Time response model of ER fluids for precision control of motors

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Abstract. For improvement of control performance or new control demands of mechatronics devices using particle type ER fluids, it will be needed to further investigate a response time of the fluids. It is commonly said around 5-mili seconds, however, the formula structure of that delay has not been clear. This study aims to develop a functional damper (attenuators), that can control its viscous characteristics in real time using ER fluids as its working fluid. ER dampers are useful to accomplish high precision positioning not to prevent high speed movement of the motor. To realize the functional damper that can be manipulated according to situations or tasks, the modeling and control of ER fluids are necessary. This paper investigates time delay affects of ER fluids and makes an in-depth dynamic model of the fluid by utilizing simulation and experiment. The mathematical model has a dead-time and first ordered delays of the fluid and the high voltage amplifier for the fluid.

1. Introduction
Particle type ER fluids have been tried to many applications of mechatronics; such as dampers (attenuators), clutches, and brakes to improve control performance or to satisfy new control demands [1]. This study aims to develop a functional damper, that can control its viscous characteristics in real time using ER fluids as its working fluid. ER dampers are useful to accomplish high precision positioning not to prevent high speed movement of the motor. It will concretely be effective in high speed and precision position control area as such industrial robots for assembly, welding, painting, etc.

Fluids of this type commonly have a response time of about 5-mili seconds. The delay needs to be taken into account when electric fields are controlled in real time. Especially, servo systems introduced with ER fluid devices have sampling times for their control loops that are about 1-mili second and so are shorter than the response times of ER fluids. The delay in this case has a strong possibility of having an effect on the performance or stability of these systems.

Though, there is little research in this area mentioning the problem. This may be because the delay is not a serious issue in the case of damping structures or engine mounts [2, 3]. Most of these studies use the damper impressed constant electric fields or constant amplitude ones, and do its viscosity as a damping force. There have been many studies to clarify the mechanism of the ER effect [1], but few have studied the speed of the response itself. Many research groups on materials observe the real behaviors of the particles, or how the response changes when composition of the ER fluid changes. These studies work on static investigation or dynamic observation at micro-level, and do not put emphasis on the modeling of ER fluids and applied control.
In direct-drive (DD) motor systems [4] without reduction gears, disturbances directly influence motor dynamics and control accuracy because of the small amount of damping. Time delays of computers and amplifiers also destabilize the controller [5]. While a time lag cannot be compensated mechanically, damping can be done with an additional mechanical damper [6]. In an earlier study, we introduced a particle type ER fluid damper for a DD motor system for fast and precise positioning [6, 7]. Viscosity of the damper was controlled continuously in real time to improve the performance of the DD system through dynamic changing of the viscosity [7]. In the reference [8], a tentative mathematical model considered the response characteristics of the particle type ER fluid were suggested and confirmed by simulation.

This paper investigates time delay affects of ER fluids and makes an in-depth dynamic model of the fluid by utilizing fine simulation and experiment.

2. Damping models of ER fluid with delay
In the previous study [8], the response of the ER damper was captured macroscopically, and the model was then experientially considered as being approximated with a time-lag of the first order and a dead-time. Here, the basic viscosity is $Q_0$ N·m·rad/s, the variance of the viscosity is $Q_1$ N·m·rad/s specified by the magnitude of the electric field, $E$ V/mm, and the rotational speed of the rotor of the damper, the dead-time is $L_Q$ s, and $T_Q$ s is the time constant. The transient response of the viscosity, $Q(s)$ N·m·rad/s, can then be written as follows:

$$Q(s) = \frac{e^{-L_Q s}}{T_Q s + 1}Q_1 + Q_0$$ (1)

However, more realistic situation was suggested that the time delay effects were inserted after the command of $E$ was outputted to the damper. That is, the electric field that accords to the command value of the viscosity at the sampling time is reflected in the system model after the time lag. In view of the damping property, the new $Q$ is affected by the angular velocity when a new $E$ has been inflicted on the system. Thus $Q$ may differ from the value of the $Q$ desired when calculating the command for the viscosity.

Those has been confirmed by experiment and simulation with a delay model of $E$ that included both dead-time and 1st-ordered delay; $L_Q = 2$ ms, and $T_Q = 3$ ms. However, the control system was so complicated, that it was unclear whether the model of delay was optimal.

3. Experimental System
A DD motor and a ER damper are set on the desk as shown in figure 1. The ER damper is for experimental purpose and simply constructed as shown in figure 2; the ER fluid is between the load inertia of the DD motor and the shallow plate fixed to the torque sensor. The gap between electrodes is 0.5 mm. The torque sensor is to detect fine share stress from ER fluids. Thus, it has been hand-made with strain gages as shown in figure 3 because commercial sensors have high possibility of nonconformity in setting accuracy. A high voltage amplifier is introduced for energizing the ER fluid, that has 100%-response time under 1 millisecond with no overshooting. The controller is constructed in a PC, which has a Pentium4-1.5 GHz CPU, 512 MB memory and ART-Linux for OS. The sampling time is under 1 ms for real time sensing.

While the angular velocity of the DD motor is controlled in regulated speed, the ER fluid energized, and then resistive torques are measured with the torque sensor. The applied electric field changes stepwise or in other way.

4. Experiments and modeling
In this section, time response of an ER fluid was measured in real time. Electric fields were applied as simple step to reconsider the brief model of the ER fluid suggested in the passed study.
The motor rotated in about 1/2 round/s (π rad/s), without speed control but applying a constant voltage in this case. The sampling time was 0.2 ms (5 kHz). Step electric fields from 0 kV/mm were applied at 1.0 s, and then removed at 2.0 s. Twenty times experiments of the same condition were carried out. Data were not filtered, but averaged from raw data, normalized by steady state value and analyzed.

Figure 4 shows the normalized data; the dotted line means the command value of the electric field, the short dashed line shows the result applied 1.0 kV/mm electric field, the solid line is the case of 1.5 kV/mm, and the dot-dashed line shows the case of 2.0 kV/mm. All results show big overshoot according to some impact load. The electrodes were always under slipping, so that those were not because of stick-slip. Rather it may be affected by the moment of the load inertia, it will be better to lighten the sensor. Electrical countermeasures against noise will also be required. Further investigation is needed on the difference of the response when 1 kV/mm. Anyway, the dead-time was around 2 ms, and the value settled into the 100%-response in about 4 ms; these were near to the value commonly mentioned.

We focused on the response when 1.5 kV/mm, and tried to identify the delay with simulation. In the simulation, the normalized output $\tau$ as follows was implemented in C language:

$$\tau = \frac{e^{-Ls}}{T_{ER}s + 1} \cdot \frac{1}{T_{HV}s + 1}$$

Where, the sampling time was 0.20 ms, the dead time $L = 1.5$ ms, and the time constant of the ER fluid $T_{ER} = 0.35$ ms, which was adjusted as the 100%-response of the ER fluid was in 2 ms. The time constant $T_{HV} = 0.18$ ms was for the high voltage amplifier; it set the 100%-response of the amplifier as 1 ms. The dead time element $e^{\frac{-Ls}{}}$ was not written in the Pade approximation, but in FIFO queue.

The responses in rising of the experiment and simulation are shown as figure 5. The simulation
result shows the 100%-response of the ER fluid was about 4 ms. While overshooting made their fitness slightly unclear, they can seem similar. On the other hand, the responses in falling are shown as figure 6. In this case, \( L \) was adjusted as zero; it implies different mechanisms of de-energized ER fluids from energized ones. Past experiments say those overshooting was at most 10%. Those in this paper might be from softness and the moment of inertia of the torque sensor, which were caused by high sensitivity of the sensor.

5. Discussions and Conclusions
In this paper, we investigated the effects of time delays from ER fluids through experiments with very small sampling time. The mathematical models of delay have been updated to more accurate ones reflected in dynamic characteristics of a dead-time and first ordered delays of the fluid and the high voltage amplifier for the fluid. Those were confirmed with simulation.

During step responses, difference of the order of the delay model between the first and higher was not apparent. Then, we used the first ordered one in this paper. Frequency responses from the other experimental device, while it has not been modeled yet, seemed having the characteristics of the first ordered delay model. In future, we will continue to confirm the validity of the order of the model, and also try to make models by more objective method.

After the modeling, we will design a controller that explicitly includes a delay for the ER dampers; it will be an algorithm to use the ER damper suiting for high speed motion clearly involving the delay model.

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