Preliminary Studies of Variable Impedance Control with an Electrorheological Fluid Device

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Abstract— **Due to the absence of in-home rehabilitation robots for the upper extremity, recovering stroke patients must travel to a clinic to access therapy. Transitioning rehabilitation robots from the clinic environment to the home could significantly increase the intensity and accessibility of therapy. To make this transition, rehabilitation robots must become smaller and less complex. In this paper we consider smart materials for integration in new actuator designs. A testbed was developed to study variable impedance control with an electrorheological fluid brake. An empirical model for torque/voltage was developed and then implemented in an open-loop controller. While this method was initially accurate, results from torque control experiments indicate that during extended durations relative error substantially increases. Experimental results also show that the system's stiffness and damping can be controlled by varying the strength of the applied electric field. The properties of the electrorheological fluid reveal potential benefits for human-robot interaction.**

I. Introduction

In the United States, where stroke is the leading cause of long-term disability, an estimated 795,000 people suffer a stroke every year [1]. A significant percentage of stroke survivors suffer from upper extremity (UE) impairment [2]. UE rehabilitation therapies available to patients today include both conventional care with a human therapist and robot-assisted therapy. Recent studies have shown that robot-assisted therapy for the upper extremity can be as or more effective than conventional therapy in helping patients recover upper extremity motor function after stroke [3-4]. Patients typically have to travel to a clinic to access a therapist or robot-assisted therapy. There is increasing concern that the intensity of post-stroke rehabilitation in the clinic environment using conventional therapy and/or robot-assisted therapy may not be adequate [5]. New therapeutic methods are required to increase the amount of rehabilitation time during stroke recovery.

Home-based rehabilitation robots could provide a means for increasing the accessibility and intensity of therapy. However, in order to transfer UE rehabilitation robots from the clinic to the home, the designs must become smaller, lighter, and less expensive. An important step for scaling UE rehabilitation robots for the home is reducing the size and complexity of the robot's actuators, or, alternatively, the number of actuators required. Recent advances in smart materials research present an opportunity for new actuator designs. Smart materials like, for example, shape memory polymers and electrorheological fluids, are materials whose properties can be altered with a stimulus such as heat or voltage. In this paper we consider if systems integrating electrorheological (ER) fluids offer potential benefits over conventional electromagnetic actuators for human-robot interaction.

First discovered in the 1940s [6], ER fluids are colloids with rheological properties that can be changed by an applied external electric field. In most ER fluids, non-conducting dielectric particles are suspended in an insulating carrier fluid. When a high field is applied the particles form chains along the field lines, and the fluid changes to a soft solid with a response time on the order of milliseconds. Because of their low inertia, low current densities, and fast response times, researchers have developed ER fluid prototype devices for clinic-based rehabilitation robots [7-9]. For this study, a custom ER brake was designed and fabricated. Our main interest is in using the ER fluid to implement impedance control [10] to ensure safe and stable interaction between the patient and robot. After developing an empirical model for the brake's torque output as a function of voltage, an open loop method for controlling the system's stiffness and damping is demonstrated. This work serves as a preliminary step to developing a variable impedance ER actuator for an in-home rehabilitation robot.

II. Experimental Setup

Fig. 1 shows the testbed developed for this study. Actuator 'B', a bipolar NEMA 34 stepper motor with a holding torque of 13 N-m, is a velocity source that rotates the brake's input shaft. The brake contains a pair of circular electrodes with a 0.3 mm gap. One electrode is fixed and the other is coupled to the input shaft. ER fluid fills the gap between the electrodes. The ER fluid is a prototype material designed by Asahi Kasei (Tokyo, Japan) to address performance issues reported in the literature such as sedimentation and levitation [11]. Our previous characterization study of the material [12] revealed a fluid with a high dynamic yield stress, a bandwidth of 30 Hz, and field dependent hysteresis. A high voltage power amplifier (Matsusada Precision Inc., Shiga, Japan) provided the external electric field across the brake's electrodes. The amplifier scales an input voltage ranging from -10 V→10 V to an output voltage ranging from -3 kV→ 3kV.

The ER brake was secured in a bearing press fit in a steel bracket. For clarity, while the device was originally designed to function as a brake, in this experimental setup the brake acts as a mechanical clutch. As shown in Fig. 1, actuator 'E', a NEMA 23 stepper motor with a 15:1 planetary gearbox, was used to

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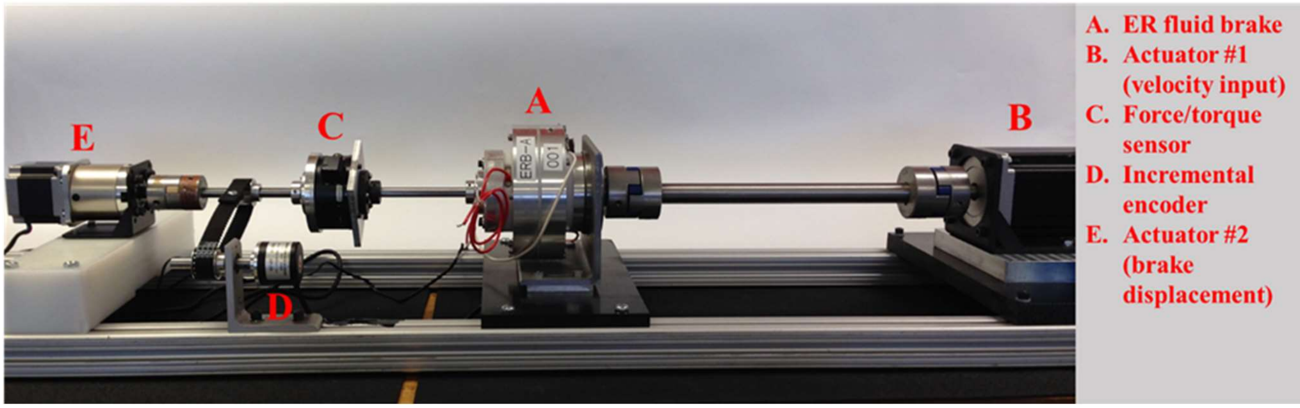

Fig. 1. Experimental setup used during the variable impedance study. One stepper motor provided a velocity source to shear the fluid internal to the brake while a second stepper motor displaced the body of the brake.

displace the body of the device while the fluid was simultaneously sheared in the opposite direction. Actuator 'E' thus replicates a human subject perturbing the ER system. A force/torque transducer (ATI Industrial Automation, Apex, NC) labeled 'C' was located in series between the brake and actuator 'E'. In the shown configuration, the sensor was used to measure the system's reactionary torque for varying electric field strengths. A 2400 pulses per revolution incremental encoder, labeled 'D' in Fig. 1, measured the brake's rotational velocity. Torque and velocity measurements were sampled with a National Instruments (Austin, TX) data acquisition board. The sampling frequency for all measurements was 1 kHz. Matlab's Data Acquisition Toolbox (Mathworks, Natick, MA) was the programming environment selected for the study. Additionally, all data was collected at room temperature.

III. RESULTS AND DISCUSSION

The ER brake's torque/voltage model was empirically determined by measuring the system's response to a 33 mHz triangular voltage signal. During application of the voltage signal the input velocity to the fluid was 30 rpm, and the brake's position was fixed by stepper motor 'E'. Because we envision using a constant velocity source in the prototype actuator design, the input velocity was maintained at 30 rpm for all experiments described in this paper. Fig. 2 shows the torque output from the rising segment of the signal. A second order regression between the torque T (N-m) and voltage V (volts) resulted in

$$T(V) = AV^2+BV+C \tag{1}$$

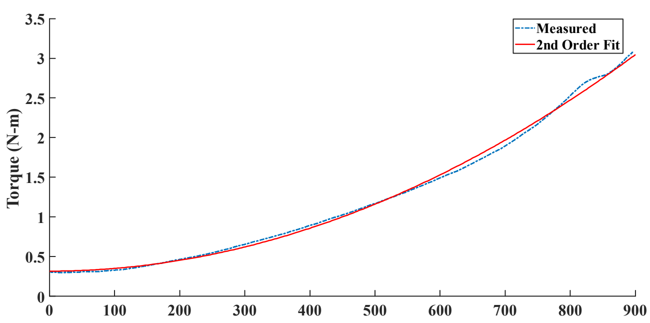

Fig. 2. Second order regression of the ER brake's measured torque versus voltage.

where A was 3.360E-6, B was 8.332E-4, and C was 0.3158. The R^2 value for the polynomial regression was 0.99.

To better understand the robustness of the empirical torque/voltage model, the brake was used as a controllable torque source. A reference torque trajectory was created with a function generator (Agilent Technologies, Santa Clara, CA). Required voltages were determined using the inverse of the empirical model. The digital controller was implemented on an Arduino Uno and was strictly open-loop. A 12 bit digital-to-analog chip (Adafruit, NY) was used to generate the analog input to the high voltage amplifier. Fig. 3 shows the reference trajectory and actual torque measurements for two different trials. The errors between the trials and reference signal are shown in Fig. 4. Initially, the open-loop controller was accurate. However, over the duration of each trial the error increased as the relative torque output rose. Likewise, error increased for successive trials, each of which used the same empirical model. The duration between trials was approximately 30 sec. Due to the short duration of each trial temperature increases were likely negligible. Prior work has shown that ER chains coarsen and form thicker columns when the electric field is applied for an extended time scale [13]. Because the fluid was not sheared at zero field between trials, we suspect that particle aggregation occurred and led to increased fluid shear stress and, therefore, increased torque over successive trials. This observation has important implications for an actuator design in that the open-loop control method presented here would not be robust.

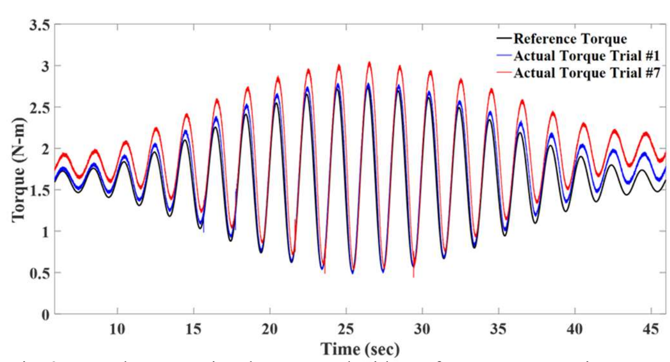

Fig. 3. Actual torques signals compared with a reference torque trajectory. The carrier wave was a 500 mHz sine wave with a 1.25 Vpp amplitude and 0.8 V offset. A 25 mHz amplitude modulation with 80% depth was applied to the reference trajectory.

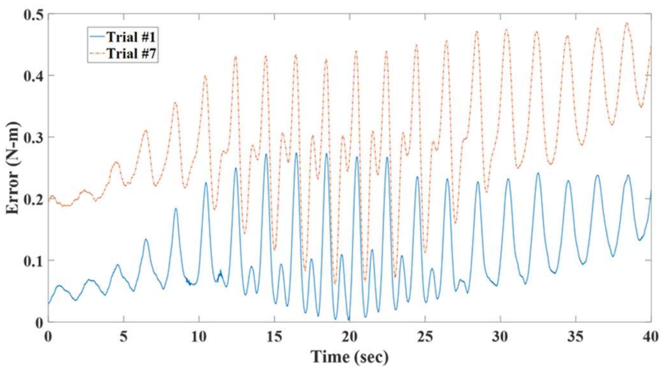

Fig. 4. Error between the measured torque(s) and reference trajectory.

Because of nonlinear effects like slow aggregation, temperature dependencies, and field dependent hysteresis, more sophisticated control methods such as adaptive control will be required.

An impedance controller regulates the dynamic relation between position/velocity and force. “Simple” impedance control has been used for UE rehabilitation with considerable success [14, 15]. This control method consists of driving a robot with torque-controlled, direct drive actuators and using motion feedback to modulate the output impedance [10]. To maximize backdriveability, any reduction should be avoided, which in the case of the MIT-Manus robot required large DC motors [16]. An ER fluid clutch could potentially decouple output impedance from a geared actuator. In theory, a smaller motor with a large gear reduction could be used to drive an ER system where voltage is used to control output impedance.

Here we examine whether voltage could be used to implement a virtual spring and virtual damper. The desired virtual trajectory of the ER system’s output shaft was zero (i.e. constant position). Actuator ‘E’ then applied perturbations to the system. For the stiffness experiment, actuator ‘E’ displaced the ER system at constant velocity. For the damping experiment, actuator ‘E’ applied a linear velocity ramp. The same inverse model described previously was used to produce the desired torque in response to the displacement and velocity. The experiments were repeated for six different stiffness and damping ratios. The results for the stiffness and damping experiments are provided in Fig.’s 5 and 6, respectively. Due to internal friction and viscous damping at zero voltage, there is an exclusion zone below approximately 0.5 N-m for which controllable stiffness and damping was not possible. To achieve lower stiffness/damping ratios, the speed of the velocity source (i.e. actuator ‘B’) would have to be reduced below 30 rpm. The results indicate that the fluid device can be used to replicate a variable spring and damper with reasonable precision.

IV. CONCLUSION

New rehabilitation robots built for the home are required to increase the intensity of UE therapy for recovering stroke patients. In this paper, we considered a prototype ER fluid as a candidate material for integration in new actuators designed for human-robot interaction. A testbed was developed to study the control of a custom ER brake. A polynomial regression of the torque response to a linear voltage ramp indicated a quadratic relationship between voltage and output torque. The inverse

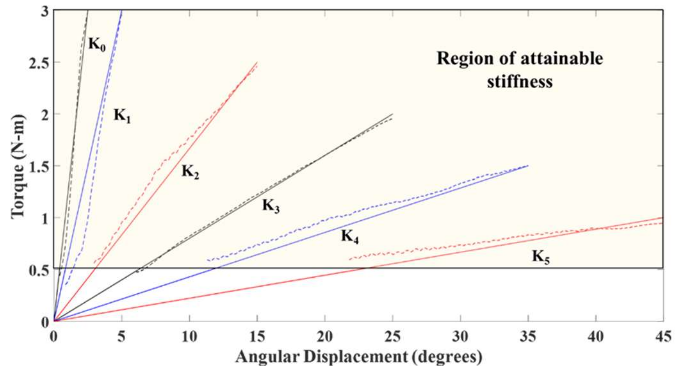

Fig. 5. Implementation of a virtual spring. The solid lines show the desired linear spring constants K_n.

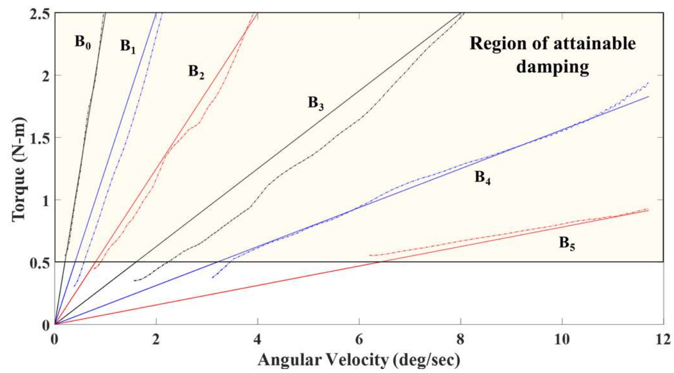

Fig. 6. Implementation of a virtual damper. The solid lines show the desired damping coefficients B_n.

torque/voltage model was then implemented on a digital controller. While open-loop control using an empirical model was initially accurate, results from torque control experiments showed that relative error increases over time due to assumed particle aggregation in the ER fluid. Experimental results also show that voltage can be used to program system stiffness and damping. Future work includes the development of an adaptive impedance controller as well as the design and fabrication of a prototype actuator with integrated ER clutches.

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