Design and Development of Compact Magnetorheological Fluid Clutch (CMRFC) with Multi-layered Disks and Micro-sized Gaps

Takehito KIKUCHI†, Kikuko OTSUKI‡, Junji FURUSHO**, Hiroya ABE***, Junichi NOMA****, and Makio NAITO*****

†Graduate School of Science and Engineering, Yamagata University, Yonezawa, Yamagata 992-8510, Japan
‡Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan
***Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan
****Kurimoto Ltd., Suminoe, Osaka 559-0021, Japan

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There is a strong demand for a human-machine-coexistent machine, e.g. a power-assist system or a computer-aided rehabilitation system, in the context of the super-aging society. In such a human-machine-coexistent system, it is important to guarantee hardware-level safety by utilizing human-friendly actuators. In this paper, we developed two types of compact MR fluid clutches (CMRFC) for human-friendly actuators, which performs about 5Nm torque by applying 1A current and have two different gap-size (50 μm and 100 μm). We tested their static torque. First, we used a conventional MR fluid as a working material of the CMRFCs. Then we used new MRF, which consist of nanosized (104 nm) Fe particles. According to the experimental results, gap-size affects not only magnetic property but also easiness of filling of MRF (or particles).

Key Words: Magnetorheological fluid / MR fluid clutch / Human-friendly actuator / Torque controllable clutch / Nano-Sized Particle

1. INTRODUCTION

Due to the increasing number of aged population, there are strong demands for life-support robot systems, for example power-assist systems and so on, to aid ADL (Activities of Daily Living) of the aged people. In order to develop safe and feasible robot systems that experience direct contact with a human, we need to develop human-friendly actuators to guarantee hardware-level safety. Pneumatic power has been used in many conventional human-friendly actuators.\(^1\)\(^-\)\(^3\) However, pneumatic actuators have low elasticity and in many case it causes difficulties for accurate control. Additionally, pneumatic actuators basically need compressors that increase complexity of the system.

In our previous studies\(^4\)\(^-\)\(^5\), we have proposed a magnetorheological (MR) fluid actuator. This actuator has three components; an actuation part (motor), a reduction part (reduction system) and a torque transmission part (MR fluid clutch). This perform high speed torque response depending on the rapid response of MR fluids\(^6\), and guarantee high safety with respect to torque, speed and energy thanks to the interposition of the clutch. This system is suitable for human-machine-coexistent systems like life-support robots.

As a first stage of the development of the MR fluid clutch (MRFC), many researchers\(^7\)\(^-\)\(^8\) have developed single disk-type (or single cylindrical) clutches as shown in Fig. 1. However, these devices require large area of the MR Fluid layers to generate large transmission torque, and it caused large size of the devices. For further advancements of the MRFC, we needed to improve torque / mass ratio and reduce amount of power supply.

Fig. 1. Basic structure of a conventional disk-type MR fluid clutch.
B., et al.\(^4\) have applied a multi-plate (multi-layered disk) structure for a high-torque MRFC. However, their device has millimeters-sized gap (0.5 ~ 1.0 mm) of the MRF layers and it causes a high magnetic resistance. High magnetic resistance, at the same time, requires high power supply for sufficient generation of the magnetic field to excite effective viscosity change of the MRFs.

In terms of the gap-size, a company, Ossur Inc.\(^10\) released a controllable prosthetic knee joint that consists of a compact MRF brake with the multi-plate structure and several ten micro-sized gaps (about 40 micro meters) of the MRF layers. It is a good idea to utilize the micro-sized gaps for reduction of the magnetic resistance and power supply; however detailed characteristics of the MRF between micrometer-sized gaps have not been unveiled. Jonsdottir F., et al.\(^11\) presented influence of parameter variations on the design of the Ossur’s MRF brakes; however this paper includes only theoretical calculations without experimental results.

In this study, we compare analytical results and experimental results of static torque of the compact MR fluid clutch (CMRFC) which has the multi-layered disks structure and micro-size (50 ~ 100 micro meters) gaps of the MRF layers. We developed two types of the CMRFC which have the same basic structure and different gap-size for the MRF layers (50 \(\mu\)m and 100 \(\mu\)m). We conducted static torque tests for these devices and compare these characteristics. Additionally, we describe a new MR fluid which consists of nano-sized (104 nm) Fe particles. This material has developed to improve characteristics of the conventional MR fluids, for example, sedimentation of particles. This material was filled in one of the CMRFC and its torque characteristics were also tested in this paper.

2. COMPACT MR FLUID CLUTCH (CMRFC)

2.1 Basic Structure

A conceptual drawing of the compact MR fluid clutch (CMRFC) is shown in Fig. 2. A coil is winded around the output shaft and it generates the magnetic flux shown by the dashed line in the drawing. Multi-layered disks are fixed on the input shaft (or casing) and the output shaft, and the MRF is filled between these disks.

As shown in this figure, multi-layer structure is utilized to amplify output torque of the device. However, to make effective use of the viscous change of the MRF, we need to impress a sufficient magnetic flux on the MRF layers.\(^6\) Because the MRFs have low magnetic permeability, it is necessary to reduce thickness of the total gap of the MRF layers for reduction of the magnetic resistance. Therefore, we suggest to utilize narrow gaps of 10 ~ 100 \(\mu\)m for the MRF layers. In fact, design parameters, for examples gap-size, diameters of disks, the number of the layered disks and the number of turns of the magnetic coil, should be decided on the basis of results of magnetic analysis and limitations of processing (or assembling) accuracy. At the same time, it is necessary to analyze not only the structure but also the material, especially MRF itself. Generally speaking, particles whose diameters are more than 1/10 of gap-size are not ensured to be filled sufficiently. Because commercial MRFs\(^12\) consist of micro-sized particles (1 ~ 10 \(\mu\)m), the particles could causes unstable responses of the device with the micro-sized gap. Therefore, in this study, we also try to develop a new MRF with nano-sized particles for the narrow gap structure.

2.2 Basic Design Method and Goal

We formulated design methods to estimate static torques of the CMRFC. An analysis is performed as follows;

1. Geometric design of a CMRFC with 3-D CAD software,
2. Magnetostatic analysis to estimate magnetic flux density with CAE (FEM) software,
3. Decision of a yield stress of the MRF based on the results of the process (2) and the characteristics data of yield stress vs. magnetic flux density of the MRF,
4. Calculation of a transmission torque based on the results of the process (3) and size-parameters.

In the process (2), we need to refer to magnetic property data (or B-H curves) of ferromagnetic materials (silicon steal etc.) and the MRF (catalogue data from the reference\(^12\)) for iterative calculations on non-linearity. A commercially produced MRF (140CG, Lord Corp.) was used as an MRF in this study. In the process (3), we referred to the characteristics data between the yield stress of the MRF and the magnetic flux density at 40 degrees C (catalogue data from the reference\(^12\)). In generally, MRFs have Bingham Flow

![Fig. 2. Basic structure of a compact MR Fluid Clutch (CMRFC).](image-url)
property and their yield stress can be controlled by application of the magnetic field. Additionally, the effect of shear rate to shear stress is not significant. Therefore we can calculate the transmission torque of the CMRFC from the yield stress of the MRF.

In this paper, we decided to develop a CMRFC which can generate approximately 5Nm as a torque with an application of the electric current of 1A. We call these device 5Nm-class CMRFC, and will discuss several design parameters of them in the following section.

Figure 3 shows an analysis result of the magnetostatic analysis of a 5Nm-Class CMRFC as an example. The analyses were mainly conducted on electromagnet part and MRF layers because other parts are made of non-magnetic materials (aluminum and plastics) and it can be assumed that the magnetic flux hardly flow into them. In this analysis we set a goal of magnetic flux density of 0.5 T, because, if the magnetic flux density is less than 0.5 T, we cannot make effective use of the viscosity change of the MRF.

According to the result of the magnetostatic analysis, we decided to use 9 input disks and 8 output disks for the target device. Therefore, the number of the MRF layer is 18. The diameter of each disk is 40 mm and the length of the MRF layer on the disk is 5 mm from the outer edge of it. We decided 50 μm as a gap size for the MRF layer in the first trial of the analysis. More detailed discussion on the gap size is conducted in the next session. The other geometric information for the magnetic core (yoke) is shown in Fig. 4.

2.3 Effect of Gap-size

As a basic model, we decide 50 μm as a gap size for the MRF layers. However, more detailed analysis is needed because the gap size relates with other factors, for example required processing accuracy, assembling accuracy, cost and so on. It is hard task to accurately maintain 50 μm-gaps for multi-layered disks. Then we analyzed more detailed condition on the gap-size with same conditions for other design parameters (the number and diameter of the disks, and so on). Figure 5 shows analytic results for each gap-size. The horizontal axis indicates electric current applied to the coil [A], and vertical axis indicates output torque of the devices [Nm]. As shown in this figure, the increasing gap-size causes the reduction of the maximum torque; however, due to the non-linear magnetic characteristics of the materials, the gap-effect becomes small in high current region. For example, torque ratio of 50 μm-gap to 100 μm-gap at 0.4 A of the electric current is about 1.6; however, that at 1.0 A is about 1.1. If we consider total cost / performance factors, it would be better to use 100 μm-gap or larger gaps in the practical devices. In this paper, we decided to develop two types CMRFC by applying 50 μm-gap and 100 μm-gap, and test their static torque experimentally.
2.4 5Nm-class CMRFC

On the basis of the multi-layered structure (Fig. 2), we developed the 5Nm-Class CMRFCs. Figure 6 shows a picture and a cross-sectional view. Table I shows specification data of the 5Nm-Class CMRFC. Multi-layered disks are fixed with an accurate gap of 50 μm or 100 μm. The MRF (Lord Corp., 140 CG) is filled between these gaps.

When we use this device as a clutch, a flange is fixed on a casing and the casing is rotated as an input part of the clutch. On the other hand, we can use this device as a compact MRF brake by fixing the casing on an immovable part. A piston mechanism is used to prevent a leak of the MRF from a thermal expansion. The core of the electromagnet is made of silicon steel. The casing is made of aluminum. The diameter of the magnetic wire is 0.2 mm.

3. EXPERIMENT

3.1 Setup

Figure 7 shows the experimental setup to test torque characteristics of the CMRFCs. This system includes following parts:

1. A direct drive motor (NSK corp., Japan) on the right hand of the system,
2. A belt-pulley system to connect the motor and target devices on the top of the motor,
3. A belt-tension-type torque sensor in the middle of the belt-pulley system,
4. A target device (CMRFC) on the left hand of the system.

Target devices in this section are the 5Nm-Class CMRFC with 50 μm-gap and 100 μm-gap. An MR fluid of Lord Corp., MRF-140CG (particle size: 1 ~ 10 μm, average 5 μm) was used as a working material. During tests, the input part (or casing) of the clutch was fixed on an immovable plate and the output shaft was rotated by the servo-motor with constant speed.

3.2 Result

Static torque tests were conducted. Rotational speed of the output shaft was controlled at 3.0 rad/s accurately. An electric current was applied at a constant value and an average transmission torque was measured. The experimental results

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total thickness [mm]</td>
<td>32</td>
</tr>
<tr>
<td>Outer diameter [mm]</td>
<td>52</td>
</tr>
<tr>
<td>Diameter of disks [mm]</td>
<td>40</td>
</tr>
<tr>
<td>Number of disks</td>
<td>9(input)+8(output)</td>
</tr>
<tr>
<td>Number of MRF layers</td>
<td>18</td>
</tr>
<tr>
<td>Gap size of MRF layers [μm]</td>
<td>50 / 100 (2types)</td>
</tr>
<tr>
<td>Number of turns of coil</td>
<td>191</td>
</tr>
<tr>
<td>Idling torque [Nm]</td>
<td>0.15</td>
</tr>
<tr>
<td>Torque at 1A [Nm]</td>
<td>&gt;5.0</td>
</tr>
<tr>
<td>Mass [g]</td>
<td>237</td>
</tr>
</tbody>
</table>

Fig. 6. 5Nm-Class CMRFC.

Fig. 7. Experimental setup for torque tests of MRFCs.
are shown in Fig. 8 (a) and (b).

Black circles mean transmission torque of experimental results. White circles mean the results of the analysis mentioned in the previous section. As shown in the figure, the experimental result for 100 \( \mu \text{m-gap} \) indicates good similarity to the analytical result. Meanwhile, the result for 50 \( \mu \text{m-gap} \) has error of 10-20% between analytic and experimental results. This would result from insufficient filling of the MRF (or particles) against 50 \( \mu \text{m-gap} \).

4. MR FLUID USING NANO-SIZED Fe PARTICLES

4.1 Purpose and Material Preparation

The majority of existing MRF is composed of micron-sized Fe particles suspended in a nonmagnetic carrier fluid. The particles may lead to unwanted abrasion of the components in contact with the fluid. Also, they are susceptible to settling in the absence of frequent mixing due to predominant gravity forces. Nanoparticle dispersed fluid would be desirable.

Figure 9 (a) shows TEM image of the spherical Fe nanoparticles used in this study. The Fe nanoparticles were synthesized by the arc-plasma method. \(^ {13} \) The diameter of the Fe nanoparticles estimated from their specific surface area was 104 nm. The saturation magnetization of the Fe nanoparticles was evaluated to be \(-190 \text{ emu/g} \) from their magnetization curve. After the surface modification with silane coupling agent, the Fe nanoparticles were dispersed in silicone oil (KF96-50cs, Shin-Etsu chemical, Japan), and the solid concentration of the Fe nanoparticles was set to 20 vol%.

We call this new material “nano-MRF” in this paper. Figure 9 (b) shows the photograph of the Fe nanoparticle-dispersed system. Thanks to the hydrophobic surface and surface effect of the nano-sized particles, we cannot find significant particle-settling for more than several months.

Figure 10 and 11 show a B-H curve and yield stress property of the nano-MRF, respectively. The B-H curve of the nano-MRF was measured by using VSM (Vibrating-Sample Magnetometer) for the examination body that distributed the particle of the same volume density to epoxy resin. The characteristic of yield stress vs. magnetic flux density was measured by using a combined system of the electromagnetic system (MR-100N, EKO Instruments, Japan) and the viscometer (RheoStress600, HAAKE, Germany). The measured temperature was 25 degrees C. With these data, we can estimate static torque of the CMRFC using the nano-MRF as mentioned in the section 2.2.

4.2 Torque Characteristics of The Nano-MRF in The 5Nm-class CMRFC

In order to test viscosity-change characteristics of the nano-MRF, we filled the fluid in the 5Nm-Class CMRFC with 50 \( \mu \text{m-gap} \) and tested torque response of it. The experimental setup and conditions are described in the previous sections.

Figure 12 shows an experimental result of static torque tests. Black circles mean transmission torque of experimental results. White circles mean the estimated torque from magnetostatic analyses. An off-state torque at the electric
current of 0.0 A is 0.28 Nm, and maximum torque at 1.0 A is about 2.7 Nm. The off-state torque is about double of that with the MRF-140CG, Lord Corp. The maximum torque is about half of that. The MRF-140CG includes Fe particles of 40 %vol. This value is just double of the new MRF. Therefore, the filling rate of particles would be strongly related to the viscosity-change of the MRF.

According to the comparison between analytic and experimental results, they indicate good similarity even when we use 50 μm-gap in the case of the nano-MRF. This would present that the nano-MRF is sufficiently filled in the 50 μm-gap, which is different from the case of the conventional MRF. We need more advanced study to clarify this fact.

5. CONCLUSION

In this paper, we developed two types of compact MR fluid clutches (CMRFC), which performs about 5Nm torque by applying 1 A current and have two different gap-size (50 mm and 100 mm). We tested their static torque. First, we used a conventional MR fluid as a working material of the CMRFCs. Then we used new MRF, which consist of nano-sized Fe particles. According to the experimental results, gap-size affects not only magnetic property but also easiness of filling of MRF (or particles). We should consider the gap-size depending on the particle-size.

REFERENCES

12) Lord Corp.: http://www.lord.com/