Vibration control of an artificial muscle manipulator with a magnetorheological fluid brake

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Abstract. Recently, proposed applications of robots require them to contact human safely. Therefore, we focus on pneumatic rubber artificial muscle. This actuator is flexible, light, and has high-power density. However, because the artificial muscle is flexible, it vibrates when there is a high load. Therefore, we paid attention to the magnetorheological (MR) fluid. We propose a control method of the MR brake considering energy of the manipulator system. By this control method, MR brake dissipates energy leading to vibration of the manipulator. In this paper, we calculated the energy and controlled the MR brake. And, we deliberated the proposal method by simulation using the dynamic model of the manipulator, and experiment.

1. Introduction

Recently, there have been advances in the development of partner robots aimed at providing life support and robots aimed at providing medical treatment and care such as power assistance [1]. These robots are expected to be safe to human when these robots contact human. Then, we developed the straight-fiber-type artificial muscle [2] as actuators. It has a high contraction percentage and high contractive force, and this muscle has a long life compared with past McKibben type rubber artificial muscle [3-6]. Moreover, these artificial muscles are lightweight, have high output, and are flexible.

However, because the artificial muscle is flexible, it vibrates when there is a high load. Moreover, the artificial muscle manipulator has a slow response because it is operated by air pressure, and there is a limit to the response of the momentary power. Therefore, we are interested in the use of magnetorheological (MR) fluid [7], because its apparent viscosity can be changed very quickly (in milliseconds) by applying a magnetic field.

Until now, we have been developed a 1-degree-of-freedom artificial muscle manipulator using MR brake and controlled vibration of the artificial muscle by simple control of the MR brake. However, this control does not consider the characteristic of the manipulator. As a result, the MR brake interfered with the artificial muscle excessively.

Thus, in this paper, we propose a control method of the MR brake considering energy of the manipulator system. By this control method, MR brake dissipates energy leading to vibration of the manipulator. And we examine this proposal method by experiment and simulation using dynamic characteristic model of the manipulator.

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2. The straight-fiber-type artificial muscle
The schematic of the artificial muscle developed at our laboratory is shown in figure 1. Table I shows the specifications of the artificial muscle used in this study. The form of this artificial muscle is tubular, and the material used is natural-rubber-latex liquid and carbon fiber. Moreover, since its structure includes a carbon fiber layer in the direction of an axis, if air pressure is supplied to this artificial muscle, the rubber membrane will expand, but the fiber stops the growth in the direction of an axis so that the membrane is mostly not extended. As a result, the muscle expands only in a radial direction and contracts in the direction of an axis. This artificial muscle is lightweight, has high output, and is flexible.

![Diagram of the straight-fiber-type artificial muscle](image)

**Figure 1.** A schematic diagram of the straight-fiber-type artificial muscle.

| Spec          | Value  |
|---------------|--------|
| Length $l$ [mm] | 187.0  |
| The length between cap and ring $l_0$ [mm] | 62.3   |
| Diameter $d_0$ [mm] | 12.3   |
| Thickness $t$ [mm] | 0.23   |
| Elastic modulus $K$ [Pa] | 800000 |
| Number of rings | 2      |

3. MR brakes
We focused on the MR brake as a way to apply MR fluid to the joint. We used the MRB-2107-3 of the LORD Co. as MR braking equipment. The overall view and the diagrammatic illustration of the MRB-2107-3 are shown in figure 2. And, the characteristics of the MR brake are shown in figure 3. As figure 3, the MR brake changes apparent viscosity by magnetic field. And relationship between its brake torque and rotational speed is low that it can ignore.

This MR brake has high speed response in units of several milliseconds. Thus, we guess MR brake can control vibration of the arm of the manipulator. This device generates friction on the surface of the disk as it changes in response to the magnetic field by arranging the MR fluid in the internal disk surroundings. It is possible to apply brakes to a rotation operation according to this mechanism. The MR brake has the following features:

- Since torque density is high, it is small, and it is high output.
- Since the structure is simple, it is strong.
- The speed of response is in units of several milliseconds.
- It can be changed continuously.
- It is stable.
- It is an energy-saving model.
4. The artificial muscle manipulator with the MR brake

Figure 4 shows the overall view of the developed one degree of freedom artificial muscle manipulator. And Table 1 shows parameters of this manipulator. The artificial muscle manipulator is arranged as two artificial muscles in parallel. Further it transmits the contractile force of the artificial muscle to the rotation axis through the belt pulley. The MR brake equipment is fixed to the first link side, and it can apply braking power to the axis of rotation. The manipulator is installed in the load cell to detect the load torque that hangs to the joint and the encoder to detect the joint angle.
5. Manipulator model

In this study, we built a manipulator model for approach against control from theory. However, this system is difficult to reproduce as simple mass-spring-damper system because there is lateness of air pressure in this system. Therefore, we built a manipulator model while considering the dynamic characteristics of artificial muscles.

The schematic view of this manipulator model is shown in figure 5. This model consists of three parts. The first part is controller using a mechanical equilibrium model [2] treating the static characteristic of an artificial muscle. Since the artificial muscles are highly nonlinear in contraction, contractile force, and pressure, they are difficult to control. This controller can linearize the characteristic of artificial muscles.

The second part is a dynamic characteristics model containing the elements related to the dynamic characteristics of the air artificial muscle system. As these elements, the speed response of a solenoid valve, the ease of passing of the air in an air tube, the pressure change in an artificial muscle, and the volume change in an artificial muscle are mentioned [8].

The third part is a load system model of the manipulator. This model is based on forward dynamics. These models were combined and considered as the manipulator model.
6. Calculation of energy for dissipation

In this section, we propose a control method considering mechanical energy in the manipulator system. And a schematic diagram of joint manipulator is shown in figure 6. In this system, load cells detect forces $F_1$ and $F_2$. These forces contain force for joint stiffness $F_0$, force by load $F_L$ and elastic force $F_e$ by inertia force of the arm.

By the proposed method, the MR brake dissipates energy leading to vibration of the arm of the manipulator. Therefore, we calculate kinetic energy of the arm and elastic energy of the artificial muscle. Then, we calculate brake torque of MR brake for dissipation of this mechanical energy.

6.1. Kinetic energy

Kinetic energy of the manipulator $W_k$ is calculated by following equation. Where, $I$ is Mass moment of inertia of the arm, and $\theta'$ is angular velocity.
6.2. Elastic energy

The artificial muscles generate vibration because of own flexibility. Therefore, we control the vibration by dissipating elastic energy using MR brake. Elastic energy of artificial muscles leading to vibration of the arm $W_e$ calculated by following equation. Where, $K_i$ is a spring constant of artificial muscles.

\[ W_e = W_{e1} + W_{e2} \]  
\[ W_{ei} = \frac{1}{2} K_i x_i^2 \]  

Next, we calculated $K_i$. The spring constant of artificial muscles $K_i$ changes with pressure values linearly [2]. Therefore, each spring constant is calculated by the following formulas. Where, $P_i$ is pressure, and $K_{ai}$ are coefficients between stiffness and pressure of artificial muscles.

\[ K_i = K_{ai} P_i \]  

Next, we calculated displacement of artificial muscle $x_i$ from the spring constant of artificial muscles and elastic force $F_{ei}$.

\[ x_i = \frac{F_{ei}}{K_i} \]  

Where, the artificial muscle manipulator is arranged two artificial muscles to parallel. Further it transmits the contractile force of the artificial muscle to the rotation axis through the belt pulley. Therefore, force $F_1$ and $F_2$ detected by load cell contain $\bigodot^1$ force for joint stiffness, $\bigodot^2$ load and $\bigodot^3$ elastic force. Thus, for detection of elastic force, we calculated difference of force $F_1$ and $F_2$. Thereby, force for joint stiffness is eliminated.

\[ F_e = F_2 - F_1 - F_L \]  
\[ F_{e1} = F_e \ (F_e > 0) \]  
\[ F_{e2} = -F_e \ (F_e < 0) \]  

Where, $F_L$ is force of load calculated from mass of load $M_2$, length of arm $l$, radius of pulley $r$ and angle of the arm $\theta$. The elastic force $F_e$ is pull force to the artificial muscles by inertia force of the arm. This elastic force acts on one of artificial muscles or another by the movement direction of an arm as $F_{e1}$ or $F_{e2}$.

\[ F_L = \frac{M_2 g l \sin \theta}{r} \]  

And, we calculated $W_e$ from (2) to (9).

\[ W_e = \frac{1}{2} \left( \frac{F_{e1}^2}{K_{ai} P_1} + \frac{F_{e2}^2}{K_{ai} P_2} \right) \]  

6.3. Dissipation energy of the MR brake

In this section, we calculated the dissipation energy by MR brake $W_m$. Figure 7 shows the schematic view of the energy dissipation by MR brake. Where, $\theta_a$ is desirable angle of the arm. In the proposed method, we dissipate energy using MR brake in the area named dissipation section $\theta_a$. Changing $\theta_a$,
we can adjust dissipated energy. From this figure, the energy $W_m$ calculated from brake torque $\tau_m$ and angular velocity.

$$W_m = \tau_m \int \dot{\theta} dt$$  

(11)

![MR Brake](image)

**Figure 7.** A schematic of the energy dispersion.

And, output torque of the MR brake $\tau_m$ is controlled for dissipation mechanical energy leading to vibration. Therefore, $\tau_m$ is calculated by following equation.

$$\tau_m = K F \left( \frac{t \dot{\theta}^2}{K_1} + \frac{F_{el}^2}{K_2} + \frac{F_{e2}^2}{K_2} \right)$$

(13)

7. Vibration control experiment by the MR brake

7.1. Simulation for decision of energy dissipation section

In this proposed method, energy dissipated by MR brake depends on width of dissipation section $\theta_\alpha$. Thus, we need to decide width of energy dissipation section. Therefore, we deliberated the section using the dynamic model of the manipulator. In this simulation, desirable angle is 60 [deg], joint stiffness is 0.1 [Nm/deg], load is 9.6[N] and dissipation section is 10 [deg] to 40 [deg].

Figure 8 shows a result of simulation, and figure 9 shows the amount of vibration and deviation area in each dissipation section. In figure 9, Integration value of speed is defined as Integration value of the magnitude of the velocity vector of the arm. This value becomes high when vibration of the arm increases. Thus, we used this value as evaluation of vibration of the arm. Therefore, we decided dissipate section so that integration value of speed and Difference area of position to step input become low. In this study, we attached weight to Integration value of speed. Therefore, we chose 30 [deg] as dissipation section.
7.2. Vibration control experiment

In this section, we experiment to lift the arm with vibration control by proposed method. In this experiment, desirable angle $\theta_d$ is 60 [deg], joint stiffness is 0.1 [Nm/deg], load is 9.6[N] and dissipation section $\theta_a$ is 30 [deg]. First, the arm raises the load to the desirable angle. Then, energy dissipation is started 30 degrees before from the desirable angle. Dissipated energy is calculated from sensor value in real time.

A result of vibration control experiment and simulation is shown in figure 10. From this figure, the dynamic model of the manipulator reproduces system of the manipulator in points of dead time, rise time and motion of the arm. And we conclude that the MR brake controls vibration of the arm successfully by proposed method, from experimental result and simulation result. And from figure 11, we confirmed that the mechanical energy in the vibration domain was dissipated.

However, there is response delay of MR brake because of coil in experimental result. Thus we need to develop a driver for the MR brake.
Figure 10. The experimental result (the dissipation section is 30 [deg]).

Figure 11. The energy change of the manipulator when the energy dissipation is applied.

8. Conclusion
We proposed the energy dissipation method for control of the MR brake. We calculated the energy leading to vibration and controlled the MR brake. Then, we applied the proposed method numerically using the dynamic model of the manipulator. As a result, we have shown that the MR brake controls vibration of the arm successfully by the proposed method. We confirmed that the mechanical energy in the vibration domain was dissipated faster.

For future works, we plan to develop a MR brake driver to improve response of the MR brake. In addition, we develop a multi-DOF manipulator using MR brake.

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