Output Torque Modeling of a Magneto-Rheological Based Actuator

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Abstract: Recent research intended to integrate robots into the anthropic domains has introduced a new set of challenges with regard to design and control of such robots. Among these challenges, human safety is perhaps one the most predominant issues. While, existing solution relies on highly specialized and high cost actuation mechanisms, a new generation of intrinsically safe robots (manipulators) that use alternative technologies is yet to prevail. There is however a general consensus that the conventional actuation mechanisms are not capable of providing intrinsic safety while maintaining the high performance of the robot. On these premisses, a new Magneto-Rheological (MR) based actuation mechanism was developed in our research group. The actuator uses a magnetic field to precisely control its output torque delivery. The actuator demonstrates remarkable mass to torque ratio and low output inertia, at the same time, its bandwidth is comparable, if not better, than current leading actuators. The output torque of the actuator however, is hysterically related to its input current which makes its control challenging. The objective of the current work is to obtain a precise open-loop model that relates the output torque to the applied input current. The advantages of the obtained model are twofold. While such a model enables accurate control of the actuator, hence the actuated mechanism; in our case a robotic arm, it also eliminates the need for a force/torque sensor for performing high fidelity force/torque control tasks. To validate the accuracy of the constructed model simulation results for the output torques are presented and compared to those measured experimentally using the prototyped actuation mechanism. Results agreements attest to the validity of the presented model.

Keywords: Human-safe robot, Actuators, MR fluid, Preisach Modeling.

1. INTRODUCTION

In recent years, research on physical human-robot interactions has received considerable attentions. Of particular interest is the subject of safety within the interactive environments, where the realization of the safety has led to the study of control and actuation mechanisms of the robot. Specifically, new actuator technologies seem to be an essential component of the future generation of human-safe robots, Ahmed et al. (2008).

Toward this objective, a new Magneto-Rheological (MR) based actuator (clutch) has been designed and developed in our research group that is capable of providing both rigid and compliant actuation. The key strategy behind this design is that the rheological properties of MR fluids are utilized to instantaneously and reversibly control the compliancy of the actuator using an applied magnetic field, Shafer and Kermani (2009b).

The main difficulty in employing such fluid is that the MR based actuator, or the so-called MR clutch, includes not only the MR fluids, but a magnetic circuit built from ferromagnetic materials to form the flux path for fluid. The magnetic circuits introduces hysteric behavior in the current-torque curve of the actuator, leading to such known problems in the control systems as tracking errors, limit cycles, and undesired stick-slip motions. To compensate for the hysteresis, a hysteresis model is often required for designing the control algorithm. Therefore, it is important to develop a hysteresis model in order to capture nonlinear characteristics of both the MR fluid and the magnetic circuit.

In this regard, hysteresis modeling can be broadly classified into two major categories: (a) physics-based modeling and (b) phenomenological modeling, Tan and Baras (2004). Physics-based models are built on basic principles of physics, examples of which are the JilesAtherton, Jiles and Atherton (1986) and Hodgdon, Hodgdon (1988) models of ferromagnetic hysteresis. Phenomenological models, on the other hand, are used to mimic the behaviors of the physical systems without necessarily providing physical

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insight into the problems. A well-known phenomenological hysteresis model for ferromagnetic as well as smart materials is the Preisach model, Adly et al. (1991), Hughes and Wen (1995), Ge and Jouaneh (1996), Gorbet et al. (1998), Cruz-Hernández and Hayward (2001), Tan et al. (2001), Croft et al. (2001), where the hysteresis is modeled as a (weighted) aggregate effect of all possible relay elements that are delayed with respect to each others. Particularly, the Preisach model has been adopted as an effective hysteresis model of ER fluids, Han et al. (2003), piezoelectric materials, Ge and Jouaneh (1997) and Shape Memory Alloys, Gorbet et al. (1998). The model can also be adopted as a potential candidate for capturing hysteretic characteristics of MR fluids.

The main contribution of this body of work is the development of a current-torque model based on the Preisach model for a new MR based actuation mechanism. The model presented in this paper encompasses the hysteresis of the magnetic circuit of the actuator and that of the MR fluids. This model is numerically identified using the data obtained from a prototype of the actuator. The verification of the identified model is performed by comparing the predicted torque values with those experimentally measured.

The paper is organized as follow. Section 2 provides a literature background on human-safe actuators. In Section 3, mechanical and magnetic models of an MR clutch along with its application in human-safe robots are discussed. Section 4 introduces a hysteresis model using Preisach modeling technique that captures the torque-current behavior of the developed prototype. Moreover, a comparison between simulation and experimental results is provided in this section. Finally, Section 5 concludes the paper.

2. HUMAN-FRIENDLY ACTUATORS

In attempts to guarantee the safety of humans within a shared workspace, much research has been focused on the development of manipulators which are intrinsically safe. That is, manipulators which by means of their mechanical properties can guarantee some level of collision safety in the absence of a controller.

Clearly, manipulators safety can be improved by reducing their effective inertia. A simple idea, though not trivial, is to generate light-weight robots. The Whole Arm Manipulator (WAM) Salisbury et al. (1988) is perhaps one of the first attempts of designing such light-weight manipulators under the new paradigm. Another approach is to remove the actuators from the links in order to reduce the link mass, hence the associated link inertia. The DLR-III successfully attained a fully integrated light-weight design by utilizing light-weight carbon composite together with partially locating the actuators at its base. This approach however, resolves only half of the problem. A dominant problem is the presence of the high frequency output impedance made by gear reduction employed between the motor and the link. Indeed, this connection reflects the rotor inertia multiplied by G_r^2 , where G_r is the gear ratio. In other words, the effective inertia experienced by a robot link can be expressed as

$$J_e = J_l + G_r^2 J_r, \quad (1)$$

Fig. 1. Cross-section of a multi-disk MR clutch

where J_l is the inertia of the link, and J_r is the rotor inertia of the motor. The reflected actuator inertia of a manipulator can in fact be much larger than that of the link inertia, Zinn et al. (2004), thereby contributing a larger share of the inertial load during collisions.

Typical rigid manipulators utilize a stiff connection between the motor and the link that results in yielding a high frequency output impedance by reflecting rotor inertia together with the link own inertia. In order to overcome this problem, variety of safe-oriented control techniques have been suggested to reduce the system output impedance, Hogan (1985); De Luca et al. (2006). However, these strategies are only effective for frequencies that are below the closed loop bandwidth of the control system, Laffranchi et al. (2009).

In contrary to the stiff approach, a wide range of studies during the past two decades, Tonietti et al. (2005); Schiavi et al. (2008); Zinn et al. (2004); Tsagarakis et al. (2009); Pratt and Williamson (1995) have tackled the problem through novel compliant actuation systems.

As an alternative, either Magneto- and Electro-Rheological (ER) fluids based clutches can be constructed such that the amount of transmitting torque can be controlled by the intensity of an applied field. Fig. 1 is the cross-section of a multi-disk MR clutch that was utilized as part of an actuation mechanism in Shafer and Kermani (2009a). 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. Rotation of the input shaft causes shearing in the fluid with respect to the output shaft. By energizing the electromagnetic coil, a field is induced in the MR fluid altering its apparent viscosity. The outer casing of the MR clutch acts as the magnetic flux path required to complete the magnetic circuit.

3. MR CLUTCH MECHANICAL AND/OR MAGNETIC MODEL

Albeit, a constant linear relationship between input current and the output torque of a conventional motor can be well represented by a simple transfer function, it is unfortunate that the relationship between applied current and torque for MR actuators, in general, is more difficult

Fig. 2. Internal view of clutch during construction, as well as experimental setup used to verify clutch capability

to model. In fact, an MR actuator suffers from a nonlinear and hysteretic relationship between the input current and its output torque. Therefore, it seems to be essential to closely investigate the current–torque relationship for reliable control and actuation. Not only is the current–torque relationship of an MR actuator governed by the inherent properties of MR fluids, this relationship is also closely related to ferromagnetic properties of material employed to provide magnetic field excitations, Magee et al. (1998).

In this regard, Brookfield and Dlodlo (1996) proposed a linear transfer function between input voltage and output torque for an Electro–Rheological (ER) rotary actuator. However, little work has been done to model the current–torque relationship, and to experimentally validate them.

Typically, a popular Bingham visco–plastic model has been widely used in literature to model nonlinear hysteretic behavior of MR–based actuators. The Bingham visco–plastic model of our new clutch has been provided in details in Shafer and Kermani (2009b), in which authors showed that the shear stress of the fluid can be controlled with the applied field as

$$\tau = \tau_y(H) + \eta \frac{dv}{dz}, \quad \tau > \tau_y \quad (2)$$

where τ is the shear stress, τ_y is the field dependent yield stress, H is the magnetic field intensity, η is the Newtonian viscosity, and $\frac{dv}{dz}$ is the velocity gradient in the direction of the field.

Fig. 3. An elementary hysteresis operator

Notwithstanding that the Bingham plastic model has proved useful in the design and characterization of MR fluid–based devices, true MR fluid behavior exhibits some significant departures from this simple model. Perhaps the most significant of these departures involves the non-Newtonian behavior of MR fluids in the absence of a magnetic field Kormann et al. (1994). Moreover, it has been reported that linear stroke MR dampers can show highly nonlinear hysteretic behavior under harmonic loading conditions, that is different from that of the Bingham model Spencer et al. (1997), Pang et al. (1998), and Wereley et al. (1998).

Our aim in this paper is to provide an adequately accurate model to describe hysteretic relationship between input current and output torque for our developed MR clutch.

4. CURRENT–TORQUE MODEL USING PREISACH APPROACH

In this section, based on the Preisach model, we will investigate the current–torque relationship of the MR clutch described in Section 3. The Preisach model Mayergoyz and Friedman (2002) is constructed as a weighted integrating of simplest hysteresis operators, i.e. rectangular loops. Consider an infinite set of hysteresis operators $\hat{\gamma}_{\alpha\beta}$ each of which can be represented by a rectangular loop on the input–output diagram as shown in Fig. 3. α and β are threshold values corresponding to "up" and "down" switching values of input, respectively. It will be assumed in sequel that $\alpha \geq \beta$, which is quite natural from the physical point of view. Outputs of the above elementary hysteresis operators may assume only two values, $+1$ and -1 . These elementary operators can be interpreted as two-position relays with "up" and "down" positions corresponding to $\hat{\gamma}_{\alpha\beta} u(t) = +1$ and $\hat{\gamma}_{\alpha\beta} u(t) = -1$, respectively. Along with the set of operators $\hat{\gamma}_{\alpha\beta}$ consider an arbitrary weight function $\mu(\alpha, \beta)$ which is often referred to as the Preisach function.

Then, the classical Preisach model can be written as follows, Mayergoyz and Friedman (2002):

$$f(t) = \iint_{\alpha \geq \beta} \mu(\alpha, \beta) \hat{\gamma}_{\alpha\beta} d\alpha d\beta \quad (3)$$

For hysteresis nonlinearities with closed major loops, the function $\mu(\alpha, \beta)$ has a finite support within some triangle T on the $\alpha - \beta$ plane. This means that outside these triangles, $\mu(\alpha, \beta)$ is equal to zero.

As it has been explained in more details in Mayergoyz and Friedman (2002), it can be shown that

Fig. 4. First order transition (reversal) curve

Fig. 5. Output result of the Preisach model in comparison with desired real data corresponding to the applied input current with 3A amplitude

$$f(t) = -F(\alpha_0, \beta_0) + 2 \sum_{k=1}^{n(t)} F(M_k, m_{k-1}) - F(M_k, m_k). \quad (4)$$

where, $F(\alpha, \beta) = (1/2)(f_\alpha - f_{\alpha\beta})$, as f_α and $f_{\alpha\beta}$ are depicted in Fig. 4.

Regarding (4), a set of experimental measurements is needed in order to drive a numerical model based on the Preisach modeling approach. To do so, first-order sampling data (i.e. f_α and $f_{\alpha\beta}$) are needed to implement the Preisach model. Particularly, considering 100 thresholds (steps) between +3.5A and -3.5A, a first-order current input has been applied to the prototype clutch in order to measure corresponding torque. Step time was considered to be 350 ms, and 200 samples were taken for each threshold (step). Then, butterworth low-pass filter was employed to clean up the measured torques. Finally, the numerical implementation of Preisach model has been constructed according to (4), using experimental measurements.

In order to test the obtained Preisach model, a bunch of sinusoidal inputs has been applied to the clutch to evaluate the extracting Preisach model. Particularly, a sinusoidal inputs with +3A, +2A, and +1.5A as well as a +2A sinusoidal input with +1A offset has been applied to the clutch. Figs 5, 6, 7, and 8 illustrate the Preisach result in comparison to actual torque measurements corresponding to input current with different magnitudes and offsets. Notice that the torque is always positive according to our design regardless of the sign of the input current.

Fig. 6. Output result of the Preisach model in comparison with desired real data corresponding to the applied input current with 2A amplitude

Fig. 7. Output result of the Preisach model in comparison with desired real data corresponding to the applied input current with 1.5A amplitude

Fig. 8. Output result of the Preisach model in comparison with desired real data corresponding to the applied current input with 2A amplitude and +1A offset

Table 1. Comparing results in terms of MSE and RMSE

	1.5A	2A with 1A offset	2A	3A
RMSE	3.0652	2.0625	3.5899	4.4481
MSE	9.3954	4.2537	12.8877	19.7853

In addition, Figs. 9, 10, 11, and 12, show current-torque curves of actual measurements and those of Preisach prediction to compare the results. Regarding the results, Mean Square Error (MSE) and Root Mean Square Error (RMSE) between the modeling output and actual output are given in Table 1 respect to each sinusoidal input.

Although, somewhat error is existed between the results of the Preisach model and real measured data, numerical

Fig. 9. Current-torque diagram; input amplitude: 3A

Fig. 10. Current-torque diagram; input amplitude: 2A

Fig. 11. Current-torque diagram; input amplitude: 1.5A

Fig. 12. Current-torque diagram; input amplitude: 2A with +1A offset

results show that even the simplest Preisach model can successfully follow the desired trajectory. The existing error can be due to several problems such as Matlab round-off error, and discretization. Also, structure of the Preisach modeling forces us to discretize input space

producing a small tolerances over the results. This problem is notable when existing tolerance between two back to back level of inputs result in up to 2 Nm difference in corresponding outputs. This problem can be somehow resolved by increasing the accuracy of the discretization. However, this implies significant growing in number of data and consequently increasing the capacity of required memory to store the data.

5. CONCLUSION

Nowadays, we are witnessing an increasing demands on Human-friendly actuators to enable future robot generations work and interact with the humans in an anthropic domains. In order to respond these demands, a new MR-based clutch has been designed and developed in our research group, which can be used to achieve intrinsic safety due to reducing reflected rotor inertia. Moreover, a superior performance than conventional actuator is expected because of employing MR fluid. Therefore, such a clutch could be a suitable candidate to be employed as an actuator for the robots in anthropic domains, where physical human-robot interaction is unavoidable. In this paper, we derived a numerical model of the clutch based on the Preisach modeling technique to describe hysteretic current-torque relationship of the clutch. The validity of the modeling result is verified by comparing experiments and simulated model output. The results illustrated an accurate approximation comparing to actual data experimentally measured from the clutch.

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