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Effect of stick-slip on magneto-rheological elastomer with a magnetic field

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Abstract: This study investigated the stick-slip characteristics of a magneto-rheological elastomer (MRE) against an aluminum plate. Herein, the MRE was manufactured, and a stick-slip tester was employed to evaluate the stick-slip performance of the MRE under different velocities and load conditions with and without a magnetic field. The fast Fourier transform (FFT) of the friction force of the stick-slip and the roughness of the aluminum plate surface were calculated to confirm the stick-slip phenomenon. After the tests, the wear surfaces were observed to evaluate the wear properties of the MRE regarding the stick-slip. Results showed that the stick-slip was smaller at lower velocity. At higher velocity, the reduction of the stick-slip under a magnetic field was more clearly observed. Moreover, the wear reduced with reduced stick-slip under a magnetic field.

Keywords: stick-slip; friction; wear; magneto-rheological elastomer

1 Introduction

Magneto-rheological (MR) materials are intelligent materials with rheological properties that can be rapidly and reversibly controlled by the application of an external magnetic field. This effect was first studied by Jacob Rabinow [1]. The MR elastomer (MRE) is a type of MR material, and its hardness or shear modulus can be changed under a magnetic field [1, 2]. Compared to the MR fluid (MRF), the advantages of the MRE include the prevention of the carbonyl iron (CI) particles from settling on them over time; the need for their storage in a container is eliminated. Moreover, the response time of the MRE is relatively short. Because of these properties, the MR effect of MREs is widely studied, and they are applied in mechanical and automotive industries [2–10]. Owing to the wide use of elastomers for mechanical applications, such as tires and vibration reduction or absorption components, the MRE can also provide a wider range of study and application opportunities.

Numerous studies have been conducted on MREs to control vibration in mechanical systems. For example, the Ford Research Laboratory (US) developed variable stiffness suspension bushings using MREs. Gong developed a real-time tunable stiffness and damping vibration isolator based on MREs and other studies [2–5]. The tribology properties of MREs have been studied because the hardness of MRE can be changed by an applied magnetic field. Lee studied the tribological properties of MREs and showed that the friction coefficient of MREs can be changed under a magnetic field [6, 7].

Stick-slip is a special tribological phenomenon that can lead to vibration, noise, wear and reduce the lifetime of friction pairs [11–13]. Therefore, studies have been performed to reduce stick-slip. The relation between stick-slip and Schallamach waves has been studied to reduce the stick-slip and wear under various loads and velocity conditions [14–17]. The generation
of stick-slip is mainly due to the difference between the static and dynamic friction forces [11–13]. Stick-slip can be reduced when the difference between the static and dynamic friction forces is reduced, which has been widely studied through various modeling methods [18, 19].

In previous studies, the friction properties of MREs have been confirmed to change under a magnetic field by changing the hardness. Moreover, it is possible to reduce the difference between the dynamic and static friction forces to reduce the stick-slip by changing the strength of the applied magnetic field. However, until now, the stick-slip properties of MREs have not been well studied, particularly through experiments. In this study, MREs were tested with various loads and velocities under a magnetic field. The friction force was measured to evaluate the stick-slip phenomenon, and the average friction force and its standard deviation (SD) were calculated. The fast Fourier transform (FFT) of stick-slip and the roughness of an aluminum plate were compared, and the wear surfaces of the MREs were observed using an optical microscope to evaluate the wear under different experimental conditions.

2 Preparation of the MRE sample

Based on previous studies that showed silicon-based MREs have the best MR effect, silicon was used as the matrix for the MREs in this study [1, 6, 7]. The fabrication process of the MRE comprises mixing, pre-configuration, solidification, and cooling. Before solidification, vacuum processing is conducted to eliminate any air bubbles in the MRE because air bubbles can affect the MR effect or durability. The thickness of the MRE specimen is set as 15 mm by considering the strength of the magnetic field, MR effect, and hardness. Figure 1 shows a photograph of the MRE. A circular plate with a diameter of 60 mm is designed to ensure the applied magnetic field is uniform.

Scanning electron microscope (SEM) images of the fabricated MRE are shown in Fig. 2. White CI particles are observed to be distributed in the black region, which is the silicon matrix. The average size and content by weight of the CI particles are about 10 μm and 79.8% ± 2.0%, respectively.

3 Experimental setup and conditions

Figure 3 shows a schematic of the stick-slip tester for the MRE. The tester comprises a power supply, push-pull gauge (IMADA DS2-50N), slider, electromagnet, and the MRE. The MRE is placed below the electromagnet, where the load is applied. The electromagnet and MRE are fixed in the plastic case, which is connected to a slider. The slider is driven by LabVIEW, and the friction force is measured by a push-pull gauge. The measured friction forces are collected in real time by a personal computer, which also controls the current through a power supply to adjust the magnetic field of the electromagnet. Undesired magnetic fields due to magnetization make it difficult to compare the results of the stick-slip properties of the MRE; therefore, all the equipment was made of plastic or aluminum, which are widely used in various mechanical systems and are not affected by the
magnetic field. The friction force is related to the hardness, which was indirectly measured for each MRE before the tests, with and without a magnetic field, using a durometer (Mitutoyo HH-336-01 shore durometer).

The detailed test conditions are described in Table 1. The stick-slip is closely related to the applied velocity and load. Because the silicone-based MRE is a soft material, it is only suited for used under low-load test conditions to prevent excessive damage. The appropriate velocity was also chosen for reducing the temperature effect on the surface of the MRE, which can cause damage under high velocity. The effect of stick-slip was studied under different velocities of 20, 10, and 1 mm/s with a fixed load of 1.0 kgf, and then under different loads of 1.2, 1.5, and 2.0 kgf with a fixed velocity of 1 mm/s. Each test was performed both with and without a magnetic field. The wear surfaces of the MREs were observed using an optical microscope.

In practical applications, MREs are mainly used in real-time control systems. By adjusting the external magnetic field, the required properties of MREs can be obtained. Real-time control tests are required to study the stick-slip characteristics of MREs when the magnetic field is varied. Tests were conducted under loads of 1.0 and 1.2 kgf with a fixed velocity of 1 mm/s or 5 mm/s. The magnetic field was applied at the middle time point of the experiment. Each test was conducted more than two times. The average friction force and SD were calculated to analyze the stick-slip.

### Table 1

| Test No. | Velocity (mm/s) | Load (kgf) | Magnetic field (80 mT) |
|----------|----------------|------------|-----------------------|
| a        | 20             | OFF        |
| b        | 20             | ON         |
| c        | 10             | 1.0        |
| d        | 10             | ON         |
| e        | 10             | OFF        |
| f        | 10             | ON         |
| g        | 1.0            | OFF        |
| h        | 1.0            | ON         |
| i        | 1.5            | OFF        |
| j        | 1.5            | ON         |
| k        | 2.0            | OFF        |
| l        | 2.0            | ON         |

### 4 Results and discussion

Before conducting the tests, the hardness of the MRE was measured with and without a magnetic field, and the results revealed that the hardness of the MRE increased to 12.5 HA under an 80-mT magnetic field, which is higher than the hardness measured when no magnetic field was applied (10.5 HA). Figures 4 and 5 show the stick-slip results of the MRE under different velocities and loads from tests a to l in Table 1.

Figures 4(a), 4(b), and 4(c) show the results of the friction force under a load of 1.0 kgf and velocities of 20, 10, and 1 mm/s without and with a magnetic field.
Figure 4(a) shows that the rate of frequency change of the friction force increased with the magnetic field. The hardness of the MRE increased and became more similar to the hardness of the aluminum plate. The difference between the hardness of friction pairs reduced, thus reducing the stick-slip. Figure 4(b) shows that the rate of frequency change of the friction force increased and the variation amplitude of the friction force decreased under the magnetic field. These results show that stick-slip can be reduced using a magnetic field under relatively high velocity conditions. Figure 4(c) shows the friction force results under a load of 1.0 kgf with a velocity of 1 mm/s. There is a small change in the frequency of the friction force but hardly any change in the amplitude with and without a magnetic field. It is assumed that the stick-slip was not affected by the magnetic field under a low velocity condition.

In theory, the dynamic friction force is not related to velocity because there is no change in the pressure and area due to the force [20]. However, the dynamic friction force was small when the velocity was increased because of the changes of the contact surface, which has been confirmed in previous studies [20–22]. It can be speculated that the dynamic friction force increases with decrease in velocity. The difference between the static and dynamic friction forces becomes small, and the stick-slip is also small.

The friction force test results under different load conditions are shown in Figs. 5(a), 5(b), and 5(c), which were obtained with a velocity of 1 mm/s and loads of 1.2, 1.5, and 2.0 kgf, without and with magnetic field. Results of the rate of frequency change of the friction force without and with the magnetic field show no differences in Fig. 5(a), which is also the case for Fig. 5(b). However, the variation amplitude of the friction force increased after 75 s during the test without a magnetic field, which was not shown in the test with a magnetic field in Fig. 5(b) and is the same as that in Fig. 5(c). A possible reason is that the surface deformation increased without the magnetic field when a high load was applied. When a high load was applied, the deformation of the MRE without a magnetic field was larger than that with a magnetic field because the hardness of the MRE without the magnetic field is lower. The larger surface deformation results in an irregular surface state, which may lead to a large change of friction force or a large stick slip.

In general, the hardness of MRE increases and the friction force decreases under a magnetic field, but the results in the figures show contradictory results. A possible reason for this is that the silicon-based MRE

![Fig. 4](https://mc03.manuscriptcentral.com/friction)

**Fig. 4** Results of friction force tests under load of 1.0 kgf without and with a magnetic field: (a) velocity of 20 mm/s, (b) velocity of 10 mm/s, (c) velocity of 1 mm/s.
is soft. The actual contact area of the MRE with the aluminum plate without a magnetic field is smaller than that with a magnetic field, which leads to a small friction force. When applying a magnetic field at the beginning of the test, the hardness of the MRE, contact area, and friction force increase compared to the case with no magnetic field. In addition, the friction force decreases with high velocity and increases with a high load, as shown in Fig. 5.

Figure 6 and Table 2 show the average friction force and the SD of tests a–l in Table 1. The friction force data were obtained from the stable friction force region. In general, the friction force with a magnetic field (tests b, d, f, h, j, and l) is larger than that without a magnetic field (tests a, c, e, g, i, and k). A possible reason for this phenomenon is the softness of the MRE (10.5–12.5 HA). The contact area and friction force under a magnetic field are larger than those without a magnetic field at the start of the tests, as previously mentioned.

The SD with a magnetic field is smaller than that without a magnetic field, except in tests a and b. The stick-slip reduces when a magnetic field is applied through the reduced SD since the difference between the static and dynamic friction forces decreases. However, tests a and b did not show the same result.

**Fig. 6** Average friction force of tests.

**Table 2** SD of tests (a)-(l) of Figs. 4 and 5.

| Test No. | Standard deviation |
|---------|--------------------|
| a       | 1.179              |
| b       | 1.288              |
| c       | 1.155              |
| d       | 0.942              |
| e       | 0.439              |
| f       | 0.226              |
| g       | 0.562              |
| h       | 0.173              |
| i       | 0.446              |
| j       | 0.325              |
| k       | 0.219              |
| l       | 0.158              |

**Fig. 5** Results of friction force tests under velocity of 1 mm/s without and with a magnetic field: (a) load of 1.2 kgf, (b) load of 1.5 kgf, (c) load of 2.0 kgf.
A possible reason is the instability of the test system under high velocity. Under high velocity conditions, the MRE may show a little displacement perpendicular to the movement direction of the MRE. This unexpected tiny displacement is assumed to increase the experiment error.

The tests show that it is possible to change the stick-slip of the MRE with a magnetic field. Another test was performed to see if the stick-slip can be controlled in real-time with a magnetic field for use in an actual application. An 80-mT magnetic field was applied after passing about half the total test distance, and the results are shown in Figs. 7(a)–7(d). Figures 7(a) and 7(b) show the results obtained with a velocity of 1 mm/s and loads of 1.0 and 1.2 kgf, respectively. All the friction forces with the magnetic field decreased by 20% compared to those when the magnetic field was not applied, but the stick-slip did not show an obvious effect under the magnetic field regarding rate of frequency changes of the friction force. Figures 7(c) and 7(d) show the results for loads of 1.0 and 1.2 kgf with a velocity of 5 mm/s. The rate of frequency change of the friction force increased in both the results under a magnetic field. The variation amplitude of the friction force also increased, as shown in Fig. 7(d). The stick-slip decreased obviously under high velocity with a magnetic field.

Table 3 shows the average friction force and SD from the results in Fig. 7. The friction force is reduced by about 20% when the magnetic field is applied. The magnetic field is not applied at the start of the test, but is applied in the middle of the test. The contact area is constant and the hardness of the MRE increases in the later part of the tests. Therefore, the friction force is decreased when a magnetic field is applied. The SD with a magnetic field is similar to that without a magnetic field under the low velocity conditions. Under the high velocity conditions, the SD with a magnetic field is clearly smaller than that without a magnetic field. It is shown that the stick-slip is significantly reduced with a magnetic field under a high velocity condition.

Fig. 7 Results of friction force tests: (a), (b) velocity 1 mm/s, load 1.0 and 1.2 kgf, respectively; (c), (d) velocity 5 mm/s, load 1.0 and 1.2 kgf, respectively.
Table 3  Average friction force and SD of tests a–d of Fig. 7.

| Test No. | Average friction force (N) | Standard deviation |
|----------|---------------------------|--------------------|
|          | Magnetic field OFF | Magnetic field ON | Magnetic field OFF | Magnetic field ON |
| a        | 10.08 | 8.47 | 0.131 | 0.192 |
| b        | 12.00 | 10.19 | 0.179 | 0.170 |
| c        | 10.14 | 7.85 | 0.409 | 0.186 |
| d        | 11.87 | 10.06 | 1.025 | 0.791 |

Figure 8 shows the FFT of the stick-slip and that of the aluminum plate surface roughness. The roughness is measured with a two-dimensional surface roughness measuring instrument (SV-3100S4 Mitutoyo). The results confirmed that the stick-slip result (Fig. 8(b)) is not directly related to the surface roughness of the aluminum plate (Fig. 8(a)). The surfaces of the MREs after the stick-slip tests were observed with an optical microscope to evaluate the wear with and without a magnetic field. Figures 9(a)–9(f) show surface images of the MREs for test conditions of 10 mm/s with 1.0 kgf, 1 mm/s with 1.0 kgf, and 1 mm/s with 1.2 kgf, respectively, whose SDs have relatively large gaps between the conditions with and without a magnetic field.

Figures 9(a) and 9(b) show surface images of the MRE under conditions of 10 mm/s and 1.0 kgf, without and with a magnetic field, respectively. The Schallamach waves [23–26] were more obvious without the magnetic field than those with the magnetic field. Figure 9(c) shows slightly heavy wear compared to Fig. 9(d), which was obtained with a magnetic field. A wear hole was found in Fig. 9(e), and the Schallamach waves were more obvious than those in Fig. 9(f), which was obtained with a magnetic field. In general, the wear of the elastomer is related to the friction force for the same material. More friction force corresponds to more wear as the surface temperature increases. The friction force increases under a magnetic field, and the wear should be more obvious than that without a magnetic field. However, the tests show the opposite results. It is assumed that the stick-slip results in wear and is reduced when a magnetic field is applied.

5 Conclusions

Stick-slip can lead to vibration, noise, wear, and reduce the lifetime of friction pairs. For this reason, the stick-slip should be reduced as much as possible. The MRE is a type of smart material that can change its properties under an external magnetic field. This property can be used to change the stick-slip to replace other materials.

In this paper, the MRE was manufactured, and a stick-slip tester was used to evaluate the stick-slip under different velocities and load conditions with and without a magnetic field. The results show that at lower velocity, the stick-slip was smaller, while at higher velocity, the reduction of the stick-slip under a magnetic field was more obvious. The change of the friction force was more stable under a magnetic field. The FFT of the friction force of stick-slip and the aluminum plate surface roughness were calculated to determine that the stick-slip phenomenon is not directly caused by the roughness of the aluminum plate under low velocity conditions. The wear surfaces were observed after the tests, and the results showed that the wear can be reduced when the stick-slip is reduced under a magnetic field. Based on this study, the MRE could potentially be applied to a wide range of various
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