Experimental Study of Magnetic Viscous Properties of Magnetic Fluids Affect on Its Sensing Performance

Hairong Cui
Department of Mechanical Engineering, Ningbo University of Technology, Cuibai Road 89#, Ningbo, Zhejiang, China.
Email: hairongcui@sina.com

Abstract. In this paper, the relationship between the magneto-viscous properties of magnetic fluids and the sensitivity of inductive horizontal sensors based on magnetic fluids is studied experimentally. The experimental model of magnetic fluid horizontal sensor is established. The magnetic viscous properties of kerosene-based magnetic fluids were prepared and analyzed. The experimental results show that the magnetic fluid with saturation magnetization between 310 Gs and 425 Gs is suitable for the magnetic fluid horizontal sensor. The sensitivity of the sensor is proportional to the magnetization coefficient of the magnetic fluid. On the premise that the magnetic fluid has good fluidity, the sensitivity of the sensor can be increased by increasing the magnetization coefficient of the magnetic fluid.

1. Introduction
The theoretical and experimental research of magnetic fluid horizontal sensor is based on the dual characteristics of magnetic fluid which has both magnetization and fluid properties[1-3]. Magnetic fluid can be used to sense the change of horizontal dip angle for a horizontal sensor. It is required that magnetic fluids have good fluidity and appropriate saturation magnetization[4-7].

The magnetic fluid based horizontal sensor requires that the viscosity of the magnetic fluid should not be too high, because the liquid fluidity is poor and the sensitivity of the sensor decreases when it is too high. And that the viscosity of the magnetic fluid should not be too low, which means that the magnetic particles in the magnetic fluid are relatively small, that is, the magnetization of the magnetic fluid decreases. If the magnetization of magnetic fluids is too low, the sensing signal will become weak or even unable to detect the change of the signal. If the magnetization is too high, the magnetic fluids will be unstable to the external magnetic field, which cannot meet the requirements of experiment and application[8,9].

Therefore, it is of practical significance to study the influence of magnetic viscous properties of magnetic fluids on the output characteristics of magnetic fluids horizontal sensors. At present, it is lack of quantitative study on the effect of magnetic viscous properties of magnetic fluid on the output characteristics of magnetic fluid horizontal sensors[10-13]. In this paper, the effect of the magnetic viscous properties of kerosene-based magnetic fluids on the sensitivity of magnetic fluid horizontal sensors is studied quantitatively by experiments.

2. Experimental Detail
2.1. Experimental Model
The structure and schematic diagram of the magnetic fluid horizontal sensor is shown in figure 1. It consists of a cylindrical container filled with a certain volume of magnetic fluid and three groups of
coils evenly distributed on it. The winding method, turn number and length of the three coils are the same. S1 and S2 are symmetrically distributed on both sides of S0. Connect the external circuit according to the graphic method: S0 external voltage source as the excitation coil to provide the excitation voltage \( V_{in} \); S1 and S2 are inversely connected in series to connect the output circuit as the induction coil to provide the output induction potential difference \( V_o \). When the measured attitude remains horizontal, the magnetic liquid level sealed in a cylindrical PMMA tube is at zero output potential difference \( V_o \) without any displacement change. When the measured attitude is slightly inclined relative to the horizontal position, the magnetic fluid flows to the lower part of the container with the inclination of the container, resulting in changes in the volume of the magnetic fluid in the induction coils S1 and S2. For the magnetism of the magnetic fluid, the change of displacement is equivalent to the movement of the core in the induction coil cutting the magnetic force line, and then the induced potential changes. The change of the induced potential difference corresponds to the change of the horizontal inclination angle of the attitude to be measured. Therefore, the horizontal inclination angle of the attitude \( \theta \) to be measured can be obtained by measuring the induced potential difference \( V_o \).

**Figure 1.** Schematic diagram of the inductive magnetic fluid horizontal sensor

2.2. Kerosene-based Magnetic Fluids

In case the viscosity of kerosene-based magnetic fluids is low, the magnetic fluids have good fluidity while maintaining high magnetization. Meanwhile kerosene is cheap and easy to obtain, which reduce the production cost. Therefore, kerosene-based magnetic fluids are selected for magnetic fluid horizontal sensors to study the influence of magnetic viscous characteristics on the output characteristics of sensors.

Uniform nano-Fe\(_3\)O\(_4\) powders are prepared by chemical coprecipitation method. Fe\(_3\)O\(_4\) powders are prepared with uniform particle size and diameter of about 10 nm. When the concentration of reactants FeCl\(_3\) and FeCl\(_2\) is 0.6 mol/L, the Fe\(_3\)O\(_4\) particles are more uniform and fine. When the time of adding surfactant is not less than 6 hours, the surface active agent is completely coated, which can effectively prevent the agglomeration and oxidation of Fe\(_3\)O\(_4\) particles[9].

Kerosene-based magnetic fluids were prepared by using Fe\(_3\)O\(_4\) magnetic particles, oleic acid as surfactant and kerosene as base carrier. The advantage of this process is that it is advantageous to the chemical equilibrium towards the formation of Fe\(_3\)O\(_4\) particles. It can increase the content of Fe\(_3\)O\(_4\) and increase the magnetic susceptibility.

Because the larger the density of the magnetic fluid is, the larger the volume fraction of solid magnetic particles in the liquid is, and the viscosity of the magnetic fluid mainly depends on the volume fraction and particle size of the magnetic particles, so the viscosity of the magnetic fluid will increase with the increase of the density of the magnetic fluid. Figure 2 shows the viscosity of kerosene-based magnetic fluids increases with the increase of the density of magnetic fluids.
Viscosity (mPa · s) 

Density × 10³ (kg·m⁻³)

**Figure 2.** Relationship between density and viscosity of kerosene based magnetic fluid

The viscosity of magnetic fluids mainly depends on the volume fraction and sizes of magnetic particles, and the magnetization of magnetic fluids depends on the properties and content of magnetic particles contained in the liquid. Therefore, on the premise of ensuring the stability of magnetic fluids, the volume fraction of magnetic particles, i.e. the increase of the content of magnetic particles, will not only increase the magnetic fluids. The saturation magnetization of magnetic fluids increases with the increase of viscosity as shown as figure 3.

**Figure 3.** Relationship between viscosity and magnetisation of kerosene based magnetic fluid

2.3. Test Parameters and Measuring Circuit

The kerosene-based magnetic fluids with saturation magnetization of 312.25Gs, 370.09Gs and 424.08Gs are selected. The experimental vessels with three different structural parameters, i.e. outer diameter/inner diameter of 20/16, 25/20 and 30/25, are combined to conduct experiments. Under the conditions of different input signal parameters and different structure parameters, the effects of different combination of experimental parameters on the sensitivity of magnetic fluid horizontal sensor are investigated.

According to the horizontal sensor model shown in figure 1, the experiment was carried out. In this experiment, the output potential difference signal was measured by three-stage amplifier circuit, and the zero-setting circuit was set up to adjust the zero position. As shown in figure 4.
3. Results and Analysis

3.1. The Influence of Magnetisation

From figure 5, it can be observed that under the same structural parameters, when the saturation magnetization of the magnetic fluid is high, the sensitivity of the corresponding magnetic fluid horizontal sensor model is high; under the same performance of the magnetic fluid, the sensitivity of the magnetic fluid horizontal sensor model with larger structural parameters is high.

![Figure 4. Measuring circuit](image)

![Figure 5. When V\text{in}=5V, f\text{in}=1.5kHz, magnetisation versus sensitivity under different structure parameters.](image)

3.2. The Influence of Relative Susceptibility

Because the magnetization coefficient of the magnetic fluid directly reflects the magnitude of the magnetization intensity of the magnetic fluid, increasing the magnetization coefficient of the magnetic fluid appropriately means increasing the magnetization intensity of the magnetic fluid, which can effectively improve the sensitivity of the sensor accordingly[7]. However, for a certain volume of magnetic fluids, the increase of the magnetization coefficient of magnetic fluids will lead to the increase of the viscosity of magnetic fluids, and the high viscosity will be detrimental to the flow of magnetic fluids, which will lead to the decrease of sensor sensitivity. Therefore, the magnetization coefficient of magnetic fluids should not be too high. The magnetization of kerosene-based magnetic fluids is proportional to the density, so we obtained magnetic fluids with different magnetization coefficients by diluting the magnetic fluids used in the experiment. The ratio of magnetization coefficient of diluted and pre-diluted magnetic fluids is set. Figure 6 shows the relationship between sensitivity and relative magnetization coefficient of magnetic fluids when the excitation voltage V\text{in} = 2V.
Figure 6 shows that the sensitivity is linearly related to the magnetization coefficient of the magnetic fluid. Therefore, on the premise of ensuring good fluidity of magnetic fluid, increasing the magnetization coefficient of magnetic fluid can correspondingly increase the sensitivity of the sensor.

4. Conclusions
Through the experimental study and analysis of the influence of the magnetic viscous properties of the magnetic fluid on the sensitivity of the magnetic fluid based horizontal sensor, the following conclusions are obtained.

(1) The magnetic fluid with saturation magnetization ranging from 310 Gs to 425 Gs is suitable for the prototype experiment of magnetic fluid horizontal sensor.

(2) The sensitivity of the sensor prototype is proportional to the magnetization coefficient of the magnetic fluid. On the premise that the magnetic fluid has good fluidity, the sensitivity of the sensor can be increased by increasing the magnetization coefficient of the magnetic fluid.

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6. References
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