Research Article

Design of a New 4-DOF Haptic Master Featuring Magnetorheological Fluid

Byung-Keun Song,¹ Jong-Seok Oh,² and Seung-Bok Choi²

¹ Division of Mechanical System Engineering, Incheon National University, Incheon 406-772, Republic of Korea
² Department of Mechanical Engineering, Smart Structures and Systems Laboratory, Inha University, Incheon 402-751, Republic of Korea

Correspondence should be addressed to Seung-Bok Choi; seungbok@inha.ac.kr

Received 26 March 2014; Accepted 22 April 2014; Published 7 August 2014

Academic Editor: Weihua Li

Copyright © 2014 Byung-Keun Song et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This work presents a novel 4-degree-of-freedom (4-DOF) haptic master using magnetorheological (MR) fluid which is applicable to a robot-assisted minimally invasive surgery (RMIS) system. By using MR fluid, the proposed haptic device can easily generate bidirectional repulsive torque along the directions of the required motions. The proposed master consists of two actuators: an MR bidirectional clutch associated with a planetary gear system and an MR clutch with a bevel gear system. After demonstrating the configuration, the torque models of MR actuators are mathematically derived based on the field-dependent Bingham model. An optimal design that accounts for spatial-limitation and the desired torque constraint is then undertaken. An optimization procedure based on finite element analysis is proposed to determine optimal geometric dimensions. Based on the design procedure, MR haptic master with the optimal parameters has been manufactured. In order to demonstrate the practical feasibility of the proposed haptic master, the field-dependent generating repulsive force is measured. In addition, a proportional-integral-derivative (PID) controller is empirically implemented to accomplish the desired torque trajectories. It has been shown that the proposed haptic master can track the desired torque trajectory without a significant error.

1. Introduction

Recently, robot-assisted minimally invasive surgery (RMIS) has attracted more and more interest from numerous researchers in the field of mechanical engineering and medical science. The ZEUS® surgical robotic system and da Vinci surgery system are the most successful commercial applications [1, 2]. A RMIS system usually consists of a master device which tells a surgery robot how to operate surgery using long surgical instruments and a surgery robot which operates under the guidance from the master device signal. The interaction information between a surgeon and a patient is only visual images taken by an endoscope attached to the tip of the laparoscopic device [3]. This information is vital, but it is very difficult to comprehend the overall scheme inside the abdomen of a patient. Accordingly, there is a chance of inaccurate operation due to the lack of physical sensing. Therefore, it is indispensable to develop a haptic master whose function is not only to generate the motion for a robot but also to reflect to the surgeon the physical constraints of the robot, such as those from the viscosity and stiffness of the touched tissue, bone, and organs.

The realization of human senses, especially touch, has been actively researched in several applications such as the automotive and robotic fields in order to accomplish greater realism and interactivity [4, 5]. A haptic system provides stimulus information such as tactile sensation or kinesthetic force to a user. The first haptic system was developed by Goertz during the 1940s for a master-slave manipulator for handling dangerous materials. Since then, various medical haptic devices featuring an electric motor, wire, and links have been studied. However, using these haptic devices it is difficult to obtain a continuous and smooth torque control. Particularly, since the active type directly transmits force to
the operator, it can cause safety problems [6, 7]. Due to this problem, haptic devices must be further developed, because the human sense of touch is far more sensitive than the sense of sight or hearing. Therefore, several researches related to haptic systems have recently been implemented using smart materials such as magnetorheological (MR) fluids and electrorheological (ER) fluids. MR fluid is actively being investigated as an actuating fluid for numerous applications [8–10]. MR clutch and brake mechanisms featuring smoothly controllable torque have been broadly researched for high stability and performance [11, 12]. It is widely known that MR fluids undergo instantaneous phase changes when they are exposed to a magnetic field. The most important change is related to the yield stress. Due to this phenomenological behavior, the MR applications have several advantages, such as good stability, reliable control performance, and compact design. These features are ideal for haptic systems. Accordingly, the advantages of MR have led to several research works for haptic devices. Li et al. [13] proposed an MR fluid-based 2-degree-of-freedom (2-DOF) haptic system featuring a gimbal structure. Senkal and Gurocak [14] developed a 3-DOF MR spherical brake, and its performance was evaluated by virtual tests. Nguyen and Choi [15] proposed a 2-DOF MR haptic device featuring a bidirectional clutch mechanism and gimbal structure. In order to apply a haptic master for RMIS applications, 4-DOF motion is required, which includes 3-DOF rotational motion (about the X, Y, and Z axes) and 1-DOF translational motion [16]. However, the research on 4-DOF MR haptic devices for medical applications using MR fluid has not been proposed so far.

Consequently, the main contribution of this work is to propose a novel 4-DOF haptic master using magnetorheological (MR) fluid which can be applicable to RMIS systems. The proposed kinesthetic force-feedback master consists of two actuators: an MR bidirectional clutch with a planetary gear system and an MR clutch with a bevel gear system. After deriving the torque models, the geometric dimensions of the MR haptic master are optimally obtained to meet the spatial-limination and torque requirements. It is demonstrated via experimental investigation that the predicted performance is successfully achieved by implementing the proposed 4-DOF haptic master. Finally, a PID controller is experimentally implemented to achieve the desired torque trajectories of the haptic device. It is shown that the tracking control performance is good without a significant error between actual and desired torques.

2. Mechanism of 4-DOF MR Haptic Master

Since RMIS is conducted using small incisions to the abdomen, the motion of an instrument is restricted to four directions (pitching, rolling, yawing, and translation motion), as shown in Figure 1. As mentioned, it is highly necessary to realize repulsive force for surgeons in RMIS. So, an MR haptic master mechanism is proposed to achieve the required motions and repulsive force-feedback, as shown in Figure 2. In addition, to send the complex motions of the operator to the repulsive force actuators, a gimbal mechanism is adopted. The proposed MR haptic master consists of two actuators. One is a bidirectional MR clutch with a planetary gear system, which can generate rolling and pitching rotational force reflections. The other is an MR clutch attached to the gripper of the gimbal mechanism for yawing and translation motion. The reflection of the motion of operator is sent from these MR actuators via the gimbal mechanism. The force reflection mechanism of the MR actuator is realized by an MR fluid. The shear stress produced when a magnetic field is applied to the MR fluid can be expressed as follows [17]:

\[ \tau = \eta \dot{\gamma} + \tau_y(B), \]  

where \( \tau \) is the total shear stress of the MR fluid, \( \eta \) is the viscosity constant, \( \dot{\gamma} \) is the shear rate, and \( \tau_y(B) \) is the dynamic yield stress of the MR fluid, which is a function of the magnetic field. Figure 3 shows the magnetic and yield stress properties of the MR fluid (MRF-132DG) from the Lord Corporation. By using a least-square curve fitting method, the approximated polynomial forms are obtained as follows [18]:

\[ \tau_y(B) = m_{MR0}B^5 + m_{MR1}B^4 + m_{MR2}B^3 + m_{MR3}B^2 + m_{MR4}B + m_{MR5}, \]

where \( B = P_{MR0}H^5 + P_{MR1}H^4 + P_{MR2}H^3 + P_{MR3}H^2 + P_{MR4}H + P_{MR5}, \)

\[ P_{MR0} = [2.7 \times 10^{-14} -6.2 \times 10^{-11} 5.64 \times 10^{-8} -2.6 \times 10^{-5} 7.56 \times 10^{-3} 0], \]

\[ m_{MR0} = [39.7215 -132.3825 119.0925 10.281 0.10815]. \]

In (2), \( B \) denotes the magnetic flux density in units of Tesla, and \( H \) denotes the magnetic intensity in units of amperes/mm.

2.1. Bidirectional MR Clutch with Planetary Gear System

In order to realize the 2-DOF force reflection along the pitching and rolling directions, a bidirectional MR clutch and a planetary gear system incorporated into a gimbal mechanism are proposed. Figure 4 illustrates the configuration and geometric features of the proposed bidirectional MR clutch. The bidirectional MR clutch is composed of two coils, two rotors, and an outer casing. The two rotors are fixed to their respective shafts, which transmit motion from a planetary gear system as a driving bioutput source. As shown in Figure 5, the driving motion of the motor is split into two different rotational motions of shafts 1 and 2. When the motor runs, the two shafts and two rotors rotate counter to each other. Due to these configurations, there are two relative shear motions
between the two rotors and the outer casing, even when the casing is stopped. The casing is fixed to a driving shaft, which is connected to the gripper of the MR haptic master. The MR fluid fully fills the space between the rotors and casing.

In order to generate bidirectional force reflection, two distinct current amplifiers are used for the coils so that the current magnitudes of these coils can be controlled independently. Since these independent magnetic field inputs cause one magnetic field to interfere with the other, a nonmagnetic partition is inserted at the middle position of the casing. When power is supplied to a coil, due to the solidification of the MR fluid between the surfaces of the rotors and the casing, the outer casing rotates according to the motion of the rotors. In this context, the direction of the torque is determined according to the excitation scheme of coils 1 or 2. Also, since the repulsive force at the gripper originates from the generated torque of the MR clutch via the gimbal structure, the terminology "repulsive torque" will be used instead of "repulsive force" in this work. The torque induced by the MR clutch consists of two elements: the dry friction torque from the sealing scheme and the fluid friction torque from the MR fluid. In order to prevent leakage of MR fluid, the oil seal is tightly connected with shaft of MR actuator. So, dry friction torque is mainly induced by the oil seal. The total generated torque, $T_{bc}$, can be expressed as follows:

$$T_{bc} = |\vec{T}_{bc1} - \vec{T}_{bc2}|,$$  

(3)

where $T_{bc1}$ and $T_{bc2}$ are the torques generated from rotors 1 and 2, respectively. These terms can be rewritten as follows:

$$T_{bc1} = T_{\text{MR}1} + T_{bi}, \quad i = 1, 2.$$  

(4)

In (4), $T_{bi}$ is the torque due to dry friction between the surfaces of the rotor’s shafts and the casing’s shaft as well as that from the sealing scheme, which can be determined experimentally. $T_{\text{MR}1}$ is the fluid friction torque due to the MR fluid, and its magnitude depends on the properties of the MR fluid and applied magnetic field. This torque is mainly induced by the friction between the rotors and casings and can be expressed as follows:

$$T_{\text{MR}1} = T_{ai} + T_{ei},$$

where

$$T_{ai} = 2\pi \left( \frac{D_{br}}{2} \right)^2 \int_0^{h_0} \tau_{\gamma,ai} (B) \, dz, \quad i = 1, 2,$$

(5)

and

$$T_{ei} = 2\pi \int_{D_{bs}/2}^{D_{bs}/2} r^2 \tau_{\gamma,ei} (B) \, dr, \quad i = 1, 2.$$

(6)

In (5), $T_{ai}$ is the induced torque between the annular faces of the rotors and the casing, and $T_{ei}$ is the induced torque between the end faces of the rotors and the casing. By substituting (1) into (5), the field-dependent torques is obtained by

$$T_{ai} = 2\pi \left( \frac{D_{br}}{2} \right)^2 \int_0^{h_0} \left( \tau_{\gamma,ai} (B) + \eta_{\gamma,ai} \right) \, dz, \quad i = 1, 2,$$

(7)

and

$$T_{ei} = 2\pi \int_{D_{bs}/2}^{D_{bs}/2} r^2 \tau_{\gamma,ei} (B) + r^2 \eta_{\gamma,ei} \, dr, \quad i = 1, 2.$$

In (6), $\eta_{\gamma,ai}$ and $\eta_{\gamma,ei}$ are the shear rates of the MR fluid at the gap between the annular faces and end faces, whose values can be determined as follows:

$$\eta_{\gamma,ai} = \frac{\tau_{\gamma,ai} |\Omega_i - \dot{\Omega}_1|}{2t}, \quad i = 1, 2,$$

(8)

$$\eta_{\gamma,ei} = \frac{r |\dot{\Omega}_i - \dot{\Omega}_1|}{t}, \quad i = 1, 2,$$

where $\Omega_1$, $\Omega_2$, and $\dot{\Omega}_1$ are the angular velocities of rotors 1 and 2 and the casing, respectively. In this paper, $t$ means gap distance between outer housing and rotor of end and annular faces. Also, in order to simplify the design process, all gap distances for annular and end faces are identically determined to be 1 mm. The yield stresses $\tau_{\gamma,ai}(B)$ and $\tau_{\gamma,ei}(B)$ do not vary significantly on the shear surfaces [19]. Consequently, for simplicity, (6) can be rewritten in a simpler form as follows:

$$T_{ai} = \frac{\pi D_{br}^2 h_0 \tau_{\gamma,ai} (B)}{2} + \frac{\pi \eta D_{bs}^2 h_0 |\Omega_i - \dot{\Omega}_1|}{4t}, \quad i = 1, 2,$$

(9)

and

$$T_{ei} = \frac{\pi \left( D_{br}^3 - D_{bs}^3 \right) \tau_{\gamma,ei} (B)}{12} + \frac{\pi \eta \left( (D_{br}/2)^4 - (D_{bs}/2)^4 \right) |\dot{\Omega}_i - \dot{\Omega}_1|}{2t}, \quad i = 1, 2.$$

(10)

2.2. MR Clutch with Bevel Gear System Attached at the Gripper.

Two actuators for the yawing and translation motions are attached at the gripper of the gimbal structure, which is the main feature of the MR haptic master. If the gripper is long and the generated torques of the actuators for rolling and pitching motions are the same, the transmitted repulsive forces along the pitching and rolling motions are proportionally small. Accordingly, in order to attain a relatively
large magnitude of the transmitted force and compact size of the MR haptic master, the length between gimbal structure and handle should be as small as possible. In consideration of these design requirements, a new mechanism for yawing and translation motion is proposed as shown in Figure 6. As shown in Figures 2(c) and 6, bevel gear and handle are devised to transfer rotational motion of MR clutch to translational motion of handle. During RMIS, an operator holds the handle of MR haptic master. In contrast to the mechanism of the bidirectional clutch for the pitching and rolling directions, this mechanism uses a servomotor as a bioutput source. When the power is supplied to the coil, the servomotor generates one directional rotation at a time. Then, the outer housing rotates according to the motion of the servomotor. If power transmission of the servomotor is required in the reverse direction, the servomotor changes its output direction. Then, the outer housing of the MR clutch rotates in the opposite direction. Additionally, an encoder is inserted to measure the command of operator for surgery robot of RMIS system.

Figure 2: Schematic configuration of MR haptic master.
Advances in Mechanical Engineering

Magnetic intensity $H$ (kA/m)

| Magnetic density $B$ (Tesla) |
|-----------------------------|
| 1.6                        |
| 1.4                        |
| 1.2                        |
| 1.0                        |
| 0.8                        |
| 0.6                        |
| 0.4                        |
| 0.2                        |
| 0.0                        |

0 100 200 300 400 500 600

Figure 3: Rheological properties of MR fluid.

Yield stress (kPa)

0 10 20 30 40 50

0 50 100 150 200 250 300

Figure 4: Bidirectional MR clutch.

Since the actuator for yawing and translation motion does not require a planetary gear system, the length between gimbal structure and handle is short. However, this mechanism has both strengths and weaknesses. This mechanism can minimize the size of the gripper, but the chance of time delay due to changes in the rotational direction is unavoidable. Since the servomotor can quickly change its rotational direction and the purpose of the MR clutch is haptic application rather than fast power transmission for a mechanical system, the time delay would hardly be noticed by the operator. As shown in Figure 7, the MR clutch is composed of a rotary disc, shaft, outer housing, and MR fluid. The rotary disc has a flux guide and an electromagnetic coil, and it is assembled into an outer housing with a specific gap fully filled with MR fluid. The flux guide is made of ferromagnetic material and is fixed to a shaft made of paramagnetic material, which is in turn fastened to the driving servomotor. In addition, a mild steel (S45C) and an aluminum are adopted as the ferromagnetic and paramagnetic materials, respectively. The outer housing is fastened to an operator. When the current input is supplied to the coil, a magnetic field is created, and fluid friction torque induced by the MR fluid is provided to the operator. In order to derive the torque model of the MR clutch, the same torque analysis of the bidirectional MR clutch is identically applied and obtained as follows:

$$T_c = T_n + T_e + T_f,$$
3. Optimal Design and Manufacturing

In this section, finite element (FE) analysis is utilized to obtain optimal geometric dimensions of the MR haptic master in order to maximize the generated torque of the MR haptic master. There are numerous factors that are important in the optimal design process such as the size, the power, and the generated torque. Because the MR haptic master is expected to be applied in low-power applications, the size and the generated torque are considered as more important factors. In the optimal design process, the optimal configurations of the MR bidirectional clutch and MR clutch are determined to maximize the generated torques, while the specific volume defined by its radius and height is constrained.

In order to obtain the optimal solutions of the bidirectional MR clutch, FE analysis is implemented for the magnetic circuit of the master and calculating the generated torque of the master. From Figure 4 and (8), it is known that the generated torque is mainly determined by the diameter of the rotor, \( D_{bc} \); the height of the coil, \( h_{bc} \); and radial width of the coil, \( b_c \). For the sake of manufacturing, the other parameters such as the gap of the MR fluid, the diameter of the rotor shafts 1 and 2, and the thickness of the partition are preset as 1 mm, 12 mm, 8 mm, and 3 mm, respectively. Also, for obtaining compact size of the bidirectional MR clutch, the constraints in (10)–(12) have to be included. In short, the optimization problem is rewritten as follows:

maximize the generated torque of the bidirectional MR clutch;
subject to

\[ t = 1 \text{ mm}, \]
\[ D_{bc} = 61 \text{ mm}, \]
\[ L = 16 \text{ mm}, \]
\[ \min DV_i \leq DV_i \leq \max DV_i, \quad i = 1, 2, 3, \]

where \( \min DV_i = [D_{br\min}, h_{bc\min}, b_{t\min}] \) and \( \max DV_i = [D_{br\max}, h_{bc\max}, b_{t\max}] \).

In (13), \( DV \) means the chosen design parameters. In order to achieve this objective, the magnetic flux density of the magnetic circuit with the varying design variables is predicted using commercial ANSYS software. Because the geometry of the bidirectional clutch is axisymmetric in this work, a 2D-axisymmetric coupled element (Plane 13) is considered for the electromagnetic analysis. Since the geometric dimensions are changed during the FE analysis process, the meshing size is specified by the number of elements for each line. Particularly, the magnetic flux density is not constant along the pole length. Therefore, in order to calculate the generated torque, an average magnetic flux density along the MR duct where magnetic flux passes should be used. In this work, the average magnetic flux density is calculated by a numerical integration of the magnetic intensity [20]. With varying design variables, the magnetic circuit analysis is repeatedly implemented. The design variables and their limits are assigned as follows: the diameter of the rotor is set as

\[ r(t, \theta) = \frac{D_{bc}}{2} \left[ \frac{h_{bc}}{2} \right] \]
45–50 mm, the height of the coil is set as 5–10 mm, and the radial widths of the coil are set as 5–10 mm with 1 mm step size. From (2), the yield stress of the MR fluid caused by the magnetic field is calculated. Once the yield stress of the MR fluid is obtained, the generated torque is calculated using (8) and listed in Table 1. Proper values are selected from the result to obtain the design objective. In other words, the design parameters which can generate the maximum repulsive torque of the MR application are determined with restricted volume. The diameter of the rotor, the height of the coil, and the radial widths of the coil are determined to be 50 mm, 6 mm, and 7 mm, respectively. The base viscosity of the MR fluid is measured by $\eta = 0.092 \text{ Pa} \cdot \text{s}^{-1}$.

Figure 8 shows the magnetic density of the bidirectional MR clutch with the obtained optimal dimensions when a current of 2 A is applied to the coil. From Figures 8(b) and 8(c), the magnitude of magnetic density in the gap between the end faces is low and the deviation of magnetic density in the gap between the end faces is relatively low. The magnitude of magnetic density in the gap between the annular faces does not vary significantly on the shear faces. So, a mean magnetic flux density can be used to simplify the design procedures. The mean magnetic flux densities at the annular face and end face of the rotors are 0.393 T and 0.6917 T, respectively. However, an optimization procedure for selecting proper design parameters can be automatically
Table 1: Predicted torque of bidirectional MR clutch according to varying design parameters.

| Diameter of rotor, $D_{bR}$ | Height of coil, $h_{bc}$ | Radial widths of coil, $b_{cc}$ | Flux density at end face (T) | Flux density at annular face (T) | Torque (Nm) |
|-----------------------------|-------------------------|-------------------------------|-----------------------------|-------------------------------|-------------|
| 50 mm                       | 5 mm                    | 7 mm                          | 0.687 T                     | 0.388 T                       | 1.459 Nm    |
| 50 mm                       | 5 mm                    | 8 mm                          | 0.689 T                     | 0.390 T                       | 1.669 Nm    |
| 50 mm                       | 5 mm                    | 9 mm                          | 0.683 T                     | 0.385 T                       | 1.706 Nm    |
| 50 mm                       | 5 mm                    | 10 mm                         | 0.684 T                     | 0.386 T                       | 1.733 Nm    |
| 50 mm                       | 6 mm                    | 5 mm                          | 0.682 T                     | 0.383 T                       | 1.822 Nm    |
| 50 mm                       | 6 mm                    | 6 mm                          | 0.675 T                     | 0.376 T                       | 1.871 Nm    |
| 50 mm                       | 6 mm                    | 7 mm                          | 0.6917 T                    | 0.393 T                       | 1.9 Nm      |
| 50 mm                       | 6 mm                    | 8 mm                          | 0.686 T                     | 0.388 T                       | 1.8478 Nm   |
| 50 mm                       | 6 mm                    | 9 mm                          | 0.686 T                     | 0.387 T                       | 1.881 Nm    |
| 50 mm                       | 6 mm                    | 10 mm                         | 0.686 T                     | 0.388 T                       | 1.771 Nm    |
| 50 mm                       | 7 mm                    | 5 mm                          | 0.685 T                     | 0.387 T                       | 1.788 Nm    |
| 50 mm                       | 7 mm                    | 6 mm                          | 0.673 T                     | 0.375 T                       | 1.746 Nm    |
| 50 mm                       | 7 mm                    | 7 mm                          | 0.674 T                     | 0.375 T                       | 1.606 Nm    |
| 50 mm                       | 7 mm                    | 8 mm                          | 0.670 T                     | 0.372 T                       | 1.83 Nm     |
| 50 mm                       | 7 mm                    | 9 mm                          | 0.680 T                     | 0.381 T                       | 1.827 Nm    |
| 50 mm                       | 7 mm                    | 10 mm                         | 0.679 T                     | 0.381 T                       | 1.845 Nm    |

implemented by designing a direction vector [19]. Based on a previous study [19], a log file for solving a magnetic circuit was built, and iteration for finding proper design parameters was executed. By utilizing the direction vector, the convergence of the objective function is accomplished. It is noted that there are no significant differences in geometry between two procedures. Since it is difficult to design the direction vector, the proposed procedure and corresponding optimization procedure are effective and considerably accurate. In detail, suppose that a direction vector is improperly designed. Then, there is chance to find inappropriate solutions. The time consumed for the optimization analysis using the direction vector is shorter than the corresponding analysis in this work. However, there is no significant difference in the calculation time when considering only a few parameters.

The optimal design technique for the MR bidirectional clutch is identically applied to the design of the MR clutch. From Figure 7 and (8), the chosen design parameters are the diameter of the shaft, $D_{cs}$, the height of the coil, $h_{cc}$, and the radial widths of the coil, $b_{cc}$. The other parameters such as gap of the MR fluid, $t$; diameter of flux guide, $D_{cR}$; and height of the flux guide, $h_{cc} + 2h_{c}$ are preset as 1 mm, 62 mm, and 32 mm, respectively. The optimization problems for the MR clutch can be presented as follows:

maximize the generated torque of the MR clutch;

subject to

$t = 1$ mm,

$D_{cR} = 62$ mm,

$h_{cc} + 2h_{c} = 32$ mm,

$\min DV_i \leq DV_i \leq \max DV_i, \quad i = 1, 2, 3,$

(14)

where $\min DV_i = [D_{cs \min} \ h_{cc \min} \ b_{cc \min}]$ and $\max DV_i = [D_{cs \max} \ h_{cc \max} \ b_{cc \max}]$.

The design variables for MR clutch and their limits are assigned as follows: the diameter of the shaft is set as 25–35 mm, the height of the coil is set as 5–10 mm, and the radial widths of the coil are set as 5–10 mm with 1 mm step size. The obtained FE solutions and calculated torque of the MR clutch are listed in Table 2. Among several results, the diameter of the shaft and the height and radial widths of the coil are determined to be 30 mm, 10 mm, and 8 mm, respectively. Figure 9 shows the magnetic density of the MR clutch with the obtained optimal dimensions when a current of 2 A is applied to the coil. The mean magnetic flux densities at the annular face and end face of the rotors are 0.506 T and 0.024 T, respectively. Finally, the 4-DOF MR haptic master with these determined design parameters was manufactured as shown in Figure 10. All significant dimensions for the manufactured clutches are given in Table 3.

4. Performance Evaluation

In order to evaluate the accuracy of the optimal design and torque models, two experiments with the manufactured clutches were undertaken. In the experiment, the torque signal is measured by a torque sensor (Senstech Corp., SDS-100) connected with the shaft of the casing. In addition, two
Table 2: Predicted torque of MR clutch according to varying design parameters.

| Diameter of shaft, $D_{cs}$ | Height of coil, $h_{cc}$ | Radial widths of coil, $b_{cc}$ | Flux density at end face (T) | Flux density at annular face (T) | Torque (Nm) |
|-----------------------------|--------------------------|---------------------------------|-----------------------------|-------------------------------|-------------|
| 30 mm                       | 9 mm                     | 7 mm                            | 0.501 T                     | 0.019 T                       | 2.718 Nm    |
| 30 mm                       | 9 mm                     | 8 mm                            | 0.500 T                     | 0.021 T                       | 2.747 Nm    |
| 30 mm                       | 9 mm                     | 9 mm                            | 0.488 T                     | 0.016 T                       | 2.638 Nm    |
| 30 mm                       | 9 mm                     | 10 mm                           | 0.488 T                     | 0.017 T                       | 2.655 Nm    |
| 30 mm                       | 10 mm                    | 5 mm                            | 0.485 T                     | 0.014 T                       | 2.695 Nm    |
| 30 mm                       | 10 mm                    | 6 mm                            | 0.494 T                     | 0.007 T                       | 2.68 Nm     |
| 30 mm                       | 10 mm                    | 7 mm                            | 0.494 T                     | 0.019 T                       | 2.7 Nm      |
| **30 mm**                   | **10 mm**                | **8 mm**                        | **0.506 T**                 | **0.024 T**                   | **2.753 Nm**|
| 30 mm                       | 10 mm                    | 9 mm                            | 0.501 T                     | 0.018 T                       | 2.747 Nm    |
| 30 mm                       | 10 mm                    | 10 mm                           | 0.503 T                     | 0.019 T                       | 2.697 Nm    |
| 31 mm                       | 5 mm                     | 5 mm                            | 0.498 T                     | 0.018 T                       | 2.669 Nm    |
| 31 mm                       | 5 mm                     | 6 mm                            | 0.499 T                     | 0.006 T                       | 2.671 Nm    |
| 31 mm                       | 5 mm                     | 7 mm                            | 0.496 T                     | 0.006 T                       | 2.675 Nm    |
| 31 mm                       | 5 mm                     | 8 mm                            | 0.489 T                     | 0.003 T                       | 2.645 Nm    |
| 31 mm                       | 5 mm                     | 9 mm                            | 0.501 T                     | 0.012 T                       | 2.573 Nm    |
| 31 mm                       | 5 mm                     | 10 mm                           | 0.500 T                     | 0.012 T                       | 2.558 Nm    |
| ...                         | ...                      | ...                             | ...                         | ...                           | ...         |

Table 3: Geometric specifications of the proposed MR haptic master.

| Parameter | Specification                                | Value |
|-----------|----------------------------------------------|-------|
| $D_{hc}$  | Diameter of bidirectional MR clutch          | 61 mm |
| $D_{br}$  | Diameter of bidirectional MR clutch’s rotor  | 50 mm |
| $D_{bs2}$ | Diameter of bidirectional MR clutch’s shaft 1| 12 mm |
| $D_{bs1}$ | Diameter of bidirectional MR clutch’s shaft 2| 8 mm  |
| $b_{R}$   | Height of bidirectional MR clutch’s rotor    | 20 mm |
| $b$       | Radial widths of bidirectional MR clutch’s casing | 10 mm |
| $b_{c}$   | Width of bidirectional MR clutch’s coil      | 7 mm  |
| $L$       | Casing length of bidirectional MR clutch     | 16 mm |
| $h_{bc}$  | Height of bidirectional MR clutch’s coil     | 6 mm  |
| $t_{p}$   | Thickness of partition                       | 3 mm  |
| $t$       | Gap                                          | 1 mm  |
| $D_{hc}$  | Diameter of MR clutch                        | 72 mm |
| $D_{gr}$  | Diameter of MR clutch’s flux guide           | 62 mm |
| $D_{cs}$  | Diameter of MR clutch’s shaft                | 30 mm |
| $h_{cc}$  | Height of MR clutch’s coil                   | 10 mm |
| $b_{cc}$  | Radial widths of the MR clutch’s coil        | 8 mm  |

Rotor shafts of the bidirectional MR clutch are rotated by a driving DC motor with revolution at 30 rpm and a bioutput gearbox. In order to achieve the maximum repulsive torque in one direction, one coil is excited with the maximum current value, while the other is turned off. The flux guide of the MR clutch is rotated by a driving servomotor with revolution at 30 rpm. Measured signals are converted to a digital signal and transferred to a computer by an NI Express Chassis A/D board (PXIe-1082), which includes a data acquisition board (PXIe-6363).

The measured torque values of the bidirectional MR clutch are plotted in Figure 11(a) for two directions and are stabilized at approximately 1.88 Nm and 1.92 Nm. From FE analysis results and torque modeling analysis for bidirectional MR clutch, simulation values of repulsive torque for two direction are calculated as 1.9 Nm, respectively. From the
results, the desired values are slightly different from the measured one. It may be caused by the manufacturing process. However, this difference is not significant. Similarly, as shown in Figure 11(b), the measured torque value of the MR clutch is approximately 2.72 Nm, while the calculated torque value of MR clutch is 2.753 Nm.

In order to evaluate control performance of the proposed haptic device, an experiment is prepared as shown in Figure 12. It is noted that the algorithm of the virtual or real slave part is not considered in this study. In order to accomplish the desired torque trajectories, in this work, a proportional-integral-derivative (PID) controller is experimentally implemented as follows:

\[ u(t) = K_p e(t) + K_i \int e(t) \, dt + K_d \dot{e}(t), \quad (15) \]

where \( e(t) \) is error signal between desired torque signal and actual torque signal measured by a 6-axis force/torque sensor (ATI Corp., Nano17). \( K_p, K_i, \) and \( K_d \) are the control gains of PID controller. In this work, the gains for PID controller are chosen by 0.3, 0.05, and 0.15, respectively. The control input calculated by the PID control is applied to MR haptic master. During control loop, the following condition is generally imposed. This condition physically means that the implementing of the controller just assures the increment of energy dissipation of the stable system:

\[ u(t) = \begin{cases} u(t), & \text{for } u(t) > 0 \\ 0, & \text{for } u(t) \leq 0 \end{cases}. \quad (16) \]

The PID controller is activated in the microprocessor to reflect the desired torque from the virtual slave. Figures 13 and 14 show control results along pitching and yawing motions. By utilizing the bidirectional MR clutch, the control results along pitching motion whose maximum torque is 2.33 Nm are obtained as shown in Figure 13(a). Figure 14(a) shows measured control results of MR clutch whose maximum torque is 2.03 Nm along yawing motions. It is clearly observed that the desired torque trajectories are well tracked by activating the proposed haptic master without substantial tracking errors. It is seen from Figures 13(b) and 14(b) that the input signal applied to the MR haptic master is lower than 2 A. Finally, more detail performance information of manufacture haptic master is listed in Table 4.

### 5. Conclusion

In this work, a novel 4-DOF haptic master was developed using MR fluid which can be applicable to the RMIS. By using a controllable MR fluid, the proposed haptic device can easily generate bidirectional active torque along 4-DOF directions. After addressing the mechanical configuration of the proposed haptic device, the torque models of the MR actuators were mathematically derived based on the Bingham model of the MR fluid. Using ANSYS, the geometric dimensions of the MR haptic master were optimally obtained to meet the spatial-limitation and torque requirements. Based on the optimal solution of the design procedure, the 4-DOF MR haptic master was manufactured. In order to evaluate the performance of the manufactured haptic device, an experimental validation was conducted. From the experimental results, it has been demonstrated that the proposed haptic master can generate the predicted torque levels required for
(a) Bidirectional MR clutch

Figure 11: Torque values obtained from experiment and simulation.

(b) MR clutch

Figure 12: Experimental apparatus for desired torque tracking control.

Figure 13: Repulsive torque tracking control result along pitching motion.
the RMIS. In addition, the tracking control experiment has been implemented to the proposed haptic master using a simple PID controller. The repulsive torque trajectories were well obtained by activating the haptic master system without causing a significant tracking error. It is finally remarked that the proposed MR haptic master will be incorporated with the surgery robot for RMIS application in the near future. In this future work, the master device and surgery robot will be integrated into the RMIS system in which the repulsive force and desired position originating from the object and operator, respectively, will be transferred to each other.

**Nomenclature**

- **Ω₁**: Angular velocities of the rotor 1 (1/s)
- **Ω₂**: Angular velocities of the rotor 2 (1/s)
- **Ω₃**: Angular velocities of the casing of bidirectional MR clutch (1/s)
- **Ωₑᵢ**: Angular velocities of the flux guide of MR clutch (1/s)
- **Ωₒᵣ**: Angular velocities of the outer housing of MR clutch (1/s).

**Conflict of Interests**

The authors declare that there is no conflict of interests.

**Acknowledgment**

This work was supported by the Incheon National University Research grant in 2013.

**References**

[1] http://www.intuitivesurgical.com.
[2] http://allaboutroboticsurgery.com/zeusrobot.html.
[3] M. C. Çavuşoğlu, F. Tendick, M. Cohn, and S. S. Sastry, “A laparoscopic telesurgical workstation,” *IEEE Transactions on Robotics and Automation*, vol. 15, no. 4, pp. 728–739, 1999.
[4] A. F. Rovers, “Haptic feedback: a literature study on the present-day use of haptic feedback in medical robotics,” DCT Report, Eindhoven University of Technology, Eindhoven, The Netherlands, 2002.
[5] “BMW 2008 iDrive Controller,” http://www.bmwworld.com/models/e65.htm.
[6] F. Pierrot, E. Dombre, E. Dégoulange et al., “Hippocrate: a safe robot arm for medical applications with force feedback,” *Medical Image Analysis*, vol. 3, no. 3, pp. 285–300, 1999.
[7] Y. Yamaguchi, J. Furusho, S. Kimura, and K. Koyanagi, “High-performance 2-D force display system using MR actuators,” in *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS ’04)*, vol. 3, pp. 2911–2917, Sendai, Japan, October 2004.
Advances in Mechanical Engineering

[8] G. L. Kenaley and M. R. Cutkosky, “Electrorheological fluid-based robotic fingers with tactile sensing,” in Proceeding of the IEEE International Conference on Robotics and Automation, pp. 132–136, Scottsdale, Ariz, USA, May 1989.

[9] H. S. Lee and S. B. Choi, “Control and response characteristics of a magneto-rheological fluid damper for passenger vehicles,” Journal of Intelligent Material Systems and Structures, vol. 11, no. 1, pp. 80–87, 2000.

[10] S. R. Hong, S. B. Choi, W. J. Jung, and W. B. Jeong, “Vibration isolation of structural systems using squeeze mode ER mounts,” Journal of Intelligent Material Systems and Structures, vol. 13, no. 7-8, pp. 421–424, 2002.

[11] S. B. Choi, S. R. Hong, C. C. Cheong, and Y. K. Park, “Comparison of field-controlled characteristics between ER and MR clutches,” Journal of Intelligent Material Systems and Structures, vol. 10, no. 8, pp. 615–619, 2000.

[12] V. A. Neelakantan and G. N. Washington, “Modeling and reduction of centrifuging in magnetorheological (MR) transmission clutches for automotive applications,” Journal of Intelligent Material Systems and Structures, vol. 16, no. 9, pp. 703–712, 2005.

[13] W. H. Li, B. Liu, P. B. Kosash, and X. Z. Zhang, “A 2-DOF MR actuator joystick for virtual reality applications,” Sensors and Actuators A: Physical, vol. 137, no. 2, pp. 308–320, 2007.

[14] D. Senkal and H. Gurocak, “Spherical brake with MR fluid as multi degree of freedom actuator for haptics,” Journal of Intelligent Material Systems and Structures, vol. 20, no. 18, pp. 2149–2160, 2009.

[15] P.-B. Nguyen and S.-B. Choi, “A new approach to magnetic circuit analysis and its application to the optimal design of a bi-directional magnetorheological brake,” Smart Materials and Structures, vol. 20, no. 12, Article ID 125003, 2011.

[16] J. Li, S. Wang, X. Wang, and C. He, “Optimization of a novel mechanism for a minimally invasive surgery robot,” International Journal of Medical Robotics and Computer Assisted Surgery, vol. 6, no. 1, pp. 83–90, 2010.

[17] S. B. Choi and D. Y. Lee, “Rotational motion control of a washing machine using electrorheological clutches and brakes,” Proceedings of the Institution of Mechanical Engineers C: Journal of Mechanical Engineering Science, vol. 219, no. 7, pp. 627–638, 2005.

[18] Y. M. Han, C. J. Kim, and S. B. Choi, “A magnetorheological fluid-based multifunctional haptic device for vehicular instrument controls,” Smart Materials and Structures, vol. 18, no. 1, Article ID 015002, 2009.

[19] Q. H. Nguyen and S. B. Choi, “Optimal design of an automotive magnetorheological brake considering geometric dimensions and zero-field friction heat,” Smart Materials and Structures, vol. 19, no. 11, Article ID 115024, 2010.

[20] Q. H. Nguyun, Y. M. Han, S. B. Choi, and N. M. Wereley, “Geometry optimization of MR valves constrained in a specific volume using the finite element method,” Smart Materials & Structures, vol. 16, no. 6, p. 2242, 2007.