 2 shows a schematic diagram of the proposed MR grease damper. The principal specification of the damper is shown in Table 1. In order to expand the dynamic range by realizing lower damping force in off-state of a magnetic field and higher damping force in on-state, a shear type structure was applied to the damper. A shear type damper requires no sealing element and sliding friction for sealing is basically zero different from a pressure type damper. In addition, there is no leakage due to the property of grease. A brass plate was inserted in a flat brass box without a top part. The gap between the plate and the inside wall of the box was 2 mm and filled with MR grease. When the plate was oscillated, shear force, which was determined by the shear stress of MR grease and the surface area of the plate contacting with MR grease, was generated as damping force. A magnetic field was applied to MR grease by an electromagnetic coil through an iron core to cross perpendicular to the direction of

Day 1 Day 30 Day 1 Day 30
(a) MR fluid (b) MR grease

Figure 1. Photographs of MR fluid and MR grease kept in static state.

shear deformation of MR grease. The damping force can be controlled by the strength of a magnetic field, which was varied by adjusting electric current in the electromagnetic coil.

3.2. Typical properties

Typical properties of the MR grease damper were measured. The damper was set to a servo-hydraulic actuator. While the servo actuator was reciprocated in the harmonic wave of constant frequency and amplitude, the displacement of the plate in the damper and the damping force were measured by a magnetic scale and load cell, respectively. The vibration frequency was set to 1, 3, or 5 Hz at the constant amplitude of 5 mm and the electric current to the coil was varied from 0 to 4 A; 0, 1, 2, 3, or 4 A by a DC power supply. In advance of the experiments above, it was experimentally confirmed that the damping force based on the eddy current loss was much smaller than that based on the characteristics of MR grease.

Figure 3 shows the hysteresis loops of damping force and plate displacement. The hysteresis loops at each electric current were superposed in figure 7. As a result, it was shown that the damping force increased with the intensity of the applied electric current, i.e., with the strength of the applied magnetic field. The hysteresis loops appeared to be rectangular shape, which means that the frictional damping was predominant in the MR grease damper. As shown in figure 7, it was found that the damping force increased with the plate frequency. In other words, as the plate velocity increased, the influence of the viscous damping of MR grease became larger in the damper.

Since the damping force in the case of the maximum velocity of 1 Hz was approximately 1 N and

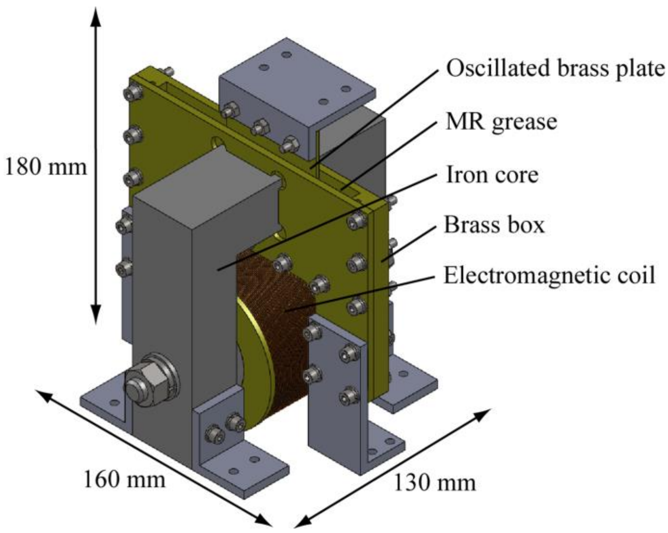
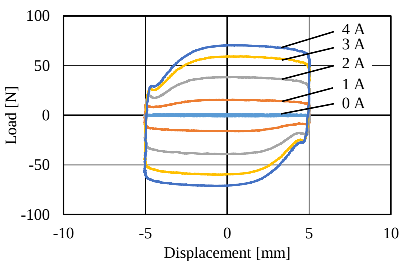


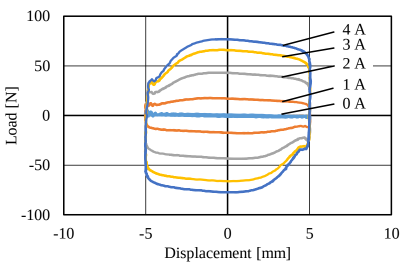
Figure 2. Schematic diagram of the shear type MR grease damper.

Table 1. Specification of the shear type MR grease damper.

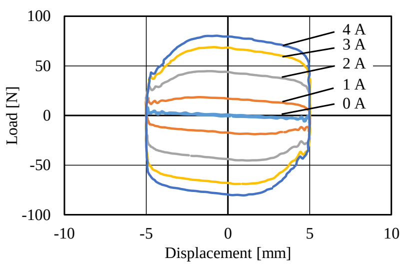
Stroke	10 mm
Gap filled with MR grease	2 mm
Area of oscillated brass plate	2100 mm^2
Height	180 mm
Width	160 mm
Depth	130 mm
Winding number of coil	125 or 1000



(a) 1 Hz



(b) 3 Hz



(c) 5 Hz

Figure 3. Hysteresis loops of damping force and displacement of the MR grease damper.

70 N at 0 A and 4 A, respectively, the dynamic range of the damping force was seventy times. It indicates that the dynamic range obtained in the present MR grease damper is more than five times as high as the conventional MR fluid damper or MR grease damper [3, 7].

4. Control algorithm

In order to verify the wide variation of dynamic characteristics of a structure by the MR grease damper and its vibration controllability, a simple semi-active vibration control was conducted for a one degree-of-freedom model structure. A control algorithm based on the skyhook damper scheme (Karnopp, et al., 1974) was used to control electric current supplied to the MR grease damper.

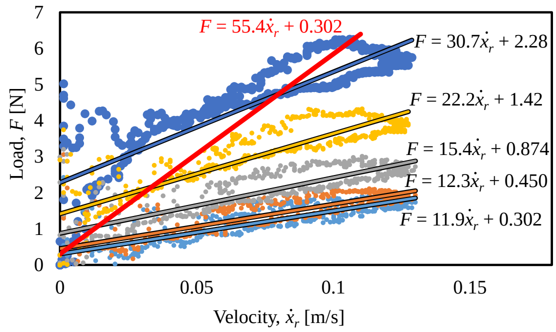
Figure 4(a) shows the relationship between damping force F and velocity of the plate in the damper $\dot{x}_r$ measured under sine excitation at the amplitude of 10 mm and the frequency of 2 Hz at the electric current I of 0, 1, 2, 3, and 4 A to the MR grease damper. The relationship was linearized by

$$\begin{aligned} F &= a(I)\dot{x}_r + b(I) \\ &= (a_2 I^2 + a_1 I + a_0)\dot{x}_r + b_2 I^2 + b_1 I + b_0 \end{aligned} \tag{1}$$

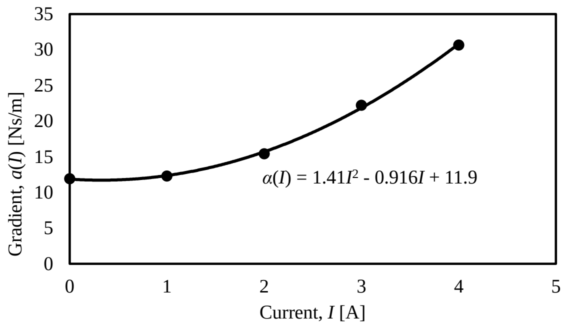
where $a(I)$ and $b(I)$ are functions of I and approximated by quadratic curves using coefficients a_0, a_1, a_2, b_0, b_1, and b_2 as shown in figures 4(b) and(c), respectively. Desired damping force can be achieved in the controllable domain plotted in figure 4(a) and was set as the velocity-proportional form of damping force given by

$$F = c_e \dot{x}_r + b_0 \tag{2}$$

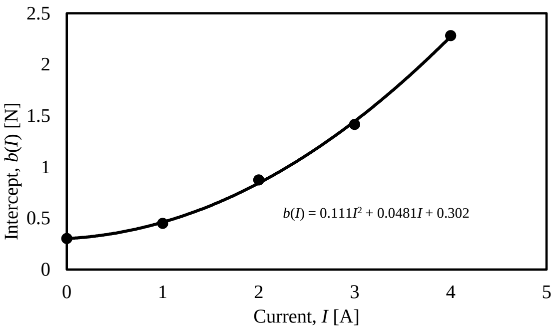
where c_e is the equivalent viscous damping coefficient and b_0 is small damping force at $\dot{x}_r = 0$ and $I = 0$. Using equations (1) and (2), the control current I_c required for c_e is obtained as the following expression.



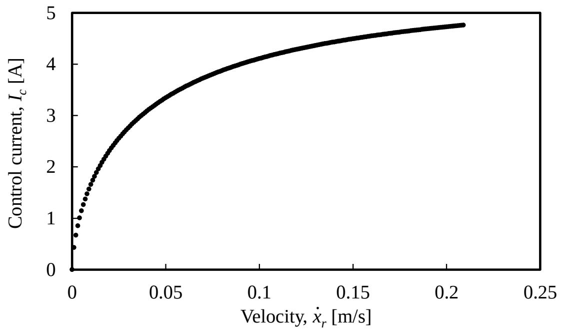
(a) Damping force vs. velocity at 0, 1, 2, 3, and 4 A.



(b) Gradient $a(I)$ vs. current.



(c) Intercept $b(I)$ vs. current.



(d) Control current vs. velocity

Figure 4. Control current required for desired damping force (red line).

$$(a_2\dot{x}_r + b_2)I_c^{\ 2} + (a_1\dot{x} + b_1)I_c + (a_0 - c_e)\dot{x}_r = 0 \tag{3}$$

$$I_c = \left| \frac{-a_1\dot{x}_r - b_1 + \sqrt{(a_1\dot{x}_r + b_1)^2 - 4(a_2\dot{x}_r + b_2)(a_0 - c_e)\dot{x}_r}}{2(a_2\dot{x}_r + b_2)} \right| \tag{4}$$

c_e which is as large as possible is determined as 55.4 Ns/m in the controllable domain as shown as the red line in figure 4(a). The relationship between I_c and $\dot{x}_r$ is shown in figure 4(d).

Considering that damping force cannot be generated in the second and fourth quadrants in figure 4 (a) due to the passivity of the damper, the control algorithm based on the skyhook damper scheme is determined by

$$I_c = \begin{cases} I_c & \text{if } \dot{x}(\dot{x} - \dot{x}_0) > 0 \\ 0 & \text{if } \dot{x}(\dot{x} - \dot{x}_0) \le 0 \end{cases} \tag{5}$$

where $\dot{x}$ and $\dot{x}_0$ signifies the absolute velocity at the control target floor of the model structure and the base part, respectively. If the MR grease damper is installed between the target floor and the base part, the following equation is obtained.

$$\dot{x}_r = \dot{x} - \dot{x}_0 \tag{6}$$

5. Semi-active vibration control experiments using the magnetorheological grease damper

5.1. Experimental setup

Figure 5 shows a schematic diagram of the experimental setup for the semi-active vibration control. The model structure was composed of a target floor plate of 1.5 kg fixed to leaf springs of 600 N/m and a base plate. The target floor plate of 100 mm in length, 200 mm in width, and 20 mm in thickness was placed at 400 mm from the base plate. The MR grease damper was installed between the floor and base plates. The base plate was fixed on two linear bearings and given forced excitation by an electromagnetic actuator.

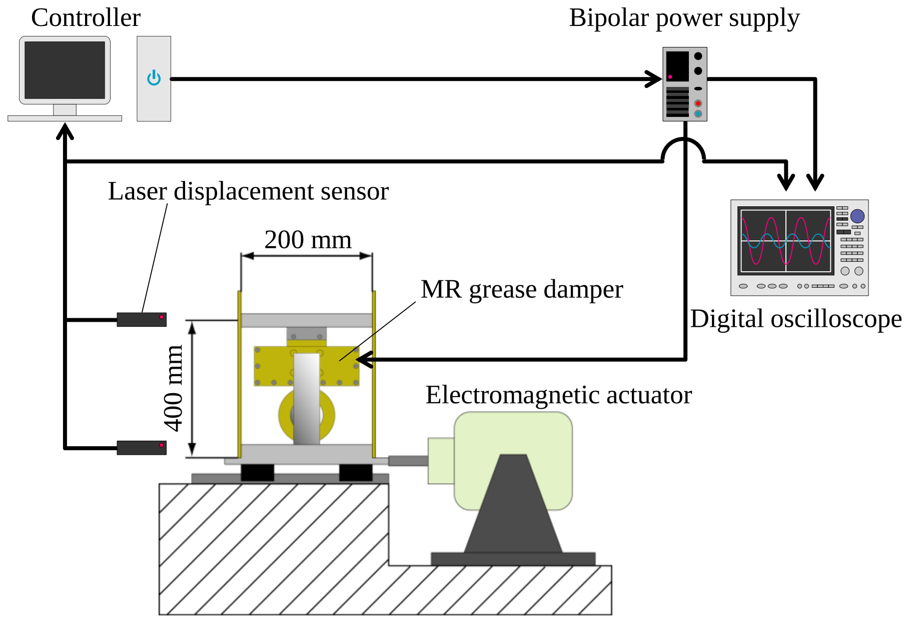


Figure 5. Schematic diagram of the experimental setup for semi-active vibration control.

Journal of Physics: Conference Series **744** (2016) 012012 doi:10.1088/1742-6596/744/1/012012

The displacement of the floor and base plates was measured by laser displacement sensors. The data of time series of displacement were acquired by an analog to digital converter of the sampling frequency of 10 kHz. The velocity of the floor and base plates was obtained by numerically differentiating the displacement using 100 samples. The control signal was calculated using the control algorithm as mentioned above and output to a bipolar power supply by a digital to analog converter at the frequency of 100 Hz. The electric current to the coil was set to 4 A in on-state and determined by the control algorithm using equations (4) and (5), and figure 4(d) in control.

5.2. Sine excitation

Figures 6, 7, and 8 show time series of the displacement of the target floor and the supplied electric current under the sine excitation of the 3 mm amplitude and the 2.5, 6.0, and 9.5 Hz frequencies, respectively. In these figures, the displacement responses in on-state, off-state, and control were superposed. When the displacement response in on-state was smaller than that in off-state at 2.5 Hz, the response in control was almost same as that in on-state by controlling the supplied electric current. On the other hand, when the displacement response in off-state was smaller than that in on-state at 6.0 and 9.5 Hz, the response in control was almost same as that in off-state.

The frequency response of the target floor is shown in figure 9. The dynamic characteristics of the model structure were highly varied by switching the electric current to the MR grease damper from

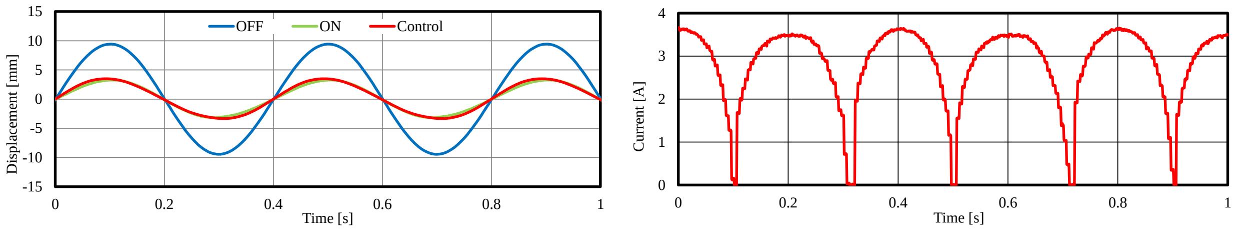


Figure 6. Time series of the displacement of the target floor and the supplied electric current under the sine excitation of the amplitude of 3 mm and the frequency of 2.5 Hz.

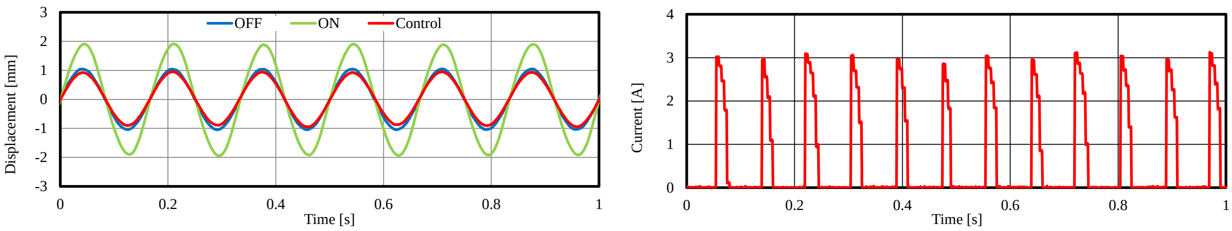


Figure 7. Time series of the displacement of the target floor and the supplied electric current under the sine excitation of the amplitude of 3 mm and the frequency of 6.0 Hz.

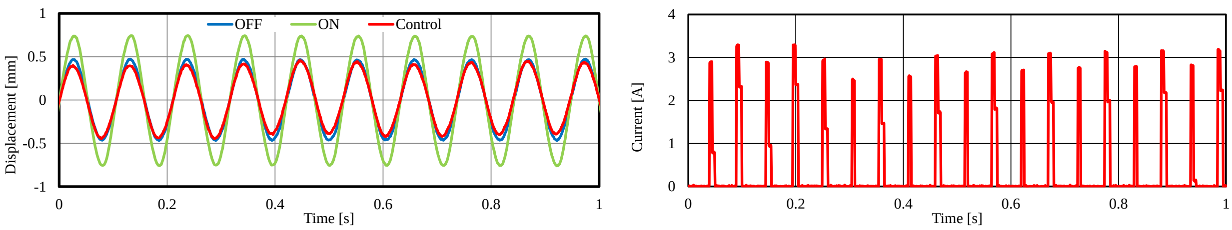


Figure 8. Time series of the displacement of the target floor and the supplied electric current under the sine excitation of the amplitude of 3 mm and the frequency of 9.5 Hz.

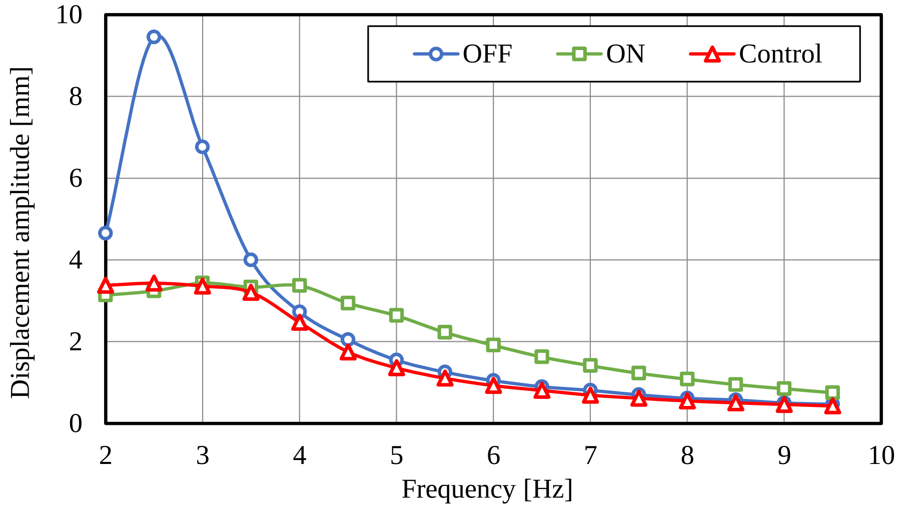


Figure 9. Frequency response of the model structure equipped with the MR grease damper under sine excitation.

off-state to on-state. The displacement amplitude in control was almost same as that in on-state in the low frequency range in which that in on-state was smaller than that in off-state. In the same manner, the displacement amplitude was almost same as that in off-sate in the high frequency range in which that in off-state was smaller than that in on-state. It is shown that the control algorithm realizes the ideal semi-active control.

5.3. Pseudo-random excitation

Figure 10 shows time series of the displacement of the target floor and the supplied electric current under the pseudo-random excitation in the range from 2.0 to 9.5 Hz. The displacement response in control was reduced compared to off-state and on-state. The reduction rate to off-state is 40.3% in maximum and 38.6% in root mean square in control while that is 25.1% in maximum and 24.1% in root mean square in on-state.

The frequency response of the target floor is shown in figure 11. In the same manner as the sine excitation, it is shown that the control algorithm realizes the ideal semi-active control. The results

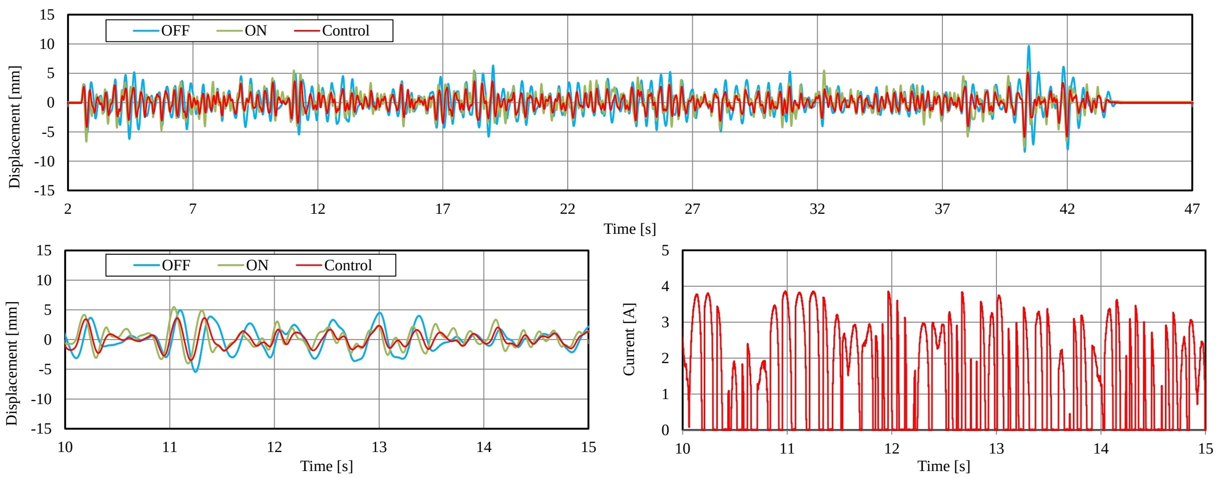


Figure 10. Time series of the displacement of the target floor and the supplied electric current under the pseudo-random excitation in the frequency range from 2.0 to 9.5 Hz.

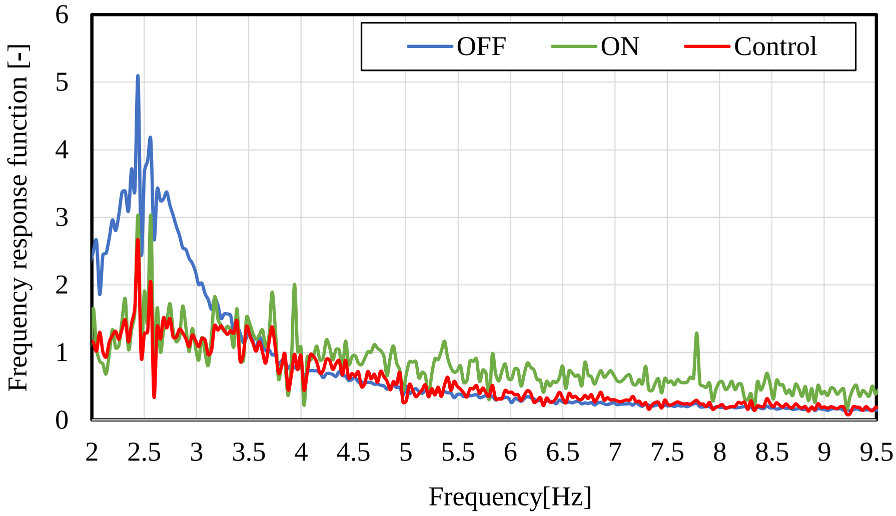


Figure 11. Frequency response of the model structure equipped with the MR grease damper under the pseudo-random excitation.

under the sine excitation and the pseudo-random excitation indicate that the semi-active vibration control is successfully conducted by the MR grease damper using the control algorithm.

6. Conclusions

In this study, MR grease was applied to a shear type damper and its performance was experimentally verified to improve the dispersion stability by using MR grease and to expand the dynamic range by adopting a shear type structure. As a result, it is confirmed that MR grease has the high dispersion stability and that the dynamic range of the present damper according to the supplied electric current is seventy times, which is more than five times as high as the conventional dampers using the MR effect. Furthermore, the MR grease damper was installed in a one degree-of-freedom model structure and its effectiveness as a semi-active damper was investigated by the vibration control experiments under sine excitation and pseudo-random excitation using a simple algorithm based on the skyhook damper scheme. The results indicate that the semi-active vibration control is successfully conducted by the MR grease damper using the control algorithm.

References

[1] Rabinow J 1948 The magnetic fluid clutch, *Transactions of AIEE* **67** 1308-1315

[2] Carlson JD, Catanzarite DM and Clair KA St 1995 Commercial magneto-rheological fluid devices *Proc. of 5th Int. Conf. on ER, MR Suspensions and Associated Technology*

[3] Shiraishi T, Miida Y, Sugiyama S and Morishita S 2011 Typical characteristics of magnetorheological grease and its application to a controllable damper *Mechanical Engineering Journal* **77**(778) 2193-2200 (in Japanese)

[4] Hoshino M. 2002 Theory of grease lubrication *JAST Journal of Japanese Society of Tribologists* **47**(1) 8-14 (in Japanese)

[5] Lugt PM 2009 A review on grease lubrication in rolling bearings *Tribology Transactions* **52** 470-480

[6] Oya Y, Miyamoto S, Morishita S and Shiraishi T 2011 Experimental study on visualization of grease flow *JAST Journal of Japanese Society of Tribologists* **56**(4) 248-255 (in Japanese)

[7] Yang G, Spencer Jr. BF, Carlson, JD and Sain MK 2002 Large-scale MR fluid dampers: modeling and dynamic performance considerations *Engineering Structures* **24**(3) 309-323

Acknowledgement

We are grateful to Kyodo Yushi Co., Ltd. for providing test samples. This work was supported by Suzuki Foundation and Charitable Trust TATSUJIRO KATO Memorial Construction Machine Research Promotion Fund.