EXPERIMENT OF SELF-SENSING AND STIFFNESS VARIATION OF MAGNETORHEOLOGICAL GEL FOR A FLEXIBLE STIFFNESS CONTROLLABLE DEVICE

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Abstract- In this paper, the properties of self-sensing and stiffness variation of a smart material magnetorheological (MR) gel is analyzed as a feasibility study of designing a flexible stiffness controllable system such as a smart joint for a robot leg. An MR gel is a special material which is soft and flexible that can change its stiffness and resistance with external magnetic field. In this study, experiments are conducted to derive the relationship among the resistance, stiffness and magnetic field. From the experiment results, the resistance of the gel could be controlled from 180kΩ up to 630kΩ and the stiffness could be controlled by 135% with magnetic field under 250mT. Thus, it can be concluded that the MR gel has a high potential as a flexible stiffness controllable system with self-sensing function.

Index Terms- Magnetorheological Gel, stiffness variable, self-sensing, stiffness control.

I. INTRODUCTION

Magnetorheological(MR) materials are smart materials that can change the viscoelastic properties such as stiffness and damping with external magnetic field. The MR materials are classified as MR fluid, elastomer or gel depending on their base matrix. Inside an MR material, there are carbonyl iron particles(CIP) which tend to align in chain structures when magnetic field is applied, that consequently change the damping and stiffness of the material. This phenomena is also known as the magnetorheolocial effect (MR effect) [1-3].

Using the controllable viscoelastic properties of MR materials, numerous applications have been researched especially for vibration isolation. Li et al. [4] proposed a vibration absorber for earthquakes with MR elastomer layers. Kim et al [5] studied a MR elastomer tunable vibration absorber (TVA) to suppress the unwanted disturbances by increasing the stiffness of MR elastomer under magnetic flux of 240mT. Shin et al [6] implemented a MR gel type of tunable vibration absorber(TVA) that could tune the frequency from 34 Hz to 74Hz. Also, there are several on-going studies to apply MR material in a variety of engineering fields such as stiffness variable joint for robotic legs.

Recently, it is found that the stiffness variation of MR elastomer and gel can be estimated by measuring the magnetoresistance of the material [7]. From the studies, there is a non-linear correlation between the stiffness of the material and the magnetoresistance, which both change with magnetic field. Using this self-sensing property of the material, additional sensors and electric components are not required to control the stiffness of the material for the level of stiffness change can be easily estimated by measuring the magnetoresistance. However, only the resistance variation of an MR gel when a DC voltage is supplied were studied in the literature. The resistance variation of MR gel when AC voltage signal is supplied should also be analyzed to comprehend the self-sensing of the material more fully.

Therefore, in this paper, the self-sensing and stiffness variation of a magnetorheological gel are studied as a feasibility study of designing a smart stiffness variable system for a robot. First, an experiment setup is designed to analyze the response of resistance variation under various magnetic field when DC and AC voltage signals are supplied.
Then, the relationship between the stiffness and the magnetic field is derived by conducting a vibration modal test. In order to control the magnetic field efficiently, a novel magnetic field generator is proposed that consumes far less energy than a typical electromagnet. From the experimental data, the correlation between the stiffness and magnetoresistance is derived.

II. EXPERIMENT OF SELF-SENSING OF MR GEL

First, a sample of MR gel of dimension Φ25x15 mm is prepared by mixing carbonyl iron particle(CIP) of 70% by weight to a mixture of carrageenan solution[7], as shown in Fig 1.

Then, an experiment is setup to measure the magnetoresistance of MR gel sample. To supply an electric voltage to the MR gel, aluminum plate with wires are connected to both ends of gel. In series to the

MR gel, a resistor of 2.2 MΩ is connected that acts as a voltage divider.

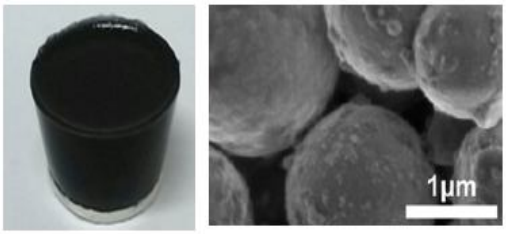


Fig 1. Sample of MR gel and the SEM image

A DC voltage of 10 V is supplied to the MR gel using a power supply and the resistance is calculated by measuring the voltage across the gel using an oscilloscope. Experiment is repeated under different magnetic field.

The initial resistance of the gel, with no magnetic field applied, is measured to be about 158 kΩ, as shown in Fig. 2. The resistance increased highly to 630 kΩ by applying 50mT of magnetic field but it decreased gradually but nonlinearly as the magnetic field increased. The gradual decrement of the resistance starting from 50mT is due to the chains formed by the embedded iron particles. As the magnetic field increases, the iron particles are forced to cluster to one another to be aligned in chain structures which consequently decrease the overall resistance. However, the phenomena of the sudden increment of resistance from 0 mT should be investigated with further experiments.

The same experiments are repeated but now with supplying AC square signal of 10 V, in order to derive the relationship between the magnetoresistance and the input voltage frequency. It is observed that the resistance of the gel decreased as the frequency of the input voltage increased. This tendency is similar to the change of impedance of a capacitor, which is inversely proportional to the input frequency. At 50 mT of magnetic field, the resistance of MR gel with AC 1kHz is measured to be 310 kΩ while it is 260 kΩ for AC 10Hz. For the same frequency, the overall resistance decreased gradually as the magnetic flux increased, as observed in DC input experiment. Also, it is interesting to note that for all results, there is a sudden jump of resistance increase from 0mT to 50mT.

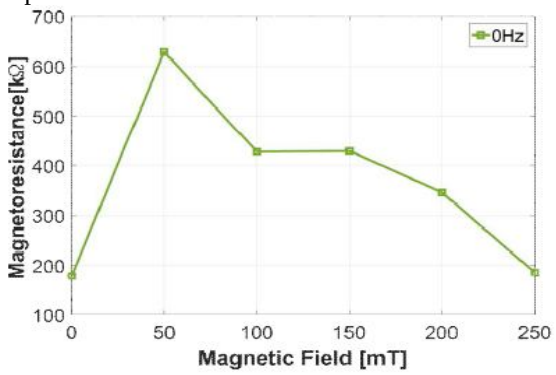


Fig 3. MR gel resistance with DC input voltage

III. EXPERIMENT ON STIFFNESS VARIATION

A. Design of Magnetic Field Generator

To control the stiffness of MR material, almost all literatures use an electromagnet to apply magnetic field. One severe disadvantage of an electromagnet is that it consumes high power to generate a constant magnetic flux continuously that leads to heating problem.

In order to solve the aforementioned problem, this paper proposed a new concept of magnetic field generator based on permanent magnets which is more energy efficient than a typical electromagnet. As shown in Fig. 4, the permanent magnets rotate inside the shield structure composed of non-ferromagnetic material by controlling a small stepper motor. Thus, a range of magnetic field can be applied to MR gel by controlling the angle(θ) of the magnet from 0 to 90 degrees. Using a gaussmeter, the range of magnetic field by the designed device is measured to be 0-164mT.

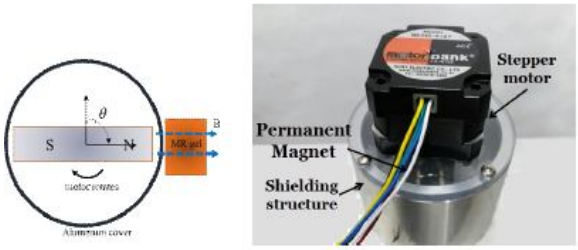


Fig 4. Proposed a compact magnetic flux generator

B. Stiffness Variation Experiment

Since it is difficult to measure the stiffness of MR gel directly, a modal test is conducted by using a shaker as shown in Fig. 5. An aluminum block of 0.116kg is placed on top of the MR gel to make a simple mass--damping-spring system as

$$m_{gel}\ddot{x} + c_{gel}\dot{x} + (k_{0,gel} + \Delta k_{gel}(B))x = F \qquad (1)$$

where x is the displacement of the block, m_g =0.167kg is the total mass of the gel and the block, c_{gel} is the damping coefficient, k_0 is the initial stiffness and Δk is the stiffness variation due to external magnetic field *B* supplied by the proposed magnetic field generator.

The modal test is conducted with sine sweep signals and the frequency response function of the MR gel system is analyzed under various magnetic field from 0 mT to 164 mT. As shown in Fig. 6, the damped resonance of the system, which is the peak of the curve, varied from about 26 Hz to 38Hz. Using the definition of damped resonance which is

$$\omega_d = \omega_n\sqrt{1-\zeta^2} \qquad (2)$$

where

$$\omega_n = \sqrt{\frac{k}{m}}, \ \zeta = \frac{c}{2m\omega_n},$$

the stiffness of MR gel can be estimated from

$$k = \frac{m\omega_d^2}{1-\zeta^2}. \quad (3)$$

From the experiment results, it is calculated that the stiffness of MR gel changed from 1.40 kN/m to 3.29 kN/m under 164mT, which is about 135% of stiffness increment.

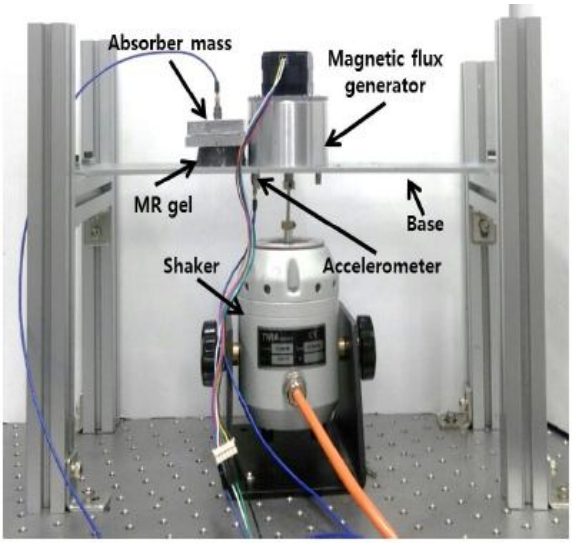


Fig 5. Experiment setup to estimate stiffness variation of MR gel

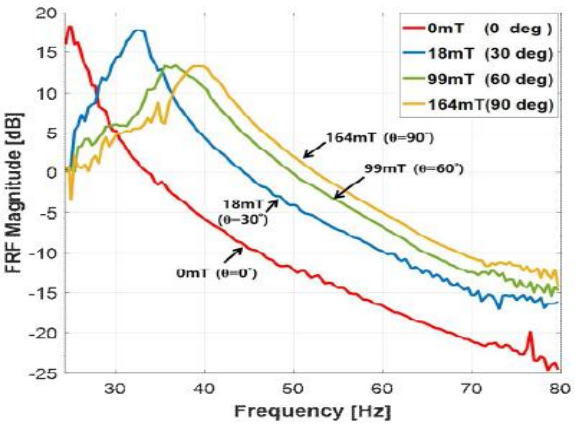


Fig 6. Variation of damped resonance frequency under different magnetic field

CONCLUSION

In this paper, experiments are conducted to analyze the resistance and stiffness variation of magnetorheological(MR) gel under magnetic field. To supply a magnetic field with low power consumption, a novel magnetic field generator is designed and tested. Also, the relationship among the stiffness, resistance and magnetic field have been derived from experiment results. It is showed that the resistance of the gel could be varied from 180kΩ up to 630kΩ and the stiffness could be controlled by 135%.

Further investigation are required to fully understand the sudden increment of resistance from its initial state without magnetic field. Also, the non-linear correlation between the stiffness and the resistance should be derived in a mathematical function in order to apply the MR gel as a self-sensing stiffness variable system.

ACKNOWLEDGEMENT

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REFERENCES

[1] J. D. Carlson and M. R. Jolly, "MR fluid, foam and elastomer devices," mechatronics, vol. 10, no. 4, pp. 555–569, 2000.

[2] C. Bellan and G. Bossis, "Field dependence of viscoelastic properties of MR elastomers," Int. J. Mod. Phys. B, vol. 16, no. 17n18, pp. 2447–2453, 2002.

[3] J. M. Ginder, S. M. Clark, W. F. Schlotter, and M. E. Nichols, "Magnetostrictive phenomena in magnetorheological elastomers," Int. J. Mod. Phys. B, vol. 16, no. 17n18, pp. 2412–2418, 2002.

[4] Y. Li, J. Li, T. Tian, and W. Li, "A highly adjustable magnetorheological elastomer base isolator for applications of real-time adaptive control," Smart Mater. Struct., vol. 22, no. 9, p. 95020, 2013.

[5] Y.-K. Kim, J. H. Koo, K.-S. Kim, and S. H. Kim, "Suppressing harmonic vibrations of a miniature cryogenic cooler using an adaptive tunable vibration absorber based on magneto-rheological elastomers," Rev. Sci. Instrum., vol. 82, no. 3, p. 35103, 2011.

[6] B.-C. Shin, J.-H. Yoon, Y.-K. Kim, and K.-S. Kim, "Note: Vibration suppression using tunable vibration absorber based on stiffness variable magneto-rheological gel," Rev. Sci. Instrum., vol. 86, no. 10, p. 106106, 2015.

[7] M. Yu, B. Ju, J. Fu, S. Liu, and S.-B. Choi, "Magnetoresistance characteristics of magnetorheological gel under a magnetic field," Ind. Eng. Chem. Res., vol. 53, no. 12, pp. 4704–4710, 2014.

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