논문 한국정밀공학회지 제15권 제8호 (1998년 8월)
Journal of the Korean Society of Precision Engineering, Vol. 15, No. 8, August 1998.

ER 클러치/브레이크 작동기를 이용한 회전운동제어

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Rotational Motion Control Using ER Clutch/Brake Actuators

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ABSTRACT

본 연구에서는 회전운동을 제어하기 위한 새로운 작동기로서 전기장에 대하여 매우 빠른 응답특성을 갖고 있는 두 쌍의 실린더형 ER(electro-rheological) 클러치/브레이크 작동기를 제안하였다. 자체조성된 ER유체의 빙햄특성모델을 실험적으로 도출하였으며, 이와 연계한 작동기 모델을 구성하여 전기장에 따른 전달 및 제동 토크를 해석한 후 알맞은 크기의 클러치/브레이크 작동기를 제작하였다. 제작된 작동기의 동적특성(시상수 등)을 작동기 모델에 고려하기 위하여 계단입력 전기장에 따른 과도응답 실험을 클러치와 브레이크 모드에서 각각 수행하였다. 제안된 작동기의 응용성을 보이기 위하여 두쌍의 작동기로 구동되는 실험실 차원의 소형 와권식 세탁기 시스템을 구성한 후 동적지배방정식을 유도하였다. 각 작동기와 연계된 PID제어기를 설계하여 세탁과 탈수시의 회전운동을 제어하였으며, 부하질량의 변화에 대한 작동기 시스템의 제어 효율성과 장시간 운전을 통한 제어 내구성 실험을 수행하였다.

Key Words : Electro-Rheological(ER) Fluid(ER유체), ER Clutch/Brake(ER클러치/브레이크), Rotational Motion Control(회전운동제어), Washing Machine(세탁기)

1. INTRODUCTION

The new generation of smart material technologies featuring sensing, actuating and control capabilities will not only have a tremendous impact upon the design and manufacture of the next generation of products in diverse industries, but also the economic climate in the international marketplace. It appears that so far, potential candidates for smart materials include electro-rheological(ER) fluids, piezoelectric materials, shape memory alloys, and optical fibers. The ER fluid belongs to a class of colloidal suspensions which exhibit large reversible changes in their rheological behavior when subjected to external electric fields.(1)

One of salient properties of the ER fluid itself is that it has a very fast response characteristic to the electric field and hence wide control bandwidth. This inherent feature has triggered

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tremendous research activities in the development of various engineering applications such as shock absorbers, engine mounts, smart structures, clutches and brakes.[(2)~(4)]

Recently, research interest in ER clutch or/and ER brake has been growing because of the potential importance of such devices for a variety of torque coupling and tension control applications. Some advantages of such devices include continuous controllability via controlling the intensity of electric field, rapid response, low power consumption and smoothness of operation. Carlson and Duclos[(5)] suggested a set of design equations for ER clutches and brakes considering key fluid parameters and operating requirements, and validated the effectiveness of the design equations by presenting transmission torques of a parallel plate-type ER clutch. Stangroom[(6)] described a potential applicability of a disk-type ER clutch to a tension control of various processing industries such as tension control of cold-rolled stripes and tension control of electro-discharge machine wire. Stevens et al.[(7)] devised a cylindrical ER clutch and experimentally demonstrated its field-dependent torque transmission capability. Johnson et al.[(8)] proposed a set of clutches to produce a high speed reciprocating mechanism. A mechatronic model to describe the dynamic performance of the ER clutch was developed and analyzed incorporating with fluid parameters including a viscosity. Oravsky and Krc-Jediny[(9)] proposed a concentric ER clutch constituting of the central part of an electrodrive, and analyzed a steady state motion of a harmonic load. More recently, Choi et al.[(10)] proposed a feedback controller for a moving tape tension system which uses a disk-type ER brake. A sling mode controller for the ER brake was formulated and experimentally implemented to undertake both tension regulating and tension tracking controls. As evident from previous studies, so far most of researches for the ER clutch/brake have focused only on the dynamic modeling and performance analysis of the field-dependent torque or/and brake. Researches on the rotational motion control using the ER clutch/brake are considerably rare. Moreover, of the research published none deals with the durability of the motion control system controlled by ER clutch/brake. Consequently, the main contribution of this paper is to show how a set of ER clutch/brake actuators can be satisfactorily employed for the rotational motion control, and also to demonstrate the practical feasibility of the control system by showing a control durability. The effectiveness of the proposed control system is confirmed by both simulation and experimental results.

A set of cylindrical type of clutch/brake actuators are manufactured on the basis of Bingham model of a chemically treated starch-based ER fluid. The dynamic characteristics of the actuators are experimentally evaluated by observing step responses of the electric field. Subsequently, the actuators are applied to a small-sized pulsator-type washing machine for rotational motion control. The control system mode is established followed by the design of PID controllers for spin-basket and pulsator motions. The controllers are then experimentally realized and control performances of washing and dehydrating motions are evaluated under various loads. In addition, control durability of the washing motion is undertaken to demonstrate a practical feasibility.

2. ER CLUTCH/BRAKE ACTUATORS

Under the electrical potential, a constitutive equation for the ER fluid has approximately form of Bingham plastic[(1)] :

$$\tau = \tau_y(E) + \eta\dot{\gamma}, \quad \tau_y(E) = \alpha E^{\beta} \tag{1}$$

Here τ is shear stress, η is viscosity, $\dot{\gamma}$ is shear rate, and $\tau_y(E)$ is yield stress of the ER fluid. As evident from Eq.(1), $\tau_y(E)$ is a function of the electric field of E and exponentially increases with respect to the electric field. In this study, for the ER fluid, chemically-treated starch and silicone oil are chosen as particles and base liquid, respectively. The viscosity of the base oil is 0.0027Pa · s and the size of the particles ranges from 26㎛ to 88㎛. The weight ratio of the particles to the ER fluid is 25%. A Couette type electroviscometer (Haake, VT-500) is employed to obtain Bingham model of the ER fluid. The shear stress is measured by applying the electric field up to 3kV/mm at each 0.5kV/mm, while the rotational speed increases up to 700rpm. The testing temperature of the ER fluid is set by 25℃. Using the linear regression method the yield stress $\tau_y(E)$ at zero shear rate is obtained by $49E^{1.73}$ Pa as the form of Eq.(1). Here, the unit of E is kV/mm.

In this work, two cylindrical ER clutch/brake actuators are devised as shown in Fig.1. The actuator(b) denoted by ER C/B_2 has a higher torque capacity than the actuator(a) denoted by ER C/B_1. Each actuator has three aluminum cylinders(electrodes) and two gaps filled with the ER fluid. The clutch mode is obtained energizing inner and middle cylinders, while the braking mode is achieved by energizing middle and outer cylinders. The MC plastic is used to ensure insulation between electrodes. By neglecting some frictions, the clutch or braking torque of the actuator consists of two components : torque from the field-dependent yield stress of the ER fluid and the torque from the viscosity of the ER fluid. The former is controllable torque and it is obtained by integrating the yield stress with respect to the area containing the ER fluid as follows.

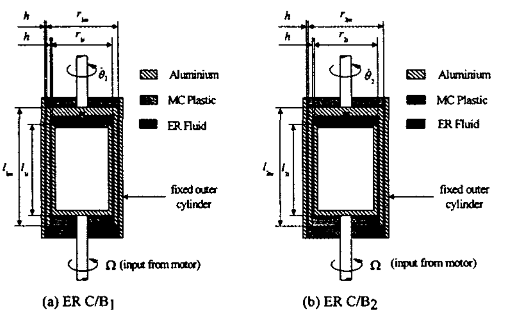


Fig. 1 Geometry of the proposed ER clutch/brake actuators

i) ER C/B_1

$$\text{clutch mode: } T_{c1}(E) = K_1 \alpha E^\beta \tag{2}$$

$$\text{brake mode : } T_{b1} = K_2 \alpha E^\beta$$

$$\text{where, } K_1 = 2\pi r_{1i}^2 l_{1i}, \quad K_2 = 2\pi r_{1m}^2 l_{1m}$$

ii) ER C/B_2

$$\text{clutch mode: } T_{c2}(E) = K_3 \alpha E^\beta \tag{3}$$

$$\text{brake mode: } T_{b2} = K_4 \alpha E^\beta$$

$$\text{where, } K_3 = 2\pi r_{2i}^2 l_{2i}, \quad K_4 = 2\pi r_{2m}^2 l_{2m}$$

On the other hand, the torque from the viscosity of the ER fluid can be obtained by considering same directional relative angular velocity (ω) of the cylinders in the clutch and brake as follows.

i) ER C/B_1

$$\text{clutch mode: } T_{c1}(\omega) = K_1 \eta \frac{r_{1i}(\Omega - \dot{\theta}_1)}{h} - K_2 \eta \frac{r_{1m}\dot{\theta}_1}{h}$$

$$\text{brake mode : } T_{b1}(\omega) = T_{c1}(\omega) \tag{4}$$

ii) ER C/B_2

$$\text{clutch mode: } T_{c2}(\omega) = K_3 \eta \frac{r_{2i}(\Omega - \dot{\theta}_2)}{h} - K_4 \eta \frac{r_{2m}\dot{\theta}_2}{h}$$

$$\text{brake mode : } T_{b2}(\omega) = T_{c2}(\omega) \tag{5}$$

From the analysis of Eqs.(2)~(5), two cylindrical clutch/brake actuators are manufactured and the photograph of the actuator ER C/B_1 is shown in Fig.2. In order to identify dynamic characteristics of the manufactured actuators, step responses are tested. Fig.3 presents step responses of ER C/B_1 and ER C/B_2 actuators in clutch mode. It is

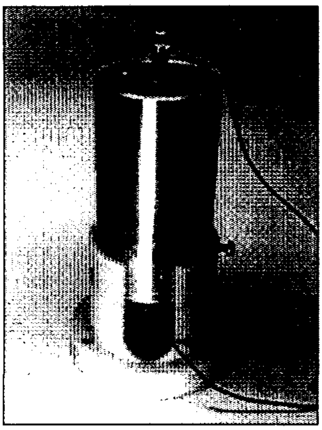
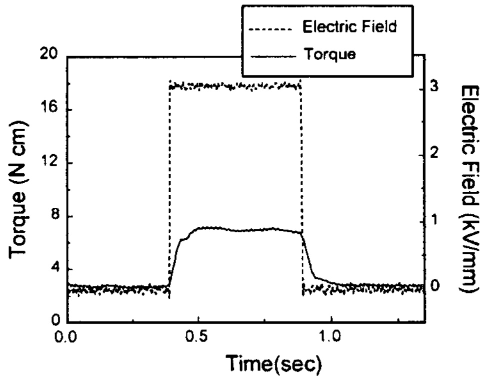
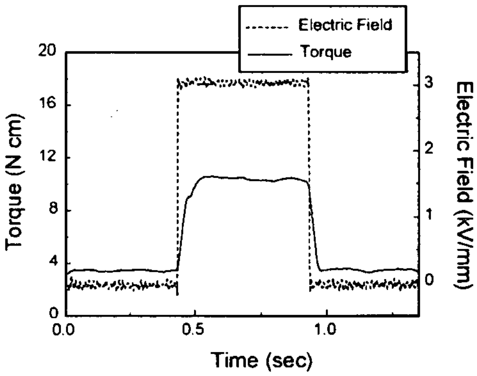


Fig. 2 A photograph of the ER C/B$_1$



(a) ER C/B$_1$



(b) ER C/B$_2$

Fig. 3 Step responses of the actuators in clutch mode

observed that by applying the electric field of 3kV/mm the clutch torque exponentially increases to a steady state value without exhibiting overshoot. This implies that the actuators behave like a first-order linear model with time constant. It is distilled that the time constants of the ER C/B$_1$ and ER C/B$_2$ are 34ms and 40ms, respectively. As expected, the response time of the ER C/B$_2$ is relatively slow due to the higher inertia effect of the cylinders. Consequently, by considering the time constants of the actuators, the total torque of each actuator can be expressed as follows:

i) ER C/B_1 (6)

$$\text{clutch mode}: \ T_{c1} = K_1\left[\alpha E^{\beta}(1-e^{-\frac{t}{\tau_1}}) + \eta\frac{r_{1i}(\Omega-\dot{\theta}_1)}{h}\right] - K_2\eta\frac{r_{1m}\dot{\theta}_1}{h}$$

$$\text{brake mode}: \ T_{b1} = K_2\left[\alpha E^{\beta}(1-e^{-\frac{t}{\tau_1}}) + \eta\frac{r_{1m}\dot{\theta}_1}{h}\right] - K_1\eta\frac{r_{1i}(\Omega-\dot{\theta}_1)}{h}$$

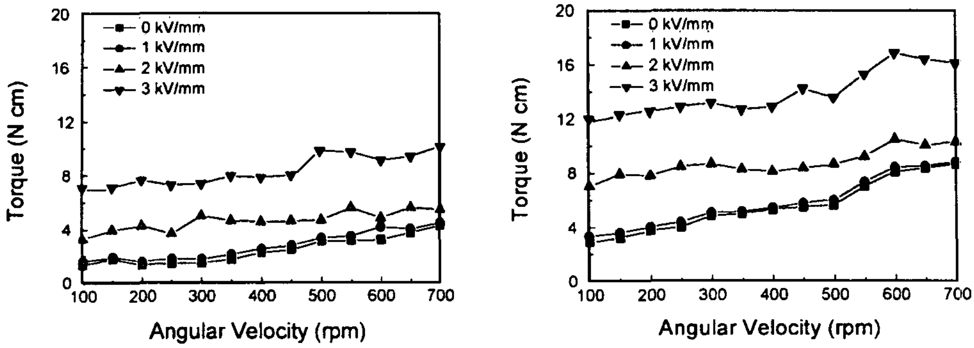
ii) ER C/B_2 (7)

$$\text{clutch mode}: \ T_{c2} = K_3\left[\alpha E^{\beta}(1-e^{-\frac{t}{\tau_2}}) + \eta\frac{r_{2i}(\Omega-\dot{\theta}_2)}{h}\right] - K_4\eta\frac{r_{2m}\dot{\theta}_2}{h}$$

$$\text{brake mode}: \ T_{b2} = K_4\left[\alpha E^{\beta}(1-e^{-\frac{t}{\tau_2}}) + \eta\frac{r_{2m}\dot{\theta}_2}{h}\right] - K_3\eta\frac{r_{2i}(\Omega-\dot{\theta}_2)}{h}$$

In the above equations, τ_1 and τ_2 represent of the time constants of the actuator ER C/B$_1$ and ER C/B$_2$, respectively.

It is herein remarked that the time constants of the actuators in brake mode are observed to be nearly same as those in clutch mode. Furthermore, it is experimentally figured out that the response time of the actuators remains to be almost same with respect to the intensity of the electric field employed in this work(0~3kV/mm). Prior to establishing control system, the torque performances of the actuators are tested and presented in Fig.4. It is clearly seen that the torque in clutch mode increases as the electric field increases at a certain angular velocity. This implies that a desired torque can be met by just controlling the intensity of the electric field



(a) ER C/B$_1$ (b) ER C/B$_2$

Fig. 4 Field-dependent torques of the actuators in clutch mode

regardless of the angular velocity. This is one of salient features of ER clutch/brake actuators.

3. SMALL-SIZED WASHING MACHINE

As mentioned in Introduction, there are numerous engineering applications utilizing ER clutch/brake actuators. Among these for rotational motion control, a pulsator-type washing machine is adopted in this work, which is widely used in Korea. The principal studies on the pulsator-type washing machine include the development of new torque transmission/barking mechanism, the reduction of noise and vibration and the formulation of effective control algorithm[11]. The application of ER clutch/brake actuator to the washing machine may get several benefits such as the design simplicity of the torque transmission/braking mechanism, and the control easiness of the rotational motion.

In this work, a small-sized washing machine featuring the proposed ER clutch/brake actuators is devised as shown in Fig.5. The rotational motion drived from the d.c. motor transmits to the pulsator and the spin-basket via the ER C/B$_1$ and the ER C/B$_2$, respectively. Thus, the desired rotational motion for washing and dehydrating processes can be satisfied by activating the pro-

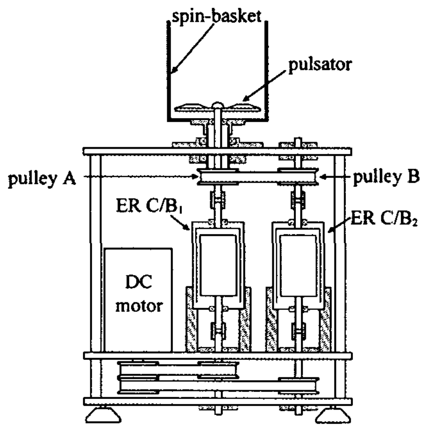
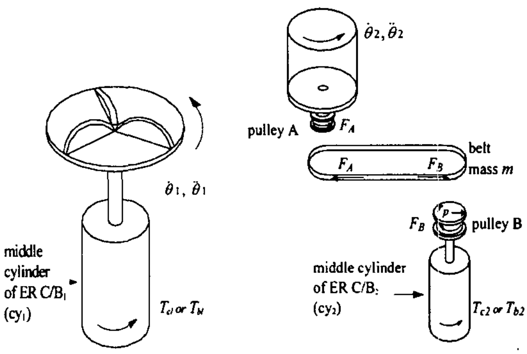


Fig. 5 A small-sized washing motion featuring ER clutch/brake actuators



(a)motion of pulsator **(b) motion of spin-basket**

Fig. 6 Free body diagram of the washing machine

posed feedback actuators. From the free body diagram of the washing machine shown in Fig.6, the dynamic rotational motion of the pulsator can be given by

$$J_1\ddot{\theta}_1 + C_1\dot{\theta}_1 = \begin{cases} T_{c1} : \text{clutch mode} \\ T_{b1} : \text{brake mode} \end{cases} \quad (8)$$

where $J_1 = J_{pulsator} + J_{cy1}$. The variable C_1 is the effective viscous damping coefficient of pulsator motion due to the viscosity of the ER fluid.

The motion described by Eq.(8) represents washing motion via the pulsator. On the other hand, during the dehydrating motion both the pulsator and the spin-basket are to be rotated with same rotational speed. The dynamic rotational motion for the spin-basket can be also easily obtained from Fig.6(b) as follows.

$$J_2\ddot{\theta}_2 + C_2\dot{\theta}_2 = \begin{cases} T_{c2} : \text{clutch mode} \\ T_{b2} : \text{brake mode} \end{cases} \quad (9)$$

where $J_2 = J_{basket} + J_{pullyA} + J_{cy2} + J_{pullyB} + mr_p^2$. The variable m is the belt mass, r_p is the radius of the pulley and C_2 is the effective viscous damping coefficient of the spin basket motion. Now, by defining state variables by $[x_1\ x_2\ x_3\ x_4]^T = [\theta_1\ \dot{\theta}_1\ \theta_2\ \dot{\theta}_2]^T$, and control variables by $[u_1 u_2]^T = [E_{c1}^{\beta}\ E_{C2}^{\beta}]^T$, the following control system model is established in the state space.

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= -\frac{C_1}{J_1}x_2 + \frac{K_1\alpha(1-e^{-\frac{t}{\tau_1}})}{J_1}u_1 + \frac{T_{c1}(\omega)}{J_1} \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= -\frac{C_2}{J_2}x_4 + \frac{K_3\alpha(1-e^{-\frac{t}{\tau_2}})}{J_2}u_2 + \frac{T_{c2}(\omega)}{J_2}
\end{aligned} \quad (10)$$

In the above equations, $T_{c1}(\omega)$ and $T_{c2}(\omega)$ are given by Eqs.(4) and (5), respectively. These torques from the viscosity of the ER fluid are treated as external disturbances. It is noted that the control system model given by Eq.(10) describes only the clutch mode. The control system model in brake mode can be obtained by replacing K_1 by K_2, K_3 by K_4, $J_{c1}(\omega)$ by $J_{b1}(\omega)$ and $J_{c2}(\omega)$ by $J_{b2}(\omega)$, respectively.

The control objective is to get desired rotational speed of the pulsator(x_2) and the spin-basket(x_4) by controlling the input fields u_1 and u_2. This can be accomplished by employing any type of modern control strategies. However, considering the simplicity of experimental realization the PID controller is adopted in this work. The forms of the controllers u_1 and u_2 in clutch mode are given by

$$\begin{aligned}
u_1(t) &= k_{p1}e_1(t) + k_{I1}\int e_1(t)dt + k_{D1}\frac{de_1(t)}{dt} \\
u_2(t) &= k_{p2}e_2(t) + k_{I2}\int e_2(t)dt + k_{D2}\frac{de_2(t)}{dt}
\end{aligned} \quad (11)$$

where $e_1(t) = x_2 - x_{d2}$ and $e_2(t) = x_4 - x_{d4}$. The variables of x_{d2} and x_{d4} are desired ones of the corresponding state variables. k_{pi}, k_{Ii} and k_{Di} represent proportional, integral and derivative gains, respectively. These gains are determined by Ziegler-Nichols tuning rule, and given as follows : $k_{p1} = 0.035$, $k_{I1} = 0.0065$, $k_{D1} = 0.0009$, $k_{p2} = 0.045$, $k_{I2} = 0.0075$ and $k_{D2} = 0.0014$. Once the control inputs of u_1 and u_2 are determined, the electric fields to be applied to the actuators ER $C/B_1(E_{c1})$ and $C/B_2(E_{c2})$ are calculated by $E_{c1} = (u_1)^{\frac{1}{\beta}}$ and, $E_{c2} = (u_2)^{\frac{1}{\beta}}$ respectively. The control input fields for brake mode are obtained in a same manner.

4. RESULTS AND DISCUSSIONS

In order to demonstrate the efficiency and practical feasibility of the proposed control system, an experimental setup is established as

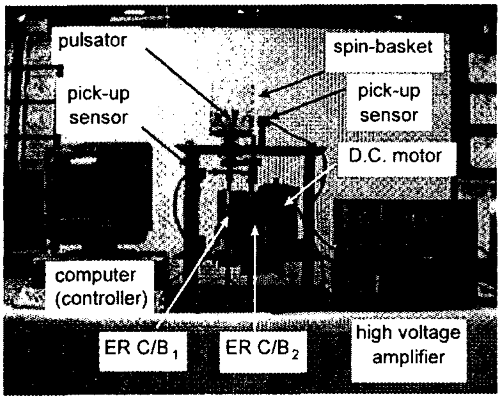
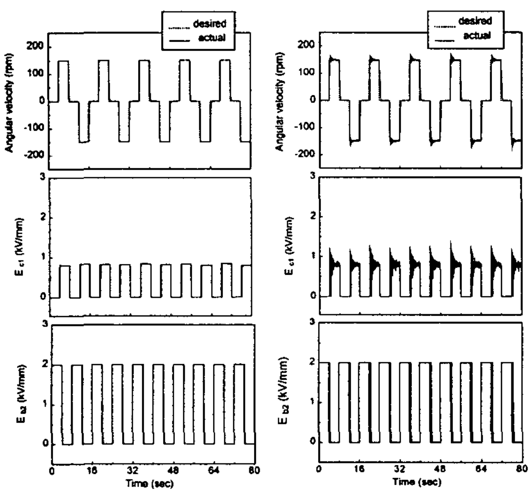


Fig. 7 An experimental apparatus for rotational motion control

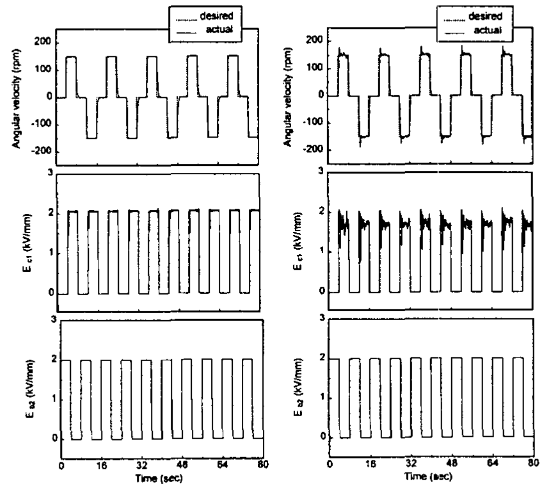
Table 1 System parameters of the control system

Parameter	value	unit
Moment of inertia of the pulsator motion (J_1)	0.0003	kg m^2
Moment of inertia of the spin-basket motion (J_2)	0.0013	kg m^2
Damping coefficient of the pulsator motion (C_1)	0.0032	Nm s
Damping coefficient of the spin-basket motion (C_2)	0.0035	Nm s
Radius of inner cylinder of ER C/B$_1$ (r_{1i})	29.5	mm
Length of inner cylinder of ER C/B$_1$ (l_{1i})	86	mm
Radius of middle cylinder of ER C/B$_1$ (r_{1m})	34	mm
Length of middle cylinder of ER C/B$_1$ (l_{1m})	112	mm
Radius of inner cylinder of ER C/B$_2$ (r_{2i})	34.5	mm
Length of inner cylinder of ER C/B$_2$ (l_{2i})	86	mm
Radius of middle cylinder of ER C/B$_2$ (r_{2m})	39	mm
Length of middle cylinder of ER C/B$_2$ (l_{2m})	112	mm



(a) simulation **(b) experiment**

Fig. 8 Washing motion control without load mass

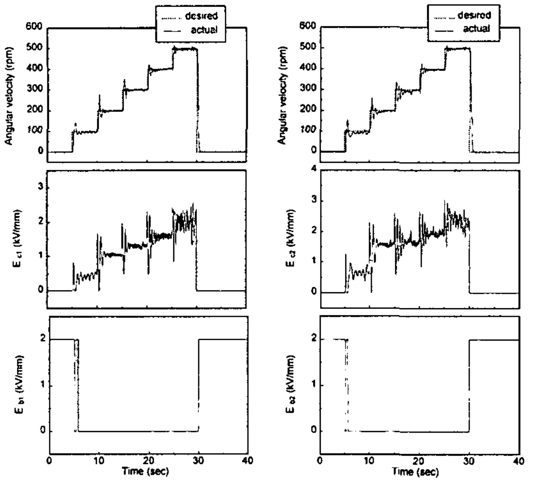


(a) simulation **(b) experiment**

Fig. 9 Washing motion control with load mass of 1000g

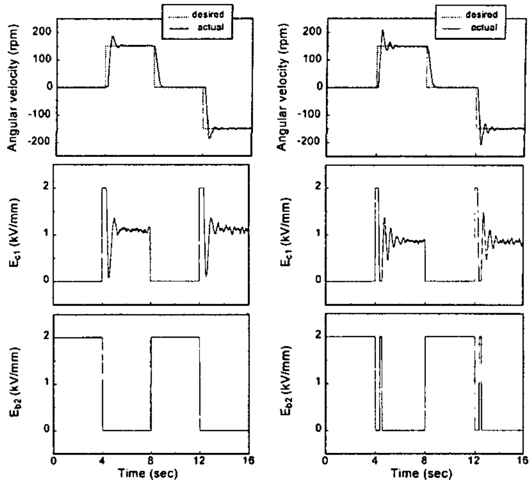
shown in Fig.7. The rotational velocities of the pulsator and spin basket are measured by pick-up sensors and are fed back to the microprocessor (controller) via the analog/digital converter. Then, the control electric fields determined from the PID controllers are applied to the actuators ER C/B$_1$ and ER C/B$_2$ through the digital/analog converter and the high voltage amplifier which has a gain of 1000. The sampling frequency for the control implementation is chosen to be 100Hz, and the program for the controller is written in Borland C language.

Fig.8 presents the simulated and the measured control responses for the washing motion without load mass. The system parameters employed are given in Table 1. The rotational motion for the washing process is activated by the pulsator. Therefore, the actuator ER C/B$_1$ plays a role of the clutch, while the actuator ER C/B$_2$ plays a role of the brake. It is clearly observed that the tracking control of the angular velocity is fairly achived by applying controlled electric fields. It is noted that the input field is saturated to avoid electric breakdown of the system. And we also



(a) pulsator (b) spin basket

Fig. 10 Measured control responses for dehydrating motion with load mass of 1000g



(a) initial (b) after 4 hours

Fig. 11 Control durability of the washing motion with load mass of 500g

have favorable agreement between the simulated and experimental results showing the validity of the proposed control system model. Fig.9 presents control responses for the washing motion in the presence of the load mass of 1000g. It is evident that the designed angular velocity is well tracked by controlling the electric fields for the actuators. Since the load mass is imposed, the input field in clutch mode to achieve same desired motion as in Fig.8 is increased. This control result may represent the robustness of the proposed control system.

Fig.10 presents measured control responses for dehydrating motion in the presence of the load mass of 1000g. In the dehydrating process, both the actuator ER C/B_1 and the actuator ER C/B_2 play as clutches during the motion, and the actuators need to be activated as brakes before and after rotational motions. We see from the results that the angular velocities of the pulsator and spin basket are fairly tracked, but exhibiting transient oscillations. The formulation of a robust control algorithm to eliminate the unwanted oscillations needs to be further investigated. It is also seen from the electric fields in Fig.10 that both actuators play as clutches in the dehydrating motion, while playing as brakes before and after the rotational motion.

As a final set of experimental test, the control durability of the washing motion is investigated and its results are presented in Fig.11. We see that control response after 4 hours' operation is not much different from that at initial operation. This result directly indicates the effectiveness and robustness of the control system with respect to variable operating conditions such as the temperature. In fact, the operating temperature of the ER fluid set by 25℃ at initial time increases up to 38℃ after 4 hours' operation. Since the yield stress of the ER fluid depends upon the temperature, the electric field required to get same tracking performance needs to be increased as shown in Fig.11(b). The control results presented in this study are quite self-explanatory justifying that the proposed ER clutch/brake actuators associated with the PID controllers may be effectively utilized for rotational motion control of many engineering applications.

5. CONCLUSIONS

A cylindrical type of clutch/brake actuator featuring electro-rheological fluid was proposed and applied to the rotational motion control of a small-sized washing machine. The sets of ER clutch/brake actuators were manufactured on the basis of Bingham model of the ER fluid, and dynamic models of the actuators were formulated by considering experimentally obtained time constants. Subsequently, a small-sized washing machine activated by ER clutch/brake actuators was devised and control system model was formulated in the state space. After designing the PID controllers, both computer simulation and experimental realization were undertaken. It has been demonstrated that tracking performances for washing and dehydrating motion control are favorable in the presence of the load mass. In addition, control durability of the washing motion was shown to be favorable by operating the system for 4 hours. The development of a robust control algorithm to improve transient control characteristics, and the application of ER clutch/brake actuators associated with time-delay dynamics to a real-sized washing machine will be undertaken as a second phase of this preliminary study.

Acknowledgment

This work was supported in part by a 1998 Research Program of Inha University. This financial support is gratefully acknowledged.

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