SHORT COMMUNICATIONS

Natural convection gas pendulum and its application in accelerometer and tilt sensor*

ZHANG Fuxue**

(Research Center of Sensor Technology, Beijing Information Technology Institute, Beijing 100101, China)

Received December 6, 2004; revised February 22, 2005

Abstract It is discovered that the natural convection gas has the pendulum characteristic, which leads to the introduction of the new concept of gas pendulum. In this paper, the buoyancy lift of natural convection gas is analyzed in a hermetic chamber, and the relationship between the buoyancy lift and the change of temperature is formulated. The experimental results show that the gas pendulum, similar to the solid pendulum and liquid pendulum, can be utilized to sense the acceleration and the tilt angle.

Keywords: natural convection, accelerometer, tilt sensor.

In the inertial technology field, it is known that the pendulum characteristics of solid or liquid have been utilized to sense the acceleration and the tilt angle[1]. In 1989, it was discovered that similar to the solid pendulum and liquid pendulum, the natural convection gas has the pendulum characteristic, and thus can be utilized to sense the acceleration and tilt angle. Because the proof mass of a gas pendulum accelerometer and tilt sensor is gas with very small mass, the accelerometer and tilt sensor can resist powerful vibration and strong shocks. The gas pendulum has many advantages that solid and liquid pendulums do not have, such as short responding time, low fabrication cost and so on. This paper summarizes the investigation in acceleration and tilt angle sensors of the gas pendulum for the past few years[2,3].

1 Pendulous phenomena of natural convection gas in a hermetic chamber

As shown in Fig. 1 (a), r_1 and r_2 represent hot wires, if a heat source is placed in a hermetic chamber, the gas nearby the heat source will move up for its higher temperature and smaller density ρ, and the gas far from the heat source will sink for its lower temperature and larger density ρ_∞, which forms the erect up natural convection gas in the hermetic chamber. When the chamber is inclined with an angle θ, it is discovered that the natural convection gas always keeps the vertical upward direction (Fig. 1 (b)). This phenomenon of natural convection gas in a hermetic chamber resembles the pendulum characteristics of solid and liquid shown in Figs. 2 and 3, respectively.

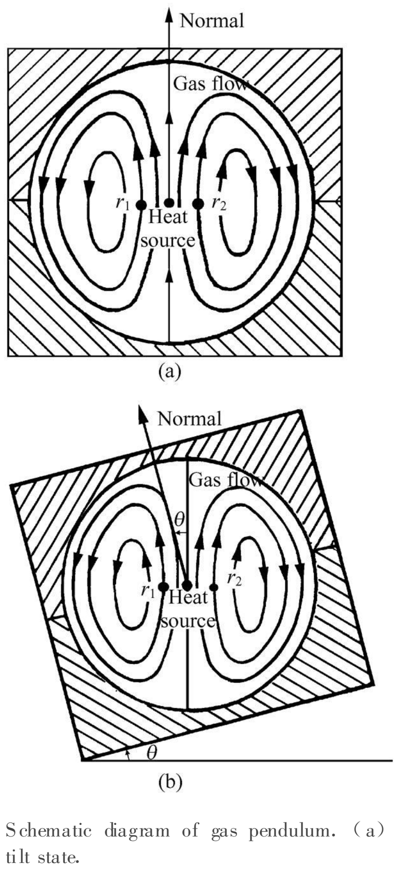

Fig. 1. Schematic diagram of gas pendulum. (a) Horizontal state; (b) tilt state.

* Supported by National Natural Science Foundation of China (Grant No. 60272001)

** E-mail: zhangfuxue@263.net

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

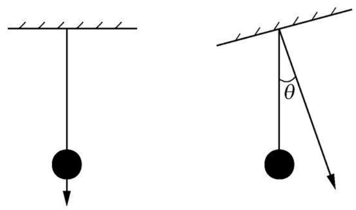

Fig. 2. Schematic diagram of solid pendulum. (a) Horizontal state; (b) tilt state.

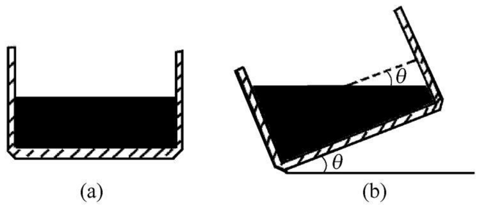

Fig. 3. Schematic diagram of liquid pendulum. (a) Horizontal state; (b) tilt state.

2 Buoyancy lift of natural convection gas in a hermetic chamber

2.1 Buoyancy lift on the surface of the Earth

According to the theory of heat transfer[4], the natural convection gas is affected by the local body force of gravity $\rho\boldsymbol{g}$ and the force $-\rho_\infty \boldsymbol{g}$, which is caused by the gas static pressure gradient. The sum of these two forces is the buoyancy lift which can be expressed as

$$\boldsymbol{F}_{\text{buolift}} = -(\rho_\infty - \rho)\boldsymbol{g}. \tag{1}$$

Here, ρ is the density of the gas heated by the heat source, ρ_∞ is the density of the surrounding unheated gas, $\boldsymbol{g}$ is the gravitational acceleration, and $\boldsymbol{F}_{\text{buolift}}$ is the driving force of the natural convection gas. Because the density of the heated gas is less than that of the unheated gas, the direction of the buoyancy lift is in the opposite direction of the gravity. Driven by the buoyancy lift, the heated gas rises vertically upward.

2.2 Buoyancy lift in absolute coordinate

Eq. (1) is the expression of the buoyancy lift in a relative coordinate regardless of the gravitational acceleration. In the absolute coordinate, when the gravitational acceleration of the hermetic chamber is considered, the local body force of gravity $\rho\boldsymbol{g}$ and the force produced by the gas static pressure gradient $-\rho_\infty \boldsymbol{g}$ should be replaced by $-\rho(\alpha - \boldsymbol{G})$ and $\rho_\infty(\alpha - \boldsymbol{G})$, respectively. The buoyancy lift can be re-expressed as

$$\boldsymbol{F}_{\text{buolift}} = (\rho_\infty - \rho)(\alpha - \boldsymbol{G}), \tag{2}$$

where α is the absolute acceleration of the chamber and $\boldsymbol{G}$ is the constant of universal gravitation. Because of the no-gravitational acceleration (the specific force) $\boldsymbol{f} = \alpha - \boldsymbol{G}$, we can obtain

$$\boldsymbol{F}_{\text{buolift}} = (\rho_\infty - \rho)\boldsymbol{f}. \tag{3}$$

From Eq. (3), we can know that the direction of the buoyancy lift is the same as the direction of the specific force $\boldsymbol{f}$ and the magnitude of the buoyancy lift is proportional to that of $\boldsymbol{f}$.

2.3 Relationship between buoyancy lift and change of temperature

In the natural convection gas, the density difference of fluid is caused by the temperature difference, and therefore the buoyancy lift is a function of the temperature difference. When the fluid pressure is a constant, the change ratio of volume caused by a unit of temperature variation is called the β— coefficient of volume expansion. Let j equal the specific volume of the fluid ($j = 1/\rho$), and β can be expressed as

$$\beta = \frac{\frac{\mathrm{d}j}{j}}{\mathrm{d}T} = \frac{1}{j}\left(\frac{\partial j}{\partial T}\right)_p,$$

where the subscript p representing the pressure is a constant. For gas, from $j = 1/\rho$, we can deduce

$$\frac{\mathrm{d}j}{\mathrm{d}\rho} = -\left(\frac{1}{\rho^2}\right),$$

$$\left(\frac{\partial j}{\partial T}\right)_p = -\frac{1}{\rho^2}\left(\frac{\partial \rho}{\partial T}\right)_p.$$

Therefore, the coefficient of the gas thermal expansion is

$$\beta = \frac{-\frac{1}{\rho^2}\left(\frac{\partial \rho}{\partial T}\right)_p}{\frac{1}{\rho}} = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p.$$

When the change of temperature is small, the density difference of gas can be approximately equal to[4]

$$\Delta\rho = \rho\beta\Delta T.$$

Therefore, the buoyancy lift of a unit volume is

$$\boldsymbol{F}_{\text{buolift}} = (\rho_\infty - \rho)\boldsymbol{f} = \rho\beta\Delta T\boldsymbol{f}. \tag{4}$$

3 Gas pendulum accelerometer and tilt sensor

Solid and liquid pendulum accelerometer and tilt sensor utilize the pendulum characteristics of solid and liquid respectively in the gravitation operation, and

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

they can measure the acceleration and tilt angle although the sensing component can use mature technologies such as capacitance, resistance or other methods[1]. Gas pendulum accelerometer and tilt sensor utilize the pendulum characteristic of the buoyancy lift generated by natural convection gas (Fig. 1). Two thermal sensing resistors r_1 and r_2, namely hotwires, in the hermetic chamber were employed to measure the acceleration and tilt angle[5,6]. Fig. 4 shows the sensing component structure of a gas pendulum accelerometer. In this structure, two hotwires r_1 and r_2 form the variable arms of the Whetstone Bridge. The invariable arms have equal resistances, i.e. R_1 equals R_2. The input axis is along the symmetry axis of the chamber. When the power is on, the hotwire heats the gas around it, and a natural convection is produced as shown in Fig. 1 (a). In the convection field, two hot wires of r_1 and r_2 are symmetric. Because they sense the same temperature, their resistances are equal. The output of the bridge circuit is zero. When the chamber is affected by acceleration, the symmetry of the natural convection field is distorted. The intension of heat gas flow heats r_2 more than it heats r_1. Therefore, the temperatures and the corresponding resistances of r_1 and r_2 are not equal to each other. The bridge outputs a voltage signal corresponding to the acceleration. The signal processing circuit is shown in Fig. 5. When the voltage signal is applied, the signal processing circuit gives an output signal corresponding to the input acceleration.

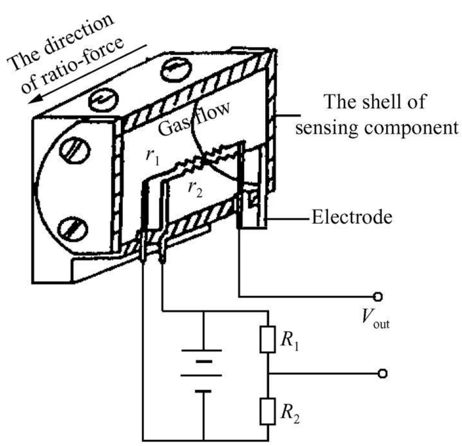

Fig. 4. Sensor component sketch map of gas pendulum accelerometer.

In the structure of sensitive element with chamber shown in Fig. 4, the two hotwires not only act as the heat source but also as the sensing element. Experimental results show that the measurement range of gas pendulum accelerometer can reach $\pm 8\boldsymbol{g}$ and the non-linearity is less than 1% FS. Fig. 6 shows the output voltage of a gas pendulum accelerometer.

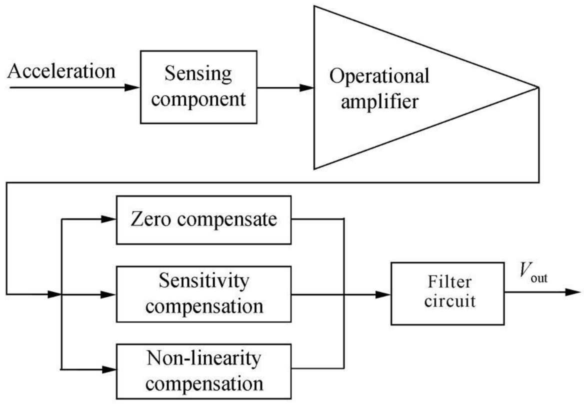

Fig. 5. Block diagram of signal processing circuit.

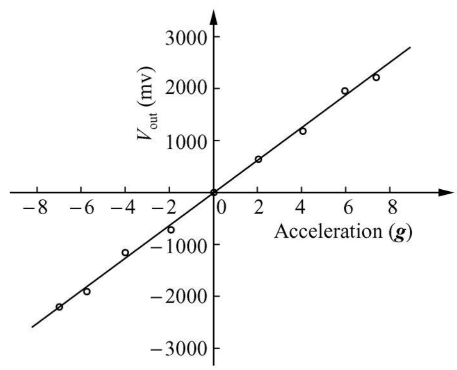

Fig. 6. Output voltage of the gas pendulum accelerometer.

In gravitational field, experiments are conducted with the structure shown in Fig. 7. The chamber is cylindrical. The two hot wires are placed in parallel with the axis of the chamber acting as the heat source as well as the sensing elements. The natural convection chamber of this structure can be used to measure

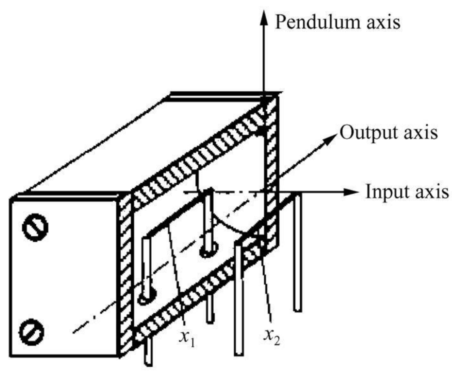

Fig. 7. Sensing element structure of the gas pendulum tilt sensor.

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

tilt angles as well. Experiments have shown that the measurement range can be as large as ±45°, and the non-linearity is less than 1% FS with the resolution less than 0.01″. The output voltage of the gas pendulum tilt sensor is shown in Fig. 8.

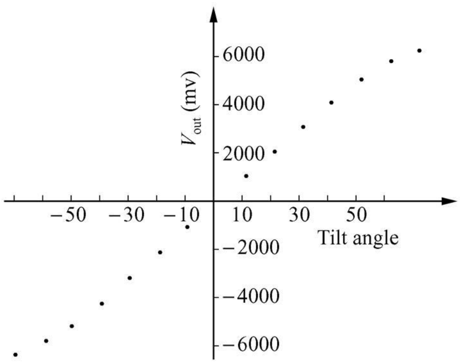

Fig. 8. The output voltage (V_{out}) of the gas pendulum tilt angle sensor.

4 Conclusion

(1) The buoyancy lift is the driving force of natural convection gas.

(2) Under the action of buoyancy lift, natural convection gas has the pendulum characteristic.

(3) The pendulum characteristic of natural convection gas can be utilized to make accelerometer and tilt sensor.

References

1 Yu B., Chen Y.X. and Guo X.Z. Inertial Technology (in Chinese), 1st ed. Beijing: Publishing House of Beijing, University of Aeronautics and Astronautics, 1994.
2 Zhang F.X. The ominidirection gas pendulum horizontal attitude sensor. The Defensive Patent of China 99 1 16757.0, 1999-08-29.
3 Zhang F.X. The gas pendulum horizontal attitude sensor. The Defensive Patent of China 99 1 18007.0, 2000-01-31.
4 Warren M.R., Games P.H. and Ejup N.G. Handbook of Heat Transfer Fundamentals, 2nd ed. New York: McGraw-Hill, 1985.
5 Zhang F.X. Pendulons characteristics of the gas flow in a hermetic chamber. Acta Electronica Sinica (in Chinese), 1999, 27(11): 141—142.
6 Zhang F.X. Gas pendulum acceleration sensor. Chinese Journal of Electronics, 2000, 9(1): 16.

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net