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Compact MR fluid clutch device for human-friendly actuator

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Abstract. In this paper, we describe a design method and experimental results of a newly developed MR Fluid clutch which has a multi-layered disks and micro-size (50 micro meters) gaps of MR Fluid. The micro-size gap works for the reduction of magnetic resistance, amount of power supply and size of the total system. Static torques of the device was predictable with conventional magnetostatic analyses. Additionally, dynamic test shows that its response time is about 20 milliseconds.

1. Introduction
Due to the increasing number of the aged population, there are strong demands for life-support robot systems, for example power-assist systems, to aid ADL (Activities of Daily Living) of the aged people. In order to develop safe and feasible robot systems that will contact human directory, we need to develop human-friendly actuators to keep firm safety at hardware level. Pneumatic power has been used in many conventional human-friendly actuators. However, pneumatic actuators have low elasticity and in many case it causes difficulties for control. Additionally, pneumatic actuators basically need compressors that cause to enlarge total systems.

In our previous researches [1], we have proposed MR Fluid Clutch-type Actuators (MRFCA). An MRFCA has three components; actuation part, reduction part and torque transmission part [1]. The MRFCA can perform high speed torque response depending on the rapid response of MR Fluids [2], and high safety thanks to the interposition of the MR Fluid Clutches (MRFC) [3] ~ [5]. From the view point of safety for human, the MRFCA is suitable for human-machine-coexistent systems like the life-support robots.

For further advancements of the MRFC, we need to improve torque / mass ratio and reduce amount of the power supply. Kavlicoglu B., et al. [4] have applied the multi-plate (multi-layered disk) structure for a high-torque MRFC. However, conventional MRFCs have millimetres-sized gap (0.5~1.0mm) of the MRF layers and it causes a high magnetic resistance. High magnetic resistance, at the same time, need high power supply for sufficient generation of the magnetic field to excite effective viscosity change of MRFs.

In this study, we describe a design method and experimental results of a newly developed MRFC which has a multi-layered disks and micro-size (50 micro meters) gaps of MRF layers. Application of the micro-size gaps works for the reduction of the size and the level of power-supply.
2. Basic Structure of Compact MRF Clutch with Multi-Layered Disks and Micro-Size-Gaps

A conceptual drawing of a compact MRF clutch (CMRFC) is shown in Fig. 1. An electric coil is rolled round an output shaft and it generates magnetic fluxes shown by dashed lines in the drawing. Multi-layered disks are fixed on the input / output shaft. The MRF is filled between these disks. MRFs have basically low relative magnetic permeability (3.5~10) [2], and that is significantly lower than ferromagnetic materials that will be used for a magnetic circuit. For example, the relative magnetic permeability of iron is more than 1000 at least. Therefore, MRF layers are most influential sources of the magnetic resistance that will cause large energy-loss.

In many previous reports [3] ~ [5], millimeter-size (0.5~1.0mm) gaps of MRF layers have been applied. On the other hand, in this study, we utilize micro-size-gaps (50 µm) to reduce the magnetic resistance of the MRF layers.

3. Development of a Compact MRF Clutch (CMRFC)

We formulated the way to estimate output torques of the CMRFC. The analysis flow for the estimation is shown as follows:
(1) Geometric design of a CMRFC with 3-D CAD software,
(2) Magnetostatic analysis for the estimation of the magnetic flux density with CAE (FEM) software,
(3) Decision of a yield stress of the MRF depending on the results of the process (2),
(4) Calculation of a maximum torque depending on the results of the process (3) and other size-parameters.

In the process (2), we need to input nonlinearity data (B-H curve) of ferromagnetic materials (silicon steel etc.) and the MRF. 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 and the magnetic flux density of 140CG, which is presented by Lord Corp. [6].

Figures 2 show a developed compact CMRFC. Specification data of this clutch is shown in Table 1. Multi-layered disks are fixed with a gap of 50 µm accurately. The MRF is filled between these gaps completely. Figure 3 shows a cross-sectional view of the CMRFC. In this figure, black broken line means a loop of the magnetic flux.
Table 1. Specifications of CMRFC

| Specification                  | Value  |
|--------------------------------|--------|
| Total thickness [mm]           | 32     |
| Outer diameter [mm]            | 52     |
| Number of disks                | 9      |
| Number of MR fluid layer       | 18     |
| Turning number of coil         | 191    |
| Idling torque [Nm]             | 0.15   |
| Maximum torque [Nm]            | 6.0    |
| Weight [g]                     | 237    |

4. Experimental Results

In this session, we evaluate torque characteristics of the CMRFC comparing with the estimation mentioned above. An experimental setup is shown in Fig.4. Input part (body) of the clutch was fixed on a turning table and rotated by constant speed (1 rad/s). A lever-arm of 250 mm was fixed on the output shaft of the clutch. We measured transmission torque by a force sensor contacting this arm with application of electric current to the coil built in the clutch.

At first, static torque tests were conducted. The experimental results are shown in Fig.5. White circles mean transmission torque under the static condition (peak torque). Black squares mean the results of the analysis mentioned in the previous session. As shown in this figure, the experimental result under the static condition indicates good similarity to the analytic result. Therefore, we can predict the maximum torque of the CMRFC with the suggested method.

Secondly, we also conducted dynamic torque tests (step-response). Time constant of step-response was about 20 milliseconds as shown in Fig.6. This results shows that the developed CMRFC has a better response time than that of conventional powder clutches. But it is not sufficient for servo-control. We have to improve dynamic characteristics with dynamic analyses in the next stage.
5. Conclusion
In this paper, we suggested a Compact MR Fluid Clutch (CMRFC) which has a multi-layered disks and micro-gaps (50 µm) structure. Design method and experimental results were described. With conventional magnetostatic analyses and geometrical calculation methods, we could estimate static torques of the CMRFCs. As experimental results, we developed a CMRFC with compact body (237g), high torque (6Nm) and rapid response (20ms).

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