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Research on the linearity of a magnetic fluid micro-pressure sensor

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ABSTRACT

A new type of micro-pressure sensor using a magnetic fluid drop with permanent magnets fixed at ends of an iron core as a sensitive element is investigated in this paper. Movement of the sensitive element inside the body with the variation of external pressure will lead to a corresponding inductance difference. The sensor supplies a signal which is proportional to the displacement of sensitive element. The determination of the working range, linearity and sensitivity depends on the tilt angle and the magnetic repulsion force. An experiment is performed to analyze the influence of different tilt angle on the linearity and sensitivity. Some characteristics of the sensor are presented.

1. Introduction

Demonstrated applications of micro-pressure sensors span a very wide range. Actual areas presently include industrial production, medical diagnosis, bioengineering, cultural relic protection and the like [1,2]. However, most of these sensors with the resistive, the photoelectric or the capacitance, have a great linearity and small size in need of the complete structure, high-cost and the difficult replacement [3–5]. So the research and application of new functional materials will be the main development direction.

Magnetic fluids, as a new functional material, are already widely used in engineering due to their outstanding magnetic and rheological properties [6,7]. One of the interesting applications was their use in sensing techniques for aerodynamic measurements, micro-pressure, inclination or acceleration [8–11]. In general, these sensing and measuring devices with magnetic fluid are based mainly on the unusual buoyancy relationships, or the relatively high permeability, such as the self-levitation of an immersed magnet [12–14] and the inductive measurement of a magnetic fluid core [15]. Up to now, the majority of the magnetic fluid pressure sensors or flowmeters work on the latter principle. A most widely used form makes use of a "U" tube which has its vertical arms half-filled with a magnetic fluid, and then the micro-pressure difference will lead to a level gap and to a corresponding inductance difference [16,17]. The type of sensor has a great linearity, however, a low sensitivity and large size will be inevitable. Another new capacitive sensor exploits the magneto-electric physical properties of magnetic fluid to convert the pressure into the measurable capacitance [18]. Its advantages and disadvantages are similar to the general capacitive sensors, however, the concentration of the magnetic particles in suspension and the temperature have some effects on the linearity, which will lead to some problems in actual usage.

In this paper, we solve these problems using two permanent magnets fixed at the ends of an iron core. The magnetic fluids strongly adhere at the magnets, thus ensuring a light mobility and excellent seal capability. Such a strategic "seal ring" of magnetic fluid makes the device possible. The iron core is made of the ordinary stainless steel (ISO 4 or ASTM 420) with a much higher permeability than magnetic fluid, so the sensor has a higher sensitivity than the "U" tube under the same conditions of size, coil and current. The design, analysis and experimental results of the sensor will be discussed in the following sections.

2. Design

The magnetic fluid micro-pressure sensor is presented in Fig. 1. It includes a cylindrical body made of glass, a sensitive element and an annular magnet. The sensitive element consists of an iron core and two cylindrical permanent magnets fixed at the ends of the iron core. The magnetic repulsion force determined by the annular magnet and sensitive element maintains the position of sensitive element in the body. Changing the forces strength (the magnetic field strength) allows modifying the working range, linearity and sensitivity of the sensor. A "seal ring" of magnetic fluid

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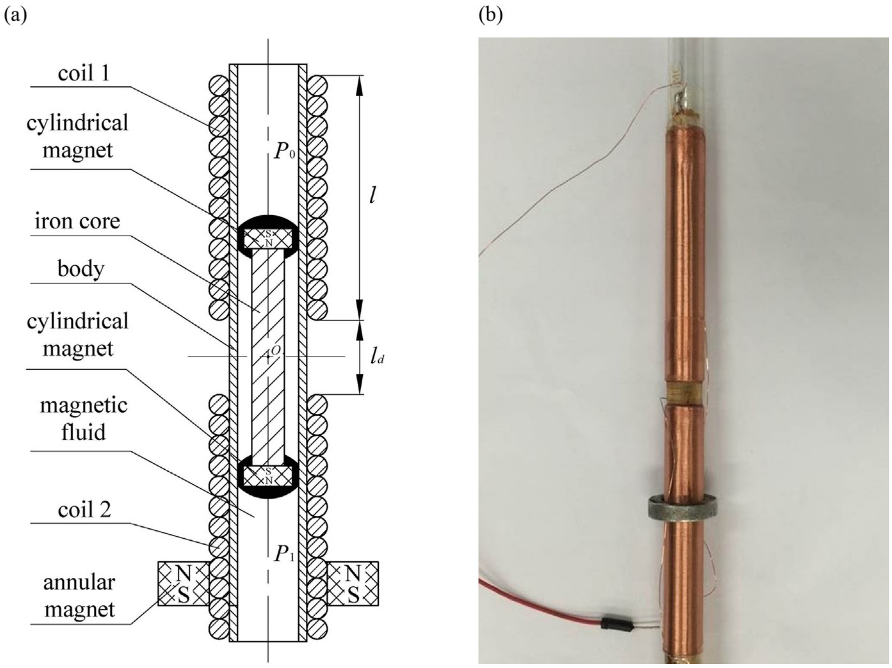

Fig. 1. (a) Scheme of the magnetic fluid micro-pressure sensor and (b) the real device.

coats the cylindrical permanent magnets. The action of the "seal ring" is twofold, i.e., it can provide the sensitive element with a light mobility due to liquid fluidity and it can keep a stable pressure difference on both sides of sensitive element. The pressure difference can exceed 2 kPa based on the equation in [19]

$$\Delta P \approx \mu_0 \int M_s dH \tag{1}$$

where the μ_0 is the permeability of the vacuum, M_s is the saturation magnetization of the magnetic fluid.

When the sensitive element moves from the initial position under the influence of external pressure, the volume distribution of iron core gradually changes in two coils, and an electronic measuring system will detect the inductive difference. The output signals depend the physical characteristic of the iron core, magnets, body and their geometry. These factors define the working range, sensitivity and linearity of the sensor. So the material selection of the iron core should not affect the linearity of the sensor, at the same time, should have a high permeability, low cost, excellent corrosion resistance and good mechanical property. The stainless steel (ISO 4 or ASTM 420) with a maximum permeability 184 will be a good choice.

In preliminary tests of an experimental model, we used the simple transformer bridge type. The sensor with two coils forms an assembly of differential transformer type. For a small displacement of the iron core, ignoring the loss resistance variation, the bridge unbalance voltage U is proportional to the inductance difference, which may be written in the form

$$U = \frac{U_0}{2} \frac{(\omega L)^2}{R^2 + (\omega L)^2} \frac{\Delta L}{L} \tag{2}$$

where U_0 is the external voltage, ω is the power source angular frequency, R is the resistance, $L = L_1 + L_2$ is the total inductance and $\Delta L = L_1 - L_2$ is the inductance difference of two coils.

3. Analysis

The magnetic circuit is not closed, which has a high magnetic flux leakage, so the inductance difference can be calculated by introducing a magnetic leakage coefficient k_0. Fig. 2 illustrates the calculation model of the inductance difference.

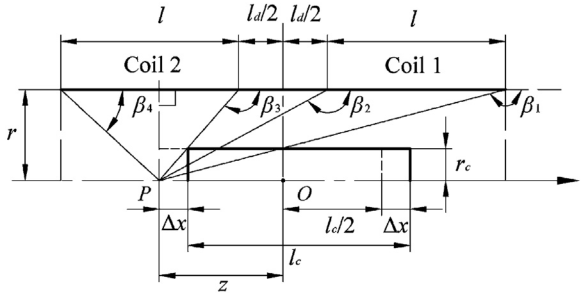

Fig. 2. The diagram of calculation model of the inductance difference.

It is assumed that the magnetic field is uniform in the coil, to a good approximation inductance L_1 and L_2 of the two coils may be written, respectively

$$L_1 = \frac{N^2}{2l^2}\mu_0 \pi r^2 \int_{l_d/2}^{l+l_d/2} (\cos\beta_2 - \cos\beta_1) dz + \frac{N^2}{2l^2}\mu_0 \pi r_c^2 \times \int_{l_d/2}^{l_c/2+\Delta x} (k_0\mu_r - 1)\left(\cos\beta_2 - \cos\beta_1\right) dz \tag{3}$$

$$L_2 = \frac{N^2}{2l^2}\mu_0 \pi r^2 \int_{-l-l_d/2}^{-l_d/2} \left(\cos\beta_4 - \cos\beta_3\right) dz + \frac{N^2}{2l^2}\mu_0 \pi r_c^2 \times \int_{-l_c/2+\Delta x}^{-l_d/2} (k_0\mu_r - 1)(\cos\beta_4 - \cos\beta_3) dz \tag{4}$$

where l is the length of each coil, l_d is the distance between two coils, N is the number of turns of each coil, l_c is the length of iron core, r_c is the radius of the iron core, μ_r is the relative permeability