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DEVELOPMENT OF THE VARIABLE FRICTION CLUTCH APPLYING THE FUNCTIONAL MEDIUM

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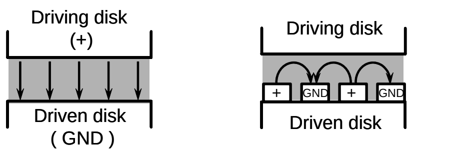
ABSTRACT
A new functional material known as electro-rheological gel (ERG) has been developed that has variable surface friction according to an applied electric field. It was expected that ERG could be applied to a machine element, because the frictional force of an ERG surface can be controlled electrically. In this study, an ERG clutch element, using the one-sided electrode configuration, was developed and the performance of the ERG clutch was numerically and experimentally evaluated. The ERG clutch shows excellent performance for static and dynamic characteristics in torque transfer.
Keywords: functional material, ER fluids, friction clutch

1. INTRODUCTION
Electro-rheological fluid (ERF) [1] is one type of functional fluid with viscoelastic properties which vary with the intensity of an applied electric field. In recent studies, we have succeeded in developing a new functional material called electro-rheological gel (ERG) [2] by the gelation of ERF. The ERG, which is composed of ER particles and silicone gel, varies its surface friction according to an applied electric field. This characteristic is called the ER effect of ERG. The mechanism for this effect is due to the changes in contact conditions at the interface between the electrode and ERG, in response to the change in intensity of the electric field. It is expected that the ERG could be used in a force transfer device, because the frictional force of ERG surface can be electrically controlled.
The present study proposes that a one-sided electrode configuration is applied to the ERG in order to simplify the wiring structure and enable application of this functional material in various fields. Fig. 1 shows the concept of electric field using both-sided and one-sided electrode configurations. As shown in Fig. 1(a), parallel lines of electric force are generated for both-sided electrodes. On the other hand, complicated electric lines are generated for the one-sided electrode configuration. The ER effect has been confirmed using one-sided electrodes with ERF [3]. In the case of ERG, it is possible to realize the ER effect under an electric field, using the one-sided electrode configuration, which passes through the ERG, as shown in Fig. 1(b). When the ERG is used in a device with a rotating part, such as a clutch, the structure can be simplified by using the one-sided electrode configuration. In this study, an ERG clutch element with a one-sided electrode configuration was developed and the performance was evaluated both numerically and experimentally.



(a) Both-sided electrodes (b) One-sided electrodes
Figure. 1 Concept of both-sided electrodes and one-sided electrodes

2. DESIGN OF ONE-SIDED ELECTRODES

2.1. Model for numerical analysis

In a past study, it was confirmed that the ER effect relies strongly on the applied electric field [2]. The electric field in a one-sided electrode configuration passes through the ERG, and is more complex than that in a both-sided electrode configuration. Therefore, the relation between the pattern of one-sided electrodes and distribution of the electric field was investigated in order to determine the design necessary to obtain an efficient ER effect. To investigate the influence of the electrode pattern, especially the electrode gap, on the distribution of the electric field in ERG, a numerical analysis of the electric field was performed. The software for numerical analysis of the electric field was ANSYS 9.0

The model for the electric field analysis is illustrated in Fig. 2. A metallic material is used as a plate opposite to the one-sided electrodes, which are placed on the ERG sheet. The opposite metal plate was electrically insulated from the outside so that the supply of an electric charge is not generated. The width of the electrodes was fixed to 1.0 mm and the gap varied from 0.2 mm to 2.0 mm. 900 V and 0 V were applied to the anode and cathode, respectively.

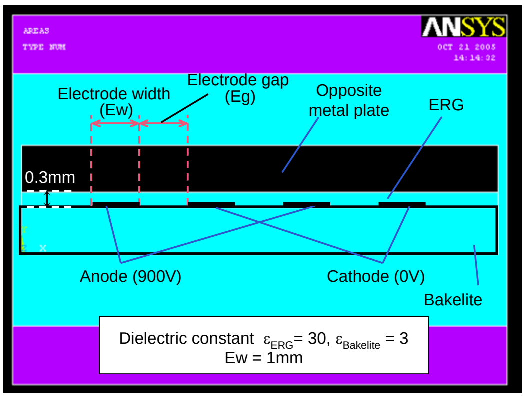


Figure 2 Model for the electric field analysis

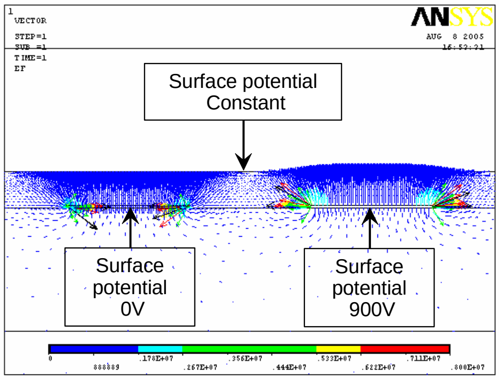


Figure 3 Distribution of electric field in opposite metal plate

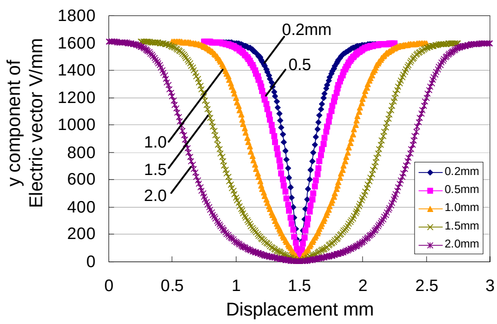


Figure 4 Distribution of y component of electric vector in case of various electrode gap of one-sided electrodes

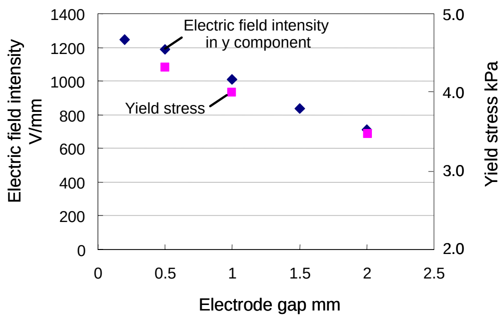


Figure 5 Relation between electric field and yield stress as function of electrode gap

2.2. Results of the electric field analysis

Fig. 3 illustrates the distribution of the electric field in the ERG for the one-sided electrode pattern. Electric lines of force are generated from the anode to the opposite metal plate and then from the plate to cathode. The ER effect is supposed to depend on the intensity of the electric field, especially the component perpendicular to the ERG surface (y component), because this effect is an interfacial phenomenon between the ERG surface and the opposite plate. The electric field intensity of the y component was evaluated for various electrode gaps on the ERG surface at the center between the two electrodes, as shown in Fig. 4. The electric field intensity above the electrodes is high, and at the middle point between the two electrodes it is almost 0 V/mm. The relationship obtained between the average value of the electric field and electrode gap is presented in Fig. 5. As the electrode gap is narrowed within the range from 0.2 to 2.0 mm, the electric field intensity increases. It was also confirmed that shear stress generated at the interface against electrode gap shows the same tendency as the intensity of the electric field.

3. DEVELOPMENT OF THE ERG CLUTCH UNIT

3.1. Structure of the ERG clutch

The electrode for an ERG clutch was designed based on the results from the numerical analysis of the electric field. The one-sided electrode configuration for the ERG clutch is shown in Fig. 6, and has a 0.2 mm electrode gap and an electrode width of 1.0 mm. Fig. 7 illustrates the structure of the ERG clutch device. The ERG on the one-sided electrode is set up with the disk of the slave shaft. The length and diameter of the master and slave shafts is 50 mm and 12 mm, respectively, and the diameter of each disk was 30 mm. To obtain an efficient ER effect, the condition of the contact between the ERG surface and the master disk is important. Thus, a low elastic rubber is inserted at the master disk, so that the master disk has uniform contact with the ERG placed on the slave side. Both

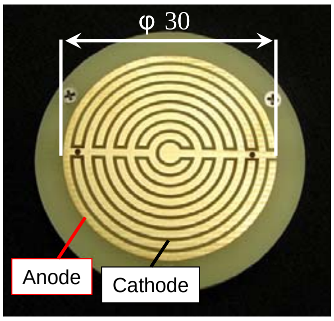
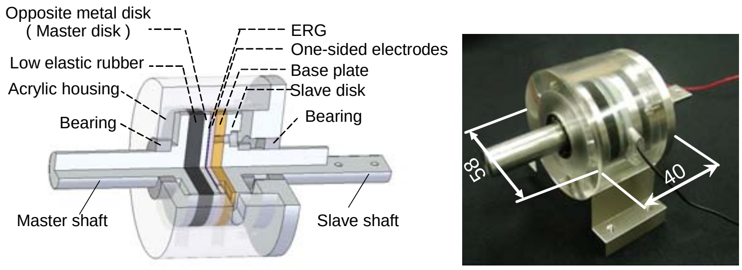


Figure 6 One-sided electrodes with 1mm width and 0.2mm gap



(a) Assembly diagram (b) Appearance

Figure 7 Structure of the ERG clutch unit

the central axes of the master shaft and slave shaft are aligned using a housing. When the shaft of the master side is rotated by the induction motor and an electric field is applied to the ERG, the torque can be transferred from the master side to the slave side.

3.2. Experimental setup and procedure

To evaluate the performance of the ERG clutch, the transferred torque was measured under various electric fields. A schematic of the experimental setup used is given in Fig. 8. The master shaft is attached directly to a motor. The lever used for measuring torque is attached to the slave shaft, and is set on a load cell. When the master shaft is rotated at constant speed and an electric field is applied to the ERG, the transferred torque is sensed as the tangential force at the top of the lever. The transferred torque can be calculated by multiplying the force by the length of the lever (46.5 mm). The rotational speed of the master shaft is adjusted to 30 min^{-1}.

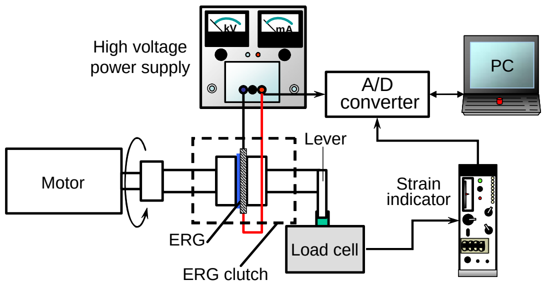
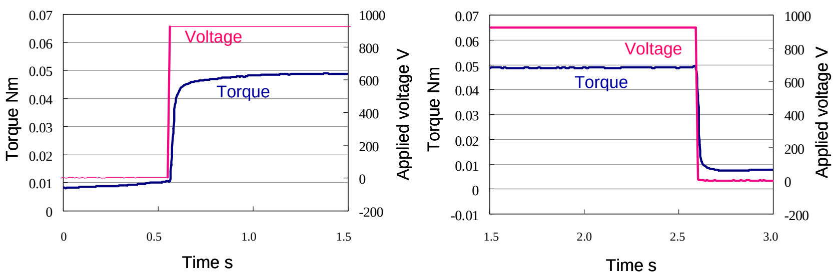


Figure 8 Experimental setup for measuring torque



(a) Voltage buildup (b) Voltage release

Figure 9 Results of step response test

Performance of the ERG clutch

An evaluation was made for the response of the transferred torque to the applied voltage. Fig. 9 shows the results of the step response test. The voltage build-up time and release time can be calculated using a time constant. Fig. 9(a) shows the relationship between the response of the transferred torque and the voltage build-up, from which the system response could be calculated. The total delay in the build-up time was calculated as 20 ms. Fig. 9(b) shows a plot of the voltage release. The total delay for the released torque is 16 ms. The response of the ER effect in the ERG to an applied electric field was almost the same as that of an ERF.

To characterize the frequency characteristics of the transferred torque, the relationship between the electric field intensity and transferred torque was investigated under an applied sinusoidal voltage (V_{max} = 900 V) at a driven motor rotation speed of 30 min^{-1}. Fig. 10 shows the results of the frequency response test at voltage frequencies of 1 and 100 Hz. Clearly, the transferred torque changed smoothly with the sinusoidal voltage. At an input voltage V_{max}, of 900 V, the torque transfer is approximately 0.063 Nm. The minimum torque transfer is 0.01 Nm, which is clearly shown in Fig. 10(a). This is the transferred torque under no electric field, which depends on the contact pressure and surface condition of the ERG. Fig. 10(b) shows the test results at 100 Hz. The transferred torque showed no significant change in response to the applied voltage. Fig. 11 shows the ratio of the amplitude of the applied electric field to that of the transferred torque. The amplitude ratio at 0.1 Hz was defined as 1, i.e., 0 dB. Fig. 12 shows the phase difference between the applied electric field and transferred torque. This indicated that the cut-off frequency for the torque transfer system was 18 Hz.

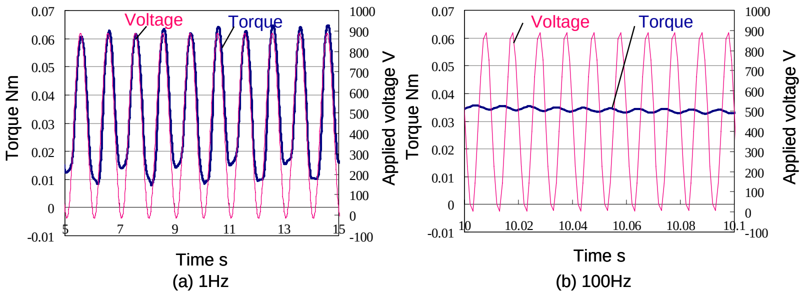


Figure 10 Results of frequency response test

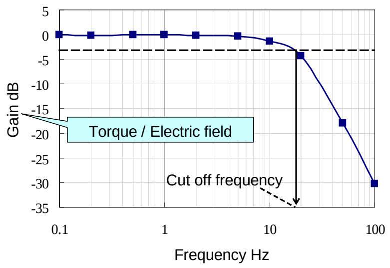


Figure .11 Relation between gain and frequency

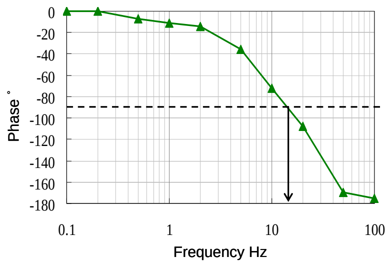


Figure.12 Relation between phase and frequency

4. CONCLUSION

This study proposes that electro-rheological gel (ERG), which changes its surface property according to an applied electric field, can be utilized for a friction clutch. In order to obtain an efficient ER effect in a one-sided electrode configuration, the relation between the electrode pattern and the ER effect was evaluated both numerically and experimentally. On the basis of numeric analysis, the shape of the one-sided electrodes for an ERG clutch was designed and the ERG clutch unit was manufactured. The ERG clutch unit shows excellent performance for torque transfer. The transferred torque changes widely and smoothly, under the application of various voltages. The response of the transferred torque to an applied electric field is enough fast for practical application, and the time constant is approximately 20 ms.

5. ACKNOWLEDGEMENT

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