Editorial

# Magneto-Rheological Technologies

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## 1. Introduction

The science of the phenomenon that a material changes its viscoelasticity when subjected to a magnetic field is called Magneto-Rheology. The function of it is called the Magnetorheological Effect or the MR effect. Typical materials of this kind include a Magneto-Rheological Fluid, which is one of the functional fluids. The MR fluid is a suspension containing micro-sized ferromagnetic particles densely dispersed within a type of oil, such as silicone oil, as a carrier medium. The MR fluid has a special feature: its viscosity (more exactly, yield shear stress) can be changed electrically, reversibly and continuously in several milliseconds order when subjected to a magnetic field [1]. In other words, the MR fluid behaves like a solid with the application of a magnetic field and becomes a liquid with fluidity in the absence of such a field. Fluid power equipment and systems can effectively use the functionality of the MR fluid to deliver functions that have not ever been seen before and to have several significant features including high-speed, easy-to-use, compactness and intelligence. Thus, fluid power systems are expected to be "smart". Technologies to create different functional materials delivering the MR effect and their application technologies are collectively called Magneto-Rheological (MR) Technology, as in the title of this article.

In addition to the MR fluid, this article also covers an MR fluid porous composite consisting of porous material impregnated with an MR fluid for higher MR effect and less sedimentation of the dispersed particles, a high-fluidity dry MR fluid consisting of oil-free ferromagnetic particles for higher MR effect and higher environmental resistance, and an MR elastomer consisting of ferromagnetic fine particles dispersed and cured within a carrier matrix such as silicone rubber. Mainly by introducing the author's research and development cases, the article discusses advanced MR technologies to create and evaluate various functional fluids and soft materials delivering the MR effect including those described above as well as technologies to apply these fluids or materials in different fields.

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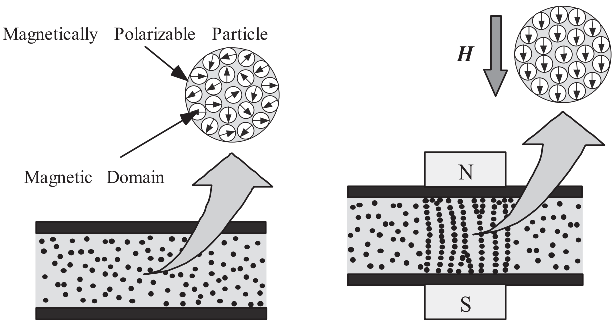
## 2. MR Fluid and Its Applications

### 2.1 MR Effect of MR Fluid

An MR fluid can change its rheological properties quickly and reversibly when it is applied with a magnetic field. This function relies on a mechanism that ferromagnetic particles having a number of magnetic domains are polarized with the application of a magnetic field and the particles are connected together to form clusters as shown in Fig. 1. This mechanism to deliver the MR effect causes the MR fluid to behave like a Bingham fluid that has a yield shear stress $\tau_y$ with the application of a magnetic field. This induced shear stress $\tau$ can be expressed by the equation below:

$$\tau = \tau_y + \eta\dot{\gamma} \qquad (1)$$

Where, $\eta$ is the plastic viscosity of the MR fluid and $\dot{\gamma}$ is the shear rate of the fluid. Fig. 2 shows the typical magneto-rheological property (flow curve: shear rate $\dot{\gamma}$ - shear stress $\tau$ curve) of a commercially available MR fluid




(a) No magnetic field (b) Under a magnetic field

**Fig. 1** Formation of particle clusters in MR fluid under a magnetic field

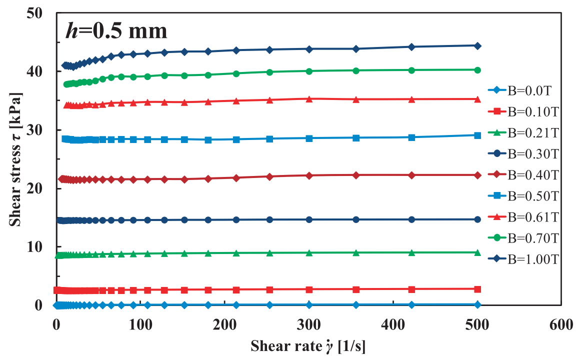



**Fig. 2** Flow curves of MR fluid (MRF-132DG)

(MRF-132DG, Lord Co.) measured with a parallel double disc rheometer (the inter-disc distance $h$ = 0.5 mm)[2]. According to the figure, the shear stress shows an almost constant value not depending on the shear rate for all the levels of the applied magnetic flux density $B$, except in the low shear rate region under a relatively high magnetic field. The yield shear stress at a shear rate of $\dot{\gamma} = 0 s^{-1}$ (the shear stress value at the point of intersection of the flow curve and the vertical axis) increases roughly proportionately with the applied flux density. However, the stress tends to be magnetically saturated when $B$ is about 0.7T or higher. With $B$ = 1.0T, the shear stress $\tau$ reaches about 45 kPa, which means that the MR fluid can deliver a considerably high induced shear stress.

## 2.2 MR Fluid Application Technologies

At present, the annual production/sales of MR fluids are on the order of 300 tons, and various equipment and systems using MR fluids, notably shock absorbers for vehicle suspension, have been commercialized and popularly used[3]. This section explains the application of MR fluid in fluid power components including dampers, brakes and clutches, and introduces different types of smart machine systems that make use of them.

To realize an MR fluid damper that can be operated reliably even during power interruption, the MR fluid damper not using any electrical control system that can change its damping force in response to the product (positive or negative) of displacement and velocity using permanent magnets and check valves, has been developed, proving the effectiveness of its application in seismic base isolation systems of building structures[4]. As shown in Fig. 3, this damper has two piston heads, each of which has an annular orifice that is applied with a magnetic field according to the opened/closed operation of a magnetic circuit depending on the displacement, and a magnetic-free bypass orifice with a check valve that is opened or closed according to the direction of flow (positive/negative damper speed). With this structure, the damper can control its damping force $f$ according to the sign of the product of displacement $x$ and velocity $v$ (increases $f$ if the product of $x$ and $y$ is below 0 or decreases $f$ if the product of $x$ and $y$ is above 0).

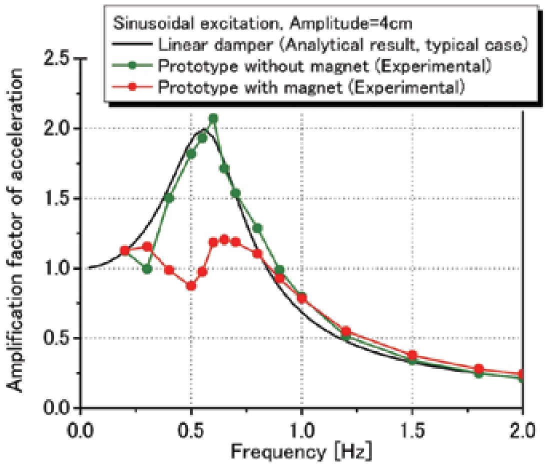



**Fig. 4** Seismic control property of SDOF base isolation system consisting of the developed MR dampers

According to the seismic control property of the single-degree-of-freedom (SDOF) base isolation system consisting of the developed MR damper (Fig. 4), the amplification factor of acceleration substantially decreases only at around the resonance frequency, proving the effectiveness of the seismic isolation control.

With the application of a magnetic field (a coil current), the MR fluid clutch can deliver the torque limiting function and the slip rotation function with a certain torque. Combining this clutch with a motor or other power source will ensure back drivability, which can be expected to contribute to higher safety and security of robots used in contact with human. An MR fluid actuator consisting of a servo motor, a multi-disc MR fluid clutch and reduction gears for power-assisted leg orthosis for rehabilitation with back drivability has been developed, in order to improve the safety and security (Fig. 5)[5]. The developed MR fluid clutch adequately meets the target design torque (approx. 4.5 Nm) and can deliver a high response speed.

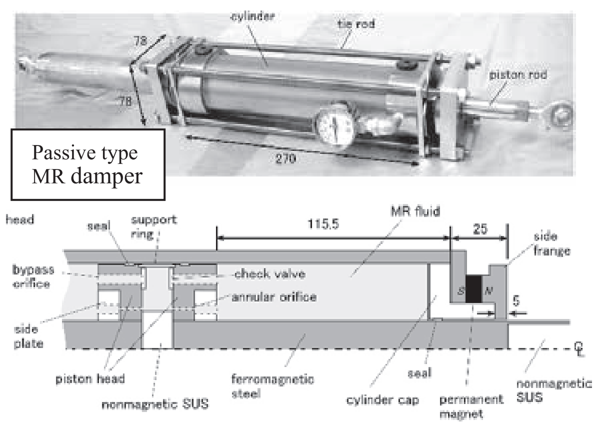



**Fig. 3** Illustration of MR damper whose damping force is variable depending on the product of displacement and velocity

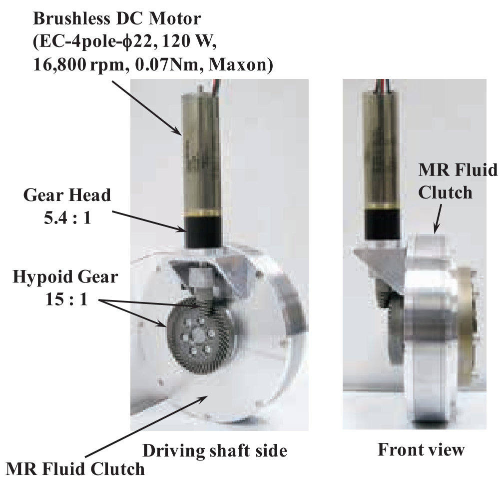



**Fig. 5** MR fluid actuator developed for use in power-assisted leg orthosis

In addition, the clutch is not dependent on the rotation speed so much and the transmission torque can be freely set only with the applied current, offering high controllability. Because of the structural safety of the MR fluid clutch with the torque limiting function, the developed MR fluid actuator can ensure back drivability and is suitable for use in the power-assisted equipment.

As a first step to apply MR fluid clutches and brakes to power transmission and control systems, we designed and developed an MR fluid brake for compact electric vehicles (EVs). We have investigated the braking characteristics and road-tested a car (super-compact EV) equipped with the brakes on the four wheels. The test has demonstrated that the MR fluid brake for this vehicle has adequate braking performance, adequate high-speed responsivity and high controllability realizing the application of the brake feeling control and the anti-lock braking control system (ABS) (Fig. 6)[6]. The MR fluid brake is expected to be commercially applied to smart mobility.

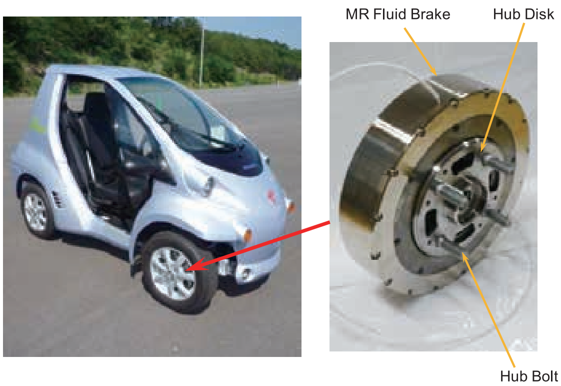
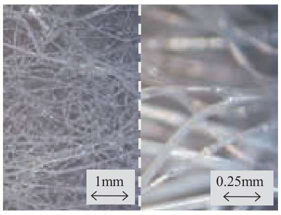



**Fig. 6** MR fluid brake for vehicles and its installation on a compact EV

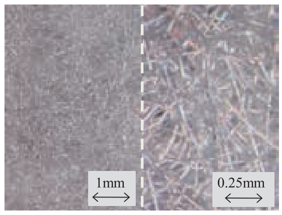
## 3. MR Fluid Porous Composite and Its Application Technologies

### 3.1 MR Effect of MR Fluid Porous Composite

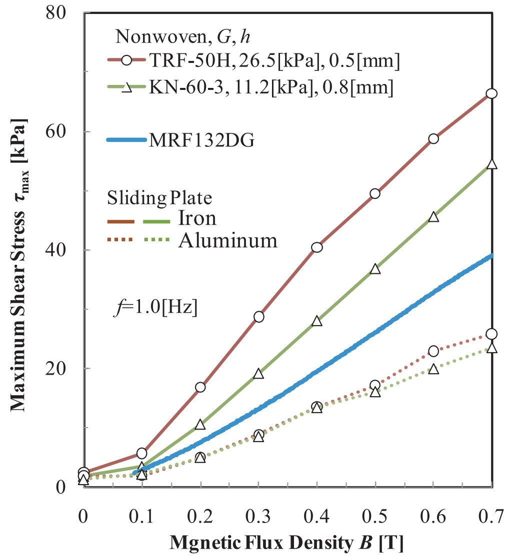
To prevent the sedimentation of dispersed particles in the MR fluid, we have developed an MR fluid porous composite consisting of a nonwoven fabric impregnated with an MR fluid since the fluid can be retained in porous material[7]. This also eliminates the necessity of using leakage prevention seals. Two types of nonwoven fabric of different lateral modulus *G* and different porous structures (Fig. 7(a) and (b)) were selected as porous materials, and then impregnated these nonwoven fabrics were impregnated with an MR fluid (MRF-132DG) to fabricate an MR fluid porous composite. The MR effect of the composites in an oscillating shear mode under a uniform magnetic field was evaluated. Fig 7(c) shows how the maximum induced shear stress $\tau_{max}$ on the displacement-shear stress hysteresis curve obtained changes with the applied flux density *B*. To investigate whether the maximum shear stress is affected by the magnetism of the contact material or not, two types of oscillating sliding plates were used: iron and aluminum. Fig.7(c) shows that




(a) KN-60-3, *t*=0.8mm




(b) TRF-50H, *t*=0.5mm




(c) Curves of maximum shear stress $\tau_{max}$ against applied flux density B

**Fig. 7** MR effect of test unwoven fabrics and MR fluid porous composite (depending on the material of contact sliding plate)

for the composites using both types of nonwoven fabric, the maximum shear stress with the iron sliding plate was generally about 2.0 to 2.5 times higher than that with the non-magnetic aluminum sliding plate, and was about 1.4 to 1.7 times higher than that of the MR fluid. Therefore, the MR fluid porous composite can be expected to remarkably improve the MR effect. It should also be noted that the nonwoven fabric of a higher lateral modulus in which finer fibers are intertwined with each other in a more complexed way (TRF-50H) shows a higher maximum shear stress.

### 3.2 MR Fluid Porous Composite Application Technologies

Coil winding may have a break or irregular winding attributable to an improper or fluctuating tension of the wire. To control the wire tension of coil winding during the production process, some equipment designed to control the pulleys for the wire with a mechanical friction or hysteresis brake are commonly used. The equipment always involves a fundamental problem related to the rotational inertia of the pulley and brake system. For non-circular coil winding in which the wire velocity substantially varies, it is unavoidable for the wire to have fluctuating tension. Fig. 8 shows a brake that was developed to resolve this fundamental problem[8]. The brake uses a mechanism that the wire is directly run through the

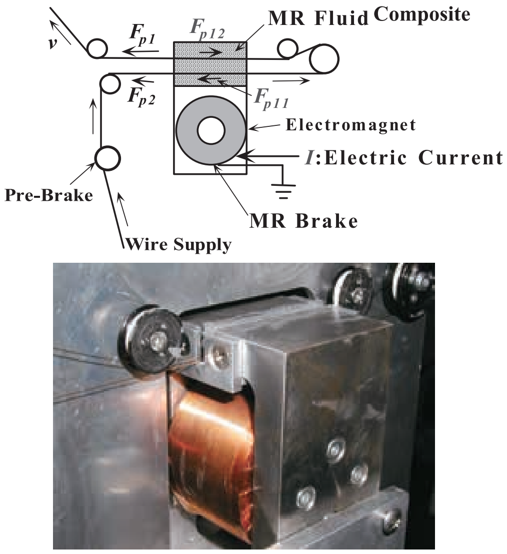
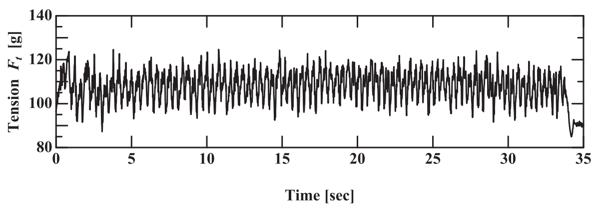
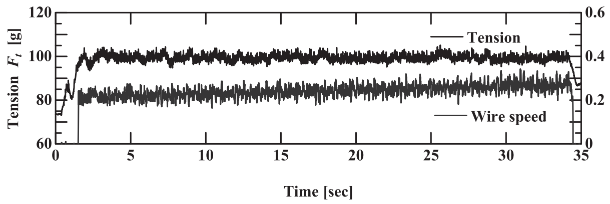



**Fig. 8** MR fluid porous composite brake developed for wire tension control system for coil winding




(a) Wire tension controller using conventional mechanical friction brake




(b) Wire tension controller using MR fluid porous composite brake applied with PID tension feedback control

**Fig. 9** Temporal tension fluctuation during non-circular coil winding test

MR fluid porous (66Nylon polyurethane foam) composite to receive braking due to the drag force (a rectangular annular electromagnet has a clearance of 2.5 mm whose both pole faces are affixed with a sheet of MR fluid porous composite each, between which the wire is run through). It has been verified that the wire tension increases roughly in proportion to the magnetic field intensity of the magnetic field applied to the MR fluid porous composite brake, thereby causing the brake to effectively serve as a tension control brake. This tension controller with the developed MR fluid porous composite brake was mounted on an actual coil winding machine to conduct tests to wind a square-shaped noncircular coil (wire diameter $d$ = 0.21 mm), for which the wire velocity always varies, at an average wire velocity $v$ = 0.28 m/sec. The tension fluctuation during the winding is shown in Fig. 9. For the tension control using a mechanical friction brake with conventional pulleys (Fig. 9(a)), the tension fluctuates with an amplitude as large as about 10 g over the whole range. On the other hand, for the tension control using the developed MR fluid porous composite brake applied with PID tension feedback control (Fig. 7(b)), the tension fluctuates with an amplitude as very small as about 2 g, which is equivalent to about 1/5 of that for the mechanical brake control. Furthermore, the temporal variation of the average tension is also suppressed to show good control performance partially because of the PID control to keep the tension almost to the setting [8].

When applying the MR fluid damper to the seismic base isolation or vibration control system of a building structure, the sedimentation of ferromagnetic fine particles dispersed in the MR fluid when it is left at rest for a long time poses a practical problem related to the reliability issue. This particle sedimentation problem can be solved by making use of the MR fluid porous composite consisting of a nonwoven fabric impregnated with an MR fluid. A 20 kN class linear motion variable damping MR damper (maximum total length 800 mm, stroke +/- 100 mm) for seismic base isolation or vibration control systems using the MR fluid porous composite based multi-disc rotary

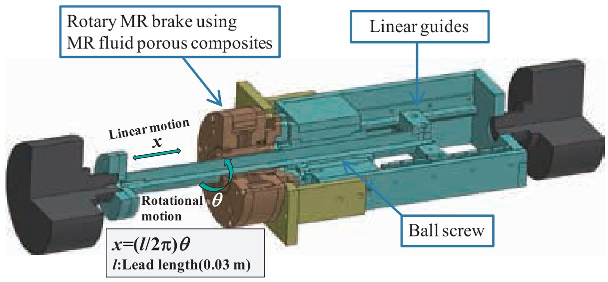



**Fig. 10** Linear motion variable damping force MR damper using MR fluid porous composite multi-disc rotary brake

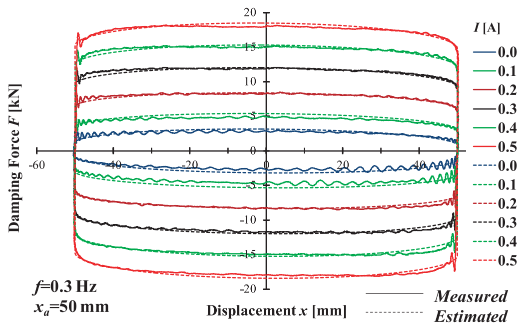



**Fig. 11** Changes of hysteresis curves of displacement $x$ - damping force $F$ with coil current $I$ at sinusoidal excitation

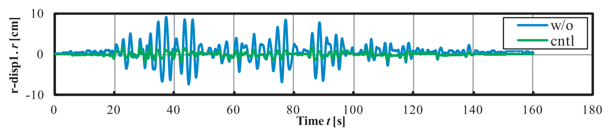



**Fig. 12** Response of SDOF isolation system using MR fluid porous composite linear motion MR dampers to Sannomaru seismic wave

MR brake and a ball screw that converts the rotation into a linear motion (Fig. 10) [9]. Fig. 11 shows the hysteresis curves of the generated damping force $F$ vs. the displacement $x$ at sinusoidal excitations ($f$ = 0.3 Hz, $x_a$ = 50 mm). The hysteresis curves show a rectangular loop for every applied coil current $I$ for all coils. The maximum damping force increases as $I$ increases and almost reaches the design value of 20 kN at $I$ = 0.5A. Fig. 12 gives an example of seismic control performance of the SDOF base isolation system using the linear motion MR damper with the MR fluid porous composite brake, which shows the responses to the Sannomaru (an enceinte in Nagoya Castle) seismic wave. The vibration displacement of an object (a building structure in this case) can be substantially reduced by applying the relative speed feedback control.

## 4. Dry MR Fluid and Its Application to Vehicle's Power Transmission/Braking System

### 4.1 MR Effect of Dry MR Fluid

When applying the conventional MR fluid to various devices, it is required that the fluid can be used properly within environmental temperatures ranging from around -40°C to 160°C. Since the carrier medium of the MR fluid is liquid such as oil, the higher viscosity at lower temperature often poses a problem. Particularly when using the MR fluid in a power transmission/braking system such as clutches and brakes, the drag torque due to the MR fluid of a higher viscosity at lower temperature substantially increases. As a solution to this problem, we have proposed and developed an oil-free dry MR fluid that uses a carrier gas, instead of the carrier liquid such as oil, within which micro-sized ferromagnetic fine particles core-shell-coated with nano $SiO_2$ fine particles are dispersed to deliver high fluidity [10]. The optimal fraction of $SiO_2$ for the greatest MR effect while maintaining the higher fluidity is about 0.49 wt%. Fig. 13 shows how the flow curve (shear stress - shear rate curve) for the dry MR fluid of $SiO_2$ = 0.49 wt% changes with the applied magnetic field. The shear stress shows an almost constant valve, independent of the shear rate for every applied magnetic flux density $B$. The shear stress $\tau$ almost reaches about 50 kPa with $B$ = 0.9T.

### 4.2 Application of Dry MR Fluid to Vehicle Brakes

We have tried to apply the developed dry MR fluid to vehicle's wheel brakes. We have developed a multi-layer

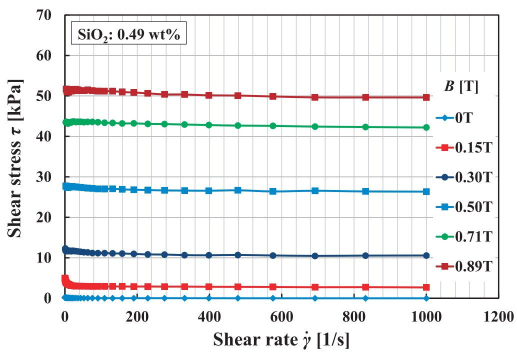



**Fig. 13** Flow curve of dry MR fluid ($SiO_2$: 0.49 wt%)


**Fig. 14** Compact EV with dry MR fluid brakes on the four wheels

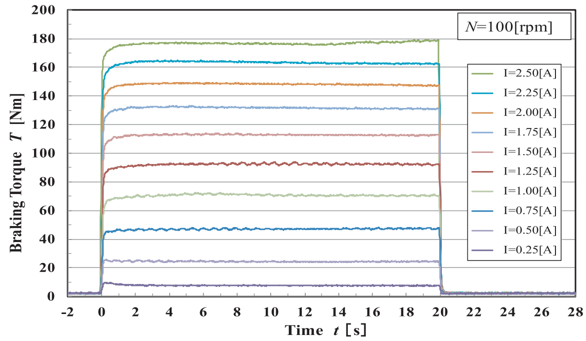



**Fig. 15** Steady-state torque characteristics of dry MR fluid brake for compact EVs

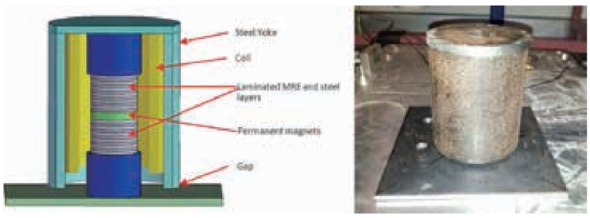
disc type dry MR fluid brake for compact electric vehicles (EVs). We have demonstrated that the brake has good braking performances by road-testing of a compact EV equipped with the brakes on the four wheels (Fig. 14). Fig. 15 shows the steady-state torque characteristics of the developed dry MR fluid brake. When the coil is applied with a current $I$ A for 20 seconds, a braking torque is quickly rose up and kept at an almost constant level. When the current is removed, it is quickly returned to the drag torque. The steady-state braking torque increases as the coil current increases and reaches the maximum braking torque of 180 Nm, which is higher than the target design torque of 160 Nm, in the application of $I$ = 2.5 A.

## 5. MR Elastomer and Its Application to Variable Stiffness Devices

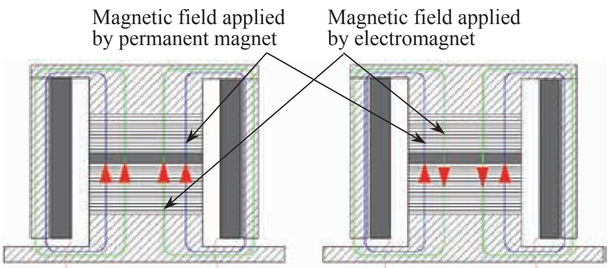
The MR fluid normally uses a liquid such as oil as the carrier medium. Silicone rubber or other similar matrix can also be used as a carrier medium, in which ferromagnetic particles are dispersed, and is cured to fabricate an MR elastomer (MRE) mainly whose elasticity (or stiffness) is variable with the application of a magnetic field [11]. A laminated MRE isolator for building base isolation has been developed that consists of alternately laminated MRE and steel layers, a permanent magnet located in the midst of the lamination and an electromagnet surrounding the lamination to make up a magnet circuit, as shown in Fig. 16(a) [12]. In this seismic base isolator, the magnetic field applied to the laminated elastomer can be increased (Fig. 16(b)) or decreased (Fig. 16(c)) depending on the direction of the application of the coil current to the electromagnet. This mechanism can provide extra control to additionally increase or decrease the primary stiffness generated with the magnetic field applied by the permanent magnet only. Fig. 17 shows the frequency transmissibility characteristics of the laminated MRE seismic base isolator depending on the current *I* A applied to the coil. According to the figure, the resonance frequency of 14 Hz ($I$ = 0A) increases with a positive current applied or decreases with a negative current applied, showing the variability from about 3 Hz to 20 Hz. An SDOF seismic isolation system consisting of four MR seismic base isolators on which an object (a building structure model) is mounted has been prepared and provided with skyhook control, demonstrating that the system can deliver effective seismic isolation control [13].

## 6. Concluding Remarks

One of the motive forces bring about technical innovation in the 21st century is new materials, particularly smart materials. The MR fluid and soft material causing the MR effect as described in this article also have a potential for achieving a great industrial or engineering breakthrough in creating high-value-added products too. Using these materials, higher-cost-performance advanced equipment and systems can be developed and commercialized to deliver unique functions by making full use of the rare smartness that the viscoelasticity can be varied with the application of a magnetic field. I hope this article will help realize the expectation.




(a) Laminated MRE seismic base isolator




(b) Application in a same direction (c) Application in different directions

**Fig. 16** Laminated MRE seismic base isolator and its magnetic field control by the direction of application of coil current

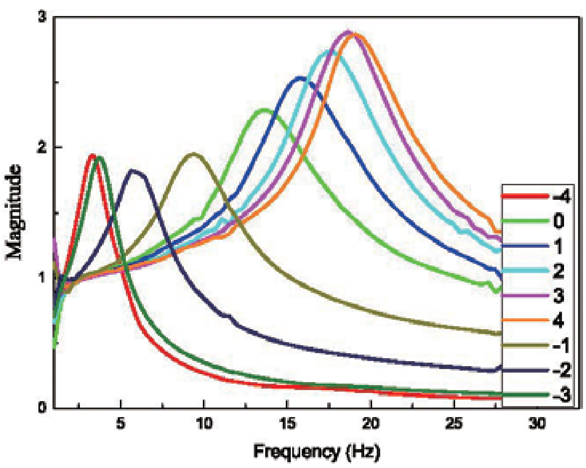



**Fig. 17** Frequency transmissibility characteristics of laminated MRE seismic base isolator with variable rigidity feature (resonance frequency change with coil current *I* A)


### References

1) Nakano, M., Yamamoto, H., Jolly, M.R.: Dynamic viscoelasticity of a magnetorheological fluid in oscillatory slit flow, Int. J. of Modern Physics B, Vol. 13, No. 14, 15&16, 2068/2076 (1999)
2) Nakano M.: Development of a magnetic-field-applicable rheometer and magneto-rheology measurement of MR fluid, Fluid Power System, Vol. 48, No. 2, 78/81 (2017)
3) Nakano M.: Trend of research & development and practical use of functional fluids, Fluid Power System, Vol. 47, No. 6, 265/271 (2016)
4) Murakami T, Sakai M, Nakano M.: Development of a passive type MR damper with variable damping characteristics dependent on the displacement and velocity, Transactions of the Japan Society of Mechanical Engineers (JSME), Series C, Vol. 77, No. 774, 257/269 (2011)
5) Nakano M.: MR fluid actuator for power-assisted equipment, Hydraulics & Pneumatics, Vol. 54, No. 3, 34/39 (2015)
6) Nakano M, Michitsuji Y.: Development of an MR fluid brake and its application to electric vehicles, Motion control and dynamic wireless power transfer for electric vehicles, Hori Y. and Yokoi Y. (editors), NTS, 116/129 (2019)
7) Nakano M.: Development of MR fluid composite and its application, Fluid Power System, Vol. 42, No. 1, 41/45 (2011)
8) Nakano M., Kumasaka T., Kudou R.: Development of MR fluid composite brake and its application to wire tension control system for coil winding, Transactions of the Japan Society of Mechanical Engineers (JSME), Series B, Vol. 75, No. 753, 993/999 (2009)
9) Nakano M, Yang J., Sun S., Totsuka A., Fukukita A.: Development and damping properties of a seismic linear motion damper with MR fluid porous composite rotary brake, Smart Materials and Structures, Vol. 29, No. 11, Article No. 115043, 1/13 (2020)
10) Nakano, M., et al.: Magneto-rheological effects and fluidity improvement of novel dry MR fluids, Proceedings of the 10th JFPS International Symposium on Fluid Power, Fukuoka, Japan, Paper No. 1B11, 1/5 (2017)
11) Tian T., Nakano M.: Fabrication and dynamic viscoelastic properties of silicone rubber-based MR elastomers with silicone oil, International Journal of Applied Electromagnetics and Mechanics, Vol. 59, No. 1, 349/355 (2019)
12) Sun S., Deng H., Yang J., Li W., Du H., Alici G., Nakano M.: An adaptive tuned vibration absorber based on multilayered MR elastomers, Smart Materials and Structures, Vol. 24, No. 4, Article No. 045045, 1/13 (2015)
13) Yang J., Sun S., Tian T., Li W., Du H., Alici G., Nakano M.: Development of a novel multi-layer MRE isolator for suppression of building vibrations under seismic events, Mechanical Systems and Signal Processing, Vol. 70-71, 811/820 (2016)