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The Accelerometer and Tilt Sensor Based on Natural Convection Gas Pendulum *

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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 have shown that the gas pendulum can be utilized to sense the acceleration and the tilt angle similar to the solid pendulum and liquid pendulum.**

Index terms - Natural Convection; Accelerometer; Tilt sensor

I. INTRODUCTION

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. In 1989, it was discovered that the natural convection has the pendulum characteristic, similar to the solid pendulum and liquid pendulum, and thus can be utilized to sense the acceleration and tilt angle [1]. 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, and have many advantages, such as short responding time, low fabrication cost and so on, that solid and liquid pendulums do not have. This paper summarizes the investigation in acceleration and tilt angle sensors of the gas pendulum for the past few years [2],[3].

Ⅱ. THE PENDULOUS PHENOMENA OF NATURAL CONVECTION GAS IN A HERMETIC CHAMBER

As shown in Fig.1.(a), 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 as shown in 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.

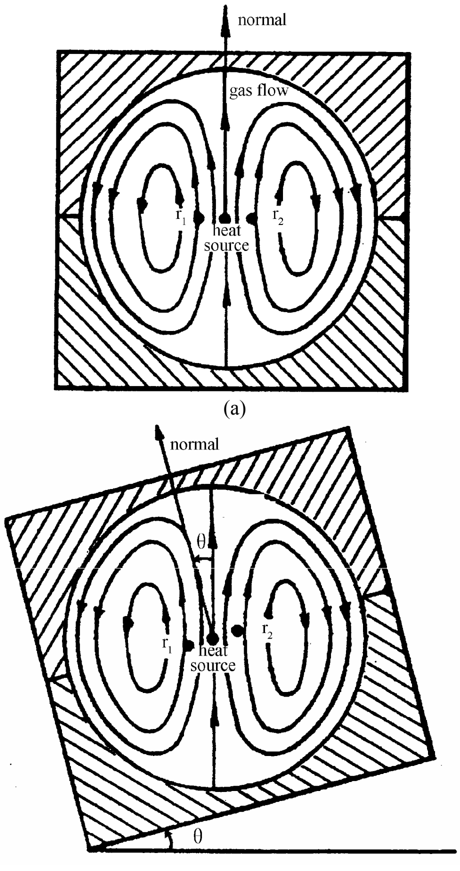

Fig.1. The phenomena of gas pendulum: (a) Horizontal state, (b) Tilt state

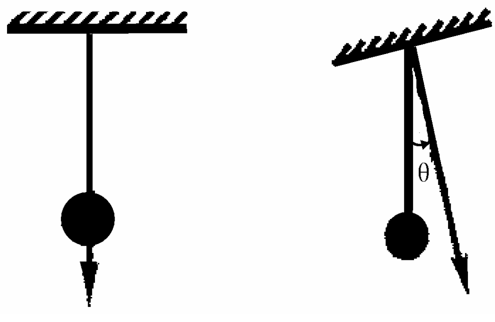

Fig. 2. The phenomena of solid pendulum: (a) Horizontal state, (b) Tilt state

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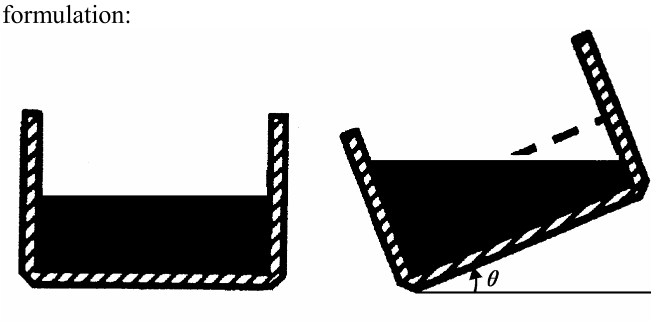
III. THE BUOYANCY LIFT OF NATURAL CONVECTION GAS IN A HERMETIC CHAMBER

A. Buoyancy Lift on the Surface of the Earth

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



(a) (b)

Fig. 3. The phenomena of liquid pendulum:(a) Horizontal state, (b) Tilt state

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

In Equation (1), ρ is the density of the gas heated by the heat source, ρ_∞ the density of the surrounding unheated gas, and $\boldsymbol{g}$ the gravity acceleration. $\boldsymbol{F}_{buolift}$ is the driving force of the natural convection gas, because this 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. By driven buoyancy lift, the heated gas rises vertically upward.

B. Buoyancy Lift in Absolute Coordinate

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

$$F_{buolift}=(\rho_\infty-\rho)\ (\alpha-G) \quad (2)$$

In Equation (2), α is the absolute acceleration of the chamber and G the gravitational acceleration. Because of no-gravitational acceleration (the specific force) $f=\alpha$-G, one obtains

$$F_{buolift}=(\rho_\infty-\rho)f \quad (3)$$

By Equation (3), it is known that the direction of the buoyancy lift is the same as the direction of the specific force f and the magnitude of the buoyancy lift is proportional to that of f.

C. 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, a unit of temperature variation causes the change ratio of volume is named β-coefficient of volume expansion. Let j equal to the specific volume of the fluid ($j=1/\rho$), and β can be expressed as

$$\beta=\frac{\frac{dj}{j}}{dT}=\frac{1}{j}\left(\frac{\partial j}{\partial T}\right)_p$$

Where the subscript p which denotes the pressure is a constant. For gas, from $j=1/\rho$, one can deduce

$$dj=-\left(\frac{1}{\rho^2}\right)dp$$

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

Therefore, the coefficient of the gas thermal expansion shown as follows:

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

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

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

IV. GAS PENDULUM ACCELEROMETER AND TILT SENSOR

Solid and liquid pendulum accelerometer and tilt sensor respectively utilize the pendulum characteristic of solid and liquid in the gravitate operation, and they can sense the acceleration and tilt angle though the sensing component can use capacitance, resistance or other methods, which are matured technologies[1]. Gas pendulum accelerometer and tilt sensor utilize the pendulum characteristic of the buoyancy lift generated by natural convection gas as shown in Fig.1. Two thermal sensing resistors r_1 and r_2, namely hotwires, in t h e

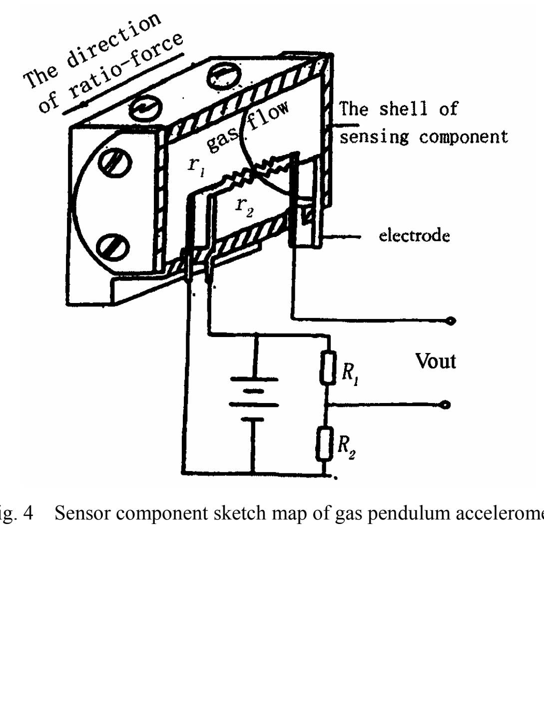


Fig. 4 Sensor component sketch map of gas pendulum accelerometer

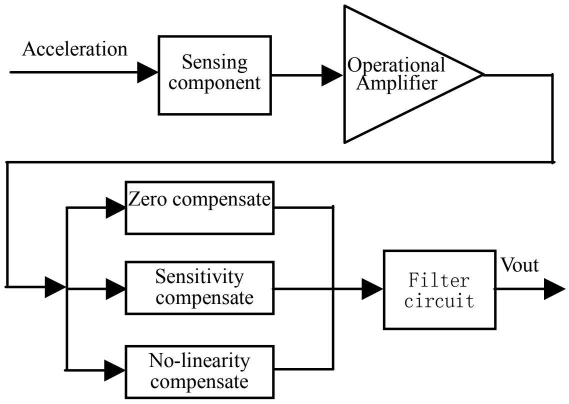


Fig. 5 Block Diagram of signal processing circuit

hermetic chamber were employed to sense the acceleration and tilt angle in [5] and [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 Wheastone 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 higher than it does 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. It processes voltage signal and gives an output signal reflection the input acceleration.

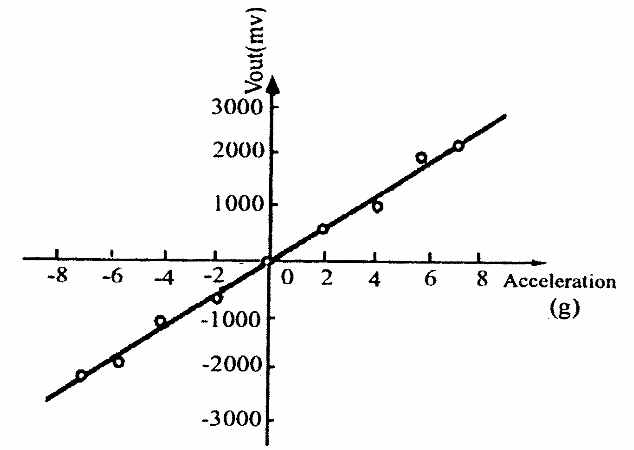


Fig. 6 Output voltage of the gas pendulum accelerometer

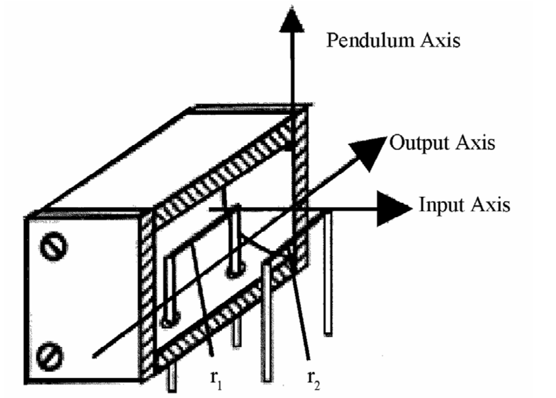


Fig. 7 Structure of the gas pendulum tilt sensor Sensing Element

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 ±8g and the non-linearity is less than 1%FS. Fig.6 shows the output voltage of a gas pendulum accelerometer.

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

V. CONCLUSION

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

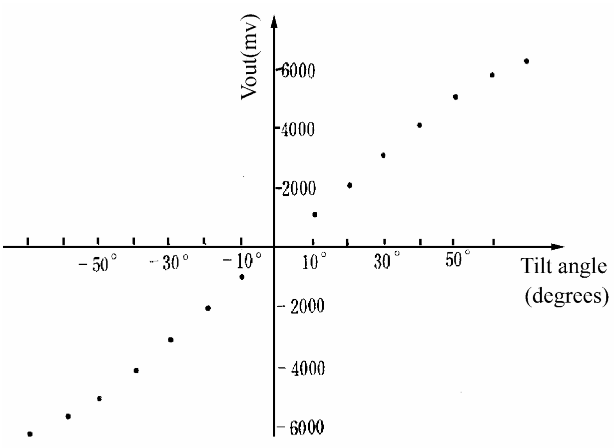


Fig. 8 The output voltage (V_{out}) of the gas pendulum tilt angle sensor gas.

2) Under the buoyancy lift affecting, natural convection gas has the pendulum characteristic.

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

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