Experimental study output voltage of a new magnetic fluid acceleration sensor

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The paper presents a new type of magnetic fluid acceleration sensor. The force between inertial magnet and repulsion magnet was computed by numerically calculation, and then the relationships between acceleration and displacement of inertial mass is obtained. The influence of distance of repulsion magnets, volume of magnetic fluid, magnetic induce of magnetic fluid and dimensions of magnetic core on output voltage of magnetic fluid acceleration sensor are studied theoretically and experimentally.

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Keyword: Magnetic fluidAcceleration, Sensor, Experimental study

1. Introduction

The sensors which have large range, high degree of linearity, high resolution ratio are determined on absolute motion and vibration, and high performances of sensor are increasing with the development of industry, so the sensors based on new material, new structure and new principle are more and more important[1].

Magnetic fluid is composed of small particles of solid, magnetic, single-domain particles(about 10nm) coated with a molecular layer of a dispersant and suspended in a liquid carrier. In magnetic fluid, magnetic and liquid states coexist, both magnetic and liquid properties influence the device performance, so magnetic fluid has a wide range of applications in some field[2, 3]. Magnetic fluid sensor is a very important application field. The sensor which used magnetic fluid has magnetic controllable and lower damp, so it can be used in some severe rugged environment[4-9].

The large volume demand for acceleration sensors is due to their automotive applications, where they are used to activate safety systems, including air bags, to implement vehicle stability systems and electronic suspension, acceleration sensors have large application area. With development of science and technology, performance and application area of acceleration sensors have high demand, magnetic fluid acceleration sensors have been aroused great interest.

Many scholars have done a lot of work on magnetic fluid sensors, much work has been done on kinds of magnetic fluid sensors in American, Japan, Germany and Romania. The first acceleration sensor, which was completely filled with magnetic fluid, was presented by R.E.Rosensweig in 1969 [10, 11]. M.K.Russell *et al* have designed a system of magnetic fluid according to the principles of magnetic fluid sensor presented by R.E.Rensweig in 1977 [12]. M.I.Piso has reviewed on some principles of inertial sensors with magnetic fluid, with direct applications to motion measurement system [13]. A magnetic fluid sample in aqueous suspension acts as inertial mass was presented by S.Baglio *et al* in 2007, the bias magnetic force, induced by the coil, attracts the magnetic fluid in its centre thus acting like an equivalent spring [14]. Another new type tilt sensor using four magnets and a magnetic fluid was presented by R.Olaru *et al* in 2005, A hysteretic effect has been encountered duce to the viscous friction forces between the thin layer of magnetic fluid adhering by surface tension to the well of the tube and the magnetic fluid from the magnetic fluid rings[15]. In this paper a type of magnetic fluid acceleration sensor has been designed and studied experimentally and theoretically. Output voltage and sensitivity of magnetic fluid acceleration sensor are studied theoretically and experimentally, and the experimental data is in a good accordance with numerical calculation.

2. Structure and Experimental Principle

The principle diagram of Magnetic fluid acceleration sensor is shown in Figure 1, includes a non-metallic material cylindrical container tight closed, having inside a mobile inertial magnet, two permanent magnets are fixed at suitable distance outside of the cylindrical container, the magnetic fluid is strongly symmetric adhered at the ends of the inertial magnets, based on the permanent magnet levitation and the magnetic fluid levitational bearing, thus ensuring sustaining and sliding the inertial magnet in the cylindrical container. When this is accelerated or tilted, an equilibrium position is obtained because of magnetic repulsion force between the inertial magnet and the magnets disposed outside of the container in the axial direction and magnetic fluid second-order buoyancy in the radial direction respectively. Two coils detect the position of the inertial magnet that depends on the device acceleration or tilt. Assumed that the volume of magnetic fluid is V, the radius of inertial magnet is r_c(=5mm), the radius of the nonmagnetic case is R_0(=8mm), the length of the inertial magnet is l_c(=20mm), the length of the nonmagnetic case is L(=200mm), the ring magnets disposed outside of the container having the external diameter being 19mm, the inner diameter being 14mm and the length being 5mm, the material of the detected coil is enameled wire, the diameter of enameled wire is 0.21mm, the number of detected coil is 2000, the resistance of detected coils is 90Ω, the framework of detected coil having the external diameter being 40mm, the inner diameter being 20mm and the length being 20 mm.

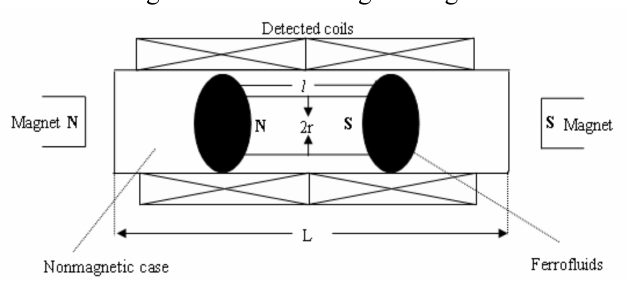

Fig. 1. Schematic of the magnetic fluid acceleration sensor.

When the tilt angle between the sensor and the level is θ, the inertial mass has a displacement x which relative to the level in the equilibrium position using a couple of repulsion magnets, the tilt angle of the sensor is proportion to the displacement of the sensor in a suitable range, the acceleration of the inertial mass is obtained from the measured tilt angle of the sensor ($a=gsin\theta$), so the acceleration of the sensor is proportion to the displacement of the sensor in a suitable range, as Fig. 2.

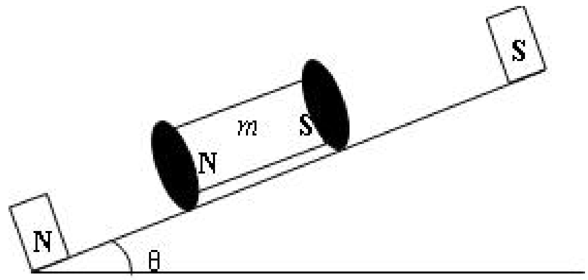

Fig. 2. Static model of the magnetic fluid acceleration sensor

The detected circuit is alternating bridge circuit is shown in Figure 3, the two identical coils are connected in two of the four measuring bridge branches[16, 17]. For small displacements of the inertial magnet, the bridge unbalance voltage is proportional with the device acceleration or tilt. The voltage is amplified, rectified and then transmitted to computer by Data Acquisition Package. The amplitude of voltage is indicating the acceleration or tilt. For each inertial magnet position, several acquisitions of the output voltage are accomplished in order to perform statistics on the data set acquired. A sampling frequency of 1kHz is used to acquire 20s of the steady-state readout circuitry output voltage. The circuit diagram of the Data Acquisition system in the experimental platform is showed, as Fig. 3.

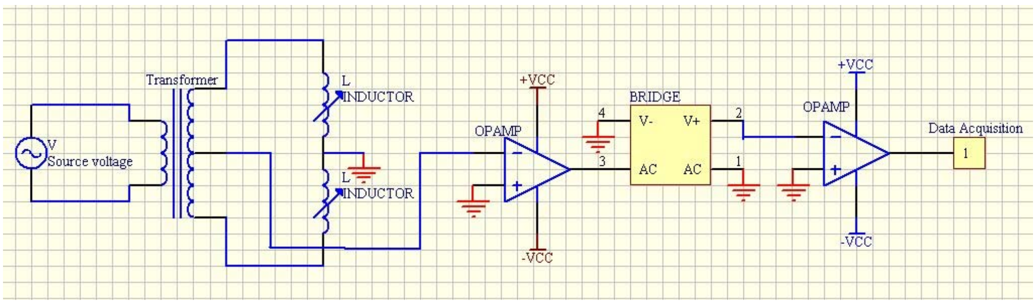

Fig. 3 The circuit diagram of the Data Acquisition in the experimental platform.

The power source is a signal of CA1640-02 function generator, the peak to peak value V_{PP} of the signal is 1mV~22V, the frequency of the signal is 0.2Hz~2MHz. To get maximum of the quality factor and according to the sampling theorem, the sampling frequency must be exceeded, so the suitable peak to peak value V_{PP} of the signal is 22V and the frequency of the signal is 1kHz[18, 19].

3. Experimental results and analysis

3.1 Magnetic fluid and physic properties

The magnetic fluid based on kerosene and magnetite particles Fe_3O_4 coated with oleic acid. The magnetization loop of magnetic fluid is showed in Figure 4, and the main characteristics of the magnetic fluid are show in Table 1.

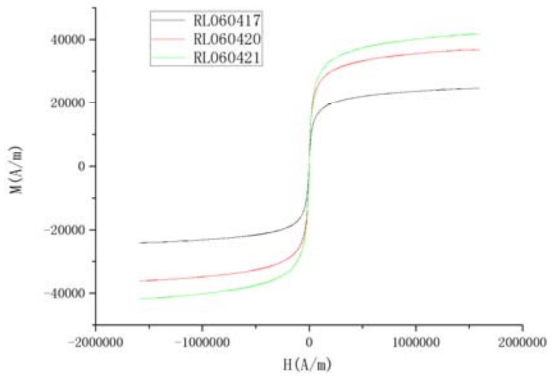

Fig. 4. Magnetization curves of kerosene based magnetic fluid

Table 1. Physical properties of kerosene based magnetic fluid

Sample No.	Saturation magnetic induction (Gs)	Saturation magnetization (kA/m)	Remanent magnetization (eum/g)	Coercive force (Oe)	Density (g/cm^3)	Viscosity (mPa·s)	Relative permeability
1	305.56	24.32	0.3022	7	1.0563	2.29	1.05
2	458.12	36.46	0.05958	-	1.2	3.7	1.1
3	523.56	41.66	0.5545	3	1.2907	5.33	1.12

3.2 The relationships between displacement of magnet core and accelerometer

According to bridge circuit, the output voltage could be written as[18]

$$U_0=\frac{U_i}{2}\frac{(wL_0)^2}{R^2+(wL_0)^2}\frac{r_c^2(\mu_r-1)(\sqrt{r_c^2+(l_c+\Delta x)^2}-\sqrt{r_c^2+(l_c-\Delta x)^2})}{[r^2(\sqrt{r^2+l^2}-r)+r_c^2(\mu_r-1)(\sqrt{r_c^2+l_c^2}-r_c)]}\times A_V \quad (1)$$

where R=90Ω, w=1000Hz, N=2000, l=0.018m, r=0.008m, l_c=0.01m, r_c=0.005m, μ_0=4π×10^{-7}H/m, A_V is the gain of operational amplifier.

According to calculate principle of magnetic force of magnets[20-23], the magnetic induction of arbitrary point among magnets can be written as

$$B_\rho=\frac{B_r}{2\pi}\int_{l+h}^{h}\frac{z}{\rho\sqrt{(r+\rho)^2+z^2}}[\frac{r^2+\rho^2+z^2}{(r-\rho)^2+z^2}E-K]dz+\frac{B_r}{2\pi}\int_{H-h+L}^{H-h}\frac{z}{\rho\sqrt{(R+\rho)^2+z^2}}[\frac{R^2+\rho^2+z^2}{(R-\rho)^2+z^2}E-K]dz \quad B_\phi=0$$

$$B_z=\frac{B_r}{2\pi}\int_{l+h}^{h}\frac{1}{\sqrt{(r+\rho)^2+z^2}}[\frac{r^2-\rho^2-z^2}{(r-\rho)^2+z^2}E+K]dz-\frac{B_r}{2\pi}\int_{H-h+L}^{H-h}\frac{1}{\sqrt{(R+\rho)^2+z^2}}[\frac{R^2-\rho^2-z^2}{(R-\rho)^2+z^2}E+K]dz$$

where $E(k)=\frac{\pi}{2}\{1-\sum_{l=1}^{n}[\prod_{j=1}^{l}(\frac{2j-1}{2j})^2\frac{k^{2l}}{2l-1}]\}=\frac{\pi}{2}[1-(\frac{1}{2})^2k^2-(\frac{1\cdot 3}{2\cdot 4})^2\frac{k^4}{3}-(\frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6})^2\frac{k^6}{5}-\cdots\cdots]$

$$K(k)=\frac{\pi}{2}\{1+\sum_{l=1}^{n}[\prod_{j=1}^{l}(\frac{2j-1}{2j})^2k^{2l}]\}=\frac{\pi}{2}[1+(\frac{1}{2})^2k^2+(\frac{1\cdot 3}{2\cdot 4})^2k^4+(\frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6})^2k^6+\cdots\cdots]$$

The magnetic induction among magnets can be obtained

$$B_g^{\ 2}=B_\rho^{\ 2}+B_\varphi^{\ 2}+B_z^{\ 2}$$

The magnetic energy and magnetic force among magnets can be written as

$$w=\frac{1}{2}\iiint\frac{B_g^{\ 2}}{\mu_0}dV=\frac{1}{2\mu_0}\int_0^H\int_0^a\int_0^{2\pi}(B_\rho^{\ 2}+B_z^{\ 2})\rho d\theta d\rho dh$$

$$F=\frac{\partial w}{\partial H}$$

The displacement of magnetic core and magnetic force can be obtained from calculate model of magnetic force between magnets.

$$F(x)=F(H+\frac{l_c}{2}+x)-F(H+\frac{l_c}{2}-x) \quad (2)$$

where x is displacement of magnetic core, H is distance of repulsion magnets, l_c is the length of magnetic core.

The displacement of magnetic core and acceleration can be obtained from $F=ma$ when the mass m is defined.

NdFeB magnet is used for magnetic core of sensor, Three dimensions of magnetic cores are employed, as Table 2.

Table 2. Dimensions of magnetic core.

Dimensions of magnetic core	External diameter Φ	Hole diameter φ	Length L	Number of pieces
10×10	10mm	—	10mm	2
10×6×0.6	10mm	6mm	0.6mm	32
10×4×1.4	10mm	4mm	1.4mm	14

According to calculate principle of magnetic force of magnets, when the dimension of magnetic core is employed 10×10, the relationship between accelerometer and displacement under different repulsion distance can be obtained, as Table 3.

Table 3 The relationships between accelerometer and displacement under different repulsion distance.

repulsion distance	$x(a)$
80mm	x=0.00124a-2.19×10$^{-5}a^2$-1.49×10$^{-7}a^3$
100mm	x=0.00192a-2.97×10$^{-5}a^2$-1.45×10$^{-7}a^3$
120mm	x=0.00276a-3.38×10$^{-5}a^2$-1.51×10$^{-6}a^3$
140mm	x=0.0038a-3.85×10$^{-5}a^2$-4.62×10$^{-6}a^3$

Table 4 The relationships between accelerometer and displacement under different dimensions of magnetic cores0.

Dimensions of magnetic cores	$x(a)$
10mm×10mm	x=0.00276a-3.38×10$^{-5}a^2$-1.51×10$^{-6}a^3$
10mm×4mm×1.4mm	x=0.00667a-1.96×10$^{-4}a^2$-1.696×10$^{-5}a^3$
10mm×6mm×0.6mm	x=0.01707a-0.00334a^2+2.64×10$^{-4}a^3$

Similarly, according to calculate principle of magnetic force of magnets, when magnetic core is employed different dimension magnets, the relationships between accelerometer and displacement under repulsion distance 120mm can be obtained, as Table 4.

Substitution the relationships between displacement and acceleration into output voltage of sensor, the simulate results of output voltage of sensor is obtained.

3.3 The relationships between output voltage and distance of repulsion magnets

When saturation magnetic induction of magnetic fluid is 305Gs, the volume of magnetic fluid is 2ml, dimension of magnetic core is 10×10, the experimental and simulate relationships between output voltage and distance of repulsion magnets, as Fig. 5.

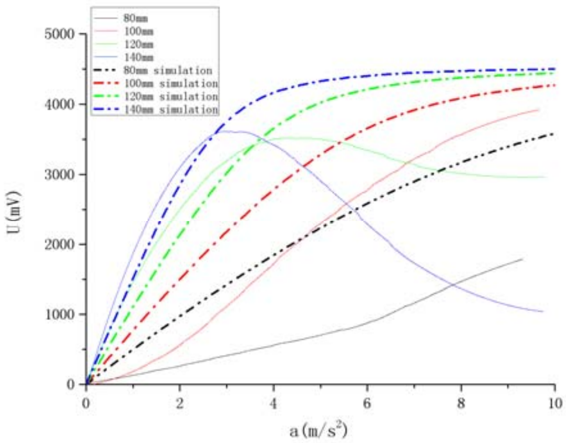

Fig. 5. The experimental and simulate relationships between output voltage and acceleration under different repulsion distances.

The output voltage of sensor is increasing with repulsion distances, the sensitivity of sensor is increasing with repulsion distances, but the linearity segment is decreasing with repulsion distances, the measuring range is decreasing with repulsion distances, simulations are not good agree with experimental results output voltage, the cause is need to be further study.

3.4 The relationships between output voltage and volume of magnetic fluid

When saturation magnetization induction of magnetic fluid is 305Gs, the repulsion distance is 120mm, dimension of magnetic core is 10×10. When the volume of magnetic fluid is increasing from 1ml to 2ml, the experimental and simulate relationships between output voltage and acceleration under different the volume of magnetic fluid, as Figure 6.

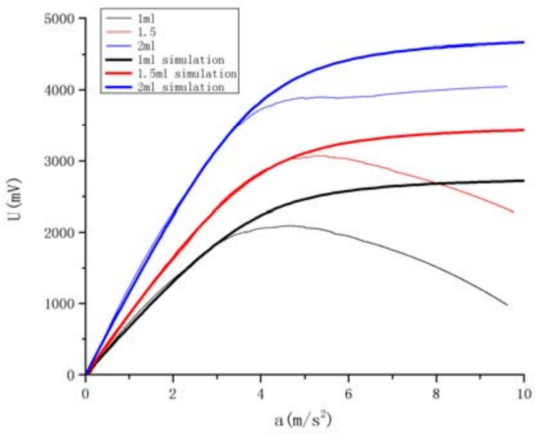

Fig. 6. The experimental and simulate relationships between output voltage and acceleration under different the volume of magnetic fluid.

The relative permeability is increasing with the volume of magnetic fluid, and relative permeability in the coil can be written as[24, 25]

$$\mu_r = f_1\mu_B + f_2\mu_{MF} \tag{3}$$

where f_1 and f_2 are volume fractions occupied by the magnet and the magnetic fluid respectively inside the coil, μ_B and μ_{MF} are their relative permeability, so μ_B =1.05, μ_{MF}=1+χ_{MF}.

Substitution relative permeability into output voltage of sensor, the simulate results of output voltage of sensor is obtained.

The output voltage is increasing with the volume of magnetic fluid in the coil, the sensitivity of sensor is increasing with the volume of magnetic fluid, simulations are good agree with experimental results in linearity segment of output voltage, this result is as same as experimental results of K. Komiya in 1988[26], but the volume of magnetic fluid is less than 3 ml, or else the acceleration sensor will become invalid. So the suitable volume of magnetic fluid is 2ml.

3.5 The relationships between output voltage and different magnetic induce of magnetic fluid

When the repulsion distance is 120mm , dimension of magnetic core is 10×10. The experimental and simulate relationships between output voltage and acceleration under different saturation magnetic induction of magnetic fluid, as Fig. 7.

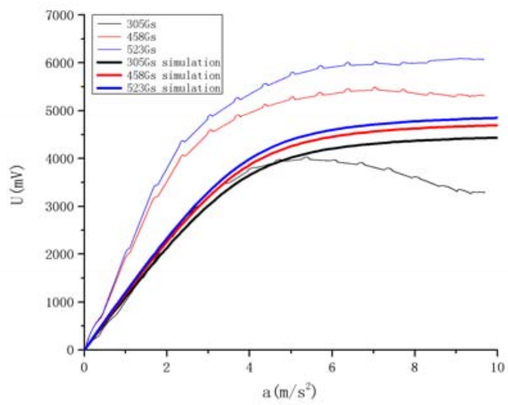

Fig. 7. The experimental and simulate relationships between output voltage and acceleration under different saturation magnetic induction of magnetic fluid.

The output voltage is increasing with the saturation magnetic induction of magnetic fluid, the sensitivity of sensor is increasing with the saturation magnetic induction of magnetic fluid. But the simulations are large different from experimental results, the reason needs to be further study.

3.6 The relationships between output voltage and different dimensions of magnetic core

When saturation magnetic induction of magnetic fluid is 523Gs, volume of magnetic fluid is 2ml, distance of repulsion magnets is 120mm, the experimental and simulate relationships between output voltage and acceleration under different dimension of magnetic core, as Figure 8.

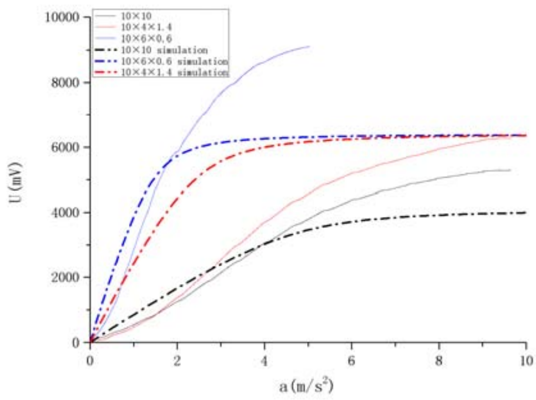

Fig. 8. The experimental and simulate relationships between output voltage and acceleration under different magnetic core.

The output voltage is increasing with hole diameter of magnetic core, the sensitivity of sensor is increasing with hole diameter of magnetic core, However, the simulations are large different from experimental results.

4. Conclusions

In this paper a magnetic fluid acceleration sensor is presented. The inertial magnet coated with a magnetic fluid, thus ensuring sustaining and sliding the inertial magnet in the cylindrical container. A couple of permanent ring magnets disposed outside of the container, an equilibrium position obtained because of magnetic repulsion force between the inertial magnet and the ring magnets disposed outside of the container. The inertial magnet was balanced by the repulsive force of magnets in the axial direction and second-order buoyancy of magnetic fluid in the radial direction, respectively.

The force between inertial magnet and repulsion magnets was obtained by numerical calculation, the relationship between acceleration and displacement of inertial magnet was obtained by simulation.

The output voltage of the sensor is in proportional with the acceleration, the output voltage of the senor increases with the acceleration, but the relationship is nonlinear. The numerical calculation is agreed with the experimental data.

The output voltage and sensitivity of sensor is increasing with repulsion distances, volume of magnetic fluid in the coil, saturation magnetic induction of magnetic fluid, hole diameter of magnetic core.

The output voltage increases with the volume of magnetic fluid, the numerical calculation is agreed with experimental data. The suitable volume of magnetic fluid is 2 ml.

Future studies are intended to outline the influence of the physical parameters of magnetic fluid, and the static and dynamic characteristic of magnetic fluid acceleration sensor in order to optimize its performance.

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