A study on the novel linear actuator using MR fluid

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Abstract: A new MR cylinder with built-in valves using MR fluid (MR valve) is proposed for fluid power control systems. The MR or Magneto-Rheololgical fluid is a newly developed functional fluid whose obvious viscosity is controlled by the applied magnetic field intensity. The MR cylinder is composed of cylinder with small clearance and piston with electromagnet. The differential pressure is controlled by the applied magnetic field intensity. It has the characteristics of simple, compact and reliable structure.

The size of MR cylinder and piston has φ60mm×259mm and φ58mm×136.5mm in face size respectively and 0.8mm in gap length. Through experiments on the static characteristics, it is found that the differential pressure is controlled by the applied magnetic field intensity under little influence of the flow rate, which corresponds to a pressure control valve. Effectiveness of the MR cylinder is demonstrated through the position control of one link MR manipulator.

Keywords: MR Fluid, MR cylinder, Static Characteristics, Dynamic Characteristics, Differential Pressure

1. INTRODUCTION

Magneto-Rheololgical (MR) fluid is composed of magnetizable particles and base fluid and represents a novel and exciting family of smart materials that have the ability to undergo rapid within a few msec, nearly completely reversible, and significant changes in their apparent viscosity on application of an external magnetic field. These fluids typically consist of fine particles of a magnetically soft material dispersed in an organic medium such as mineral or silicone oil. When magnetic field is applied to the MR fluid, the magnetizable particles form clusters and the flow resistance increases, which results in the apparent viscosity increase. If this fluid is employed, we can make a valve device which does not have any mechanical element. In the absence of a magnetic field, MR fluids exhibit a relatively small apparent viscosity and therefore flow similar to commonly encountered dispersions such as paints.

Its strong points are that it saves energy consumption and it does no harm to the environment. MR fluid, which is applicable to the realization of high lever fluid power, is expected to be controllable fluid which is simple, compact and reliable structure without moving parts. MR fluids are already in limited commercial use, such as in home exercise equipment capable of high torque ant low speed and are also being considered in a number of automotive applications including continuously variable semi-active shock absorbers and adaptive engine mounts.

MR fluids also have significant potential for overcoming the deficiencies of electro-hydraulic actuators for vibration control, because they are very stable with respect to the variation of temperature with an effective operating range of -40 ~ 150˚C, and can potentially perform much faster than conventional hydraulic servo systems. The most important property of MR fluids is their ability to achieve these significant yield stresses with low voltage power supplies, which are highly reliable. The fibrillated structure, a colloidal gel-like material, exhibits a respectable yield stress and is therefore capable of being used as an enabling material for controllable actuators in mechanical systems. As a result, MR fluids have recently attracted considerable attention for a variety of applications, including vibration control.

Previous application research has been done with a bellows driven manipulator by using MR fluid. The problem, however, is that actuator's maximum extension rate is too small.

In this study, we have developed an actuator using MR fluid that consists of a piston part and cylinder part and an MR fluid between them. First, F.E.M analysis is performed to do exact experiments without trial and error. Next, basic experiments are examined to investigate the characteristics of the actuator. In this paper, a MR cylinder with built-in valves is proposed for fluid control systems.

2. PROPOSITION AND FABRICATION OF MR CYLINDER

2.1 Proposition of MR cylinder

Schematic diagram of MR cylinder is shown in Fig. 1

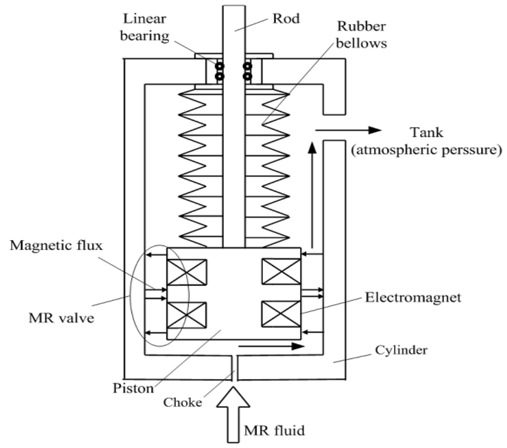

Fig. 1 Schematic of the MR cylinder

Fig.1 is fabricated. Our proposed MR cylinder controls the differential pressure by magnetic field which results from gap between piston and cylinder. According to the previous research, which compared with MR valve and bellows driven actuator, MR cylinder has the advantage of small size and big stroke.

Orifice is installed in the supplying port of cylinder and MR fluid is supplied into the cylinder and the pressure in the chamber of piston is controlled by the intensity of the magnetic field in the piston. And bellow, which is made of rubber, is installed around the rod of the interior of cylinder, and it blocks the invasion of MR fluid's particle.

2.2 Fabrication of MR cylinder

The piston made of soft magnetic iron has φ58mm in outer diameter and 36.5mm in length. The cylinder made of low carbon steel has φ60mm in inner diameter and 259mm in length respectively. The specifications are the supply pressure 0.7Mpa, the maximum extending force 1.6Kn with the applied current of 1.5A. The gap between the piston and cylinder is h=1mm.

As the material of piston and cylinder, small retained magnetic flux should be selected.

First, we will investigate its magnetic circuit, and then we calculate design parameter to find out cylinder's generated force. Eq. (1) presents differential pressure of magnetic circuit, we can substitute design data and get magnetic flux. Design parameters in the experiments are shown in Table 1.

$$\Delta P = \frac{2\times 2l\times k}{h}\times B_g = \frac{4k}{\pi\sigma}\times\frac{\Phi}{Dh} = \frac{k}{h\sigma}\times\frac{D_c^2 B_2}{D} \qquad (1)$$

Fig. 2 is magnetic diagram of MR cylinder. Because magnetic saturation happens greatly in B_g, we must take care of designing. Magnetic flux can be represented as Eq. (2)-(4), which is shown in Fig. 2.

$$B_g = \Phi / \pi D l \sigma \qquad (2)$$

$$B_1 = \Phi / \pi D_c l \qquad (3)$$

Table 1 Design data for MR cylinder

Notation	Design data
D (mm)	58
μ_0 (Hm^{-1})	4π x10^{-7}
μ_s	2
k (kPa/T)	41
B_g (T)	0.1
B_1, B_2, B_3 (T)	0.55
h (mm)	0.6
σ	2
d (mm)	0.5
I_{max} (A)	1.5
α	0.5

$$B_2 = \Phi / (\pi D_c^2/4) \qquad (4)$$

l and Dc can be derived form eq. (2) and Eq. (3) The magnetic flux and current can be expressed as Eq. (5)

$$\Phi = \frac{NI}{R} = \frac{\pi\alpha\mu_0\mu_s}{4}\times\left[\frac{Dll_1(D-D_c)}{hd^2}\right]\times I = \frac{\pi\alpha\mu_0\mu_s I}{4hd^2}\times Dll_1(D-D_c) \qquad (5)$$

Inserting l, Dc and design parameters into Eq. (5), the last parameter l_1 can be calculated. As the result, pressure difference becomes 0.35MPa. Because estimated value corresponds to about half of target, it should be presented a way that can compensate the loss. Pressure loss due to the base viscosity is designed to be sufficiently small for the MR valve to control the differential pressure ΔP irrespective of the flow rate. MR actuator produces generated force by magnetic flux intensity flowing onto gap between piston and cylinder. If we compose magnetic circuit by 1 electromagnet, flowing magnetic flux is limited by the magnetic saturation of piston and cylinder. Hence, to increase the magnetic flux under magnetic saturation in the magnetic core, two electromagnets with 160 turn's coils are located in face to face. And we can prove generated force by arranging electromagnet by series by different polarity. Therefore, in this paper, we assumed that magnetic flux's leakage coefficient is 2.0 and used two electromagnets of 160 turns. By the above design, the differential pressure of 0.7MPa can be obtained. In the design of the number of electromagnet, the weight and output power of cylinder should be considered and 2 electromagnets are used in this paper.

Fig.3 shows 1-link MR manipulator that is designed to know MR cylinder's characteristics. There are two specifications which are arm length 0.5m, rotational angle range 60° . The contraction displacement is transformed to the joint angle through a chain and a sprocket.

The MR fluid is a newly devised low base viscosity one using lightweight Mn-Zn ferrite particles with average diameter of 2.7μm. The MR fluid of 2.3×10^{3}kg/m^3 and the MR effect coefficient k=41kPa/T.

Pumping of the fabricated MR fluid is performed. For experiments, a diaphragm pump (Nikuni Co. 25HYS-V. 6.9 MPa, 300cm^3/s) is used without affection of the dispersed particles. Two accumulators (bladder type 1000 cm^3 and in-line type 30 cm^3) are installed.

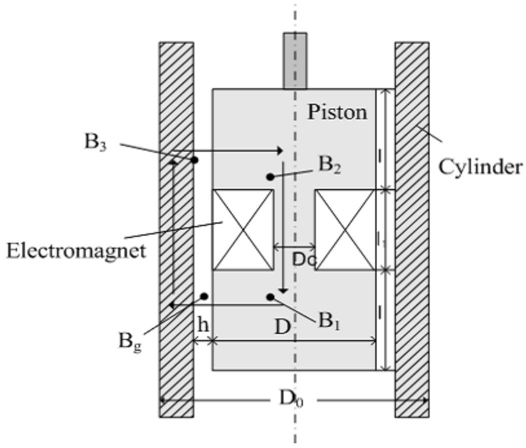

Fig. 2 Magnetic Diagram of MR cylinder

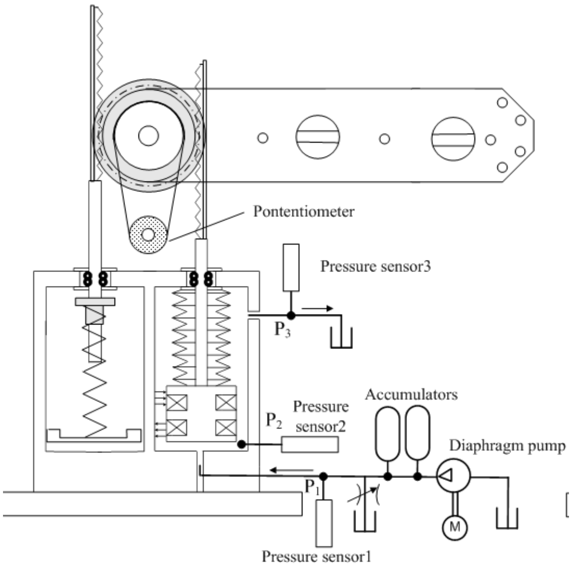

Fig. 3 Experimental setup of the MR cylinder

At the outport of cylinder, a relief valve and accumulators (bladder type 1000 cm^3 and in-line type 30cm^3/s) are installed. The pressure, the joint angle of arm and current are measured by computer.

3. F.E.M. (FINITE ELEMENT METHOD) ANALYSIS USING ANSYS

3.1 The Modeling of Solenoid

Viscosity of working fluid between cylinder and piston decides the differential pressure of piston on both ends. According to the external appearance and size of the magnetic field, the apparent viscosity of fluid is changed. Therefore, we should know the intensity of magnetic field which occurs in the solenoid, to achieve correct performance estimation of the cylinder. At this stage, the analysis of magnetic flux with respect to the change of important design parameters such as shape and material of the coil was investigated. Through previous analysis of the piston, we are able to reduce the fabrication time about manufacturing and do analysis within actual state based on design parameter and material property. In this research, ANSYS is used to figure out the streamline and intensity of magnetic field. Fig. 4 is model of solenoid. There are 2 solenoids on upper and down direction.

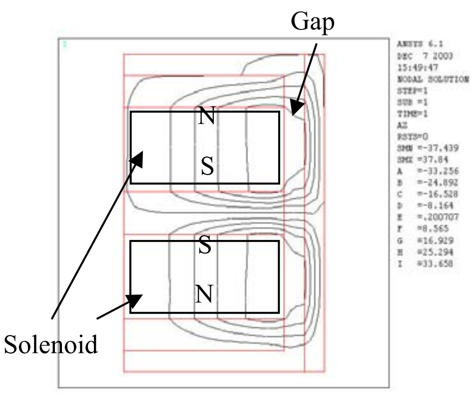

Fig. 4 Magnetic flux

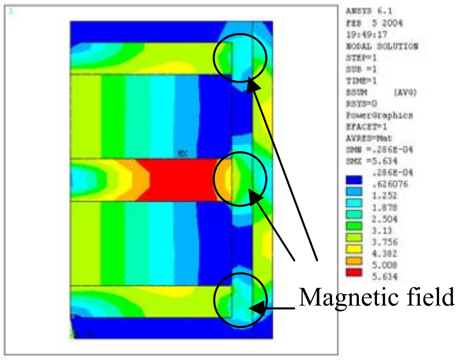

Fig. 5 Intensity of Magnetic field

If variable current is inputted, a magnetic field is formed. Each solenoid is arranged the other way. This is method to generate strong intensity of magnetic flux.

3.2 F.E.M. analysis

As the ANSYS model, we adopted CATIA solid model. After creating mesh of cylinder by using free mesh, the material properties and the boundary conditions are defined. Note that the scale has been omitted by the author, as ANSYS normalizes all results to some arbitrary value. It is only the ratios of results that are quantitatively useful.

The simulation results of ANSYS are shown in Fig. 4 and 5. Fig. 4 is magnetic flux and Fig. 5 is intensity of magnetic field. From the simulation results, the generated magnetic field flows in the vertical direction with respect to the gap.

In Fig. 5, the intensity of magnetic field, which is formed from 2 electromagnets arranged by series, becomes about double in the middle part of piston. Because of the arranged polarity of upper and lower electromagnet in the opposite polarity, the intensity of a magnetic field becomes double. Because polarity becomes gradually from the middle part, intensity of a magnetic field increases.

4. EXPERIMENTS OF MR CYLINDER

4.1 Static characteristics

To investigate the frequency response of fabricated MR cylinder, low frequency sinusoidal input with the magnitude of bias current 0.75A was applied. Fig. 6 shows the measured static characteristics. The joint angle is measured counterclockwise from horizontal. The differential pressure of piston ΔP(=P2-P3) and joint angle of arm are looked like nonlinear, but we got same results in an every experiment. As shown in figure, when an input current is 1.5A and the differential pressure is 0. 40MPa, generated force is 1.1kN. Differential pressure comparing with design value is small.
For MR fluid used this experiment, the characteristics of the MR fluid are measured before and after use. The results are shown in Fig. 6 In using 2 port MR valve[(2), (7)], left Fig. 7 is as shown the performance of intensity of magnetization at applied magnetic field intensity. And shown in right Fig. 7 the performance of shear stress at magnetic flux density.

Because MR fluid has irregular particle form at first time, shear stress generates larger. After pumping, because scattered particle is worn away by pumping and attrition between particle decreases, change of shear stress decreases.

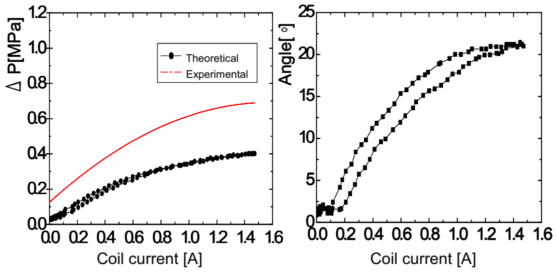

Fig. 6 Static characteristic of a manipulator using the MR cylinder

Although MR cylinder that experiment in this paper is designed after understanding variable characteristics, from this results, we could know an important facts that need to consider characteristics of the MR fluid after pumping. Measured result of magnetic flux density between piston and cylinder, simulation result of Equation (1) displayed dotted line in Fig. 6. Because there was seldom magnetic flux leakage, theoretical values become about double of designed values. There is big difference comparing with experimented value. It is caused by the eccentric and slant fo the piston. Causes of hysteresis of ΔP that happen in current 0A is due to residual magnetism of magnetic circuit.

In right figure of Fig. 6, hysteresis of arm joint angle is large value when we compares with ΔP. However, because of contraction or attrition between sprocket and chain, these phenomenons are happened. Because weight of arm and piston is bigger than generated force by MR cylinder, arm joint angle don't change to about 0.1A.

Through experiments on the static characteristics, it is found that the differential pressure is controlled by the applied magnetic field intensity under little influence of the flow rate, which corresponds to a pressure control valve. The differential pressure increases linearly with some hystereses when the magnetic field intensity increases. The differential pressure of 0.4MPa is obtained with the input current of 1.5A.

4.2 Dynamic characteristics

To know dynamic characteristics of the MR cylinder, we investigate step response of a manipulator. The experimental results are as shown in Fig. 8, Fig. 9 Fig. 8 shows the step responses of the MR cylinder with fixed arm. Fig. 9 shows the step responses of the joint angle. At first stage, the joint does not rotate due to friction and the differential pressure rises like the MR cylinder in Fig. 8 After starting joint rotation, the differential pressure is once reduced and then increased. The

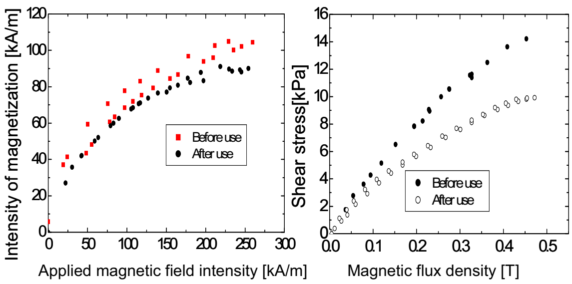

Fig. 7 Characteristic of the MR fluid before and after use

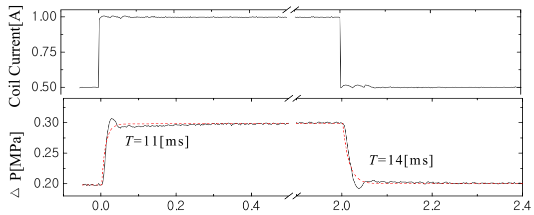

Fig. 8 Step response of MR valve

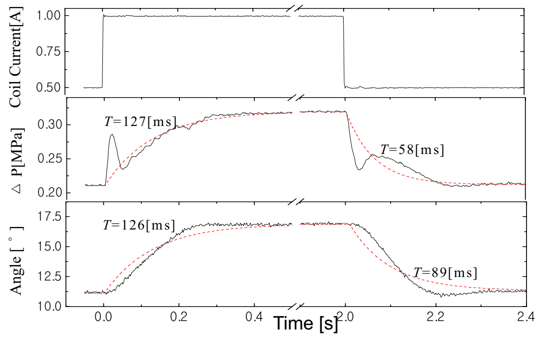

Fig. 9 Step response of a manipulator using the MR cylinder

rotational velocities of the joint are saturated determined by the upstream restriction.

Also, time constant of ΔP approximated by least-squares method. In the figures, although overshoot which did not look is happened, this is just thought because of stationary air of inner pipe.

5. CONCLUSIONS

In this paper, a new MR cylinder which uses low base-viscosity MR fluid is proposed. Through F.E.M. analysis, MR cylinder is fabricated. Its performances and characteristics, also, are clarified and confirmed by experiment. The proposed MR cylinder controls differential pressure by magnetic field which results from gap between piston and cylinder. According to previous research, which compared with MR valve and bellows driven actuator, MR cylinder has the advantage of small size and big stroke.

To generate high pressure difference of MR cylinder, Optical design of piston parts was achieved by FEM analysis. When input pressure of 1MPa is given and input current is 1.5A, we will design MR cylinder to make piston differential pressure of 0.4MPa and to generated force of 1.1MPa. And the rising time is 126ms in step response of a manipulator using the MR cylinder. In this paper, effectiveness of the MR cylinder is demonstrated through the position control of one link MR manipulator.

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