Short Research Article

Research on Theory and simulation of magnetic liquid micro differential pressure sensor

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ABSTRACT

With magnetic liquid micro differential pressure sensor as the research object, using the finite element analysis software COMSOL, magnetic liquid micro differential pressure sensor are analyzed and calculated by first hall element in the location of the magnetic field change curve, and then analyzed the magnetic liquid micro differential pressure sensor restoring force curve, analyzes the three different change trend of the spacing between the initial magnetic field force, And the change equation of magnetic force is fitted. Finally, the pressure resistance of the magnetic liquid micro-differential pressure sensor is calculated to ensure the integrity of the magnetic liquid sealing ring in the range of measurement, so that it has good sealing performance. The results show that when the distance between two cylindrical permanent magnets L=10mm, the magnetic flux density B at the central axis changes approximately linearly with the distance. The recovery force curve of permanent magnet has good linearity in the spacing range of 24mm ~ 40mm. The sensor has a four-stage magnetic liquid sealing ring, the overall pressure resistance value is four times the unilateral pressure resistance capacity, the theoretical pressure resistance value of magnetic liquid is 5000Pa.

Keywords: magnetic liquid; Micro differential pressure; The sensor; Finite element analysis.

1. INTRODUCTION

Magnetic liquid is a new kind of material with special function. It is the only kind of liquid magnetic material that can exist at room temperature. [1] Magnetic liquids can exist stably in various external environments without precipitation and separation. Its unique properties include buoyancy properties (magnetic liquid can levitate objects with a density greater than its own), superparamagnetism (no remanence and coercivity after removing the magnetic field), magnetic liquid has a wide range of industrial applications, such as sealing, dampers, sensors, lubrication, biomedicine. [2]

One of the applications of magnetic liquids is sensors. Sensors can sense the changes of various information in industrial production and convert and transmit the measured information. [3] Microdifferential pressure sensors can measure small changes in pressure. It is generally considered that the range of micro pressure is within ±60KPa, [4] the low pressure range is within ±6MPa, the medium pressure range is within ±60MPa, and the high pressure range is above 100MPa. Compared with other ranges of pressure, the measurement of micro pressure has higher requirements for linearity, accuracy and other characteristics.

The pressure range measured by the micro differential pressure sensor is ±60kPa, which requires the accuracy and anti-interference ability of the sensor. There are various kinds of micro differential pressure sensors, mainly including ultrasonic,capacitive, piezoresistive, resonant, optical fiber and inductive micro differential pressure sensors. [5] capacitive and pressure resistance decay differential pressure sensor is more traditional type of sensor, has been in the oil, chemical industry, metallurgy, electric power, textile, electronics, medicine, food, environmental protection and other fields is widely used, in the process of production can be more precise control of very small non corrosive gas differential pressure, flow rate, air pressure, etc. [6]

In this paper, the structure model of magnetic liquid micro-differential pressure sensor is established, its working principle is discussed, and the formula of maximum pressure resistance of magnetic liquid is analyzed and deduced. COMSOL finite element simulation software is used to analyze the following contents: the magnetic field at the location of Hall element detection, the relationship between the magnetic field force variation and the magnetic field gradient variation at the magnetic liquid ring.

2. STRUCTURE AND WORKING PRINCIPLE OF MAGNETIC LIQUID MICRO DIFFERENTIAL PRESSURE SENSOR

2.1. Structure of Magnetic Liquid Microdifferential Pressure Sensor

The magnetic liquid micro-differential pressure sensor studied in this paper takes the Hall element as the detection element and the permanent magnet adsorbs the magnetic liquid as the displacement element. The whole model can be regarded as a spring model. The cylindrical permanent magnet 1, the cylindrical permanent magnet 2 and the permanent magnet support frame together constitute moving parts. The magnetic poles of the two cylindrical permanent magnets are arranged relative to each other and bonded to the outside of the permanent magnet support frame, and the magnetic liquid is adsorbed to form the magnetic liquid seal ring. [7] The model of the sensor is shown in Figure 1

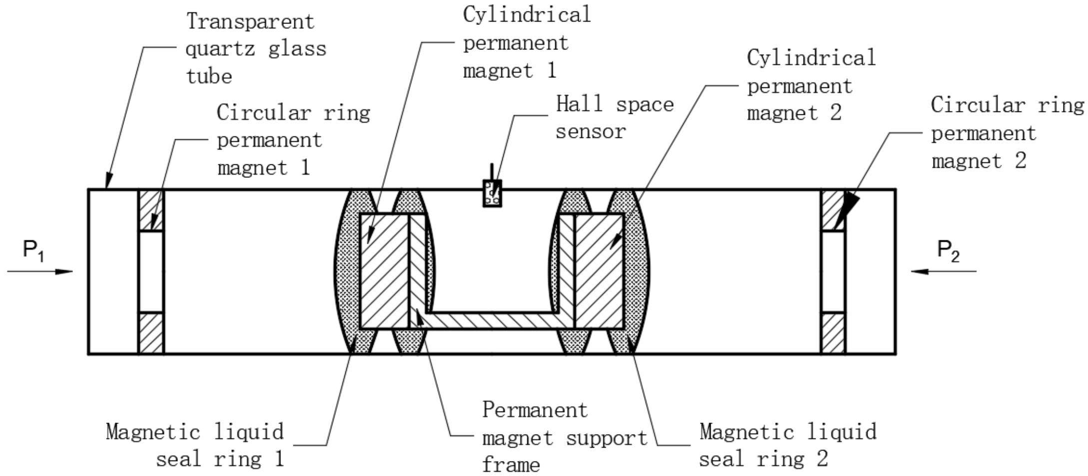


FIG. 1 Structural model of magnetic liquid micro differential pressure sensor

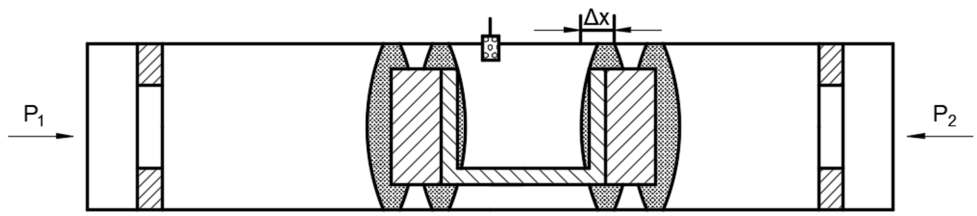


FIG. 2 Working principle of magnetic liquid micro differential pressure sensor

2.2. Working Principle of Magnetic Liquid Micro Differential Pressure Sensor

When a certain amount of magnetic liquid is injected into the glass tube, the moving parts are suspended in the middle of the transparent quartz glass tube. The moving parts will not have rigid friction with the glass tube wall, which improves the sensitivity and accuracy of the sensor system. Circular ring permanent magnets 1 and 2 are fixed at both ends of the glass tube to provide recovery force to moving parts. The Hall element is inserted vertically into a transparent glass tube and changes in the magnetic field in the tube can be detected.

In the initial state, the intermediate permanent magnet remains stationary, at this time the Hall element is located in the middle of the two cylindrical permanent magnets, the distance between the ring permanent magnet and the cylindrical permanent magnet at the left and right ends is equal, the magnetic induction intensity B=0, and the output voltage of the Hall element is 0. When magnetic liquid micro differential pressure sensor on ventilation with different sizes of the pressure P_1 and P_2 (assuming P_1 greater than P_2), This is shown in Figure 2， intermediate moving parts as to the right along the axis direction delta x, cause shell outer space of the magnetic field changes, the hall element of magnetic induction strength increases, the output has a linear relation with the micro differential pressure as the voltage signal of delta ΔU, The output voltage signal increases with the moving distance Δx of the moving part.

2.3. Pressure Analysis of Magnetic Liquids

The magnetic liquid micro-differential pressure sensor can be regarded as a four-stage sealed pressure resistant structure [8,9]. In the figure, points 1, 2, 3 and 4 are points on the surface of magnetic liquid. Points 1 and 4 are on the air side, and points 2 and 3 are on the magnetic liquid side, according to Bernoulli equation of magnetic liquid

$$P^* + \frac{1}{2}\rho v^2 + \rho g h - \mu_0 \bar{M} H = C \quad (1)$$

We can get:

$$P_2^* - P_3^* = \mu_0[(\bar{M}H)_3 - (\bar{M}H)_2] \quad (2)$$

At the interface between the air and the liquid of the magnetic liquid, the normal component M_n of the magnetization is 0, so the boundary condition of the magnetic liquid dynamics is [10] :

$$P_3^* = P_4 \qquad P_2^* = P_1 \quad (3)$$

The pressure expression of a single magnetic liquid sealing ring can be expressed as follows:

$$\Delta P = P_1 - P_4 = \mu_0 \int_{H_3}^{H_2} M dH = \mu_0 M \Delta H \quad (4)$$

The above equation gives the bearing capacity of a single magnetic liquid seal ring in the magnetic liquid micro-differential pressure sensor. The magnetic liquid micro-differential pressure sensor in this paper can be regarded as a four-stage magnetic liquid seal structure, so the maximum measuring range of the micro-differential pressure sensor can be determined theoretically.

3. FINITE ELEMENT SIMULATION ANALYSIS OF MAGNETIC LIQUID MICRO DIFFERENTIAL PRESSURE SENSOR

COMSOL finite element analysis software is used to calculate the magnetic field distribution between cylindrical permanent magnets and the magnetic field force curve between circular and circular permanent magnets and cylindrical permanent magnets.

3.1. Simulation Analysis of Magnetic Field at The Detection Position of Hall Element

The magnetic field change at the detection position of the Hall element affects the output voltage, assuming the formula $\Delta B = K_B \Delta x$ of the magnetic field change, where K_B is the magnetic field coefficient. COMSOL finite element analysis method is used to calculate the change of magnetic induction intensity B at the position of the axis of permanent magnet.

There are two cylindrical permanent magnets with the same material (N35) and the same size (Φ7×3mm), and their axes are located on the same horizontal line. The spacing of the two cylindrical permanent magnets L=10mm is used for static analysis, as shown in FIG. 3. The magnetic flux density B at the central axis of two cylindrical permanent magnets is solved, and the variation of its magnetic flux density B with distance is shown in FIG. 4. Within this range, the value of magnetic flux density B approximately changes linearly.

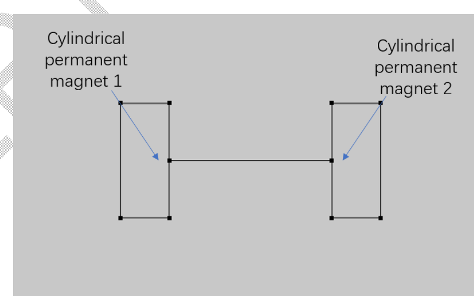


FIG. 3 Magnetic field analysis model

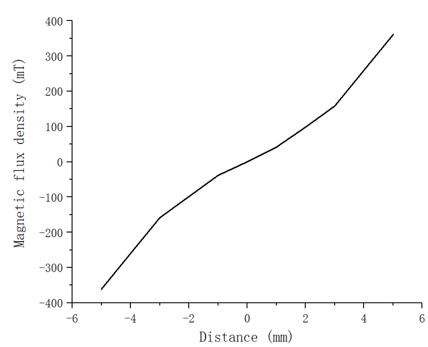


FIG. 4 Change curve of B value of magnetic flux density

In the process of magnetic field analysis, because the function of the circular and annular permanent magnets at both ends is to provide recovery force, they have little influence on the magnetic induction intensity at the detection position, so their influence is not considered in the simulation process. The sensor structure can be regarded as axisymmetric structure. Since the relative permeability of magnetic liquid is very low (μ_r=1.04), which is basically the same as the relative permeability of air (μ_r=1), it can be approximated as air calculation, which has achieved the purpose of simplifying the calculation. Figure 5 of scalar magnetic potential distribution and Figure 6 of magnetic induction intensity distribution are obtained by simulation.

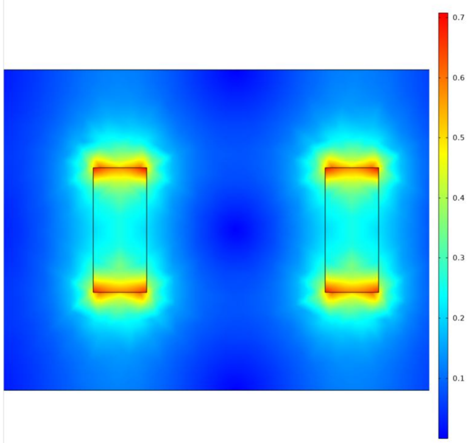


FIG. 5 Magnetic induction intensity distribution

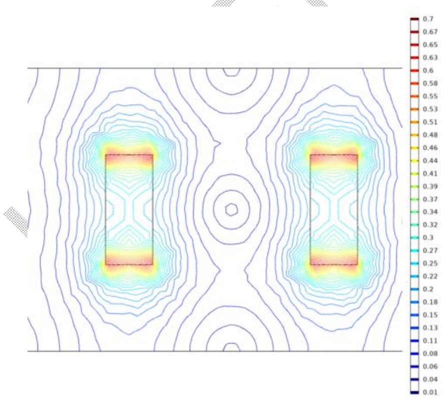


FIG. 6 Contour of magnetic induction intensity distribution

Both cylindrical permanent magnets adopt axial magnetization. The difference is that the direction of magnetization of the left cylindrical permanent magnet is from left to right, while the direction of magnetization of the right cylindrical permanent magnet is from right to left. The magnetic field around the two cylindrical permanent magnets is symmetrically distributed, with the magnetic field gradient and intensity at the pole being the largest and decreasing away from the pole.

3.2. Simulation analysis of recovery force of cylindrical permanent magnet and circular ring permanent magnet

According to the above analysis of the working principle of magnetic liquid micro differential pressure sensor, when the micro differential pressure sensor produces pressure difference on both ends, in the middle of the moving parts in the mobile stabilized after a distance, the pressure is equal to the permanent magnets on the moving parts of restoring force, is equal to the permanent magnets on both ends of the moving parts and sensor on both ends of the annular permanent magnet force difference between the magnetic field. In order to get the changing law of the restoring force on the moving parts, it is necessary to analyze and calculate the magnetic force between the permanent magnets.

A cylindrical permanent magnet and a circular permanent magnet are placed on the same axis with opposite poles, and the material parameters of the two permanent magnets are exactly the same, and the brand is N35. COMSOL software was used to add domain point probes, and parametric scanning was used to obtain the magnetic field forces of two permanent magnets with different spacing. According to the results of parametric scanning, the variation curve of magnetic field forces can be obtained as shown in FIG. 8

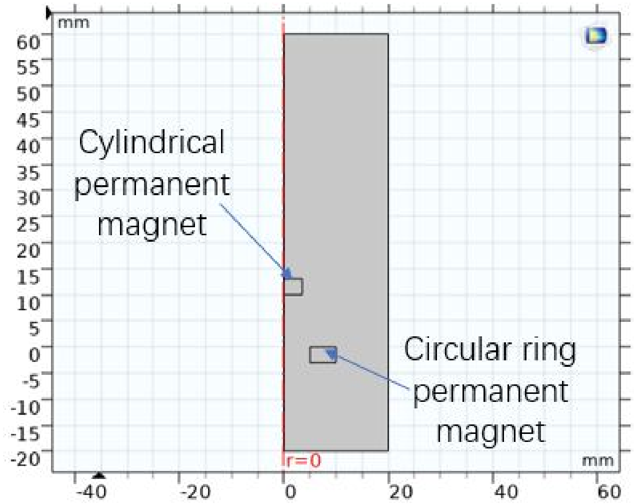


FIG. 7 Magnetic field force analysis model

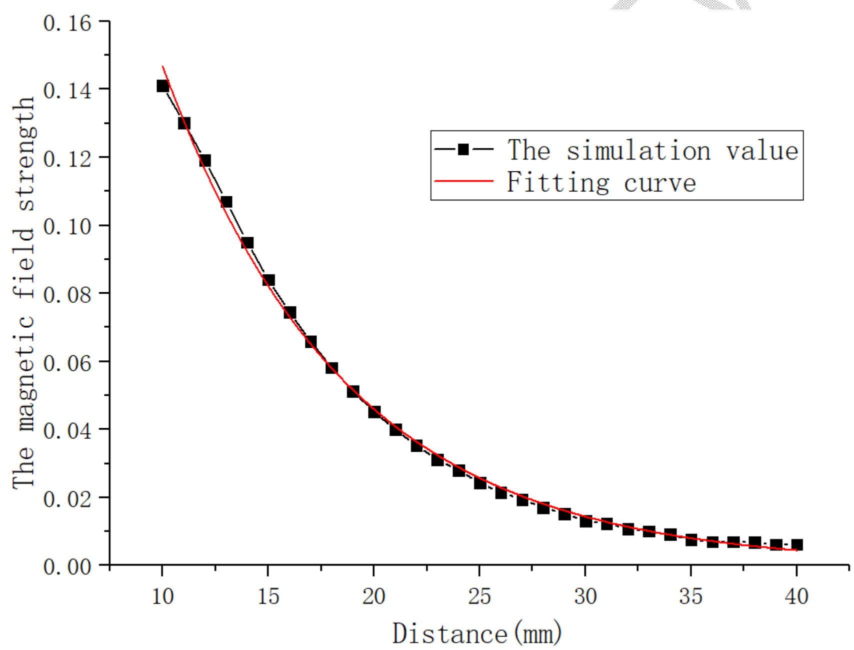


FIG. 8 Variation curve of magnetic field force between permanent magnet

The recovery force curve of the permanent magnet in the above figure has good linearity in the spacing range of 24mm ~ 40mm. The following is to carry out nonlinear fitting of the dot plot in ORIGIN software. Taking $y = ab^x$ as the fitting objective function, the correlation coefficient can be 0.99824. In the measuring range, the magnetic force between the cylindrical permanent magnet and the circular permanent magnet has good linearity. And the parameter values of the fitting curve shown in the table are obtained:

$$y = 0.4685 \times 0.8904^x \quad (5)$$

The recovery force curve of the permanent magnet shown in the figure has good linearity in the displacement range of 24mm-34mm.

Assuming that the initial point of the second-order magnetic liquid micro-differential pressure sensor system is: $y_0 = f(x_0)$, the Taylor series around $y_0 = f(x_0)$ can be written:

$$y = f(x_0) + \left(\frac{df(x)}{dx}\right)_{x=x_0}(x - x_0) + \frac{1}{2!}\left(\frac{d^2f(x)}{dx^2}\right)_{x=x_0}(x - x_0)^2 + \cdots \quad (6)$$

Ignoring high-order small quantities can be written as:

$$y = f(x_0) + \left(\frac{df(x)}{dx}\right)_{x=x_0}(x - x_0) \quad (7)$$

Namely

$$y - y_0 = k(x - x_0) \text{ or } \Delta y = k\Delta x \quad (8)$$

The N pole of the restoring force magnet of the magnetic liquid micro differential pressure sensor is opposite to the N pole of the adjacent magnet in the moving part, as shown in Figure 9. The distance between the two N-extreme surfaces above is set to D_0.

When magnetic liquid micro differential pressure sensor on the left side of the pressure increase, the moving parts in a transparent quartz glass tube to the right, at this time on the left side of the annular permanent magnet between 1 and cylindrical permanent magnet spacing increases, the left side of the magnetic field force F_1 is reduced, and the right side of the circular permanent magnet 2 and the cylindrical permanent magnet spacing decreases, and the magnetic field force F_2 increased. The overall variation of magnetic force is shown in FIG. 10. The intersection point of the variation curves of magnetic force F_1 on the left and F_2 on the right is the initial spacing D_0. At this point, the restoring force given to the moving part by the restoring force magnets at both ends is the same, so the moving part is balanced at this position

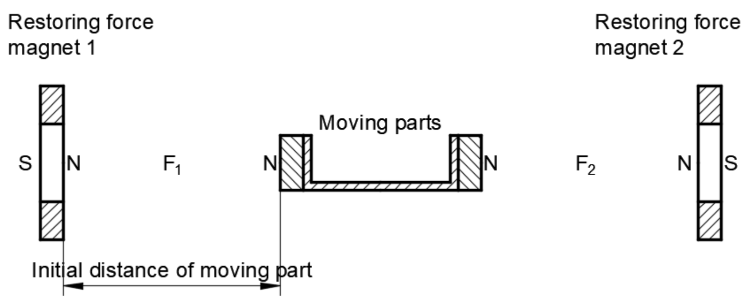


FIG. 9 Magnetic pole relationship between permanent magnets

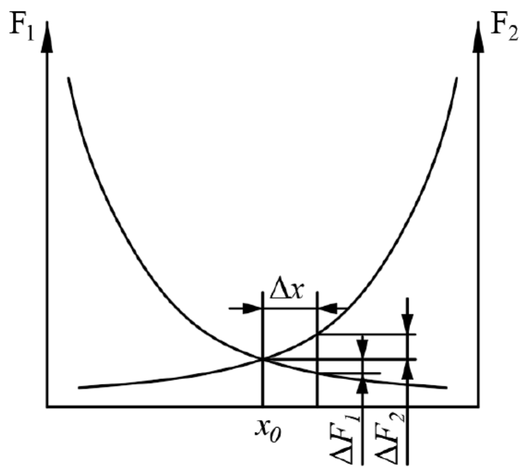


FIG. 10 Recovery force Schematic diagram of the magnetic field force of a permanent

When the moving part moves to the left and right because of the external pressure, the changes of the magnetic force on the left and right sides are ΔF_1 and ΔF_2 respectively, and one term increases while the other term decreases. Two curve in intersection point, the equalization of the slope by the selected magnetic field force change spacing is small, and change the magnetic field force for the linear fitting, so that the two slope in change interval are equal, set to k, is the same on both ends of the magnetic field strength variation, so the moving parts of the whole for restoring force change as （$\Delta F_1 + \Delta F_2$）, that is, total slope is a single twice the slope of the curve.

Combining with the previous formula, we can know that:

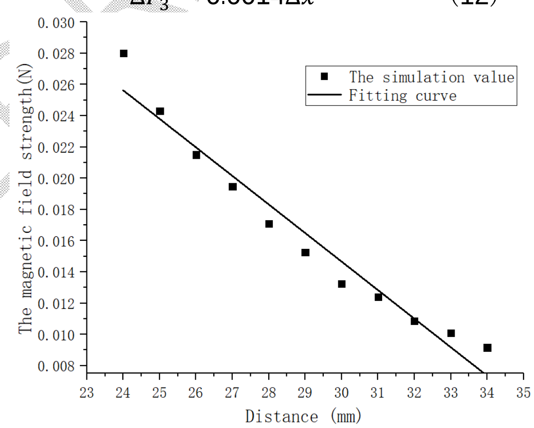
$$\Delta F = 2k\Delta x \quad (9)$$

When the initial spacing D_0=29mm, 32mm and 35mm, the magnetic force of moving parts in the range of 10mm is simulated and fitted, and different magnetic force models corresponding to each initial spacing can be obtained. As shown in FIG. 11, the corresponding overall recovery force changes as follows:

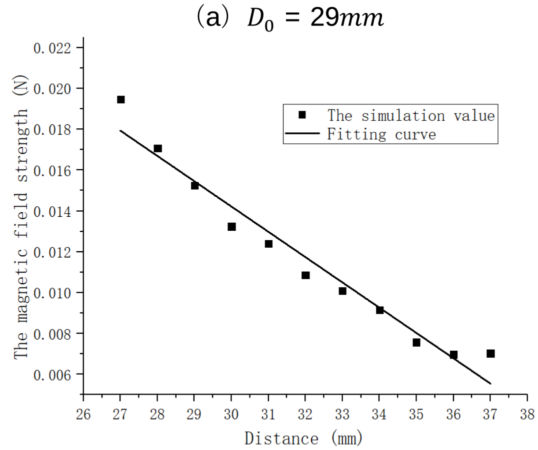
$$\Delta F_1 = 0.0036\Delta x \quad (10)$$

$$\Delta F_2 = 0.0024\Delta x \quad (11)$$

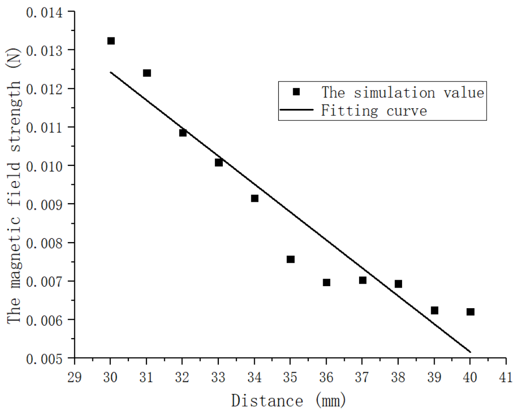
$$\Delta F_3 = 0.0014\Delta x \quad (12)$$



(a) $D_0 = 29mm$



(b) $D_0 = 32mm$



(c) D_0 = 35mm

FIG. 11 Variation curve of magnetic field force and of permanent magnet

According to the above analysis, for the initial spacing of the above three cases, when the magnetic field force ∆F is the same, the larger the initial spacing is, the larger the moving distance of the moving part is, and the more sensitive the moving part of the final sensor is to the pressure difference. When there is a small pressure difference change outside, the greater the change of magnetic field at the detection position of Hall element, the greater the change of the same output voltage signal, that is, the higher the sensor sensitivity. But at the same time, the linearity of the sensor will decrease, the range will decrease, and the overall size of the sensor will also increase.

3.3. Simulation Analysis of Pressure Resistance of Magnetic Liquid Micro Differential Pressure Sensor

In the working state, the moving parts of the magnetic liquid micro differential pressure sensor move in the transparent quartz glass tube, and the magnetic liquid plays the role of sealing and supporting. When the external pressure is too high, the magnetic liquid seal ring will fail, which makes the Hall element unable to measure the effective pressure difference. Therefore, it is very important to study the pressure resistance of the magnetic liquid in the magnetic liquid micro pressure difference sensor to determine the range of the sensor.

When the external pressure is too big lead to magnetic fluid seal failure, must be a magnetic liquid contact with transparent acrylic tube rupture, so this place to find the solution of the magnetic field strength, the magnetic liquid in COMSOL micro differential pressure sensor to carry on the physical modeling, analysis model is established and analyzed the results as shown in figure 12 and 13, respectively.

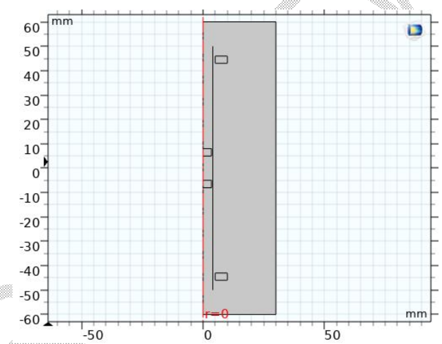


FIG. 12 Calculation of edge flux density model

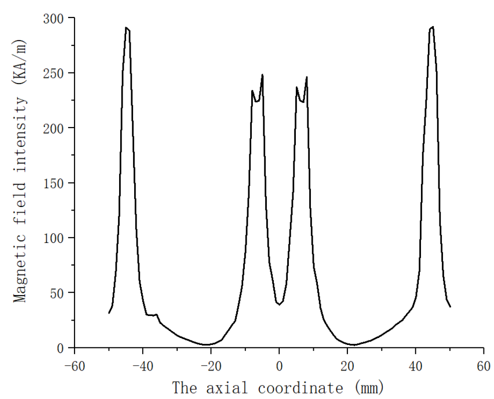


FIG. 13 Variation curve of magnetic flux density at the edge

As can be seen from the figure, the magnetic field gradient ∆H=25KPa of the one-sided magnetic liquid from the cylindrical permanent magnet, so the pressure resistance value of a single magnetic liquid sealing ring is:

$$\Delta P = \mu_0 M \Delta H = 4\pi \times 10^{-7} \times \frac{500}{4\pi \times 10^{-3}} \times 25 \times 10^3 = 1250Pa \qquad (13)$$

The sensor has a four-stage magnetic liquid sealing ring, that is, the overall pressure resistance value is four times the unilateral pressure resistance capacity, so the theoretical pressure resistance value of magnetic liquid is 5000Pa.

It is worth noting that this calculation is made in the case of ignoring the magnetic leakage of the micro-pressure differential sensor of magnetic liquid, but the magnetic leakage can not be avoided in the laboratory, so the theoretical value is larger than the experimental value.

4. CONCLUSION

Through theoretical analysis and simulation calculation of the magnetic liquid micro-differential pressure sensor, the following conclusions can be obtained:

1. When the distance between two cylindrical permanent magnets L=10mm, the magnetic flux density B at the central axis changes approximately linearly with the distance.

2. The recovery force curve of permanent magnet has good linearity in the spacing range of 24mm ~ 40mm.

3. The sensor has a four-stage magnetic liquid sealing ring, the overall pressure resistance value is four times the unilateral pressure resistance capacity, the theoretical pressure resistance value of magnetic liquid is 5000Pa.

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