

Review Article

Use of Magnetic Fluid in Accelerometers

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Magnetic fluid accelerometer is designed based on the special physical properties of magnetic fluid. Compared with the conventional acceleration sensors, magnetic fluid accelerometer has stronger shock resistance capability, higher sensitivity, lower energy consumption, and better performance in low frequency response. It satisfies the growing requirements of acceleration sensors. In this paper, the dynamic model and the theory of magnetic fluid accelerometers were presented. The structure characteristics of typical magnetic fluid accelerometers were investigated, and the development trend of magnetic fluid accelerometers in the future was also predicted. Besides, a novel accelerometer with linearity better than 1.5% and sensitivity better than 75 mV/g was proposed.

1. Introduction

Magnetic fluid is composed of magnetic nanoparticles, surfactant, and carrier. Since magnetic fluid was invented in 1963 by Stephen Papell from NASA [1], this novel functional material has been studied over half a century. Magnetic fluid shows both liquidity and paramagnetism which makes a great quantity of engineering applications become possible. Now, the applications of magnetic fluids involved a plenty of mechanical engineering fields. And one of the main applications of magnetic fluid is the use in sensors.

Compared with the conventional sensors, magnetic fluid sensors have stronger shock resistance capability, higher sensitivity, lower energy consumption, and better performance in low frequency response [2–5].

Because acceleration is the only intrinsically measurable quantity for a moving system [3], scholars around the world have been researching and studying magnetic fluid accelerometers for several decades. R. E. Rosensweig proposed the first magnetic fluid accelerometer in 1969, which is based on the second order levitation principle of magnetic fluid [2]. In 1977, Russell from England succeeded in obtaining a patent of magnetic fluid supported linear accelerometer in America [6], and that took a big step forward in commercial application of magnetic fluid sensors. The research group led by Piso in Romania proposed various structures

of magnetic fluid accelerometers during the early 1980s to mid-1990s [3, 4]. Since then magnetic fluid accelerometers have been developing quickly; both theoretical and experimental researches have been studied and a few of those accelerometers have been successfully adopted in particular engineering fields such as oil prospecting [5]. In recent years, the magnetic fluid accelerometers have been further improved. The research team from Italy have designed a series of magnetic fluid accelerometers with good performance [7–12]. Li et al. studied the dynamical characteristics of a ferrofluid accelerometer [13, 14]. Cao et al. built a novel model of magnetic fluid accelerometer and optimized it with the help of analyzing the simulation result [15]. Yang et al. proposed a new type of accelerometer with magnetic fluid membrane as the inertial mass and the experimental result showed to be in good agreement with the theoretical analysis [16]. Liu et al. analyzed the influencing factors of the second-order levitation in magnetic fluid accelerometer [17]. He et al. studied the second-order levitation with experimental method [18].

In this paper, the working principle of magnetic fluid accelerometer is presented. A variety of magnetic fluid accelerometers with different forms and the structure characteristics of them are given. The development trend of magnetic fluid accelerometer in the future is also predicted. Besides, a novel accelerometer with good linearity and high sensitivity was proposed.

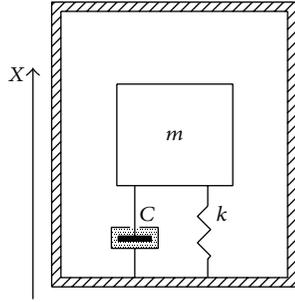


FIGURE 1: Second-order inertial system diagram.

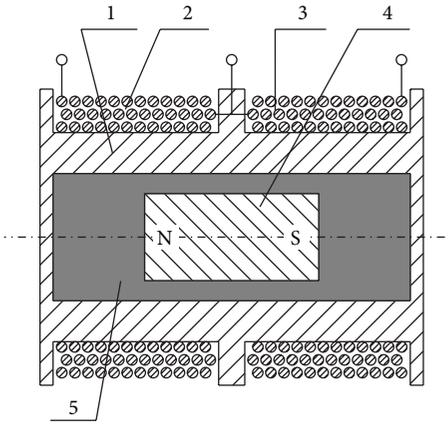


FIGURE 2: Typical model of magnetic fluid accelerometer: 1—housing, 2, 3—inductive coils, 4—permanent magnet, and 5—magnetic fluid.

2. Dynamic Model of Magnetic Fluid Accelerometer

An accelerometer is usually composed of five parts including inertial mass, elastic element, damper, housing, and transducer [2, 19]. It can be noted that the dynamic model of accelerometer could be described as a two-order inertial system shown in Figure 1. The rectangle frame with shadows represents the housing and it moves along the x -axis in the global coordinate system. A mass m moves along the x -axis in the housing which is connected with elastic element and damper described by elastic constant k and damping coefficient C , respectively.

The system can be described as

$$m \left(\frac{d^2 y}{dt^2} + \frac{d^2 x}{dt^2} \right) = -C \frac{dy}{dt} - ky, \quad (1)$$

$$\frac{d^2 y}{dt^2} + \frac{C}{m} \frac{dy}{dt} + \frac{k}{m} y = -\frac{d^2 x}{dt^2} = -a,$$

where x is the displacement of the housing in the global coordinate system, y is the displacement of the mass relative to the housing, a is the acceleration of the housing, and t is time.

Figure 2 shows the typical model of magnetic fluid accelerometer [2]. It consists of housing, permanent magnet,

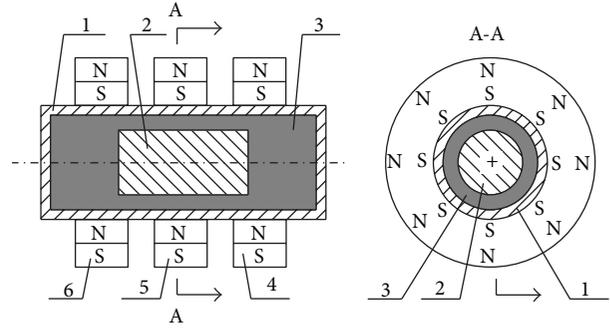


FIGURE 3: Uniaxial magnetic fluid accelerometer: 1—cylindrical shell, 2— inertial mass, 3—magnetic fluid, 4, 5, and 6—permanent magnet ring.

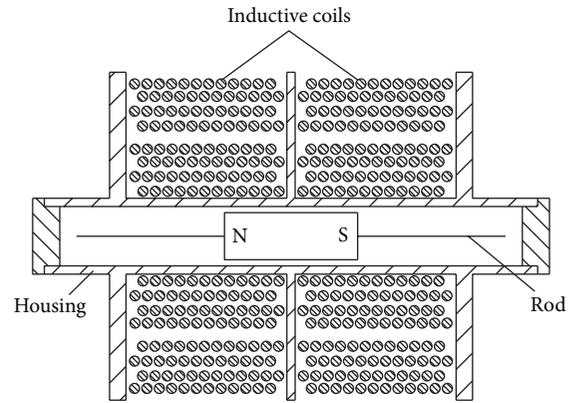


FIGURE 4: Uniaxial magnetic fluid accelerometer.

inductive coils, and magnetic fluid. In this model, permanent magnet acts as the inertial mass. The elastic constant k is related to the restoring force of the system and the damping coefficient C is related to the frictional resistance of the system, that is, viscosity of magnetic fluid.

3. Theory of Magnetic Fluid Accelerometer

Theory of magnetic fluid accelerometer involves FHD (FHD is short for ferrohydrodynamics) and electromagnetism. The Navier-Stokes equation should be written as follows [19–21]:

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p^* + \mu_0 M \nabla H + \eta \nabla^2 \mathbf{v} + \rho \mathbf{g}, \quad (2)$$

where ρ is the density of magnetic fluid, \mathbf{v} is the velocity of magnetic fluid, η is the viscosity of magnetic fluid, M is magnetization, and H is magnetic field strength.

The Bernoulli equation of magnetic fluid in isothermal and steady-state conditions should be written as follows [19–22]:

$$p^* + \frac{1}{2} \rho V^2 + \rho g h - \mu_0 \int_0^H M dH = C, \quad (3)$$

$$p^* = p + p_s + p_m,$$

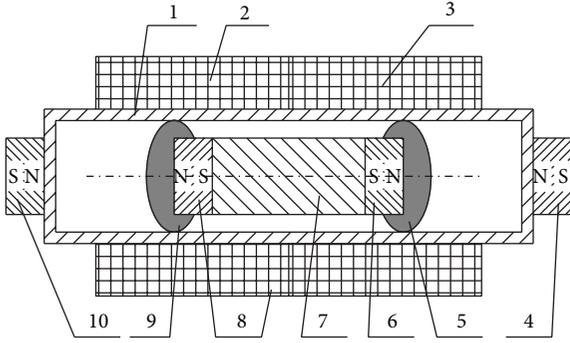


FIGURE 5: Inductive magnetic fluid accelerometer: 1—housing, 2, 3—coils, 4, 10—magnet, 5, 9—magnetic fluid, 6, 8—supporting magnets, and 7—magnetic core.

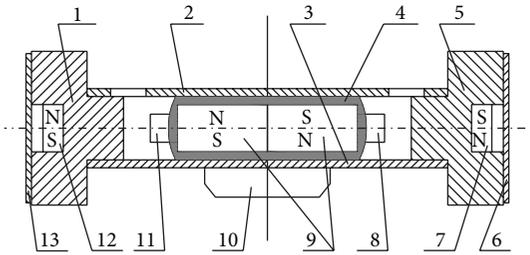


FIGURE 6: Uniaxial hall accelerometer: 1, 5—end covers, 2, 3—housing, 4—magnetic fluid, 6, 13—side caps, 7, 9, and 12—permanent magnets, 8, 11—bars, and 10—hall element.

where p is the fluid pressure, p_s is the magnetostrictive pressure and p_m is the fluid-magnetic pressure, and μ_0 is vacuum permeability.

The unique levitation characteristic of magnetic fluid includes the first-order levitation principle and the second-order levitation principle. It is generally used in magnetic fluid accelerometers for not only supporting the inertial mass in the magnetic fluid but also generating the restoring force.

The first-order levitation principle of magnetic fluid is that there will be a force generated when a nonmagnetic body immersed in the finite magnetic fluid region is brought to the boundary that separates magnetic fluid from the nonmagnetic region under a nonuniform magnetic field [20, 23]. To be more precise, once the nonmagnetic body deviates from the centre position of the magnetic fluid region, the restoring force comes out. The calculation equation of restoring force F_1 generated by the first-order levitation principle of magnetic fluid is given as follows [20, 23]:

$$F_1 = -\oint_S \left(\frac{1}{2} \mu_0 M_n + \mu_0 \int_0^H MdH \right) \mathbf{n} dS, \quad (4)$$

where \mathbf{n} is the unit normal vector and M_n is the normal component of M .

In the foregoing, we consider a nonmagnetic body immersed in magnetic fluid. Now we can get the second-order levitation principle of magnetic fluid by replacing the nonmagnetic body with permanent magnet and removing the external magnetic field. It is similar with the first-order

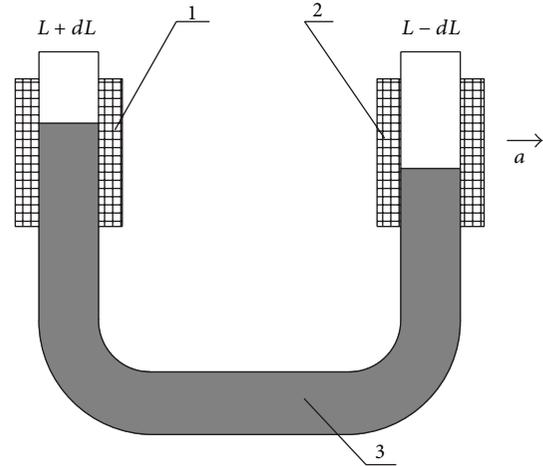


FIGURE 7: U-shaped tube magnetic fluid accelerometer: 1, 2—inductive coils and 3—magnetic fluid.

levitation principle of magnetic fluid. There will be a restoring force when the permanent is brought to out of the centre position of magnetic fluid area. In other words, the permanent magnet would be exactly at the centre position of the magnetic fluid area if there is no other external force exerted on it and the gravity of the permanent magnet can be neglected. The calculation equation of restoring force F_2 generated by the second-order levitation principle of magnetic fluid is given as follows [20, 23–25]:

$$F_2 = \oint_S \left[\left(H_n B_n - \int_0^H BdH \right) \mathbf{n} + H_t B_n \mathbf{t} \right] dS, \quad (5)$$

where \mathbf{n} is the unit normal vector and \mathbf{t} is the unit tangential vector, H_n is the normal component of H , H_t is the tangential component of H , and B_n is the normal component of magnetic flux density \mathbf{B} .

In addition, the restoring force of magnetic fluid accelerometer could be generated by any other available forms of force such as interaction force between two magnets or the gravity of inertial mass.

4. Typical Magnetic Fluid Accelerometers

Figure 3 shows a uniaxial magnetic fluid accelerometer [3, 26]. The inertial mass 1 is made by aluminum. There are three annular permanent magnets wounded outside the cylindrical housing. Those magnets are set for generating magnetic field to keep the inertial mass suspension in magnetic fluid 3 and offer the restoring force through the first-order levitation principle of magnetic fluid. The capacitance as the transducer consists of annular magnet and inertial mass. The sensitivity is better than 10^{-6} ms^{-2} and time response is better than 30 milliseconds [3].

Figure 4 shows another uniaxial magnetic fluid accelerometer [6]. The permanent magnet immerses in magnetic fluid which is filled in the housing. However, unlike the first one, the restoring force is generated by the second-order levitation principle of magnetic fluid. There are two rods from each end

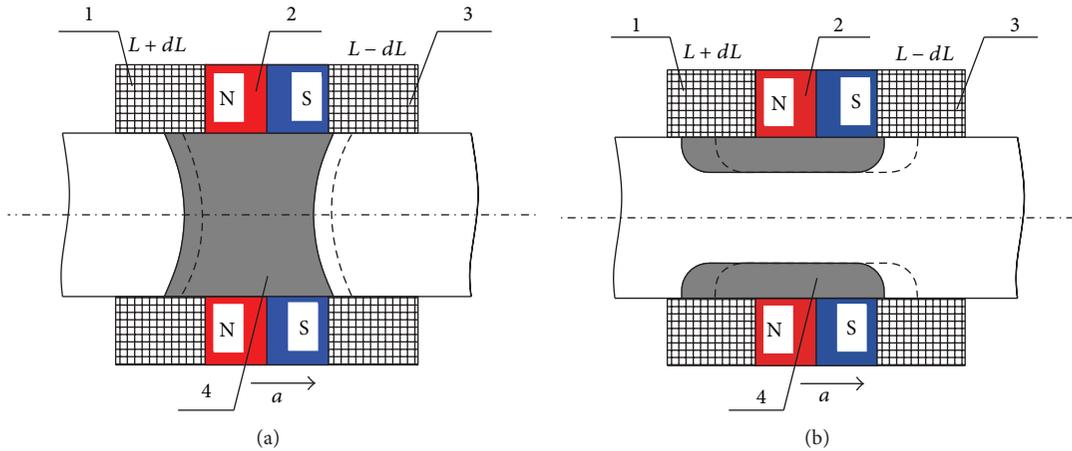


FIGURE 8: Inductive magnetic fluid accelerometer: 1, 3—inductive coils, 2—permanent magnet, and 4—magnetic fluid.

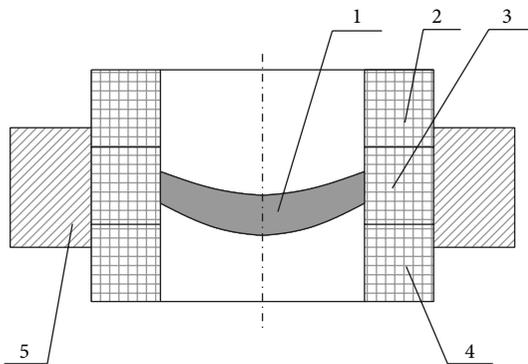


FIGURE 9: Schematization of an accelerometer detecting the vertical direction: 1—magnetic fluid, 2, 4—sensing coils, 3—primary coil, and 5—annular magnet.

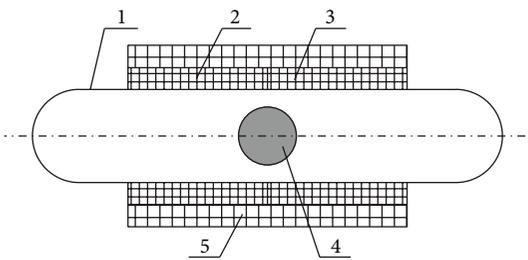


FIGURE 10: Accelerometer with a magnetic fluid drop as inertial mass: 1—glass tube, 2, 3—sensing coils, 4—magnetic fluid, and 5—drive coil.

of the permanent magnet to protect the magnet crashing the housing when the acceleration exceeds the limit. When the accelerometer works, the inductive coils outside the housing transform the displacement of inertial mass into electrical signal as output.

Another accelerometer which is based on the second-order levitation principle of magnetic fluid was proposed in [27–29]. Figure 5 shows the structure. The inertial mass is composed of two supporting magnets and a magnetic core.

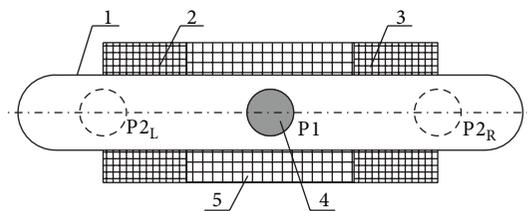


FIGURE 11: A kind of accelerometer with a time domain readout strategy: 1—glass filled with deionized water, 2, 3—sensing coils, 4—magnetic fluid, and 5—actuation coil.

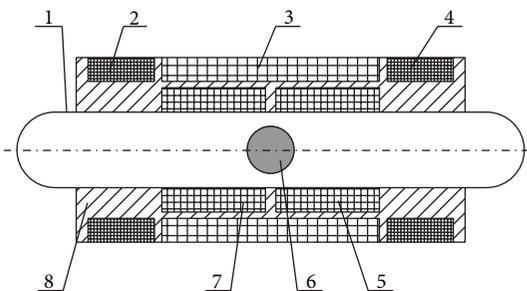


FIGURE 12: Magnetic fluid accelerometer with exciter coils: 1—glass filled with deionized water, 2, 4—sensing coils, 3—retainer coil, 5, 7—exciter coils, 6—magnetic fluid, and 8—support.

The magnetic core sticks to the supporting magnets and aims at improving the sensitivity of the accelerometer. It can be noticed that in previous accelerometer (see Figure 3) the housing is full of magnetic fluid. However, unlike the one in Figure 4, there is just a little of magnetic fluid coating each supporting magnet. Hence the second-order levitation principle of magnetic fluid in here is just in order to keep inertial mass suspension. The restoring force is offered by the interaction force between the magnet outside the housing and one supporting magnet. And the restoring force can be adjusted through replacing the magnetic cores with different length.

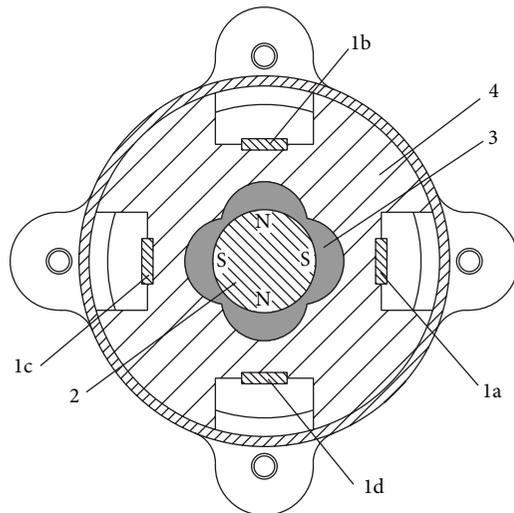


FIGURE 13: Biaxial hall accelerometer: 1a, 1b, 1c, and 1d—hall element, 2—permanent magnet, 3—magnetic fluid, and 4—shell.

A uniaxial accelerometer was described in [30] (see Figure 6). The main components include the housing, the end covers, the permanent magnets, and the hall element. Being similar to the accelerometer described in [27], the restoring force is generated by the interaction force between the permanent magnets. However, the transducer part for detecting the displacement of the inertial mass in this accelerometer is the hall element rather than the coils in Figure 5. The side caps are set for blocking the outside magnetic field.

There is an accelerometer using magnetic fluid as inertial mass proposed by Popa et al. (see Figure 7) [3, 31, 32]. The U-tube is filled with magnetic fluid. Two identical inductive coils are wound on the tube walls. When the accelerometer is working, the height of magnetic fluid in U-tube changes from equal to different. Because the relative permeability of magnetic fluid is more than 1, the inductive coils can detect the height change of magnetic fluid and output the electrical signal. It is worth noting that the restoring force here is generated by gravity of magnetic fluid itself.

Figure 8(a) presents another magnetic fluid accelerometer which is composed of cylindrical housing, annular magnet, inductive coils, and magnetic fluid [3, 33]. Magnetic fluid is restricted by the magnetic field. In initial position, the volume of magnetic fluid in each inductive coil is equal. When the accelerometer is working, the inductance values of the inductive coils change along with the change of magnetic fluid's volume. If we change the intensity of magnetic field or the volume of magnetic fluid, the shape of magnetic fluid will shift into annular as shown in Figure 8(b). The linearity of the accelerometer is better than 1% up to a 30 Hz frequency and static resolution is better than 10^{-3} g in the range 0~1 g [3].

There is an accelerometer using magnetic fluid membrane as inertial mass was presented in [16] (see Figure 9). The magnetic fluid membrane is restricted by the annular magnet 5. The primary coil 3 produces an alternating magnetic field. In a static state, the shape of magnetic fluid membrane is an arc due to the gravity. However, the shape of magnetic fluid

membrane will deform once the acceleration in the vertical direction exists. Then the induction voltage difference of the two sensing coils changes in proportion to the acceleration.

Another type of inductive accelerometer using magnetic fluid as inertial mass was proposed in [7, 8] (see Figure 10). It consists of glass tube, magnetic fluid, sensing coils, and drive coils. The glass tube is filled with deionized water and the drop of magnetic fluid immerses in the centre of deionized water. The drop of magnetic fluid as inertial mass moves along the horizontal direction in the glass tube. The drive coil was set for generating magnetic field to provide restoring force and keep the suspension status of the magnetic fluid drop. The sensing coils wound outside the glass tube are set for detecting the displacement of the magnetic fluid drop. The measuring range is 0~0.35 g [7].

Based on the accelerometer in [7], there are two improved structures. The first was described in [9] (see Figure 11). Compared with the structure in Figure 10, it has an extra actuation coil mounted between the two sensing coils. The $P2_L$ and $P2_R$ are control positions. When the accelerometer receives an acceleration, the magnetic drop moves along the axial direction. Once the sensing coils detect that the magnetic drop gets to the $P2_L$ or $P2_R$, the actuation coil will change the magnetic field to turn the magnet drop to the opposite direction; repeat this process continually. The value of acceleration can be detected by the frequency of the magnetic fluid drop's movement.

To improve the sensitivity of the magnetic fluid accelerometer in [7], another structure was presented in [10] (see Figure 12). Besides the same components in Figure 10, there are two exciter coils wound on the glass. The function of these two exciter coils is to make the magnetic drop move at the resonance frequency of the whole system. This structure turned out to be effective for improving both sensitivity and resolution [10].

Those magnetic fluid accelerometers mentioned above are all uniaxial. There are also multiple axes magnetic fluid accelerometers. Figure 13 presents a biaxial hall magnetic fluid accelerometer [29, 34]. It was proposed by Takaharu Idogaki from Japan. The cavity in the shell is petaloid and is full of magnetic fluid. The disk magnet levitates in the magnetic fluid. Around the cavity there are four hall elements for detecting the variation of the magnetic field inside the cavity to obtain the displacement of the disk magnet in two perpendicular directions. This accelerometer has been applied in automotive and aviation fields.

A biaxial accelerometer with nonmagnetic inertial mass made of aluminum was presented in [3, 28] (see Figure 14). The inertial mass is suspended in the magnetic fluid and the elastic Al rod which is connected to the inertial mass provides the restoring force. The movements of the inertial mass will be detected via four quarter-cylindrical electrodes. It is important to notice that this accelerometer is sealed in a cylindrical shell made of low-carbon steel to provide magnetic screen. The sensitivity is 10^{-6} ~ 10^{-9} ms^{-2} /bit [3, 28]. This accelerometer can be applied for measuring earthquakes and tides.

Another biaxial accelerometer was described in [29] (see Figure 15). There are reference electrodes mounted on the top of the cavity and detection electrodes on the button

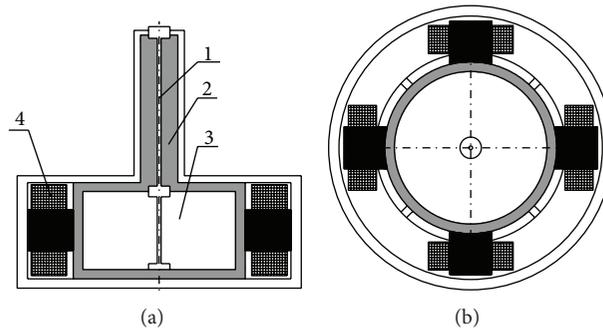


FIGURE 14: Biaxial accelerometer with nonmagnetic mass: (a) profile drawing and (b) sectional drawing: 1—elastic rod, 2—magnetic fluid, 3—inertial mass, and 4—electromagnet.

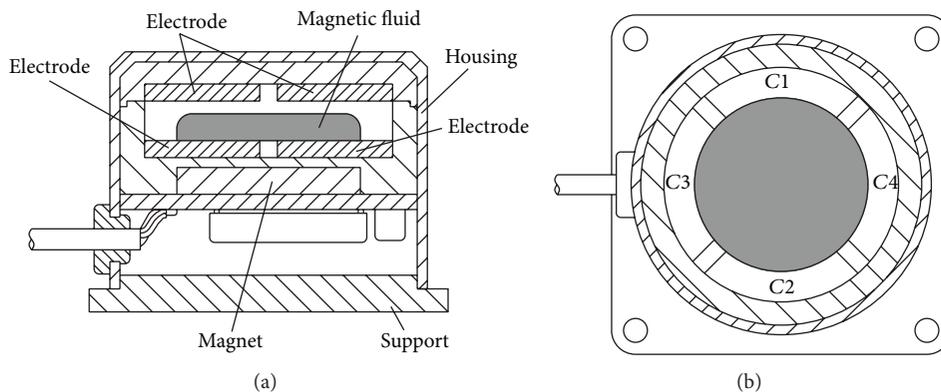


FIGURE 15: Profile drawing and sectional drawing of capacitive magnetic fluid accelerometer.

of the cavity. Magnetic fluid was set between the reference electrodes and the detection electrodes as the inertial mass. Thereby the accelerometer can be detected while the magnetic fluid moves in the horizontal plane by means of a change in the capacitance between electrodes.

The scholars from Italy proposed a prototype of magnetic fluid biaxial accelerometer in 2010 (see Figure 16) [11]. The magnetic fluid is set in the housing which is filled with deionized water. The permanent magnet is mounted underneath. Due to the Rosensweig effect, spikes emerge on the magnetic fluid volume (see Figure 17). The planar coils implemented under the magnetic fluid are able to detect the displacement of magnetic fluid spikes when an external acceleration exists.

Italian scholars also proposed a magnetic fluid accelerometer which can measure linear accelerations of three axes. The characteristic is described in [12] (see Figure 18). The inertial mass is magnetic fluid spike. It sticks to the wall of the glass tube and keeps its shape through the 4 disk magnets around the glass tube (the other two are not shown in Figure 18). The acceleration is detected by the measurement of the spike via the infra-red devices. The response time of this accelerometer is less than $900 \mu\text{s}$.

It is noted that those magnetic fluid accelerometers mentioned before only are able to measure the linear acceleration. However, there are also magnetic fluid accelerometers that can measure both linear acceleration and angular acceleration. Figure 19 presents one of them [35]. The accelerometer

looks like a cube. Apart from the housing, magnetic fluid, and a nonmagnetic body as the inertial mass, the main structure of this accelerometer contains six driving coils and twelve sensing coils. In other words, there are one driving coil and two sensing coils in each direction of the cube. The nonmagnetic body keeps suspension in the magnetic fluid. For both linear acceleration and angular acceleration, total six degrees of freedom accelerations can be measured.

5. A Novel Magnetic Fluid Accelerometer

A novel inductive magnetic fluid was proposed by the author of this paper recently (see Figure 20). It is composed of end covers, housing, inductive coils, cylindrical permanent magnet, and magnetic fluid. The two inductive coils are wound on the outside circumference of the housing. The magnets are set in the cavity of the housing with a little magnetic fluid coating each end. The second-order levitation principle of magnetic fluid provides the suspension of the magnet. It is important to notice that, unlike those accelerometers mentioned above, the restoring force of this accelerometer is generated by the cone angle inside the housing. When the magnet is out of the centre position, the magnetic fluid at one side closer to the end cover will be squeezed. It has effect on the distribution of the magnetic field inside the cavity, which makes the magnetic fluid at one side closer to the end cover be subject to the force larger than the force on the other side. The

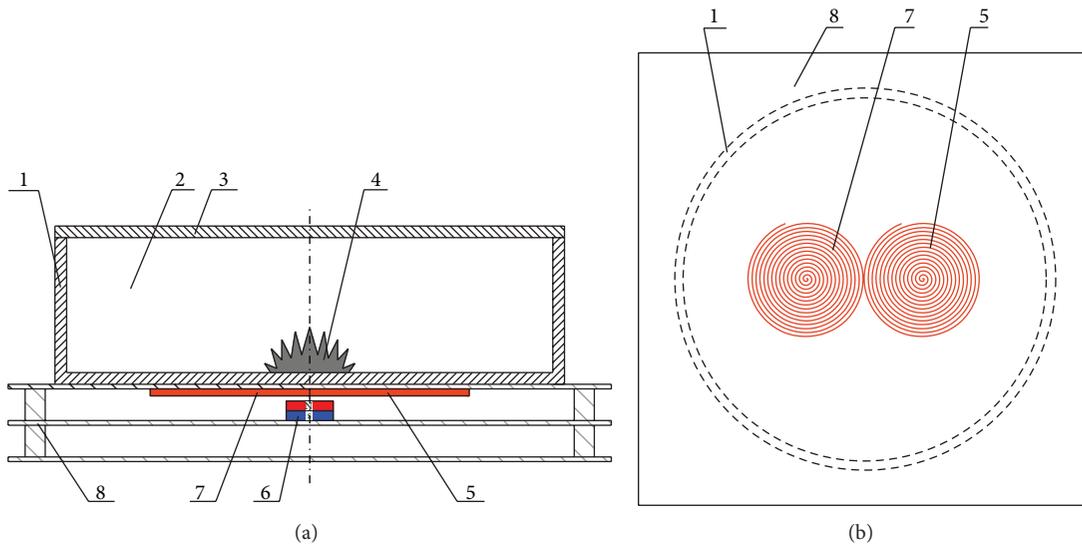


FIGURE 16: Experimental prototype of magnetic fluid accelerometer: 1—housing, 2—deionized water, 3—glass top, 4—magnetic fluid, 5, 7—coils, 6—permanent magnet, and 8—support. (a) Assembled prototype and (b) positions of the planar coils.

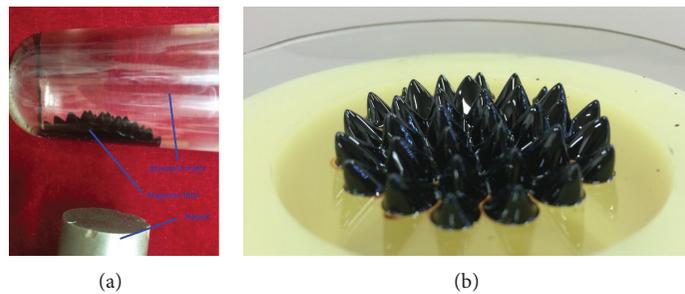


FIGURE 17: The photographs of Rosensweig effect.

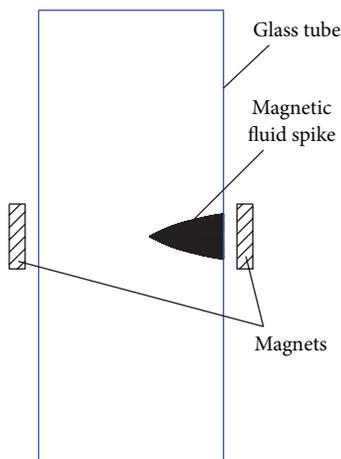


FIGURE 18: Accelerometer with magnetic fluid spike as inertial mass.

difference of the two forces is equal to the value of restoring force.

The magnetic fluid accelerometer has good performance in sensitivity and linearity. According to the linear fit of the

experimental data in Figure 21, the linearity is better than 1.5% in range of 0~0.32 g and the sensitivity is better than 75 mV/g.

6. Conclusions

To sum up, the inertial mass in magnetic fluid accelerometers can be one out of nonmagnetic body, magnet, or magnetic fluid. And the restoring force can be chosen from levitation principle of magnetic fluid or any other available forms. The combination of such options of inertial mass and restoring force is capable of getting different types of magnetic fluid accelerometers.

With rapid development of science and technology, the performance requirement of accelerometers is becoming higher and higher. Compared with the conventional accelerometers, magnetic fluid accelerometer has stronger shock resistance capability, higher sensitivity, lower energy consumption, and better performance in low frequency response [2–5]. Consequently, magnetic fluid accelerometer can satisfy people’s requirement and has a great potential of applications. It could be applied to oil well drilling, seismometry, measurement of tide, robotics, automotive industry,

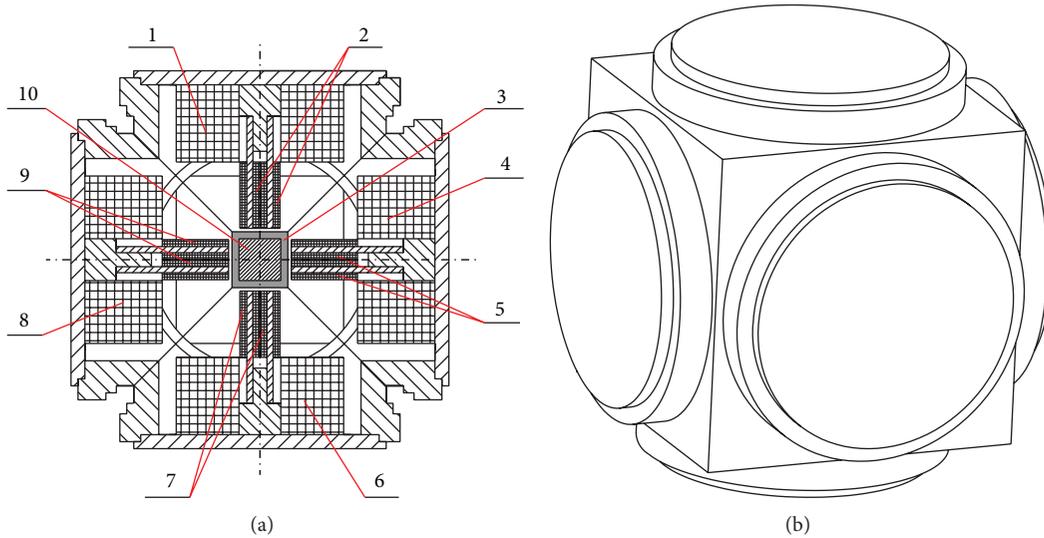


FIGURE 19: Magnetic fluid accelerometer with six degrees of freedom: (a) sectional view: 1, 4, 6, and 8—driving coils, 2, 5, 7, and 9—sensing coils, 3—magnetic fluid, and 10—inertial mass; (b) 3D model.

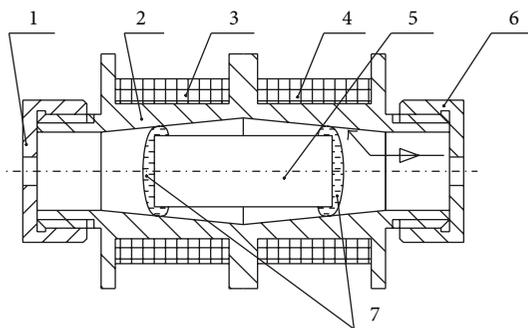


FIGURE 20: Profile drawing of the novel accelerometer: 1, 6—end cover, 2—housing, 3, 4—inductive coils, 5—cylindrical permanent magnet, and 7—magnetic fluid.

aerospace technology, and so forth [2–4, 8, 11, 21, 36]. A few of magnetic fluid accelerometers have been tested and applied in practical projects.

Over several decades, the technology of magnetic fluid accelerometers is growing up. Recent research indicates that the study of magnetic fluid accelerometer mainly focuses on these aspects including miniaturization and integration of structure and design of multiple axes measurement. Besides, the magnetic screen problem is worthy of being taken into consideration. Without the magnetic screen, the magnetic fluid accelerometers could be disturbed by the external magnetic field.

With the further development, it could be expected that magnetic fluid accelerometers will play an important role in multiple engineering fields.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

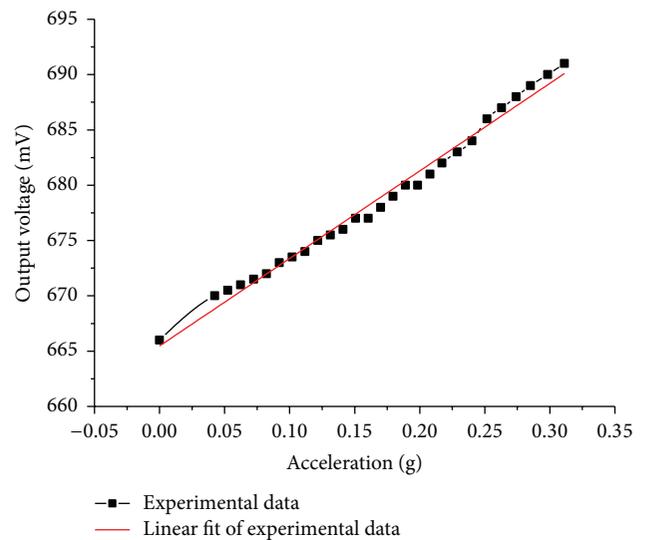


FIGURE 21: Experimental curve of accelerometer.

Acknowledgments

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References

- [1] S. S. Papell, “Low viscosity magnetic fluid obtained by the colloidal suspension of magnetic particles,” Patent US: 3215572, 1965.
- [2] R. L. Bailey, “Lesser known applications of ferrofluids,” *Journal of Magnetism and Magnetic Materials*, vol. 39, no. 1-2, pp. 178–182, 1983.

- [3] M. I. Piso, "Magnetofluidic inertial sensors," *Romanian Reports in Physics*, vol. 47, pp. 437–454, 1995.
- [4] M. I. Piso, "Applications of magnetic fluids for inertial sensors," *Journal of Magnetism and Magnetic Materials*, vol. 201, no. 1–3, pp. 380–384, 1999.
- [5] K. Raj and R. Moskowitz, "Commercial applications of ferrofluids," *Journal of Magnetism and Magnetic Materials*, vol. 85, no. 1–3, pp. 233–245, 1990.
- [6] M. K. Russell, "Magnetic liquid supported linear acceleration sensor," US:4047439, 1977.
- [7] S. Baglio, P. Barrera, and N. Savalli, "Novel ferrofluidic inertial sensors," in *Proceedings of the IEEE Instrumentation and Measurement Technology Conference (IMTC '06)*, pp. 2368–2372, April 2006.
- [8] B. Andò, A. Ascia, S. Baglio, and N. Pitrone, "Magnetic fluids and their use in transducers," *IEEE Instrumentation & Measurement Magazine*, vol. 9, no. 6, pp. 44–47, 2006.
- [9] B. Andò, S. Baglio, and A. Beninato, "A ferrofluid inclinometer with a time domain readout strategy," *Procedia Engineering*, vol. 47, pp. 586–589, 2012.
- [10] B. Andò, A. Ascia, and S. Baglio, "A ferrofluidic inclinometer in the resonant configuration," *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 3, pp. 558–564, 2010.
- [11] B. Andò, A. Ascia, S. Baglio, and A. Beninato, "A ferrofluidic inertial sensor exploiting the rosenzweig effect," *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 5, pp. 1471–1476, 2010.
- [12] B. Andò, S. Baglio, and A. Beninato, "A inertial sensor exploiting a spike shaped ferrofluid," in *Proceedings of the IEEE Instrumentation and Measurement Technology Conference (I2MTC '11)*, pp. 1–5, Binjiang, China, May 2011.
- [13] Q. Li, D. C. Li, X. Z. He, and W. M. Yang, "Study on relationship between output characteristic of accelerator sensor and ferrofluid," *Journal of Electronic Measurement and Instrument*, vol. 25, no. 3, pp. 246–252, 2011.
- [14] Q. Li, Z. Yuan, Y. Yang, J. Lv, and H. Xiang, "Dynamical characteristics of a ferrofluid acceleration sensor," *International Journal of Applied Electromagnetics and Mechanics*, vol. 42, no. 3, pp. 471–477, 2013.
- [15] D. Cao, G. X. Liu, and T. B. Cheng, "Model building and dynamic simulation of magnetic fluid accelerometer," *Modern Manufacturing Engineering*, vol. 11, pp. 15–17, 2011.
- [16] W. Yang, Q. Yang, R. Yan, S. Liu, and W. Yan, "Theoretical and experimental researches on magnetic fluid acceleration sensor," *International Journal of Applied Electromagnetics & Mechanics*, vol. 33, no. 1–2, pp. 655–663, 2010.
- [17] G. X. Liu, W. P. Wang, D. Cao et al., "Factors analysis of magnetic fluid inertial sensor in the second-order Buoyancy," *Science Technology and Engineering*, vol. 7, no. 1, pp. 56–59, 2007.
- [18] X.-Z. He, S.-S. Bi, D.-C. Li, and W.-M. Yang, "Experimental study on the second-order buoyancy of magnetic fluid," *Gong-neng Cailiao/Journal of Functional Materials*, vol. 43, no. 21, pp. 3023–3027, 2012.
- [19] D. C. Li, *Theory and Applications of Magnetic Fluid Seals*, China Science Press, 2010.
- [20] R. E. Rosensweig, *Ferrohydrodynamics*, Cambridge University Press, Cambridge, UK, 1985.
- [21] D. C. Li, *Theory and Applications of Magnetic Fluid*, China Science Press, 2003.
- [22] C. Q. Chi, *Ferrohydrodynamics*, Beijing University of Aeronautics & Astronautics, 1993.
- [23] R. E. Rosensweig, "Fluidmagnetic buoyancy," *AIAA Journal*, vol. 4, no. 10, pp. 1751–1758, 1996.
- [24] R. E. Rosensweig, "Buoyancy and stable levitation of a magnetic body immersed in a magnetizable fluid," *Nature*, vol. 210, no. 5036, pp. 613–614, 1966.
- [25] A. S. Kvitantsev, V. A. Naletova, and V. A. Turkov, "Levitation of magnets and paramagnetic bodies in vessels filled with magnetic fluid," *Fluid Dynamics*, vol. 37, no. 3, pp. 361–368, 2002.
- [26] M. I. Piso, "Magnetic fluid axial accelerometer," Patent RO: 100632, 1991.
- [27] R. Olaru and D. D. Dragoi, "Inductive tilt sensor with magnets and magnetic fluid," *Sensors and Actuators A: Physical*, vol. 120, no. 2, pp. 424–428, 2005.
- [28] M. I. Piso, "Biaxial accelerometer," Patent RO: 98569, 1990.
- [29] N. N. Higashi-Matsuyama, "Acceleration or inclination sensors," Patent US: 4676103, 1987.
- [30] A. G. Pristup, "Magnetofluidic unidirectional accelerometer," Patent US:2007/0214889, 2007.
- [31] N. C. Popa, I. Potencz, L. Vekas, and G. Giula, "Transducer for the measurement of slopes vs. the horizontal," Patent RO: 98430, 1989.
- [32] N. C. Popa, I. De Sabata, I. Anton, I. Potencz, and L. Vékás, "Magnetic fluids in aerodynamic measuring devices," *Journal of Magnetism and Magnetic Materials*, vol. 201, no. 1–3, pp. 385–390, 1999.
- [33] M. I. Piso, "Statical and dynamical acceleration transducer," Patent RO:100632, 1991.
- [34] I. Takaharu, "Two-dimensional acceleration sensor," Patent US no. 4984463, 1991.
- [35] D. V. Simonenko, P. Falls, and A. E. Suprun, "Magnetofluidic acceleration sensor with active suspension," Patent US 7296469, 2007.
- [36] P. Liao, D. C. Li, H. R. Cui, and H. P. Xu, "Preliminary research on magnetic fluid accelerometer," *Journal of Functional Materials*, vol. 35, pp. 573–576, 2006.

