Development of 1-DOF manipulator with variable rheological joint for instantaneous force

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Abstract. Highly rigid actuators such as a geared motor or hydraulic actuator are widely used in industrial robots. To obtain high-speed motion, actuators need to increase the actuator output. However, to increase high-rigidity actuators output, it is necessary to make actuators larger. In contrast, humans perform motions with instantaneous force such as jumping or throwing by using muscles. These instantaneous forces are realized by accumulating potential energy to the muscles and the muscles releasing the energy in a short time. Therefore, in this study a 1-DOF manipulator with variable rheological joint for instantaneous force using an artificial muscle and a magnetorheological (MR) brake was developed. In this paper, the method of generating instantaneous force for this manipulator was proposed. Further, the experiment of the proposed method was also conducted. As a result, generating instantaneous force by proposed method was realized.

1. Introduction
High-rigidity actuators such as motors and hydraulic actuators are widely used in industrial robots. To obtain a high-speed motion, actuators need to increase their own output. However, to increase high-rigidity actuators output, it is necessary to make actuators larger. Therefore, it has problem that the robot weight increases as actuators output increases. In contrast, humans perform motions such as jumping or throwing with instantaneous force by using muscles. To obtain instantaneous force, muscles need to increase their own output than usual. These instantaneous forces are realized by accumulating potential energy to the muscles and the muscles releasing the energy in a short time. Since, muscles have high compliance and can change viscosity at high-speed, they can generate such instantaneous force. Therefore, actuators for generating instantaneous force need a high compliance and a high-speed rheological change, which is difficult to achieve with high-rigidity actuators such as motors and hydraulic actuators.

Kovac et al. [1] developed a miniature jumping robot using a motor and spring. However, the elastic coefficient of the actuator used by Kovac et al. was constant, and the instantaneous force and position could not be controlled independently. Although Niiyama et al. [2] developed a jumping robot using the pneumatic artificial muscle, the jumping operation of this robot is designed by trial and error, and the air pressure control capabilities are not adequate. Furthermore, the reported studies do not allow for viscosity control and control of the motion generated by the instantaneous force is not sufficiently developed.

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Therefore, in this study it was focused on a pneumatic artificial muscle with a high compliance and a MR brake using MR fluid that can change apparent viscosity at high-speed. Applying these features to the joint of the robot, the robot can generate instantaneous force in the same way as human. Then, the 1-DOF manipulator using artificial muscle and MR brake for instantaneous force was developed. Furthermore, since this manipulator can control the viscosity and elasticity independently, it was presumed that this manipulator can control instantaneous force and position independently. Here, a method of generating instantaneous force for the manipulator using the artificial muscle and a MR brake were described. Also an experiment in which instantaneous force generated was described.

2. Straight-fiber-type artificial muscle

Figure 1 shows the diagrammatic illustration of the Straight-fiber-type artificial muscle [3] used in this study. The artificial muscle has a tubular shape and is made of natural latex rubber. The muscle structure includes a carbon fiber layer in the direction of length. Consequently, when air pressure is supplied to the muscle, it will only expand in the radial direction and contract in the direction of length. The contractile force is then used as an actuator. The straight-fiber-type artificial muscle has a high contraction percentage, high contractile force, and a long lifespan compared to the McKibben-type artificial muscle [4]. Straight-fiber-type artificial muscle has non-linear characteristic and variable elasticity.

3. MR brake

In this study, a MRB-2107-3 of the LORD Co. as an MR brake device is used. Figure 2 shows a schematic diagram of the MR brake device. Table 1 shows the specification of the MR brake. This MR brake consisted of a coil, a rotor, and MR fluid. The MR fluid, which is applied to the magnetic field from a coil, produces friction between the rotors. This friction force acts as the brake torque. Applying the MR brake to a manipulator realized the variable rheological joint. Since, MR brake is friction brake, MR brake can hold the rotor not to be rotated. Therefore, it was presumed that the artificial muscle can accumulate potential energy by applying MR brake to a manipulator. Further, the artificial muscle can release the energy quickly because MR brake has a high-speed response.
### Table 1. Specification of the MR brake

| Parameter name       | Value          |
|----------------------|----------------|
| Diameter             | 920 mm         |
| Length               | 360 mm         |
| Weight               | 1.4 kg         |
| Maximum torque       | 5.65 Nm        |
| Minimum torque       | <0.34 Nm       |
| Max current value    | 1 A            |
| Temperature range    | -28.9~71.1     |

### 4. 1-DOF manipulator with variable rheological joint

Figure 3 shows the overall view of the developed one-degree-of-freedom (1-DOF) artificial muscle manipulator with variable rheological joint. Table 2 shows the specification of the manipulator. Two artificial muscles are arranged in parallel. The system transmits the contractile force of the artificial muscle to the rotation axis through the belt pulley. Drive torque generated by contractile force of the artificial muscle is very high compared with brake torque of MR brake. Therefore, it cannot be hold the joint rotation only to apply the MR brake directly. For that reason, the MR brake is fixed to the first joint through the gears. As a result, it is possible to apply the brake to the rotation axis and it can be accumulated more potential energy in the artificial muscle. A load cell and a pressure sensor are attached to each artificial muscle. Further, encoder is attached to the joint.

![1-DOF manipulator](image)

**Figure 3.** 1-DOF manipulator.

### Table 2. Specification of the manipulator.

| Parameter name                  | Value          |
|---------------------------------|----------------|
| Mass of 1st link                | 0.8 kg         |
| Length of 1st link              | 270 mm         |
| Center of gravity of the 1st link| 140 mm         |
| Movable angle                   | 0~120 deg      |
5. Method for generating instantaneous force
The following steps are proposed as a method for generating instantaneous force in the manipulator. Figure 4 shows overview of the proposed method. (1) Hold the joint rotation with the MR brake, (2) Accumulate potential energy in the artificial muscle by applying initial air pressure and (3) Generate instantaneous force by releasing the arm. This is called the MR method.

Figure 4. Overview of the MR method.

6. Relationship between volume and pressure of the artificial muscle
In the MR method, No initial pressure is added in the muscle during the manipulator drive. For this reason, the steady-state position of the arm depends on the initial pressure of the artificial muscle. Therefore, it is necessary to calculate the initial pressure to raise the load to the desired arm angle. However, this pressure changes with the volume change and contractile force of the muscle. Thus, experimental relationships between the volume and pressure of the artificial muscle were obtained. In the experiment, the initial pressure is applied to the artificial muscle, and the pressure and contraction are recorded. Figure 5 shows the experimental result. Figure 5 shows that pressure is proportional to volume. This relationship does not depend on the initial pressure. The relationship can be expressed approximately as follows:

\[ P_0 = -0.0014 \left( V_0 - V_d \right) + P_d \]  

(1)

Here, \( P_0 \) is the initial pressure, \( P_d \) is the pressure at the desired angle, \( V_0 \) is the volume at the initial angle, and \( V_d \) is the volume at the desired angle.

7. Instantaneous force generation experiment
In the instantaneous force generation experiment, the initial pressure was calculated by using equation (1) with the desired arm angle of 60 degrees. Further, we defined instantaneous force as power. This power is calculated as follows:

\[ W = F \cdot r \cdot \theta \cdot s^{-1} \]  

(2)

Here, \( W \) is power of the artificial muscle, \( F \) is contractile force of the artificial muscle, \( r \) is the radius of belt pulley, \( \theta \) is the angle of the joint, and \( s \) is the sampling time.
y = -0.0013x + 0.1735
y = -0.0014x + 0.2392
y = -0.0014x + 0.2691

Figure 5. Relationship between volume and pressure of the artificial muscle.

Figure 6 shows the result of response of angle, while Figure 7 shows that of power. Table 3 shows dead and rise times and maximum power of each response. Step response is the response of the arm when air pressure is applied to the artificial muscle by step input. In the experimental result of using the MR method, the dead time decreased by 68%, and the rise time decreased by 11% compared with the step response. Further, maximum power increased by 280% compared with the step response. From that result, instantaneous force generation by MR method was realized. The steady-state position of the arm corresponded to the desired arm angle. Therefore, the initial pressure calculated by equation (1) is useful to control the arm driven by the MR method.

In this experiment, the response of using the MR method oscillated. Because, MR brake was not controlled after starting the manipulator driving. However, applying vibration control using a MR brake [5], vibration of the arm could be controlled easily.

Figure 6. Experimental result of the angle.
8. Conclusion
In this research, a method of generating instantaneous force for a manipulator with a variable rheological joint was proposed. The proposed method realized the generation of instantaneous force. As a result, the dead and rise times decreased and maximum power significantly increased compared to the step response.

References
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