Development of a New Magnetorheological Actuator for Force Feedback Application

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***Abstract*—In this study, a new configuration of Bidirectional Magneto-Rheological Actuator (BMRA) is proposed, optimally designed and experimentally evaluated. The BMRA has two discs rotating in opposite directions at the same speed. The two discs are placed inside a housing which is connected to the haptic devices. The BMRA has two coils placed directly on each side of the housing. The coils are separated with the Magnetorheological Fluid (MRF) by a thin wall of the housing. With this configuration, the inner face of the side housing, which is interfaced with the MRF, is continuous. This allows the MRF duct being manufactured more easily and accurately. After the introduction of the proposed configuration, braking torque of the proposed BMRA is analyzed based on Bingham-plastic rheological model of the MRF. Optimization of the proposed BMRA is then performed considering maximum torque and mass of the actuator. Based on the optimal result, detailed design of the BMRA is conducted and a prototype of the BMRA is manufactured. Experimental works on the prototype is then performed and performance characteristics of the proposed BMRA are figured out.**

***Index Terms*—Magnetorheological Fluid (MRF), MRF actuator, force feedback**

I. Introduction

In modern Industry, the application of telemanipulator is very necessary, especially for robots working in hazardous environment (polluted, radioactive) or extreme environment (adventure robots). Basically, a telemanipulator system consists of a slave manipulator and a master operator. An important issue to deal with in a telemanipulator system is the lack of information on forces and torques at the end-effecter of the slave manipulator to the master operator. The lack of this information reduces the accuracy and flexibility of the system. Therefore, a telemanipulator system with a force feedback system to the operator (haptic telemanipulator system) is very significant.

In recent years, with the fast development in research and application of smart materials, especially the MRF, several researches on haptic system featuring MRF have been performed. Kim K H *et al.* [1] have designed and manufactured a 5-DOF haptic hand featuring 5 linear MR brakes. The results showed that the haptic hand can fair reflect required forces to the fingers of human operator (8N). However, the off-state force is quite high, around 2N. This is a big challenge for the system to reflect a true force to the operator. Scott W *et al.* [2] have designed and manufactured a 5-DOF haptic glove featuring 5 linear MR brakes. The maximum force can reach up to 6N. However, the off-state force is still high in this case (1.5N) and the brake general size are somewhat large: 50x12x12mm. Conrad B *et al.* [3] have designed and manufactured a 3-DOF haptic glove featuring 3 rotary MR brakes in order to feedback the force to the thumb, the point (index) and the middle finger. The general dimensions of the MR brakes are: D=25mm, L=15mm, the maximum force at the finger tips can reach up to 17N. Li W H *et al.* [4] have researched on a 2-DOF haptic joystick featuring 2 rotary MR brakes. The general dimensions of the MR brakes are: D=156mm, L=21mm, the moment of the brake can be changed from 0.5Nm to 6Nm. Nguyen Q H *et al.* have performed several researches on force feedback system using MRF [5], [6].

Although there have been several researches on MRF based haptic system, however, in previous researches MR brakes are used and off-state friction force (uncontrollable force), which significantly affect performance of the haptic system, is inevitable. In addition, traditional configurations of MR brakes were used in which the coils are placed on the cylindrical housing. This results in "bottle neck" problem of magnetic circuit and manufacturing difficulties. The main technical contribution of this work is to develop and investigate a new configuration of bidirectional MRF actuator (BMRA) for haptic application with two coils placed directly on each side of the housing. With this configuration, the off-state friction force can be eliminated, the "bottle neck" problem of magnetic circuit can be alleviated and manufacture difficulties can be improved

II. The Proposed Bidirectional MRF Actuator

In this study, a configuration of the BMRA is introduced and its actuating torque is analyzed based on

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Bingham-plastic model of MRF. Fig. 1 shows the configuration of the proposed BMRA. As shown in the figure, The BMRA has two discs rotating in opposite directions at the same speed. The two discs are placed inside a housing which is connected to the haptic devices. The space between the rotary discs and the housing is filled with MRF. The BMRA has two coils placed directly on each side of the housing. The coils are separated with the Magnetorheological Fluid (MRF) by a thin wall of the housing. With this configuration, the inner face of the side housing, which is interfaced with the MRF, is continuous. This allows the MRF duct being manufactured more easily and accurately. In order to prevent the leaking of MRF, radial lip seals are employed. As an electric current is applied to the coil 1, a magnetic field in the housing and disk 1 is generated and the MRF in the gap between the disc1 and the housing becomes solid-like instantaneously. This results in a controllable torque transmitted from disk 1 to the housing connected with the output shaft. On the other hand, as an electric current is applied to the coil 2, a magnetic field in the housing and disk 2 is generated and the MRF in the gap between the disc 2 and the housing becomes solid-like instantaneously. This results in a controllable torque transmitted from disk 2 to the housing. By controlling the applied currents to the coils, an expected bidirectional torque can be obtained at the output shaft.

By assuming that the MRF rheologically behaves as Bingham plastic fluids and by the assumption of a linear velocity profile in the MRF ducts, the induced transmitting torque of the MRA can be respectively determined as follows [7], [8].

In the above, T is the output torque, T_1 and T_2 are respectively the transmitting torque from disk 1 and disk 2 to the housing, T_{sf} is the friction torque between the housing and the seals at shaft 1. R_d is the outer radius of the disks, R_i is the inner radius of the active MRF volume which is almost equal to the radius of the shaft flange, R_s is the shaft diameter at the sealing, d is the gap size of the MRF ducts between the discs and the housing, d_o is the gap size of the annular MRF duct at the outer cylindrical face of the discs, t_d is the thickness of the discs, Ω is the angular velocity of the rotor, R_{ci} and R_{co} are the inner and outer radius of the coils. μ_{d11}, μ_{d12}, μ_{d13}, μ_{d14} are respectively the average post yield viscosity of MRF denoted by MRF1, MRF2, MRF3 and MRF4 relating to disk 1 and τ_{yd11}, τ_{yd12}, τ_{yd13}, τ_{yd14} are the corresponding yield stress, μ_{d21}, μ_{d22}, μ_{d23}, μ_{d24} are the average post yield viscosity relating to disk 2 and τ_{yd21}, τ_{yd22}, τ_{yd23}, τ_{yd24} are the corresponding yield stress.

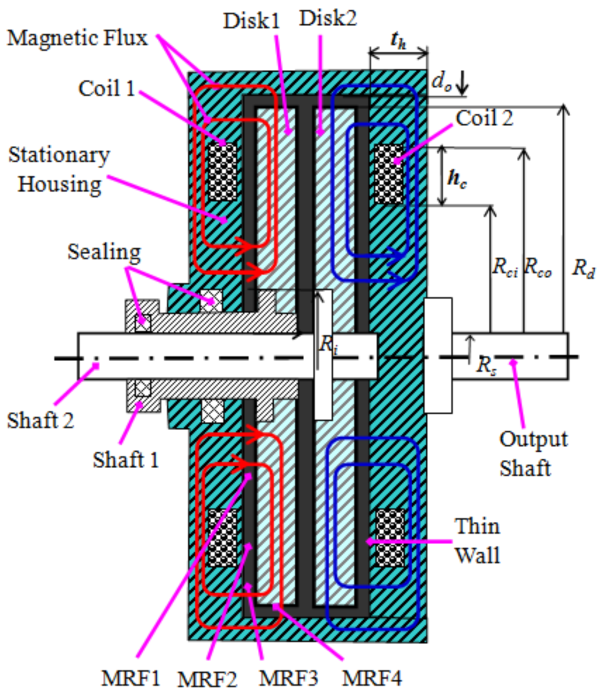

Figure 1. Configuration of the proposed bidirectional MR actuator

$$T = T_1 - T_2 + T_{sf} \tag{1}$$

$$\begin{aligned} T_1 = {} & \frac{\pi\mu_{d11}R_{ci}^4}{2d}[1-(\frac{R_i}{R_{ci}})^4]\Omega + \frac{2\pi\tau_{yd11}}{3}(R_{ci}^3 - R_i^3) + \frac{\pi\mu_{d12}R_{co}^4}{2d}[1-(\frac{R_{ci}}{R_{co}})^4]\Omega + \frac{2\pi\tau_{yd12}}{3}(R_{co}^3 - R_{ci}^3) \\ & + \frac{\pi\mu_{d13}R_d^4}{2d}[1-(\frac{R_{co}}{R_d})^4]\Omega + \frac{2\pi\tau_{yd13}}{3}(R_d^3 - R_{co}^3) + 2\pi R_d^2 t_d(\tau_{yd14} + \mu_{d14}\frac{\Omega R_d}{d_o}) \end{aligned} \tag{2}$$

$$\begin{aligned} T_2 = {} & \frac{\pi\mu_{d21}R_{ci}^4}{2d}[1-(\frac{R_i}{R_{ci}})^4]\Omega + \frac{2\pi\tau_{yd21}}{3}(R_{ci}^3 - R_i^3) + \frac{\pi\mu_{d22}R_{co}^4}{2d}[1-(\frac{R_{ci}}{R_{co}})^4]\Omega + \frac{2\pi\tau_{yd22}}{3}(R_{co}^3 - R_{ci}^3) \\ & + \frac{\pi\mu_{d23}R_d^4}{2d}[1-(\frac{R_{co}}{R_d})^4]\Omega + \frac{2\pi\tau_{yd23}}{3}(R_d^3 - R_{co}^3) + 2\pi R_d^2 t_d(\tau_{yd24} + \mu_{d24}\frac{\Omega R_d}{d_o}) \end{aligned} \tag{3}$$

III. Optimal Design of the BMRA

In design of actuator for haptic application, besides the transmitting torque, another issue that should be taken into account is their mass. It is obvious that the mass of the BMRA should be as small as possible to reduce the BMRA size and cost. In addition, smaller mass of the MRA can reduce the effect of inertia in the haptic systems. Therefore, the optimization problem in this study is to find optimal value of significant geometric dimensions of the BMRA that can produce a certain required transmitting torque while the BMRA mass is minimized. The BMRA mass can be approximately calculated by

$$m_b = V_{d1}\rho_d + V_{d2}\rho_d + V_h\rho_h + V_{s1}\rho_s + V_{s2}\rho_s + V_{MR}\rho_{MR} + V_c\rho_c \tag{4}$$

where V_{d1}, V_{d2}, V_h, V_{s1}, V_{s2}, V_{MR} and V_c are respectively the geometric volume of the disc1, disc 2, the housing, the shaft1, the shaft 2, the MRF and the coils of the BMRA. There parameters are functions of geometric dimensions of the BMRA structures, which vary during the optimization process. ρ_d, ρ_h, ρ_s, $\rho_{MR,}$ and ρ_c are density of the discs, the housing, the shafts, the MRF and the coil material, respectively. The method to solve optimization problem of MR brakes and actuators are mentioned in detail in [7]-[10].

In this research, silicon steel is used for magnetic components of the BMRA such as the housing and the discs, the coil wires are sized as 21-gage (diameter = 0.511mm) and the MRF is the commericial one made by Lord Corporation, MRF132-DG. Table I shows the optimal solution of the BMRA when the transmitting torque in disk 2 rotational direction is constrained to be greater than 5Nm with 2% of accuracy, the convergence rate is set by 0.1%. In this case, no current is applied to coil 1 while a current of 2.5A is applied to coil 2. The shaft radius is set by R_s=6mm considering the strength of the shaft. As shown in the results, at the optimum, transmitting torque can reach up to 5Nm as constrained and the mass of the optimized BMRA is 1.616kg

TABLE I. OPTIMAL SOLUTION OF THE BMRA

Design parameter (mm)	Performance
Coil: n_{wc}x n_{hc}=5x17 turns; R_{ci}=34.28 No. of turns: 85 Housing: R=49.8, t_h= 7.83 (t_{h1}=4.78), L=26.96 Disc: R_i=14.28, R_d=47.3, t_d= 4.15 MRF duct gap: 1	Max. Current: 2.5A Max. Torque: 5Nm Mass: 1.616 kg Power Cons.: 21.7 W Coil Resistance(Ω): R_c= 1.736

IV. EXPERIMENTAL VALIDATION

In order to validate the above optimal results, experimental results of the optimized BMRA prototypes are obtained and presented. Fig. 2 shows the experimental setup to test performance of the BMRA. In the figure, a servo DC motor with gear-box controlled by the computer at a constant angular speed of 2πrad/s. The motion from the motor is transferred to the two shafts of the BMRA through a bevel gear system. The torque generated by the BMRA is measured by the static torque sensor. Once the experiment process is stated, a step current signal from the computer is sent to the current amplifier. The output current from the amplifier, a step current of 2.5A, is applied to the coils of the BMRA.

Fig. 3 shows step response of prototypes BMRA when a current of 2.5A is applied to the coils of at the time of 0.5s. The results show that, at steady state, the average absolute value of torque in the shaft 2 direction is around 4.6Nm, which is a little smaller than that obtained from the optimal design solution (5Nm). This mainly come from the lost of magnetic field to the ambient and at the contact between the magnetic parts of the MRBs. It is also seen that the average value of the measured torque at the steady state in the shaft 1 direction is around 4.9Nm which is greater than that in the shaft 1 direction as expected. From the above, a good correlation between experimental results and static modeling based on FEA can be assumed. From the results, it is also worthy to note that the time response of the proposed BMRA is around 0.12s. This time response is small enough for haptic applications.

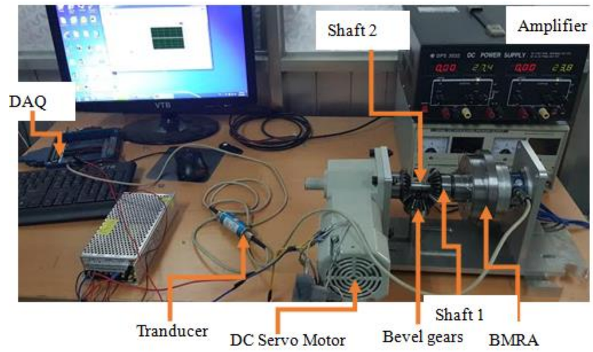

Figure 2. Experiment setup to test performance of the MRA.

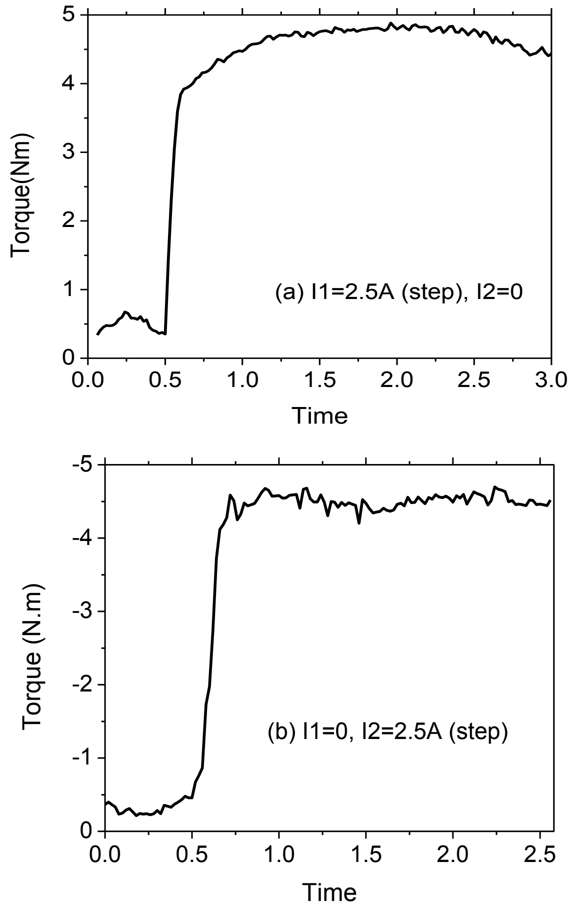

Figure 3. Step responses of the prototype BMRA

V. CONCLUSION

In this study, a new configuration of Bidirectional Magneto-Rheological Actuator (BMRA) was proposed, optimally designed and experimentally evaluated. The BMRA has two discs rotating in opposite directions at the same speed. Two coils of the BMRA are placed directly on each side of the housing. The coils are separated with the

Magnetorheological Fluid (MRF) by a thin wall of the housing. This configuration allows the MRF duct being manufactured more easily and accurately. After the introduction of the proposed configuration, braking torque of the proposed BMRA was analyzed based on Bingham-plastic rheological model of the MRF. Optimization of the proposed BMRA was then performed considering maximum torque and mass of the actuator. Based on the optimal result, a prototype of the BMRA was manufactured. Experimental works on the prototype showed that the average absolute value of torque in the shaft 2 direction is around 4.6Nm, which is a little smaller than that obtained from the optimal design solution (5Nm). It was also seen that the average value of the measured torque at the steady state in the shaft 1 direction is around 4.9Nm which is greater than that in the shaft 1 direction as expected. From the results, it is also worthy to note that the time response of the proposed BMRA is around 0.12s, which is suitable for haptic applications.

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