A novel inertial sensor exploiting magnetic fluid

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Abstract. Narrow available frequency range and low linearity of traditional magnetic fluid inertial sensors make them unpractical. A novel inertial sensor exploiting magnetic fluid is designed to solve these shortcomings. Through simulation and experiments, characteristics of magnetic fluid such as damping effect and levitation effect are studied. It shows that magnetic fluid has excellent damping effect which can be controlled by magnetic field. In order to improve the frequency response, both levitation and damping effect are used in sensors. Cylindrical permanent magnet is employed as the inertial mass, which can transform acceleration to the change of magnetic field. Linear hall sensor with high sensitivity is the transducer installed on the position where magnetic field gradient of cylindrical permanent magnet is maximal and has best linearity. Verification experiments of the designed sensor are conducted on vibration platform. Experimental results give that application of magnetic fluid for inertial sensor optimizes its performance greatly. Available frequency range of the designed sensor is increased by 256% after using magnetic fluid as damping material. This paper provides a reference for research on magnetic fluid and its application in inertial sensors.

1. Introduction
Magnetic fluid is a kind of intelligent material, which is a stable colloidal levitation of magnetic nanoparticles in liquid carrier [1]. Characteristics of magnetic fluid can be controlled by magnetic field. Due to special physical performance, it has been applied in different areas including aviation, machine tools, sensors and so on [2-3]. Sensors are the core of industrial reform. As a result, application of magnetic fluid in inertial sensors has attracted attention of many scholars in recent years [4-6]. Different inertial sensors have been designed and tested. Due to the restriction of structure, current sensors are mostly used under low frequency conditions (below 15 Hz) [7-8]. Although the application of magnetic fluid in inertial sensors has achieved some achievements, the existing inertial sensors has poor practicality because of large volume and low linearity. Research strategies for magnetic fluid performance are inadequate and comprehensive, so that advantages of magnetic fluid are not fully utilized in their design. In other words, it will bring bad effects if magnetic fluid is used in wrong ways. Thus, it is vital to study the magnetic fluid and realize best application in sensors.

In this paper, characteristics of magnetic fluid under the action of magnetic field has been researched. In order to make full use of the advantages of magnetic fluid, special structure of sensors is designed. Magnetic fluid is used as the main damping component of the inertial sensor. The available frequency range of the inertial sensor has been broadened greatly. In addition to this, magnetic fluid can avoid mechanical friction and improve the service life of sensors. Both simulation and experiments are conducted to verify the feasibility and effectiveness to apply magnetic fluid in inertial sensors.
2. Material and sensor design
In order to verify the feasibility of using magnetic fluid in inertial sensors and use sensors to study magnetic fluid properties in turn, a sensor with new structure is designed. In this section, material used in our research and the design of sensor will be introduced in detail.

2.1. Material
Magnetic fluid is a stable colloidal levitation of magnetic nanoparticles in liquid carrier. Magnetic nanoparticles form a rigid chain structure under the action of magnetic field, so that magnetic fluid is polarized along the direction of magnetic field. Due to the physical changes, magnetic fluid has many special characteristics. As figure 1 shows, magnetic fluid is attracted by permanent magnet evenly because of its magnetorheological effect. During the movement, the carrier liquid is forced to flow around the magnetic nanoparticle chain, resulting in an increase of the magnetic fluid viscosity. Under the action of a gradient magnetic field, the magnetic fluid can suspend an object that is denser than itself. These two characteristic are called separately as damping effect and levitation effect, which are the research focus of this paper.

![Figure 1. Magnetorheological effect of magnetic fluid](image)

The material model used in this paper is list in table 1.

| Attributes                          | Value       |
|------------------------------------|-------------|
| Liquid carrier                     | Kerosene    |
| Diameter of magnetic nanoparticle (nm) | 1           |
| Viscosity(Original) (Pa · s)       | 1           |
| Viscosity(under the action of magnetic of field) (Pa · s) | 1.149       |
| Saturation magnetization (kA/m)    | 31.8        |

2.2. Sensor design
As illustrated in figure 2(a), the designed sensor has six components. The inertial mass is two identical cylindrical permanent magnets, while the spring is a single cantilever spring piece. Permanent magnets are mounted symmetrically at the end of the cantilever. Upper and lower part of the casing are connected by screws. Spring piece is fixed between these two parts of casing. Internal cavity is filled with magnetic fluid. Besides this, high sensitivity linear Hall element is mounted at the central position of upper casing. The sensor is a second-order spring vibration system. The vibration mode is shown in figure 2(b). After being added magnetic fluid, the vibration parameters changes. Magnetic fluid is completely magnetized under the action of the gradient magnetic field formed by the permanent magnet. Due to the effect of the levitation and damping effect, the system stiffness is increased by $k_f$ and the damping coefficient is increased by $c_f$. Because magnetic fluid is strongly attracted by the magnet surface due to the magnetic force, it can be considered as added inertial mass $m_f$. 
The detailed information of components is shown in table 2.

**Table 2.** The detailed information of components.

| Components      | Model         |
|-----------------|---------------|
| Outer casing    | Photosensitive resin |
| Permanent magnet| NdFeB35       |
| Spring material | 65Mn steel    |
| Linear Hall element | EQ-730L     |

The detection principle of the inertial sensor designed in this paper is shown as follows:

- The sensor is activated by external acceleration.
- Permanent magnets run out of the balanced position because of inertial force.
- Magnetic field strength of the position where Hall element is installed changes.
- Hall element converts magnetic field into electrical signal output.

In summary, the acceleration can be converted to the electrical signal, so as to realize the acceleration measurement. The vibration signal of sensor will be used to analyse the physical properties in the following sections.

### 3. Research on properties of magnetic fluid

Damping and levitation effect are main research focuses in this paper. With the designed sensor as platform, effects mentioned can be researched. Theoretical and experimental research on the damping and levitation effect will be introduced in this section.

#### 3.1. Levitation effect

Levitation effect means that magnetic fluid can suspend an object that is denser than itself. Because the inertial mass used in the sensor is permanent magnet, second-order levitation force produced by magnetic fluid is the main research point.

#### 3.1.1. Theoretical calculation

Firstly, theoretical analysis is conducted. The calculation result will be used to confirm simulation parameters. The calculation of the levitation force is based on a magnetic fluid micro-element. When suspending in magnetic fluid, physical force and surface stress of the magnet are balanced (see equation (1)).

\[
\int_3 T_m dS = \int_1 f_m dV
\]  

(1)
Where $T_m'$ represents surface stress tensor, $dV$ represents the volume of magnetic fluid micro-element, $dS$ represents its surface area and $f_m'$ represents physical force of per unit volume magnetic fluid.

According to the divergence theorem, equation (2) holds.

$$f_m' = \nabla \cdot T_m'$$

Assuming that the magnetic field strength is parallel to the magnetic induction, the surface stress tensor of the magnetic fluid can be obtained (see equation (3)).

$$T_m' = -(p + Q_M + L_M)I + BH$$

Where $p = p(\rho_f, T)$, $Q_M = \int_0^H \mu_0 \frac{\partial (\nu M)}{\partial \nu} dH$, $L_M = \frac{1}{2} \mu_0 H^2$, $p$ is hydrostatic pressure, $T$ is temperature, $\mu_0$ is vacuum permeability, $M$ is magnetization, $\rho_f$ is magnetic fluid density and $\nu$ is magnetic fluid specific volume.

Equations (4) is the boundary conditions at the interface between magnetic fluid and permanent magnet.

$$B_n^+ - B_n^- = 0, \quad H_n^+ - H_n^- = 0$$

Where superscripts $+$, - respectively indicate the outer and inner surfaces of the interface.

Substituting equation (3) and equation (2) into equation (1) and taking boundary conditions into consideration, second-order levitation force can be calculated (see equation (5)).

$$F_n = \int_n \left[ - \left( T_m' + \frac{1}{2} \mu_0 M_s^2 \right) \right] ndS$$

Where $T_M = \mu_0 \int_0^H M dH$, and subscripts $n$ represents the normal components.

Accordng to equations (5), second-order levitation force can be calculated. However, parameters can be quantized. Simulation based on certain assumptions is the choice. Mirror method is used to carry out the simulation. The magnetic field generated by the permanent magnet is equivalent to the magnetic field generated by the mirror magnet, and the second-order levitation force of the permanent magnet is the interaction force with the mirror magnet. The residual magnetic vector of the mirrored permanent magnet is opposite to that of the original permanent magnet. The calculation formula of residual magnetic vector is shown as equations (6).

$$\mathbf{J}_{img} = \frac{\mu_r - \mu_i}{\mu_r + \mu_i} \mathbf{J}_0$$

Where $\mu_r = 1$ represents the mirror area relative permeability, $\mu_i = 1.15$ represents the relative permeability of the magnetic fluid. Under these circumstances, residual magnetic vector of primary magnet $\mathbf{J}_0$ is 890 kA/m and that of mirror magnet $\mathbf{J}_{img}$ is 42.831 kA/m. This value is substituted into the simulation model as a parameter.

3.1.2 Simulation and experiments. As shown in figure 3(a), the second-order levitation force is converted to the repulsive force of the permanent magnet and the two mirror magnets in sealed container. However, in open container, since one end is a free surface, the levitation force is the repulsive force between the suspended permanent magnet and one mirror magnet, as shown in figure 3(b). In order to reduce the amount of calculation, levitation force of permanent magnet in open container is simulated. The result is further superimposed to obtain the levitation force of the permanent magnet in the sealed container.
Simulation is conducted based on finite element analysis software: Comsol Multiphysics. Figure 4 shows free split tetrahedral meshing of the simulation model. Since the container is bilaterally symmetrical, the forces in the x and y directions are balanced with each other. Only the force in the z direction is calculated. The distance is set between the two permanent magnets to 0~5mm at the interval of 0.1mm.

After the simulation results are obtained, the levitation force under the actual model is studied through experiments. As illustrated in figure 5, the magnet is attached to the end of the connecting rod which is connected to the push-pull force meter. Force meter is fixed to the displacement stage. During the experiment, the stage was first adjusted downward until the magnet was completely immersed in the magnetic fluid, and the push-pull force gauge was set to zero. Therefore, the influence of the Archimedes buoyancy is removed. The height of the stage is adjusted according to the displacement read through the displacement meter. As a result, the levitation force of magnet at different immersion heights can be obtained.

Since there is no analytical relationship between the levitation force and the levitation distance, the simulation and the experimental data are polynomial fitted. The fitting graph is shown in figure 6. Figure 6 shows that the experimental and simulation data are basically in the same order of magnitude. As the levitation distance increases, the levitation force and the rate of its change gradually decreases. Since the levitation force is affected by many complicated factors including the magnetic field and actual parameters of the magnet. Simulation parameters are too difficult to be consistent with that in experiments because of the manufactured error. Many factors in the simulation cannot be fully considered, resulting in some errors between the simulation and experimental results. However, in order to judge the frequency expansion degree of the sensor after using magnetic fluid, this paper mainly focuses on the order of magnitude of levitation force research result. In this respect, the experimental and simulation results are in agreement. The results show that the levitation force of
magnetic fluid is so small that it can be ignored in expansion of available frequency range. It will be used to offset the gravity of permanent magnet so as to eliminate the zero drift of the sensor.

Figure 6. Fitting graph of experimental result

3.2. Damping effect

Damping effect means that damping ratio of vibration system using magnetic fluid as damping material can be influenced by magnetic field. Damping coefficient is a dynamic parameter. It is too difficult to measure it because magnetic fluid and permanent magnet are sealed in the inertial sensor. In this paper, vibration attenuation method is used to study the damping coefficient of magnetic fluid. Vibration attenuation curve is measured after tapping the sensor. Spring stiffness and the system damping ratio are calculated according to equations (7) (8).

\[
\frac{1}{j} \ln \frac{A_i}{A_{i+j}} = \frac{2\pi \xi}{\sqrt{1-\xi^2}}
\]  

(7)

\[
f = \frac{j}{T_{i+j} - T_i}
\]  

(8)

Where \( A_i \) and \( A_{i+j} \) represent two peak amplitude with j-th oscillation, \( T_i \) and \( T_{i+j} \) represent the corresponding time, \( \xi \) represents damping ratio.

Figure 7 shows the results of a single tap test on the inertial sensor without magnetic fluid. According to the attenuation curve and equation (7) (8), natural frequency and damping ration are obtained. The same method is used in the inertial sensor with magnetic fluid sealed inside. The result is shown in table 3.

In order to choose the best damping ratio for inertial sensor, experiments are repeated under sensors with different springs and magnetic fluid. Based on the experimental results, suitable spring and magnetic fluid are chosen to adjust the damping ratio to 0.56. This damping ratio can make available frequency range the widest.

Experimental results show that the distance between permanent magnet and the sensor casing has an effect on the damping effect of magnetic fluid. In addition to this, the magnetic field acted on the magnetic fluid is the key factor to affect the damping effect. Experiments introduced in this section guide the sensor structure design.

| Condition                  | Natural frequency /Hz | Damping ratio |
|----------------------------|------------------------|---------------|
| Without magnetic fluid     | 2029                   | 0.0735        |
| With magnetic fluid        | 1852                   | 0.1729        |
4. **Verification experiments**

Hall element is the measurement component of the inertial sensor. Through simulation and experiments, the position where magnetic field has best gradient is chosen to install the Hall element. It can make sensitivity of the inertial sensor best. This part will not be introduced in detail because it is not the focus of this paper.

Base on the results obtained in previous sections, parameters of sensor structure are determined. The designed sensor is manufactured and verification experiments are conducted on the vibration platform, which can provide 50g (gravity acceleration) at 30kHz. Figure 8 shows the manufactured sensor. The diameter of the sensor is smaller than 1cm. As shown in Figure 9, the standard acceleration sensor and the magnetic fluid sensor are mounted on the vibration platform.

The vibration platform is controlled to vibrate at different acceleration amplitudes and frequencies. At a frequency of 100 Hz, the acceleration amplitudes is controlled from $20 \cdot m/s^2$ ~ $60 \cdot m/s^2$ with the interval of $5 \cdot m/s^2$. Figure 10 shows the sensor output. It indicates that the sensor designed in this paper has a good linearity in response to acceleration.

In order to verify the effect on the sensor brought by magnetic fluid, the frequency response experiments are also conducted on the vibration platform. The vibration platform is controlled to vibrate from 160Hz to 750Hz with the interval of 12.5Hz at the amplitude of $35 \cdot m/s^2$. According to second-order frequency response function, the experimental results are fitted. As illustrated in figure 11, the available frequency range of the sensor without magnetic fluid is 0~161.6Hz with the allowable error as 10%. When the sensor is added by magnetic fluid, the frequency range is 0~575.5Hz. The available frequency range is extended by 256%, which indicates that magnetic fluid has perfect properties to improve inertial sensors.

Moreover, the designed sensor is used to measure the rotor vibration in order to verify its practicality. The experimental platform is shown in figure 12. Standard sensor and magnetic sensor are installed at the same position of the rotor. The standard sensor used in this experiment is piezoelectric inertial sensor, which serves under 5kHz. The rotor is controlled to run at 24.2Hz. The results are compared in both time and frequency domain.
As illustrated in figure 13, information in time and frequency domain gained from two sensors are similar. It reflects that the magnetic sensor designed in this paper is capable of measuring the rotor vibration in reality. From figure 13(b), the rotary frequency of the rotor from magnetic fluid sensor is much clearer than that from standard sensor. It proves that magnetic fluid sensor has better performance than standard sensor in low frequency.
5. Conclusions
A novel inertial sensor using magnetic fluid is designed in this paper. Simulation and experiments are conducted to study the characteristics of magnetic and the feasibility of using it in inertial sensor. The results show that magnetic fluid can be used to improve the available frequency range of inertial sensor. The innovations of this study mainly lie in: 1) Novel inertial sensor structure using magnetic fluid is designed to verify the feasibility to use magnetic fluid in inertial sensor. The simple structure keeps the sensor in low cost and good performance. 2) The levitation and damping effect of magnetic fluid are studied. Results show that magnetic fluid has good damping effect under the action of magnetic field. When the permanent magnet is small, the suspended force is so small that it can be ignored. 3) The innovative sensor structure and intelligent material magnetic fluid are combined. Experimental results show that the designed sensor has good performance in low frequency and magnetic fluid has a positive effect on extending the available frequency range.
This paper provides a strategy for studying the levitation and damping effect of magnetic fluid. It also gives a new idea for the research and improvement of acceleration sensors.

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