Research on Driving System of Hydraulic Robot Based on Ferrofluid

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Abstract. In the driving system of hydraulic robot, the mechanical components are large and complex due to some factors such as material performance and structural design. Based on the magnetorheological properties of ferrofluid, a novel hydraulic driver method is presented based on the principle of jet pipe servo valve. Adding a magnetic field in the air field of the valve body directly controls the deflection and offset of the ferrofluid, and realizes the directly control from the electric/magnetic to fluid. The mathematical model of ferrofluid flows in the air field under magnetic field is established based on the ferrohydrodynamics (FHD). The experimental results show that the millimeter-level deflection has met the actual engineering needs of the hydraulic driving system.

1. Introduction
Ferrofluid, is a stable colloidal suspension, which has the fluidity of liquid and the magnetism of solid magnetic materials. It has been widely used in mechanical seals[1], hyperthermia[2], aero-propellers[3], magnetic targeting drug delivery[4,5], dampers, acoustic-optic wave transmitters[6]. It can also be used to the temperature sensor by using the properties of its magnetization varying with temperature[7].

Hydraulic drive system is an important part of robot. The electro-hydraulic servo driving system consisting of electrical signal processing unit and hydraulic output unit that has the characteristics of high control accuracy, high output power, compact structure and high power-mass ratio. However, hydraulic components also have some shortcomings, such as strict tolerance requirements, high manufacturing cost, large volume.

In recent years, the micro-fluidic control technology based on Magneto Hydro Dynamics (MHD)[8] is one of the most advanced technology fields. How to avoid the mechanical structure and achieve the control effect of fluid directly through electromagnetic field is the focus of the research. LENORODRIGUEZ et al[9] developed a flexible bionic robot based on ferrofluid, which imitates the worm movement of amoebas. The magnetic material is driven by magnetic field to act; ABDUL et al[10] summarized the structure and mathematical model of several magnetorheological valves. The valve body is relatively fixed, using magnetorheological properties of ferrofluid to control the pressure difference between the inlet and outlet of the valve by controlling the magnitude of the exciting current, which is simpler and more stable, but the design has not got rid of the constraints of the traditional mechanical components; SALLOOM[11,12] put forward a new type of magnetorheological proportional directional valve, simulation and experimental results show that the design can replace the traditional hydraulic valve to control actuator; LIU Han-dan[13] established the momentum equation of ferrofluid in blood vessel under the action of magnetic field, and obtained the approximate
solution of water-based magnetohydrodynamic model in blood vessel by perturbation method, including the micro-ferrofluid in fixed track or pipeline[14-16].

Combining ferrofluid and hydraulic mechanical valve, a new driving method is proposed based on the hydraulic driving system. The magnetic function of the hydraulic fluid is realized through the modification of the hydraulic fluid, and the flow direction of the hydraulic fluid is changed directly by the electromagnetic field.

2. Dynamic Control Mechanism of Ferrofluid

Ferrofluid, as a special functional fluid, is subjected to magnetic force after magnetization under the magnetic field. There is no remanence and hysteresis after demagnetization. The magnetization characteristic curve of # L-25 oil-based Fe₃O₄ ferrofluid is used in the experiment and simulation as shown in Fig.1.

![Fe₃O₄ Oil-based Magnetization Characteristic Curve](image)

The magnetic stress $Q$ is introduced to describe the effect of magnetic field on ferrofluid [17]. $Q$ is defined as:

$$Q = \int_{B_0}^{H} \mu_0 (\phi \rho M) dH + \frac{1}{2} \mu_0 H^2 \cdot \mathbf{i} + B \otimes H$$  

(1)

Where $\mu_0$ is the vacuum permeability; $\phi = \rho^{-1}$ is the specific volume of ferrofluid; $H$ and $M$ represent the magnetic field intensity and magnetization intensity respectively; $B$ is the magnetic induction intensity; $\mathbf{i}$ is the unit tensor.

In the linear magnetization stage of ferrofluid, it is considered that the magnetization curve of this part is approximately a straight line, and the permeability $\mu$ is independent with the magnetic field strength $H$. The magnetic force density of the remaining part of ferrofluid except the gas-liquid contact surface is [18]:

$$f_m = \nabla \cdot Q = \nabla \left[ \frac{H^2}{2} \rho \left( \frac{\partial M}{\partial \rho} \right)_T \right] - \frac{H^2}{2} \nabla \mu$$  

(2)

$$\mu = \mu_0 (1 + \chi)$$  

(3)

Where $\rho$ is the density of ferrofluid, $T$ is the temperature, and $\chi$ is the susceptibility. In this stage, the magnetic force on the ferrofluid is approximately square with the intensity of the applied magnetic field. At this time, the ferrofluid has a faster response speed.

In the saturated magnetization stage of ferrofluid, it is considered that the average magnetic moment $m_a$ of magnetic particles is a certain value and is independent of the specific volume of magnetic particles $\phi$. At this time, the magnetic force density can be reduced to[18]:
\[ f_m = \mu_0 (M \cdot \nabla) H \quad (4) \]

Where \( M \) is the magnetization. In the stage of saturation magnetization, \( M \) is considered to be a constant value. Formula (4) shows that the magnetic density at this time is linearly related to the external magnetic field intensity. Under different magnetic field intensities, the velocity and magnetic force of ferrofluid will have different responses. The magnetic field influences the flow of ferrofluid by magnetic force.

The structure of the jet tube hydraulic valve is mainly composed of coil, armature, jet tube, nozzle, valve core, as shown in Fig. 2. The jet tube is fixed with armature and coil, and the fluid is ejected from the nozzle of the jet tube into two receiving holes connected with both ends of the valve core. When a control signal is input to the coil, the armature is acted by force and moment, and deflects with the jet tube and nozzle. The deflection angle is proportional to the magnitude of the moment. The hydraulic fluid ejected from the nozzle also deflects, which increases the pressure of one of the receiving holes and decreases the pressure of the other. The pressure difference between the two ends of the valve core causes the valve core to be driven, and the displacement generated is proportional to the size of the input control signal.

![Figure 2. Structure of Jet Pipe Servo System](image)

On the basis of traditional mechanical valves, the flow direction of high-pressure liquid flow is directly controlled by electromagnet to replace the mechanical valve core components, and the system pressure is reversed. The one-dimensional control principle is shown in Fig. 3.
Figure 3. The one-dimensional control principle

Ferrofluid is directly injected into the valve body after being pressurized by a hydraulic pump, and the magnetic field is added in the direction perpendicular to the direction of liquid flow injection. By changing the magnetic field intensity, the displacement of magnetic fluid at different angles and distances is controlled. When the magnetic field intensity is zero, the fluid returns to the original injection direction without any hysteresis.

3. Coupled flow model of magnetic field and flow field

The magnetic solid particles in ferrofluids are nano-scale, which can be regarded as macromolecules. The velocity and temperature lag between the magnetic particles and the carrier fluid are neglected. The ferrofluids are analyzed as homogeneous phase fluids, assuming that the two phases are always in equilibrium[19].

FHD model is used to solve hydrodynamic problems driven by magnetization. Based on Navier-Stokes equation of FHD model, the momentum equation of incompressible fluid is obtained as follows:

\[ \frac{D(\rho u)}{Dt} = f_s + f_b \]  \hspace{1cm} (5)

\[ \nabla \cdot u = 0 \]  \hspace{1cm} (6)

Where \( u \) is the velocity of the fluid; \( f_s \) and \( f_b \) are surface tension and volume force. After expansion, the following can be obtained:

\[ \rho \left( \frac{\partial u}{\partial t} + u \cdot \nabla u \right) = \varepsilon \frac{\rho \kappa \nabla \alpha}{\frac{1}{2}(\rho_s + \rho_f)} + \rho g - \nabla p + \eta \nabla^2 u + \frac{\mu_s \chi}{2} \nabla H \]  \hspace{1cm} (7)

Where \( \eta=const \) is hydrodynamic viscosity, \( \nabla p \) is pressure gradient, \( g \) is gravitational acceleration, and the first term on the right side of equation \( \varepsilon \frac{\rho \kappa \nabla \alpha}{\frac{1}{2}(\rho_s + \rho_f)} \) is surface tension of ferrofluid.

Interface tracking between two phases is accomplished by its volume ratio equation. For one of the phases, there are:

\[ \frac{\partial \alpha}{\partial t} + u \cdot \nabla \alpha = \frac{S_{\alpha_s}}{\rho} \]  \hspace{1cm} (8)
Where $a_q$ is the volume ratio of the q phase, and $\sum_{q=1}^{n} a_q = 1$, $S_q$ is the volume ratio of this phase.

The source phase of the phase, according to formula (7), contains custom magnetic, gravitational and viscous forces.

The interface between ferrofluid and air is the electrical insulation boundary, so the induced current density is 0. The magnetic induction equation of the model is [11]:

$$\frac{\partial B'}{\partial t} + (\mathbf{u} \cdot \nabla) B' = \frac{1}{\mu \sigma} \nabla^2 B' + (B \cdot \nabla) \mathbf{u}$$

(9)

Where the magnetic field $B'$ represents the sum of the external magnetic field $B$ and the induced magnetic field $b$; $\sigma$ is the conductivity of ferrofluid. Combining the governing equation with the magnetic induction equation, the source phase in the momentum equation is defined by the transport equation provided by the finite volume method. The numerical solutions of the ferrofluid model under different magnetic field intensities are obtained.

4. Numerical simulation and results analysis

4.1. Eulerian Model and UDF Development

In order to simulate the flow of ferrofluid in the valve body, the simplified model as shown in Fig. 4 takes the inlet diameter of ferrofluid as 1 mm, the diameter of valve body as 150 mm, and the height as 150 mm. The center of the fluid inlet is the coordinate origin, the velocity direction is $Z$ direction, and the magnetic force direction is $y$ direction.

![Figure 4. Eulerian model and meshing graph](image)

An Eulerian two-phase flow model consisting of liquid phase and air phase of ferrofluid is established. The Eulerian model is the most complex multi-phase flow model in Fluent. By introducing additional control equations, each phase in the multi-phase flow is solved, and its pressure and exchange coefficient are shared by each phase.

The liquid-liquid governing equation provided by Fluent finite volume algorithm for Eulerian model is [20]:

$$\frac{\partial (\rho_q u_q)}{\partial t} = -\nabla p + m_{pq} u_q + \rho_q F_q + \rho_q g$$

(10)

Where $\rho_q$ is the density of $q$ phase, $u_q$ is the velocity of $q$ phase, $m_{pq}$ is the mass transfer between $p$ phase and $q$ phase, and $F_q$ is the external volume force.

In the process of solving, there is no pressure and velocity input in the air phase, so mass transfer between the fluid phase and the gas phase is neglected. According to the momentum conservation equation (7), $F_q$ includes viscous force and magnetic force. Eulerian model can specify the momentum
source phase for a single phase, so the magnetic force and gravity of the fluid phase are UDF(User-defined functions) written in C to describe independently.

The density of oil-based Fe₃O₄ ferrofluid is 1050 kg/m³, the viscosity coefficient is 0.035 kg/(m.s) without magnetic field, the injection velocity of magnetic fluid is $V_z = 7$ m/s, the direction of adding magnetic force is y-positive, and the gravity is z-positive. The momentum equation was solved by Phase Coupled SIMPLE algorithm. 8 groups of magnetic field intensity from 0 to 0.3 T were selected to analyze the liquid phase distribution and dispersion of ferrofluid under magnetic field.

4.2. Analysis of simulation results

Fig.5 and Fig.6 are the nephogram and velocity vector graph of liquid-liquid flow. The liquid column of ferrofluid deflects along the Y direction under the action of magnetic force. When the magnetic field is weak ($B = 0.06$T), the displacement of the liquid column is small, because the weak magnetic field is not enough to overcome the high-pressure fluid force. With the increase of magnetic field and discharge distance, the velocity of liquid Y direction of ferrofluid increases, and the deviation becomes obvious gradually.

![Nephogram for different magnetic field intensities](image)

Figure 5. Liquid phase nephogram under different magnetic field intensities

The trajectory is established from the liquid entrance of the model, the Y coordinates of some trajectories as shown in the Fig.6.

![Trajectory points](image)

Figure 6. Liquid trajectory of trajectory points

Because of magnetic force, the displacement of liquid phase of ferrofluid gradually increases with the increase of time (the outflow distance). The displacement of ferrofluid column under different magnetic field intensities and different flow velocities is shown in Fig.7. Considering the divergence degree of fluid injection and the loss of fluid pressure, the extraction distance of liquid column is 30 mm. When the outflow distance is 30 mm, the displacement of ferrofluid column along Y direction at 0.08 T is 1.3 mm, which meets the scale requirement of hydraulic micro-drive in industrial applications.
Figure 7. The offset of ferrofluid column in Y direction

With the increase of magnetic field intensity (0-0.3 T), the displacement of ferrofluid increases gradually. When the magnetic field intensity is greater than 0.25 T, the ferrofluid reaches saturation state, and the increment of the displacement decreases. When the velocity of flow is determined, the offset increases with the increase of magnetic field. With the increase of jet velocity, the displacement of ferrofluid along the direction of magnetic force decreases gradually, but the variation law of the curve is basically unchanged.

The experimental results are consistent with the deviation calculated by numerical calculation. The model simulates the flow of high-pressure ferrofluid in the valve body under the action of magnetic field. The experimental device is shown in Fig.8.

Figure 8. Experimental of hydraulic driving system

5. Conclusion
On the basis of the hydraulic drive system, a micro-drive control scheme based on ferrofluid is proposed. The mathematical model and Eulerian model of ferrofluid injection in air are established. The response of ferrofluid in the magnetic field is reflected by the velocity and offset of liquid phase along the magnetic field direction in the model. The simulation and experiment verify that:

- External magnetic field intensity and fluid susceptibility are two main factors affecting the flow of magnetic fluid.
By adjusting the magnetic field, the displacement of high-pressure ferrofluid flow can be effectively controlled, and the direction of pressure output can be effectively controlled by controlling the position of the falling point of ferrofluid jet.

This scheme provides a new technical idea for intelligent driving control of robots, and has a certain reference value for liquid divertor and liquid cladding design of fusion reactor in Tokamak. It is expected to be applied in practical engineering.

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