2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Application of Magneto-Rheological Fluid Based Clutches for Improved Performance in Haptic Interfaces

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Abstract— **The two main objectives in designing a haptic interface are stability and transparency. The dynamics of the actuators employed in a haptic interface have a significant effect on these goals. In this article, the potential benefits of Magneto-Rheological Fluid (MRF) based actuators to the field of haptics are discussed. Devices developed with such fluids are known to possess superior mechanical characteristics over conventional servo systems. This contributes significantly to improved stability and transparency of haptic devices. In this study, this idea is evaluated from both theoretical and experimental points of view. First, the properties of such actuators which motivated this research are discussed. Next, two single degrees-of-freedom (DOF) haptic interfaces are used in a virtual wall experiment. These devices take advantage of an MRF-based clutch and a brushless DC motor at their core, respectively. The results of both devices are compared and show the superiority of the MRF-based clutch. In addition, design and analysis of a small-scale MRF-based clutch, suitable for a multi-DOF haptic interface, is given and its torque capacity, inertia, and mass are compared with those of conventional servo systems. Conclusions drawn from this investigation indicate that MRF clutch actuation approaches can indeed be developed to design haptic interfaces with improved stability and transparency.**

I. Introduction

Haptics studies the use of force and tactile feedback in order to simulate the interaction with remote or virtual objects. Such feedback allows the user to commit appropriate force control actions through the haptic interface for safe and proper manipulation. In this regard, haptic sensation should be convincing enough to provide the user with a plausible feeling of being directly in contact with the remote or virtual environment. This desirable attribute is called transparency. The stability of a haptic systems is another crucial issue in designing such systems. However, it is known that transparency and stability are conflicting design criteria [1].

The actuators and mechanisms used in designing a haptic interface play an important role on the quality of force feedback, as well as the stability of the system. This fact makes the design of a haptic interface twofold challenging. In order to have a transparent system, it is of utmost importance that while a haptic device is capable of recreating the forces that occur during contact with stiff objects, it exhibits low friction, damping, and inertia in order to sustain transparency during motion in free space. Poor dynamics and control of manipulation can affect the sense of touch, in particular when rigid instruments or actuators are used [2]. Heavy and/or cumbersome haptic systems generate artifacts which negatively affect the quality of the virtual presence [3]. Furthermore, the use of active actuators (e.g., electrical motors) in haptic devices may degrade the problem of stability [4] due to generation of energy, the problem of reflected slave forces, and induced master motion mechanisms, especially in systems with time delay [5]. In addition, such actuators can exhibit oscillations and jerks [6], which not only can cause uncomfortable forces for the user, but are highly problematic in delicate operations [7]. Most current haptic systems take advantage of passivity-based and small-gain approaches in order to guarantee the stability [8][9]. However, such approaches are considered to be conservative and in turn result in degraded transparency. Hence, to effectively operate such systems, long and costly amount of training is required.

Actuators based on Magneto-Rheological Fluid (MRF) have been proposed as an alternative for use in haptic devices [2]. MRFs exhibit a very unique characteristic: the viscosity and shear stress of these fluids can be intelligently controlled using an applied magnetic field. Several passive and semi-active actuators have been developed by taking advantage of this feature. Such systems exhibit remarkable characteristics, including high yield stress, low mass-torque and inertia-torque ratios, compact size, intrinsic passivity, and precision controllability [10]. It is expected that the superior characteristics of MRF-based actuators in comparison to active actuators will enable the design of a more transparent and stable haptic interface. An investigation into this idea is presented in this paper. An important contribution of this paper is that it shows the effect of MRF-based actuators in improving stability and transparency of haptic interfaces from a practical point of view, by taking advantage of a large-scale setup. Moreover, by providing the design and analysis of a smaller scale MRF-based actuator, this study lays the ground work for developing a multi-DOF haptic interface that can be integrated in a surgical training environment. To this end, first, intrinsic properties of such actuators, which have an impact on stability and transparency, are discussed in Section II. Experimental evaluation on the performance of a 1-DOF haptic interface which takes advantage of an MRF-based clutch is presented in Section III. The well-known virtual wall benchmark is used for this purpose and the results are compared with another 1-DOF haptic device

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978-1-4799-3684-7/14/$31.00 ©2014 IEEE

with a DC motor at its core. Although the clutch used in Section III is bulky, it serves as a proof of concept. Conclusions drawn from these results indicate that indeed the haptic interface with an MRF clutch exhibit improved stability and transparency in comparison to its standard counterpart. Furthermore, the design and analysis of a small-scale MRF-based clutch is given in Section IV. The suitability of the design is assessed by modeling the torque-mass, and torque-inertia ratios, as well as output torque capacity. The results show the promising potential of these actuators for integration in a multi-DOF haptic interface with improved stability and transparency.

II. Advantages of MRF in Haptic Interfaces

This section studies the effect of MRF-based actuators on the performance of haptic devices from a theoretical and mechanical point of view.

MR Fluids are a suspension of micrometer-sized ferrous particles in a carrier fluid. When subjected to an externally applied magnetic field the particles form columns and align themselves in the direction of the applied field. Consequently, the columns act to resist shearing or flow of the fluid. The apparent yield stress of the fluid is dependant on, and increases with the intensity of the applied magnetic field. Using MRF, an actuation system can be constructed such that the amount of transmitted torque/force can be controlled by the intensity of an applied field. The MRF exhibit such behavior in three operational modes, namely shear, flow, and squeeze modes [11]. Various actuators have been developed based on these operational modes, namely dampers, brakes, and clutches. Overall, such actuators can be used in order to design compact, light weight, low inertia, low friction, high bandwidth, and high torque haptic devices which can contribute to transparency. Several applications of MRF-based actuators in force and tactile feedback devices have been reported in the literature. These devices can be roughly categorized into four types (a) force displays in the forms of knobs, joysticks, parallel-link displays, etc. [6][12], (b) tactile displays in the forms of pinch grasps, haptic black boxes, etc. [2][13][14], (c) hand masters in the forms of ground-mounted mouses, body-mounted gloves, and exoskeletons [4][15], and (d) rehabilitation devices [16].

A haptic device should be capable of generating large forces/torques in order to mimic interaction with stiff objects. MR Fluids are capable of producing high shear stress. Such shear stress is bounded and is limited to the physical properties of MRF, i.e., magnetic saturation [17]. Nevertheless, MRF can produce high yield stresses typically in the range of 50 to 100 kPa, dependent on their chemistry. Hence, MRF can be used to design actuators capable of transmission or generation of high passive/semi-active force and torque.

While a haptic device should be able to generate high torques, it is highly desirable that it exhibits low inertia. Use of gear reduction for increasing the torque capacity of electrical motors results in a significant aggravation of inertia. The reflected actuator inertia of a manipulator can in fact be much larger than that of the link inertia, thereby contributing a larger share of the inertial load [18]. On the other hand, MRF-based actuators have the characteristic of replacing the reflected rotor inertia of the motor with the reflected inertia of the clutch output shaft [10]. It is shown that MRF-based clutches demonstrate superior output inertia characteristics over the low-inertia servo motors [12][17].

Heavy and cumbersome haptic interfaces affect the quality of force feedback. It is highly desirable that a haptic device has low mass-torque ratio. Light weight and compact size of such actuators allow the user to experience a more plausible interaction [19]. MR devices can be made substantially more compact and lighter in comparison to electrical motors for comparable performance [11]. In fact, such actuators exhibit superior mass-torque ratio over the commercially available servo motors [17].

High bandwidth of the actuation system is essential for transparency of a haptic device. MRF respond to an applied field on the order of few milliseconds [17]. However, actuation response becomes delayed due to field propagation [20]. Nevertheless, MRF-based actuators are considered as high bandwidth systems which can permit very high bandwidth control, which is essential for mirroring fast motions [19].

The main problems with MRF-based devices is their nonlinear behavior and temperature dependency. MRF-based actuators exhibits hysteresis due to the use of ferromagnetic materials. This translates to a hysteresis relationship between the input current and the output torque which leads to tracking errors, unwanted harmonics, and undesired stick-slip motions [21]. To develop accurate output torque to input current relationships, it is important to both understand and model the actuator hysteresis [21]. This is still an open area of research. Another important issue is the temperature dependency of MRF. These fluids behavior change with a variation in the device temperature. Hence, it is desirable to integrate temperature sensors and include their output in the modeling and control of the system.

III. Experimental Validation: Haptic Rendering of Virtual Wall

In order to evaluate the effect of MRF-Based on the transparency and stability of haptic devices, results of virtual wall display obtained by experimentation on two single-DOF haptic displays are presented and compared in this section. The first haptic interface consists of a prototype MRF-based clutch (designed and constructed in our research group [17]). The result of this system is then compared with that of a haptic interface which takes advantage of an active actuators, namely a brushless DC motor (Maxon EC-60).

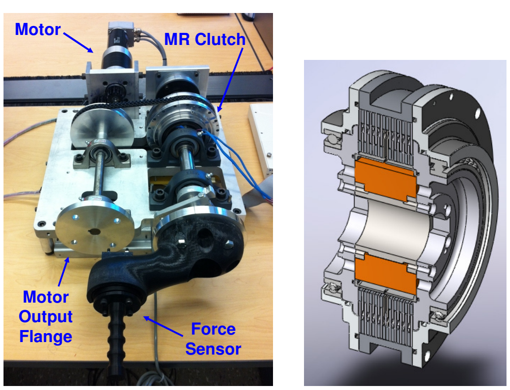
Remark: It should be noted that the prototype clutch used in this section, was initially designed for industrial applications and it is not suitable for haptic application. Nevertheless, this setup provides a good ground to study the benefits that such actuators can bring into haptic devices.

A. Experimental Setup

The experimental setup is shown in Fig. 1. The two considered single-DOF haptic devices are as follows;

MRF-Based Haptic Interface: This actuation mechanism used an MRF-based clutch at its core [17]. Fig. 1(b) shows the cross-section of a typical multi-disk MR clutch. The input shaft breaks out into a set of input disks which are aligned in parallel to a set of output disks attached to the output shaft. MR fluid fills the volume between input and output disks. A driver motor applies a constant torque to the input shaft. By energizing the electromagnetic coil, the viscosity of MRF, and thus the compliancy of the clutch can be controlled.

In this setup, the input shaft of the clutch was driven by a servo amplifier which was set up in constant torque mode. A handle was connected to the output shaft of the clutch and the user could interact with the interface using this handle. An ATI Gamma F/T sensor was placed on the handle in order to measure the forces applied by and to the human hand. Although this setup is only capable of generating forces in one direction [17], it is suitable for our experiment since all the forces experienced from the wall are in the same direction. It should be noted that, the output torque of the clutch is only controlled through regulating the magnetic field of the clutch. The Maxon motor had no role in output torque control and it ran in constant torque mode in a single direction. In order to control the output torque of the clutch, first the Hall sensor was used to measure magnetic field density in the clutch. Next, the Bingham Visco-Plastic (BVP) model [21] was used to estimate the shear stress by using magnetic field flux density. Having the shear stress, and consequently the output torque, a PID controller generates current as input of clutch to control output torque via the National Instruments (NI USB-6229) multifunction I/O device. The highest achievable control frequency using such an I/O device was 500 Hz.



(a) (b)

Fig. 1. (a) Snapshot of the experimental setup. The mechanism takes advantage of MRF-based clutches as part of the actuator. (b) Sectional view of prototype MRF-based clutch

Electrical Motor-Based Haptic Interface: The setup in Fig. 1 can also be used to study the performance of a motor in a haptic device. The handle, connected to the output shaft of the clutch, can be moved and connected to the output flange of Maxon EC-60 motor, while belt is disconnected (Fig. 1). In this way, the motor can be used as a 1-DOF haptic interface. The built-in PID controller in the EPOS motion controller was used to control the output torque.

B. Results

Using the aforementioned setup, several experiments were performed to compare the stability and transparency of MRF-based clutches with electrical motors when implemented in a 1-DOF haptic interface of virtual wall. The virtual wall was implemented as a virtual torsional spring with stiffness K_W and a virtual rotational damper with damping coefficient B_W. At the frequency of 500 Hz, interaction with a virtual wall with different stiffness and damping was tested using both setups. The user holds the handle and makes several contacts with the virtual wall in each case.

First, a virtual wall with stiffness of $K_W = 10\ \frac{Nm}{rad}$ and damping of $B_W = 10\ \frac{Nms}{rad}$ was considered. In this case, due to the low stiffness, the wall exhibits high compliancy and it deforms. Fig 2(a) presents the results of interacting with the wall using the clutch and then the motor as haptic device. These plots depict the torque applied by the wall and the torque generated by the actuator. In addition, they depict the position of the handle with respect to the wall (the wall starts at 0 deg). As can be seen, the clutch exhibits much higher transparency when the user makes contact with the wall. In fact, the root mean square (RMS) of the errors between the torque of virtual wall and the torque felt by the user hand are 0.119 Nm and 0.667 Nm for the clutch and the DC motor, respectively.

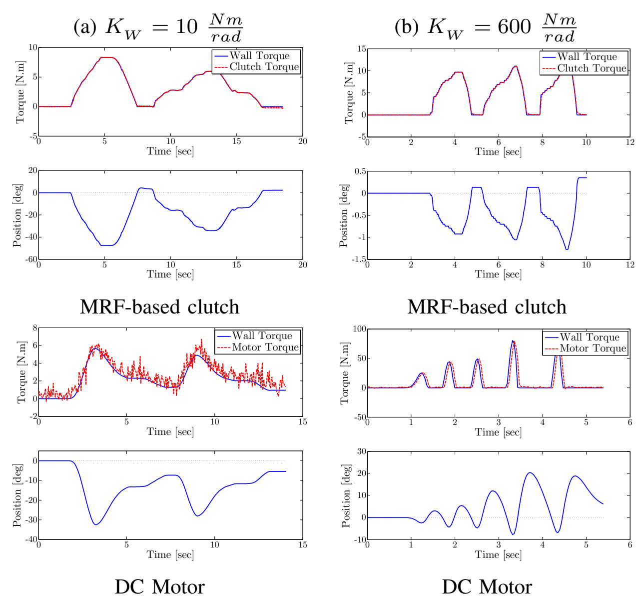


Fig. 2. Results of interaction with the virtual wall at 500 Hz with damping $B_W = 10\ \frac{Nms}{rad}$ and different stiffness for MRF-based clutch (top row) and DC motor (bottom row). The virtual wall starts at 0 deg position.

The superiority of the MRF-based clutch becomes more evident when the virtual wall becomes stiffer (i.e., $K_W = 600\ \frac{Nm}{rad}$ and $B_W = 10\ \frac{Nms}{rad}$). The results of such interaction are depicted in Fig. 2(b). In this case, the clutch exhibits a few ripples in the output torque when contact is made with the wall (0 deg). However, these ripples are damped out after a few cycles. The RMS error of the torque is 0.185 Nm for the clutch. As can be seen, the user is capable of making

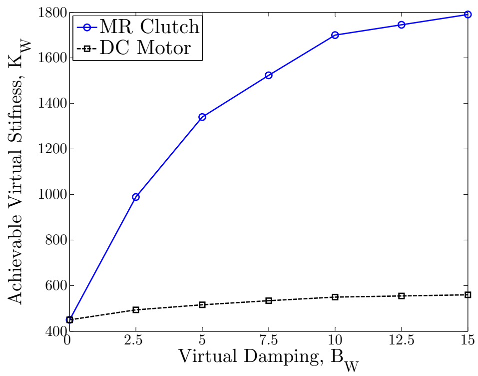


Fig. 3. Maximum achievable virtual stiffness K_W $[\frac{Nm}{rad}]$ for different virtual damping B_W $[\frac{Nms}{rad}]$ at 500 Hz for MR clutch and DC motor

several stable contacts with the wall. However, in the case of the DC motor, the system becomes unstable as contact is made, and the user loses control. This is evident in the position of the handle in the bottom plot of Fig. 2(b). This result shows better performance of the MRF-based clutch for use in haptic devices. In fact, the clutch remains stable for $K_w < 1700$ $\frac{Nm}{rad}$. A comparison between the transparency of the two systems in the tests performed is given Table I.

TABLE I
TRANSPARENCY OF THE MRF-BASED CLUTCH AND DC MOTOR FOR DIFFERENT STIFFNESS OF THE VIRTUAL WALL

K_W $[\frac{Nm}{rad}]$	RMS of error in Torque Display $[Nm]$	
	MRF-based clutch	DC Motor
200	0.105	0.803
400	0.137	0.940
600	0.185	Unstable
1000	0.185	Unstable
1700	Unstable	Unstable

In another experiment, the maximum achievable stiffness with each of the haptic interfaces were obtained for several values of virtual damping B_W. Fig. 3 presents the results. The maximum achievable virtual stiffness in case of the motor is limited due to constant physical damping. However, in the case of MR clutch, higher *Z-width* is achieved. This in fact shows the suitability and superiority of MRF-based actuators for use in haptic devices.

IV. Preliminary Study and Design of a Small-Scale MRF-Based Clutch

The promising results obtained in Section III motivated us to move toward the design and manufacturing of a small-scale version of an MRF-based actuator for application in a haptic interface. This section provides the results of the preliminary study and design of such an actuator. Manufacturing of the proposed MR clutch in this section is currently underway. The end goal of this project is to implement such actuators into a multi-DOF haptic interface which will be integrated in a surgical training environment (will be reported in the near future).

A. Proposed Clutch Structure

Two major approaches in designing MRF-based clutches have been identified in the literature, namely multiple disks and drum-based designs [22]. The former has the same structure as that of the prototype industrial MR clutch in [17]. In drum-based design, the MRF is placed in the gap between two concentric cylinders. By taking advantage of a cylindrical coil inside the inner cylinder the shear stress between the two surfaces can be controlled [23]. Modified and hybrid versions of these two designs also exist [24]. The drum-based design is known to exhibit higher torque-volume ratio [22]. On the other hand, they exhibit higher friction and inertia as the size of the actuator increases [17]. Thus, the drum-based approach is a good candidate when a compact and high-torque capacity actuator is desired. One major drawback of such design is that the volume of MRF energized by the magnetic field is limited. Since the axis of the coil is collinear to the axis of inner cylinder in this design, the magnetic field is applied to the MRF, only at the two end of the coil. Hence the majority of the MRF gap is not activated when operating. In this study, a new design – called armature-based – is proposed in order to improve the performance of the drum-based approach by increasing the effective MRF volume.

The structure of the armature-based actuator is similar to that of a DC motor, i.e., Figs. 4(a,b). In this design, MRF fills the gap between a cylindrical casing and an armature, both made out of ferromagnetic materials. The wire windings on the armature creates magnetic field perpendicular to the surface of the MRF gap. Spacers, made of light and nonmagnetic materials, fill the armature stack slots in order to avoid drag forces created by the fluid accumulated between the armature poles. A hall sensor will be fixed on the top of one of the poles to measure magnetic field strength. As opposed to DC motors, commutation is not required in this design since there is no need for alternating poles. Numerical analysis of the proposed design is given in Section IV-B.

Fig. 4(c) describes the operation of this actuator. A constant input speed/torque is applied to the outer casing of the clutch, e.g., using a motor. Then, through controlling the magnetic field, the output speed/torque is controlled and is applied to the output link through cables/belts. It should be noted that the clutch is only capable of providing unidirectional motion. In section IV-C, the expansion of the proposed design into a multi-DOF system is discussed.

B. Analysis and Comparison with Conventional DC Motors

In order to obtain the torque capacity of the proposed design, first finite element modeling (FEM) was used in order to study the magnetic field inside the actuator. This work took advantage of FEMM Software [25] in order to perform the FEM. Fig. 5 depicts the magnetic field paths inside the actuator. The armature-based design creates a uniform and strong magnetic field which improves the torque capacity.

Using the obtained FEM, the magnetic field intensity $\mathbf{H}$ at the MRF gap can be obtained. BVP model is used to calculate the shear stress τ at the gap,

$$\tau = \tau_y(\mathbf{H}) + \eta\omega r_{MR} w_{MR}^{-1} \quad (1)$$

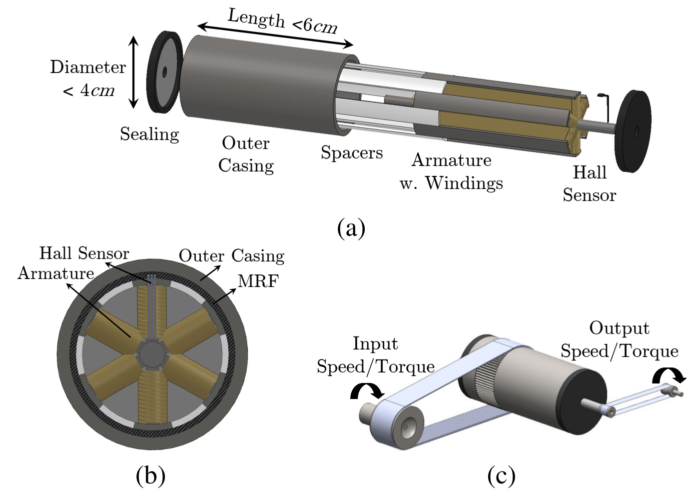


Fig. 4. (a) Exploded and (b) cross-sectional view of the proposed small-scale MRF-based clutch. (c) Description of the proposed clutch operation.

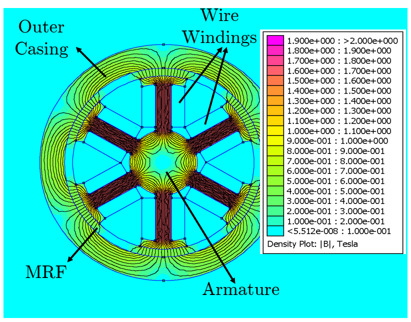


Fig. 5. Magnetic field inside the system, obtained using FEMM [25].

where τ_y is the field-dependent yield stress, η is the newtonian viscosity, ω is angular velocity between casing and armature, and $r_{_{MR}}$ and $w_{_{MR}}$ are radius from armature shaft and thickness of the MRF gap, respectively. Data relating the yield stress τ_y of a fluid are generally published by the manufacturer and can be up to 50-100 KPa. The viscosity η of the carrier fluid is typically in the range of 0.1-0.3 $Pa.s$. Hence, in this study, we consider the torque transmitted solely by the field dependent yield stress of the MRF. Calculating the value of τ_y, the magnitude of generated braking torque T will be obtained as,

$$T = N_p \tau_y A_{_{MR}} R_{_{arm}} \tag{2}$$

where N_p is the number of armature poles, $A_{_{MR}} = (2N_P)^{-1} R_{_{arm}} L_{_{arm}}$ is the area of MRF activated at each pole, and $L_{_{arm}}$ and $R_{_{arm}}$ are the length and outer radius of the armature, respectively. It can be seen in (2) that the amount of torque a clutch can produce highly depends on the strength of the magnetic field created at MRF gap. In order to create stronger magnetic field, larger numbers of wire windings turns and higher electrical current are required. The number of wire turns and the wire gauge (maximum safe current) is limited due to the available space in armature stack slots, as well as, the limit on the mass and inertia of the armature. On the other hand, the dimensions of the armature poles and shaft can limit the field created due to magnetic saturation. If the smallest area $A_{_{min}}$ of the armature magnetic circuit is designed to be much smaller than MRF gap area ($A_{_{min}} \ll A_{_{MR}}$), then that part can become saturated (i.e., $\frac{\phi}{A_{_{min}}} \gg \frac{\phi}{A_{_{MR}}}$, where ϕ is magnetic flux), and in turn significantly reduces the magnetic field at the MRF gap.

As mentioned above, the effective inertia of the armature and the weight of the clutch are also important factors with regard to transparency of a haptic interface. The effective inertia of the armature $J_{_{arm}}$ is,

$$J_{_{arm}} = J_{_{shf}} + N_p J_{_p} + J_{_w} \tag{3}$$

where $J_{_{shf}}$, $J_{_p}$, and $J_{_w}$ are the moments of inertia of the armature shaft, pole, and wire winding, respectively. Next, the weight of the clutch $M_{_{cl}}$ can be obtained as,

$$M_{_{cl}} = \rho_{_{st}}(V_{_{shf}} + N_p V_{_p} + V_{_{cs}}) + \rho_{_{MR}} V_{_{MR}} + M_{_w} \tag{4}$$

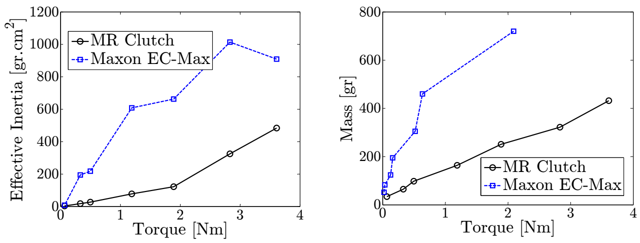
where $\rho_{_{st}}$ and $\rho_{_{MR}}$ are density of steel and MRF, respectively, $V_{_{shf}}$, $V_{_p}$, $V_{_{cs}}$, $V_{_{MR}}$ are the volume of the armature shaft, pole, outer case, and MRF gap, respectively, and $M_{_w}$ is the mass of wire windings. Derivation of these values are not included in this paper for the sake of brevity.

In order to assess the suitability of the proposed design, a comparison with Maxon the EC-max DC motors [26] is performed. This series of motors includes some of the most powerful and versatile small-scale DC motors. To perform the comparison, the armature-based MR clutches with the exact dimensions of the Maxon motors and six poles ($N_p = 6$) are considered. Then, their torque capacity, reflected inertia, and weight are compared. Table II presents the torque capacity of the motor and the clutch with similar dimensions. The results show the superiority of the clutch in comparison to the Maxon motors.

TABLE II
COMPARISON BETWEEN TORQUE CAPACITY OF MAXON EC-MAX AND MR CLUTCH WITH SAME DIMENSIONS (TORQUES [mNm])
Note: ECXX YYW = EC-MAX *XX*, *YY* WATT

Motor Model	EC40 120W	EC40 70W	EC30 60W	EC30 40W	EC22 25W	EC22 12W	EC16 8W
Diameter [cm]	4	4	3	3	2.2	2.2	1.6
Length [cm]	8	5.5	6	4	4.5	3	3
Nominal Torque	168	94	63	34	23.	10.9	8.2
Stall Torque	2090	636	519	160	127	35.5	22
Same-Dimension Clutch Torque	3610	2830	1890	1190	497	330	68

Next the mass and effective inertia are compared. Fig. 6 presents a comparison of the inertia-torque and mass-torque ratios. MR clutches exhibit lower ratios, which demonstrates its suitability for use in a haptic interface. One should note that in order to have a fair comparison between the inertia of the actuators, the reflected inertia of the DC motors is calculated as $J_{_{eq}} = G_r^2 J_{_{rot}}$, where $J_{_{rot}}$ is the rotor inertia of the DC motor [26]. G_r is the gear ratio required to create output motor torque comparable to that of the clutch, i.e., $T_{eq} = G_r T_{stall}$. The stall torques (and not the nominal torques) of the motors are considered in these results. However, this is not considered in comparison of the actuators mass.



(a) (b)

Fig. 6. (a) Inertia to torque (with gear reduction) and (b) mass to torque (without gear reduction) relationships for Maxon EC-max and MR clutch

C. Implementation in a Multi-DOF system (Future Work)

The use of MRF-based clutches in a multi-DOF haptic device can be addressed using the concept of Pluralized Antagonistic Distributed Active Semi-Active actuation [10]. In this configuration multiple MR clutches can be driven by a single motor, which is located at the base. The single motor applies a constant unidirectional speed/torque to *all* sets of clutches, also through a system of cables and pulleys. A set of two clutches are employed to apply torques to each joint through cables and pulleys [10]. The two MR clutches antagonistically provide opposite directions with respect to each other at the joint. By taking advantage of the small-scale MRF-based clutches in such a configuration, a lightweight and compact multi-DOF haptic interface is under development for a surgical training environment.

V. Concluding Remarks

MRF–based actuators exhibit promising characteristics for applications in haptic devices. Low output inertia, low mass-torque ratio, superior performance and bandwidth, precision controllability of output torque, and intrinsic passivity of MRF-based actuators are important characteristics for haptic interfaces. The results of the virtual wall experiment conducted in this paper on a large-scale prototype of an MRF-based clutch support these claims and demonstrate the desirable performance of such actuators when used in a haptic device. This provides a strong motivation for developing small-scale MRF-based actuators as a lightweight and compact actuating systems. Specifically, such actuators are well suited for haptic devices which are required to provide high-torque capacity, while having better stability and transparency. Our preliminary studies on the small-scale armature-based clutch supported this claim.

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