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Linear Torque Actuation using FPGA-Controlled Magneto-Rheological Actuators*

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Abstract— **In recent years, Magneto-Rheological (MR) clutches have been increasingly used for realizing compliant actuation. One difficulty in using MR clutches is the existence of nonlinear hysteretic behaviors between the input current and output torque of an MR clutch. In this paper, a new closed-loop, Field-Programable-Gate-Array (FPGA) based control scheme to linearize an MR clutch's input-output relationship is presented. The feedback signal used in this control scheme is the magnetic field acquired from hall sensors within the MR clutch. The FPGA board uses this feedback signal to compensate for the nonlinear behavior of the MR clutch using an estimated model of the clutch magnetic field. The local use of an FPGA board will dramatically simplify the use of MR clutches for torque actuation. The effectiveness of the proposed technique is validated using an experimental platform that includes an MR clutch as part of a compliant actuation mechanism. The results clearly demonstrate that the use of the FPGA based closed-loop control scheme can effectively eliminate hysteretic behaviors of the MR clutch, allowing to have linear actuators with predictable behaviors.**

I. INTRODUCTION

During the past two decades, a wide range of compliant actuators have been proposed and developed within the context of Human-Compatible, and Human-Friendly Robots. The main idea behind introducing compliance in the actuation is to reduce the effective impedance of the actuator for leveraging the safety properties of the actuator. Pneumatic muscle-like actuators are perhaps among the earlier forms of compliant actuators (e.g. McKibben muscles [1]). The output impedance of pneumatic actuators is typical low due to the close-to-zero inductance of the compressible gas in the actuator. Unfortunately, the compliance of pneumatic actuators results in a reduced controllable bandwidth of these actuators.

Compliant actuators have also been realized mechanically. Series Elastic Actuator (SEA) [2] is an initial attempt to reduce the actuator's impedance using an elastic element placed between the input motor and the output load. Within its controllable bandwidth, SEA has a very low output impedance, and beyond its bandwidth, SEA impedance matches the stiffness of the elastic coupling [3]. Nonetheless, similar to pneumatic actuators, SEA suffers from a limited controllable bandwidth. To address this issue, Variable Stiffness Actuator (VSA) was proposed as an alternative compliant actuation solution [4]. VSA also integrates an elastic element into its transmission path, but unlike SEA, the stiffness of the transmission coupling is variable. This allows VSA to become more compliant during high velocity tasks and stiffer during low velocity tasks to provide both improved performance and safe actuation. Instead of incorporating an elastic element, Series Damper Actuator (SDA) incorporates a rotary damper into its transmission path for increasing the bandwidth [5]. This configuration allows the output force/torque of the actuator to be controlled based on the relative angular velocity between the motor and the damper. While SDA has a slightly better bandwidth than VSA, the bandwidth is still below the demand of most high performance applications. To take advantage of both VSA and SDA concepts in one unit, Variable Impedance Actuator (VIA) was proposed [6]. A combination of a variable elastic element and a variable damping element is used to connect the input and output parts in VIA. This connection allows VIA to change its stiffness without compromising the bandwidth. Similar to VIA, Double Actuator Unit (DAU) proposed in [7] uses two actuators and a planetary gear train to immediately reduce joint impedance following the detection of a dynamic collision.

In recent years, the use of Magneto-Rheological (MR) fluids for realizing compliant actuation has received increasing attentions. In comparison to compliant actuators mentioned above, MR actuators can provide larger controllable bandwidth and safe actuation inherent in the design. A compliant actuation using an MR clutch to couple an input motor to an output load was studied in [8]. This actuator provided a maximum torque of 5 Nm. Later, the transient response of the actuator was improved to near 30Hz by replacing Aluminum with an engineering plastic in all connecting parts of the MR clutch [9]. An MR actuator with a locking mechanism was used as an assistive knee brace in [10]. The MR device acted as a brake when the lock was on and as a clutch when the lock was off. The locking mechanism was used to fix the shaft of the MR actuator to the brace. Dual Differential Rheological Actuator (DDRA) is another MR fluids based compliant actuator [11]. DDRA couples two different MR brakes, each of which moved at the same speed but in opposite directions. The coupled MR brakes generate an output torque with an applied magnetic field. The controllable bandwidth of DDRA is limited to 4Hz and the hysteresis of the MR brakes have not been addressed.

In our previous body of work, we developed a new actuation mechanism known as Distributed Active Semiactive Actuator (DASA) using MR clutches [12]. This is a novel

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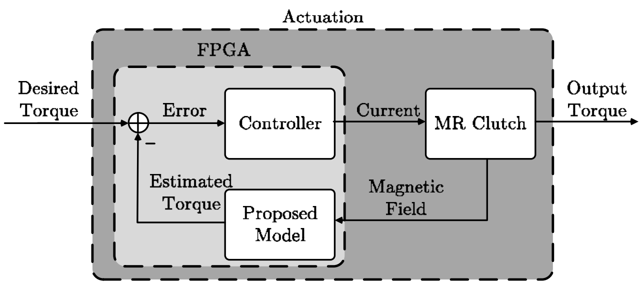

Fig. 1. The block diagram of the proposed control scheme.

actuation concept whose full details and advantages have been reported in [13]–[15]. DASA has high torque-to-mass and torque-to-inertia ratios and in comparison to similar actuation concepts features a more compact structure [13]. The performance of the actuator in terms of the controllable bandwidth and time response competes with servo motors within the same torque range [12]. The use of MR clutch in DASA, however, presents a nonlinear hysteretic relationship between the input current and output torque of the actuator. This nonlinear relationship poses a challenge in controlling the actuator. In order to overcome this shortcoming, a new hysteresis model to replicate the nonlinear relationship between the actuator input and output was developed [16]. However, it has been shown that the shear stress of MR fluids has a linear relationship with the applied magnetic field [12]. In other words, the output torque of DASA was almost linearly proportional to the intensity of the applied magnetic field and the nonlinear behavior of the actuator mainly stemmed from hysteretic relationship between the magnetic field and the input current of the actuator.

The main contribution of this paper is to present a closed-loop control scheme that linearizes the behavior of DASA. The feedback signal used for the closed-loop control is the magnetic field information obtained from a proprietary arrangement of embedded hall sensors in DASA. Using the magnetic field information and the hysteresis model of the actuator, the controller can linearize the output torque of the actuator in relation to its input current. The closed-loop controller is implemented on a Field-Programable-Gate-Array (FPGA) board which makes it possible to be embedded into the future generation of DASA. Given the relatively linear relationship of the actuator torque with respect to its internal magnetic field, it is possible to perform high fidelity force/torque control without using any external force/torque sensor. The use of hall sensors provides a reliable, compact, and more importantly viable alternative to external force/torque sensors. This concept is validated in this paper through a set of experiments performing on a prototyped DASA with FPGA based control. This technique allows DASA to fully exhibit predictable and linear input-output characteristics. A block diagram of the proposed closed-loop, FPGA based control scheme is shown in Fig. 1.

The remaining of the paper is organized as follows. Section II reviews the structure of the MR clutch used in this paper for validating the results. Section III discusses the FPGA based closed-loop scheme for controlling torques/forces using MR clutches. Section IV presents experimental results for torque control using estimated torque values and compares the results with that using actual torque measurements. Section V concludes the paper.

II. MR CLUTCH

MR fluids, carrying micrometer-scale particles, are a kind of smart materials whose viscosity can be changed using an external magnetic field. This property of MR fluids allows to accurately control the shear stress of the fluid by controlling the intensity of an external magnetic field. A clutch-like mechanism, also known as MR clutch, is often used as means of materializing this concept through bounding the amount of transmitted torque based on the intensity of an applied magnetic field. This form of torque transmission lends itself to a new type of compliant actuator also referred to MR actuator. In our previous body of work, we designed and developed a novel MR actuator known as Distributed Active Semiactive Actuator (DASA) [14] [15]. In this actuation mechanism an electric motor (active component) is coupled to one or more MR clutches (semi-active component), where all clutches receive their power from the motor (distributed actuation). The electric motor provides a rather constant power and each MR clutch controls the transmission of torque to its output shaft independently. Since the focus of this paper is on hysteresis compensation, we consider a unit MR clutch as a building block of our actuation concept DASA. Fig.2 demonstrates the cross-section of a typical multi-disks style MR clutch. The input shaft breaks out into a set of output disks attached to the output shaft. MR fluids fill the volume between input and output disks. By energizing the electromagnetic coil, the shear stress of MR fluids can be controlled by an applied magnetic field, which leads to altering of output torque [13].

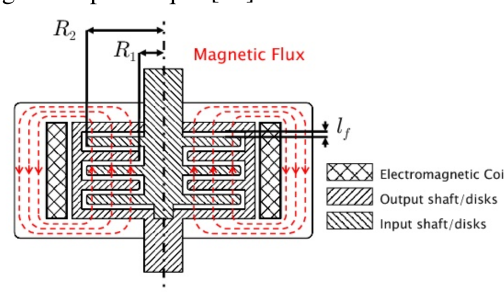

Fig. 2. Cross-section of a multi-disk MR clutch.

III. TORQUE CONTROL IN THE MR CLUTCH

Unlike electric motors that feature linear relationship between their input current and output torque, in an MR clutch, the input and output are nonlinearly related with hysteresis. This hysteretic behavior is mainly caused by the ferromagnetic components of an MR clutch [17] and is demonstrated in Fig. 3. We applied sinusoidal input currents with different frequencies to an MR clutch and Fig. 3 shows that the magnetic filed inside the MR clutch and the output torque are nonlinear with the input current.

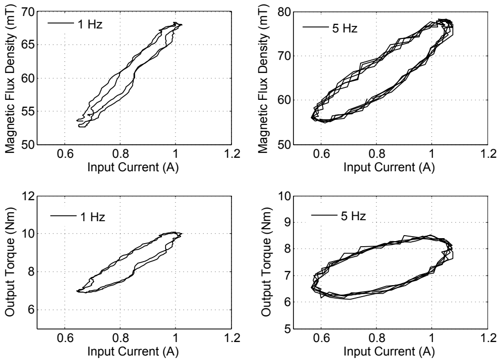

Fig. 3. Hysteretic behavior for an MR clutch.

One way to cope with this shortcoming is to employ an external torque sensor to provide the feedback signal for a closed-loop control system that regulates the torque. Despite availability of multi-axis force/torque sensors, this technique cannot provide favorable results due to other undesired effects such as friction, backlash, cogging effects of the actuators, measurement noise, and modeling errors. Notwithstanding, the high cost of the sensors and unreliable nature of the results in applications that concern interactions with the human present additional challenges. An alternative solution to deal with nonlinear behavior of an MR clutch is to compensate it, if not eliminating it, at the design level. This can be achieved using magnetic field information of the MR clutch to first estimate the output torque of the clutch and then compensate for any error. The estimation can be done accurately given the linear relationship between the shear stress of MR fluids and applied magnetic field. An analogy can be drawn between this technique and that previously used in Series Elastic actuators [2] and Hydro Elastic actuators [18] for estimating the actuator torque, in which an encoder measures the deflection of an spring. The same concept that eliminate hysteresis by embedding hall effect sensors inside an MR brake was proposed in [19]. However, the relationship between magnetic filed and output torque in [19] does not consider dynamic behaviors of an MR brake. In this paper, we discuss the use of hall sensor to measure the internal magnetic field of the MR clutch and to estimate the output torque of the clutch accurately. Since the input of the MR clutch is the electric current, the technique presented here results in a linear relation between the input current and output torque of the MR clutch. An FPGA based closed-loop control algorithm is used to perform this linearization technique. This technique results in a fully linear torque actuator assuming a gray-box input-output view of the MR actuator.

A. Control Scheme

As described in the previous section, the linear relation of the output torque to the magnetic field intensity is a major advantage in an MR clutch. This linear relationship allows controlling the output torque of the MR clutch accurately in a configuration shown in Fig. 4. In this figure, a simple PID controller provides a reference current for the MR clutch for generating the desired output torque value. The PID controller compares the estimated value of the output torque with its desired value as the input error signal. The estimated value of the output torque is obtained using the model described in the following sections. The model provides an accurate estimation of the output torque given the one-to-one relation of the output torque to the applied magnetic field. The intensity of the magnetic field is measured using a proprietary arrangement of embedded hall sensors inside our MR clutch. The error between the desired output torque and its estimated values provides a reference signal for a current source that drives the electromagnetic coil inside the MR clutch. The proposed model used for estimating the output

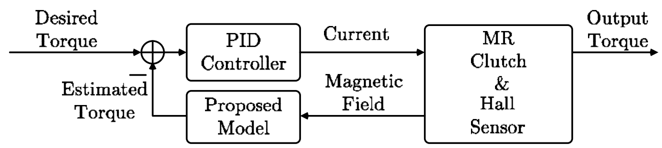

Fig. 4. Closed-loop control configuration using embedded hall sensors.

torque of the MR clutch consists of two parts: a static model and a dynamic model. Each part of this model is elaborated in the following sections.

B. Static Model

It has been shown that the visco-plastic Bingham model is a good candidate for representing the static behavior of the output torque in an MR clutch [20]–[24]. The Bingham model is a geometrical based model, which relates the shear stress to the yield stress and shear rate of MR fluids in MR clutches. With shear stress, the static output torque of the clutch can be obtained by integrating the shear stress. A model of the MR clutch based on the Bingham model was developed to predict the rheological properties of our actuator in a previous body of work [13], [16]. According to this model, the shear stress can be presented as:

$$\tau = \tau_y(B) + \eta \frac{dv}{dz}, \tau > \tau_y \tag{1}$$

where τ is the shear stress, τ_y is the field dependent yield stress, B is the magnetic field, η is the Newtonian viscosity, and $\frac{dv}{dz}$ is the velocity gradient in the direction of the field. The viscosity η of the carrier fluid is typically in the range of 0.1 to 0.3 Pa-s. The second term in (1) can be ignored due to its negligible effect on the estimated values of the output torque. In fact, the contribution of the first term in (1) is within the range of kPa-s torque for typical MR fluids, whereas for the second term this value does not exceed a few Pa-s.

Assuming the configuration depicted in Fig. 2 for an MR clutch, the torque produced by a circumferential element at a radius r is given by,

$$dT = 2\pi r^2 \tau dr. \tag{2}$$

Integrating (2) across the output disks and substituting (1), the static output torque of the MR clutch can be obtained as follows

$$T_s \simeq \frac{4}{3} N\pi\tau_y(B)(R_2^3 - R_1^3). \tag{3}$$

where N is the number of output disks, and $R1$ and $R2$ are the inner and outer radius of the disks, respectively.

Moreover, considering the linear relationship between yield stress and magnetic field, we have:

$$\tau_y(B) = cB, \tag{4}$$

where c=56.135 is a constant.

Substituting (4) into (3) yields the output torque of MR clutch as a static function of the magnetic field B:

$$T_s \simeq kB. \tag{5}$$

where $k = 4cN\pi(R_2^3 - R_1^3)/3$ is a constant that depends on geometrical parameters of the clutch.

C. Dynamic Model

While the Bingham model can accurately estimate the output torque of an MR clutch statically, there are some discrepancies between the estimated values of the torque and its actual value measurement in dynamic mode. The presence of mechanical components within an MR clutch is perhaps the main factor that differentiates the dynamic behavior of an MR clutch from its static model. Not unlike any other mechanical system, the disk's inertia in an MR clutch, fluidic friction, and the gravity can affect the dynamic behavior of the clutch. Another factor that is specific to MR clutches is the various response time of the MR fluid in different parts of the clutch. Using finite element analysis, it has been shown that the magnetic field is stronger near the coil location and weaker elsewhere (e.g. in [25], [26]). As a consequence, the MR fluid reacts with different time responses in different locations of an MR clutch. Taking all these issues into consideration, it is very difficult, if not impossible, to develop a physic-based dynamic model for an MR clutch and is outside the focus of the current study.

In order to include the dynamic behavior of an MR clutch in the modeling, we use a well-known Auto Regressive with eXternal input (ARX) technique [27, ch. 10]. The ARX model is basically a linear difference equation between the input and output, which relates next output value to the previous observations. Using the ARX model, a dynamic model for estimating the output torque can be constructed. The input to this model is the static torque obtained in (5) and the output is the estimated dynamic torque value. The resulting model is given by,

$$\begin{aligned} \hat{T}(t) \quad &= \quad -a_1\hat{T}(t-1) - ... - a_n\hat{T}(t-n) \\ &\quad\quad +b_1T_s(t-1) + ... + b_mT_s(t-m), \end{aligned} \tag{6}$$

where $\hat{T}$ is the estimated value of the output torque and T_s is the static torque obtained in (5).

D. Implementation on FPGA

In order to implement the PID controller and the model proposed previously for linearizing the MR clutch, a Field-Programable-Gate-Array (FPGA) board is employed a closed-loop feedback configuration. The FPGA board implements the PID controller and the proposed model with Verilog Hardware Description Language (HDL). An FPGA-based controller provides a fast and flexible platform for linearizing MR clutches using various functions and configurations. More importantly, the use of FPGA technology facilitates its future integration in the design of an MR clutch and DASA as a fully embedded component.

IV. Experimental Results

A set of experiments to validate the proposed model and the effectiveness of the overall control scheme is presented in this section. In the experimental setup the MR clutch prototype is driven by a servo amplifier (Maxon 4-Q-DC Servo-amplifier ADS 50/5) configured in torque mode for providing the command current. A static load cell (Transducer Techniques SBO-1K) is mounted on the output shaft for torque measurements and a hall sensor (TLE 4990 Infineon Technologies) is integrated inside the MR clutch for magnetic filed measurements. The location of the hall sensor was embedded into an aluminum disk which is aligned in parallel to the output disks. Because the relative permeability of TLE 4990 is close to aluminum, we can achieve uniform distribution of magnetic filed on that aluminium disk and the measurements from TLE 4990 is proportion to the magnetic field of MR fluids. A servo motor (Maxon EC 60) provides the rotational input to the MR clutch. A National Instruments (NI USB-6229) multifunction I/O device is employed to provide reference torque values for the actuator and to acquire the output signals from the load cell. The sampling frequency for collecting experimental data is set to 500 Hz. The proposed model and the PID controller are implemented on a spartan-3E starter kit board from Xilinx.

A. Validation of the Proposed Model

The one-to-one relationship between the magnetic field and the output torque is an explicit advantage in MR clutches and the main assumption behind developing the proposed model. This assumption can be validated by applying a sinusoidal current to our MR clutch prototype and observing the changes in the output torque with respect to changes in magnetic field. Fig. 5 shows these changes for an applied 1 Hz sinusoidal input current. As observed in this figure, despite minor lagging effects (due to dynamic characteristic), the MR clutch demonstrates a one-to-one relationship between its output torque and its magnetic field that justifies the use of Bingham model in static modes.

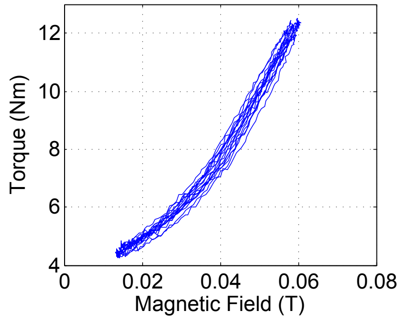

Fig. 5. Output torque vs. magnetic field for a 1Hz sinusoidal input current.

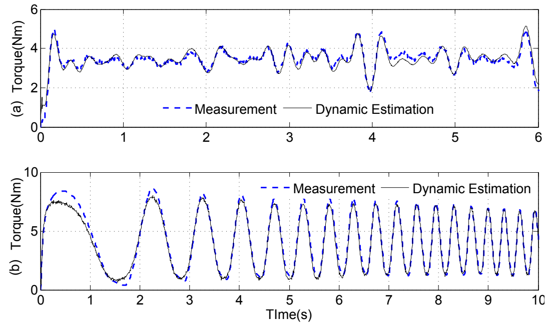

Fig. 6. Torque measurement versus dynamic estimation, (a) Multi-Sine input current, (b) Swept-Sine input current.

Multi-Sine[1] and Swept-Sine[2] signals are usually used to validate (or invalidate) the accuracy of a model, given their richness in exciting all possible modes of a dynamic system [27, ch. 13]. To this effect, both Multi-Sine and Swept-Sine signals were applied to the clutch to validate the accuracy of our proposed model. The Multi-Sine current signal was the average of 10 sinusoids with different frequencies selected uniformly within the range of 2Hz to 5Hz. The frequency range of the Swept-Sine current signal was chosen in the same range. Figs. 6 depicts the predicted versus measured output torques corresponding to the Multi-Sine and Swept-Sine signals. The results show that the prediction results follow closely the actual measurements. In fact, the Root Mean Square Errors(RMSEs) between the estimated and the actual torque values are 0.1635 Nm and 0.3527 Nm for the Multi-Sine and Swept-Sine signals, respectively. Moderate errors at the beginning of the results are associated with the low frequency components of the input signals, where the proposed dynamic model shows the least accuracy. This is because that the model is identified with more weight being put on the higher frequencies, and it can be addressed by adjusting the identification signals depending on the intended application for the MR clutch. Nonetheless, the results show a very accurate estimation for high frequency which is usually more desirable for control purposes.

B. Torque Control Experiments

The performance of the proposed FPGA based closed-loop controller is evaluated in this section. Two configurations are considered to control the output torque of the MR clutch. In the first configuration, the proposed FPGA based method is utilized along with magnetic field measurements for estimating the output torque used as feedback signal in the closed-loop control. In the second configuration, the actual torque measurements are used in the closed-loop control as feedback signal. Both configurations use a PID controller in their control loop. The error signal in the first configuration is computed using the estimated and the desired torque values, while the actual torque measurements are used for error calculations in the second configuration. Several desired torque signals were considered. In each case, the PID controllers were optimised to obtain the best possible control results. Fig. 7 shows the results for a square, 1 and 5 Hz sinusoids, and a Multi-Sine desired torques. In this figure, Measured 1 and Measured 2 refer to the load cell measurements in the first and second configurations, respectively. These results clearly validate the efficacy of the proposed model for tracking a desired torque using the MR clutch, where no external torque measurements are used in the control loop. The results closely match those that are obtained using actual torque measurements. While there is

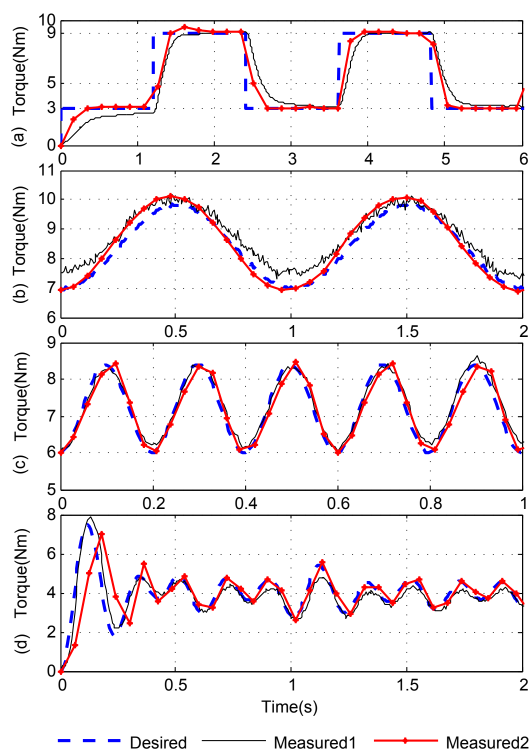

Fig. 7. Torque control for (a) square, (b) 1Hz sinusoidal, (c) 5Hz sinusoidal, and (d) Multi-Sine reference torque.

a slight difference between the results of the two configurations, it can be clearly seen that accurate torque control

[1] $i(t) = \sum_{k=1}^{n} \mu_k cos(\omega_k)$, where μ_k and ω_k, $k = 1, ..., n$ are amplitudes and frequencies of sinusoids, respectively.

[2] $i(t) = Asin(\frac{1}{2}(\frac{2\pi(f_2-f_1)}{n})^2 + 4\pi f_1)$, where A, f_1, f_2 and n are amplitude, normalized start frequency, normalized stop frequency and number of samples of Swept-Sine signal, respectively.

is achieved in both configurations. One should however, note that the first configuration requires no additional torque sensor which is the main significance and contribution of the current work. Moreover, it is reasonable to assume that improving the accuracy of the dynamic model can lead to a more accurate torque control.

V. Conclusion

In this paper, a novel FPGA based closed-loop control scheme was proposed for linearizing the output torque of an MR clutch as a function of its input current. In the proposed scheme, the FPGA board regulates the output torque of the MR clutch using its magnetic field measurements acquired by a set of embedded hall sensors. Using this information, the output torque of the clutch is first estimated and is then used to provide the required feedback for adjusting the input current of the clutch accordingly. To this effect, the FPGA board implements a PID controller to eliminate the error between the estimated and desired torque values. A set of experiments were conducted to validate the efficacy of this technique. The results clearly demonstrated that an MR clutch could act as an entirely linear torque actuator to follow any reference torque signal.

References

[1] B. Tondu and P. Lopez, "The mckibben muscle and its use in actuating robot-arms showing similarities with human arm behaviour," *Industrial Robot: An International Journal*, vol. 24, no. 6, pp. 432–439, 1997.

[2] G. Pratt and M. Williamson, "Series elastic actuators," in *Intelligent Robots and Systems 95.'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on*, vol. 1, pp. 399–406, IEEE, 1995.

[3] M. Zinn, B. Roth, O. Khatib, and J. Salisbury, "A new actuation approach for human friendly robot design," *The international journal of robotics research*, vol. 23, no. 4-5, pp. 379–398, 2004.

[4] A. Bicchi and G. Tonietti, "Fast and soft-arm tactics [robot arm design]," *Robotics & Automation Magazine, IEEE*, vol. 11, no. 2, pp. 22–33, 2004.

[5] C. Chew, G. Hong, and W. Zhou, "Series damper actuator: a novel force/torque control actuator," in *Humanoid Robots, 2004 4th IEEE/RAS International Conference on*, vol. 2, pp. 533–546, IEEE, 2004.

[6] A. Bicchi, G. Tonietti, and R. Schiavi, "Safe and fast actuators for machines interacting with humans," in *Robotics and Automation, 2004. TExCRA'04. First IEEE Technical Exhibition Based Conference on*, pp. 17–18, IEEE, 2004.

[7] B. Kim, J. Park, and J. Song, "Double actuator unit with planetary gear train for a safe manipulator," in *Robotics and Automation, 2007 IEEE International Conference on*, pp. 1146–1151, IEEE, 2007.

[8] N. Takesue, H. Asaoka, J. Lin, M. Sakaguchi, G. Zhang, and J. Furusho, "Development and experiments of actuator using mr fluid," in *Industrial Electronics Society, 2000. IECON 2000. 26th Annual Confjerence of the IEEE*, vol. 3, pp. 1838–1843, IEEE, 2000.

[9] N. Takesue, J. Furusho, and Y. Kiyota, "Fast response mr-fluid actuator," *JSME International Journal Series C*, vol. 47, no. 3, pp. 783–791, 2004.

[10] J. Chen and W. Liao, "Design, testing and control of a magnetorheological actuator for assistive knee braces," *Smart Materials and Structures*, vol. 19, no. 3, p. 035029, 2010.

[11] P. Fauteux, M. Lauria, M. Legault, B. Heintz, and F. Michaud, "Dual differential rheological actuator for robotic interaction tasks," in *Advanced Intelligent Mechatronics, 2009. AIM 2009. IEEE/ASME International Conference on*, pp. 47–52, IEEE, 2009.

[12] A. S. Shafer and M. R. Kermani, "Design and validation of a magnetorheological clutch for practical control applications in human-friendly manipulation," in *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, pp. 4266–4271, IEEE, 2011.

[13] A. S. Shafer and M. R. Kermani, "On the feasibility and suitability of mr fluid clutches in human-friendly manipulators," *Mechatronics, IEEE/ASME Transactions on*, no. 99, pp. 1–10, 2011.

[14] A. S. Shafer and M. R. Kermani, "Magneto-rheological clutch with sensors measuring electromagnetic field strength," Apr. 14 2011. WO Patent/2011/041890.

[15] A. S. Shafer and M. R. Kermani, "Magneto- and electro- rheological based actuators for human friendly manipulators," Nov. 1 2009. United States Patent U.S. Provisional Patent, Serial No. 61/272,597. 2009.

[16] P. Yadmellat and M. Kermani, "Adaptive modeling of a magnetorheological clutch," *Mechatronics, IEEE/ASME Transactions on*, in press, doi: 10.1109/TMECH.2013.2292594.

[17] P. Yadmellat, A. S. Shafer, and M. R. Kermani, "Development of a safe robot manipulator using a new actuation concept," in *Robotics and Automation, IEEE International Conference on*, pp. 337–342, IEEE, 2013.

[18] G. Pratt and D. Robinson, "Force-controlled hydro-elastic actuator," Dec. 17 2002. US Patent 6,494,039.

[19] O. Erol, B. Gonenc, D. Senkal, S. Alkan, and H. Gurocak, "Magnetic induction control with embedded sensor for elimination of hysteresis in magnetorheological brakes," *Journal of Intelligent Material Systems and Structures*, vol. 23, no. 4, pp. 427–440, 2012.

[20] P. Yadmellat and M. R. Kermani, "Adaptive modeling of a fully hysteretic magneto-rheological clutch," in *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, pp. 2698–2703, IEEE, 2012.

[21] D. Wang and W. Liao, "Magnetorheological fluid dampers: a review of parametric modelling," *Smart Materials and Structures*, vol. 20, p. 023001, 2011.

[22] R. Phillips, "Engineering applications of fluids with a variable yield stress," 1969.

[23] J. Carlson, "What makes a good mr fluid?," *Journal of intelligent material systems and structures*, vol. 13, no. 7-8, pp. 431–435, 2002.

[24] M. Jolly, J. Bender, and J. Carlson, "Properties and applications of commercial magnetorheological fluids," *Journal of Intelligent Material Systems and Structures*, vol. 10, no. 1, pp. 5–13, 1999.

[25] M. Avraam, *MR-fluid brake design and its application to a portable muscular rehabilitation device*. PhD thesis, Ph. D. thesis, Université Libre de Bruxelle, Bruxelle, Belgium, 2009.

[26] P. Kielan, P. Kowol, and Z. Pilch, "Conception of the electronic controlled magnetorheological clutch," *Przeglad Elektrotechniczny*, vol. 3, pp. 93–95, 2011.

[27] L. Lennart, "System identification: theory for the user," *PTR Prentice Hall, Upper Saddle River, NJ*, 1999.