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力平衡式真空微电子加速度传感器的机电耦合特性

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摘要：力平衡式真空微电子加速度传感器的惯性敏感元件不仅受弹性力的作用，同时还受静电力的作用，其总刚度为机械刚度和由静电力引入的电学刚度之和。本文利用平行板电容器模型计算发射电极间的静电力，并引入一个修正系数描述发射锥尖阵列的影响，对传感器性能进行了理论分析。分析表明，提高偏置电压可以改善传感器的线性度和灵敏度，通过调节偏置电压来调整系统的刚度和阻尼比可使其具有更好的动态特性。由于静电吸合效应的影响，质量块的位移必须小于偏置电极间初始间距的 1/3，系统才能稳定。为了获得较好的动态特性，需要确定一个由偏置电压决定的优化工作点。实验结果表明，当设置发射电压和反馈偏置电压分别为 1.953 V 和 5.478 V 时，该真空加速度传感器的灵敏度达到 557 mV/g，非线性度为 0.95%，传感器系统具有良好的性能。

关　键　词：机电耦合；力平衡；真空微电子；加速度传感器
中图分类号：TP212.12　　**文献标识码**：A

Electromechanical coupling characteristics for force-balanced vacuum microelectronic accelerometer

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Abstract: The inertia sensitive component of a force-balanced vacuum microelectronic accelerometer is effected by both the elastic force and the electrostatic force, and its total stiffness is the sum of the mechanical stiffness of the beams and the equivalent stiffness produced by the electrostatic force. In considerasion of the effect of emitting tip array, this paper introduces a revised constant α greater than 1 to compute the actual electrostatic force by using the model of a parallel plate capacitor. The analysis shows that the linearity and sensitivity of the vacuum microelectronic accelerometer has been improved by increasing preload deflection voltages, so the stiffness and damping ratio of the system can be adjusted by modulating the voltage between the two deflection electrodes. Considering the affect by a

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pull-in, the displacement of proof mass must be less than one-third of the original distance between two deflection electrodes. Moreover, in order to obtain good dynamic characteristics, an optimum working point determined by the preload deflection voltage must be set. The experimental results show that the nonlinearity and sensitivity of the accelerometer are 0.95% and 557 mV/g when the deflection voltage and the emission voltage are 5.478 V and 1.953 V, respectively, which indicates that the sensor has good performance.

Key words: electromechanical coupling; force balance; vacuum microelectronics; accelerometer

1 Introduction

At present, miniaturization, intelligence and integration have become the development trend of accelerometer. The closed-loop force-balanced vacuum microelectronic accelerometer using feedback control technology and sensor technology has become a hotspot. In this paper, force-balanced vacuum microelectronic accelerometer is analyzed with electrostatic force balance technique. The feedback voltage changes with the acceleration. Under the effect of the feedback force, the mass is kept in the balance position to make the emission current constant[1]. So the external acceleration can be evaluated by measuring the feedback voltage[2]. Since the existence of feedback electrostatic force, the system is no longer a pure mechanical system. A deep analysis of the influence of feedback electrostatic force to total stiffness, sensitivity, linearity and working point of the accelerometer is achieved in this paper.

2 Analysis of mechanical characteristics

IntelliSuite is used to analyze the mechanical characteristics of the accelerometer. The model with 4-L-beams/mass structure is shown in Fig. 1. The size of the proof mass is 2 100 μm×2 100 μm×80 μm. The size of each long beam and each short beam are 2 290 μm×100 μm×20 μm and 90 μm×200 μm×20 μm respectively. The material is silicon. Because the mass is thicker than the beams and the mass is symmetrically constrained and almost no deformation, the mass block should be meshed largely. On the other hand, the beams which are greatly deformed should be divided into smaller grids[3]. Fig. 2 shows the analysis results of the mass block is applied an acceleration of 10 g on z axis. The largest displacement of the mass is 2.21 μm. Thus, the stiffness of the structure is 38.4 N/m[4-5].

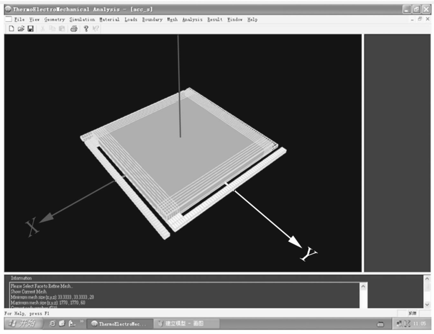

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Fig. 1 Three dimensional model of sensitive components of vacuum microelectronic accelerometer

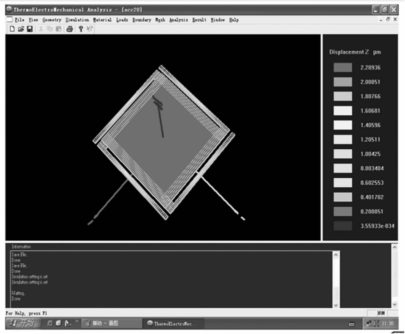

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Fig. 2 Analysis results of mechanical characteristics

When the accelerometer is working at low frequency, the typical mass-spring-damper model can be adopted to analyze the sensor. Thus, the resonant angle frequency and the steady state sensitivity of the sensitive element can be expressed as

$$\omega_0=\sqrt{k_m/m},\ S=m/k_m,$$

where m is the total mass of the mass block, and k_m is the stiffness of the beams[6].

3 Influence of electrostatic force on characteristics

The structure of the accelerometer is shown in Fig. 3 which consists of a pair of deflection electrodes, the anode and the cathode. The cathode is making up of a tip array with the density of about 36 000/mm^2. When there is a deflection voltage between the deflection electrodes and an emission voltage between the anode and the cathode, the electrostatic force applied on the mass should be the sum of the electrostatic force between the deflection electrodes and the electrostatic force between the anode and the cathode. It can be expressed as

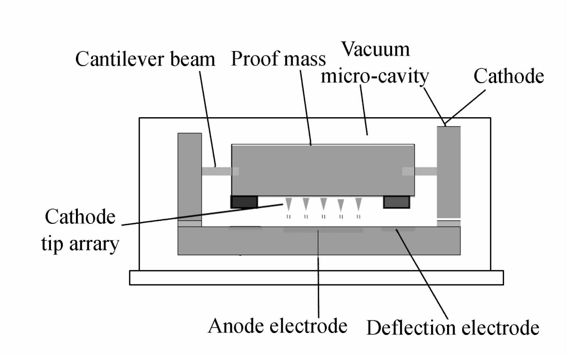

Fig. 3 Structure diagram of vacuum microelectronic accelerometer

$$F_e=-\frac{\varepsilon A_f U_f^2}{2d^2}-\alpha\frac{\varepsilon A_e U_e^2}{2d^2}\ , \tag{1}$$

where ε is the permittivity, d is the distance between the anode and the cathode, A_f and A_e are the area of the deflection polar plate and the emission area respectively, and U_f and U_e are the preload deflection voltage and the emission voltage. Because of using the model of parallel plate capacitors to compute electrostatic force between the emitting electrodes and the existence of emitting tip array, a revised constant α greater than 1 must be introduced when computing the actual electrostatic force between the emitting electrodes, which is very important for determining the total stiffness of the system.

When the external acceleration is zero, the proof mass will be kept in equilibrium state under the effect of electrostatic force and elastic force applied on the mass block. Then,

$$F_m=k_m\Delta d=-F_e=\frac{\varepsilon A_f U_f^2}{2d^2}+\frac{\alpha\varepsilon A_e U_e^2}{2d^2}\ , \tag{2}$$

where $\Delta d=d_0-d$ is the size of elastic deformation of the cantilever, k_m is the stiffness of the cantilever beam, and d_0 is the original distance between the anode and the cathode.

When an external acceleration is applied on the mass, there will be a very small displacement x. Hence, the electrostatic force applied on the mass block can be expressed as

$$F_e(x)=-\frac{\varepsilon A_f U_f^2}{2(d-x)^2}-\frac{\alpha\varepsilon A_e U_e^2}{2(d-x)^2}\ , \tag{3}$$

where U_f is the voltage applied on the deflection electrodes which is the sum of the preload deflection voltage U_{def} and the feedback voltage U_{fb}.

But, the proof mass are approximately kept in the balance position under the effect of the feedback forces, that is to say, $d-x\approx d$. Therefore

$$k_e=\frac{\partial F_e(x)}{\partial x}\approx-\frac{\varepsilon}{d^3}(A_f U_f^2+\alpha A_e U_e^2)\ , \tag{4}$$

where k_e is the equivalent stiffness produced by the electrostatic force[4]. So the total stiffness should be equal to the sum of the stiffness of the cantilever and the equivalent stiffness produced by the electrostatic force, that is

$$k=k_m+k_e=k_m-\frac{\varepsilon}{d^3}(A_f U_f^2+\alpha A_e U_e^2)\ , \tag{5}$$

According to the analysis of force-balanced accelerometer above, in order to make the accelerometer work stably, there must be a sufficient elastic stiffness to offset the effect of the electrostatic force, thus

$$k_m + k_e > 0$$

Therefore, the damping ratio and steady sensitivity of the system can be given as

$$\xi = b/2\sqrt{m(k_{\mathrm{m}} - k_{\mathrm{e}})},\ S = m/(k_{\mathrm{m}} + k_{\mathrm{e}}).$$

So, the damping ratio of the system can be adjusted by modulating the preload deflection voltage applied on the feedback electrodes. If the damping ratio could be adjusted by modulating the circuit, a small overshoot and a short stability time are gotten, that is to say, better dynamic characteristics can be obtained[6]. Because of adopting of electrostatic force feedback which reduces the total stiffness, the system has lower resonant frequency and higher sensitivity.

4 Effect of preload deflection voltage on linearity and working point

When the mass is in steady state under the effect of the external acceleration a, the proof mass will be approximately kept in the balance position[7]. Thus,

$$ma = F_{\mathrm{m}} - \frac{\varepsilon A_f}{2d^2}(U_{\mathrm{def}} + U_{\mathrm{fb}})^2 - \frac{\alpha\varepsilon}{2d^2}A_{\mathrm{e}}U_{\mathrm{e}}^2. \quad (6)$$

The external acceleration is given by substituting formula (2) into formula(6)

$$a = -\frac{\varepsilon A_{\mathrm{f}} U_{\mathrm{def}}}{md^2}U_{\mathrm{fb}} - \frac{\varepsilon A_{\mathrm{f}}}{2md^2}U_{\mathrm{fb}}^2. \quad (7)$$

According to the equation above, the external acceleration can be measured by measuring feedback voltage. Moreover, the preload deflection voltage has great influence on the linearity of the accelerometer. The relationship between the acceleration and the feedback voltage the is shown in Fig. 4 and Fig. 5 respectively the preload deflection voltage is 2 V and 10 V. It is seen from the figure that the accelerometer's linearity could be improved by increasing the preload deflection voltage. When U_{def} is much larger than U_{fb}, the influence of the quadratic term could be neglected[8]. Therefore, there is a linear relationship between acceleration a and feedback voltage U_{fb} approximately. That is

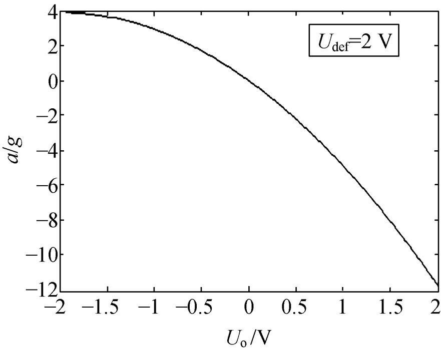

Fig. 4 Relationship between input and output when deflection voltage is 2 V

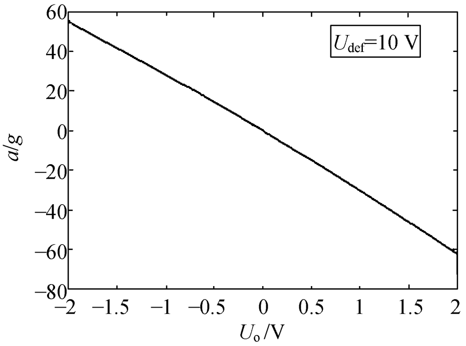

Fig. 5 Relationship between input and output when deflection voltage is 10 V

$$a = -\frac{\varepsilon A_{\mathrm{f}} U_{\mathrm{def}}}{md^2}U_{\mathrm{fb}}. \quad (8)$$

But on the other hand, affected by the electrostatic force, higher preload deflection voltage will induce pull-in. Only when the displacement of proof mass is less than one-third of the original distance between the deflection electrodes, the accelerometer can avoid pull-in[1]. When the sensor is working at 0 g and +1 g, the equations of the force of the mass are given as

$$k\Delta d = \frac{\alpha\varepsilon A_{\mathrm{e}} U_{\mathrm{e}}^2}{2d^2} + \frac{\varepsilon A_{\mathrm{f}}(U_{\mathrm{def}} + U_{\mathrm{fb+}})^2}{2d^2} + mg\ , \quad (9)$$

$$k\Delta d = \frac{\alpha\varepsilon A_{\mathrm{e}} U_{\mathrm{e}}^2}{2d^2} + \frac{\varepsilon A_f U_{\mathrm{def}}^2}{2d^2}\ , \quad (10)$$

where $\Delta d = d_0 - d$ is the size of elastic deformation of the cantilever, and $U_{\mathrm{fb+}}$ is the feedback voltage when the sensor is working at $+1g$. Moreover, the feedback voltage can be zero by adjusting the circuit when the acceleration is zero. Therefore, the working point and the revised constant α could be estimated by measuring the preload deflection voltage and feedback voltage. That is

$$\Delta d = d_0 - \sqrt{-\frac{\varepsilon A_{\mathrm{f}}}{2mg}(U_{\mathrm{fb}}^2 + 2U_{\mathrm{def}}U_{\mathrm{fb+}})}\ , \quad (11)$$

$$\alpha = -\frac{k\Delta d A_{\mathrm{f}}(U_{\mathrm{fb+}}^2 + 2U_{\mathrm{def}}U_{\mathrm{fb+}})}{2mgA_{\mathrm{e}}U_{\mathrm{e}}^2} - \frac{A_{\mathrm{f}}U_{\mathrm{def}}^2}{A_{\mathrm{e}}U_{\mathrm{e}}^2}\ . \quad (12)$$

5 Test

To test the non-linearity and sensitivity of the accelerometer, a system including high precision dividing head, oscillograph (Agilent Technologies DSO6014A), high precision d. c. voltage source etc. is established. The accelerometer 10＃ is tested by using 12 points method. Output curve of static rolling experiment in gravitational field is shown in Fig. 6, while the deflection voltage and the emission voltage are 5.478 V and 1.953 V respectively, where abscissa is turnover angle and ordinate is the corresponding output voltage. By using least squares fitting, the output fitting curve of accelerometer is obtained which is shown in Fig. 7. The results show that the accelerometer has a sensitivity of 557 mV/g and a non-linearity of 0.95% which shows that the sensor has good performance[9].

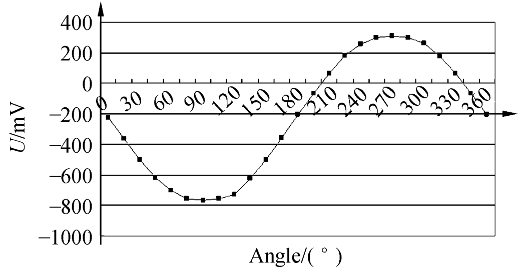

Fig. 6 Output curve of static rolling experiment in gravitational field

More accelerometers are tested for the performance contrast with accelerometer 10＃.

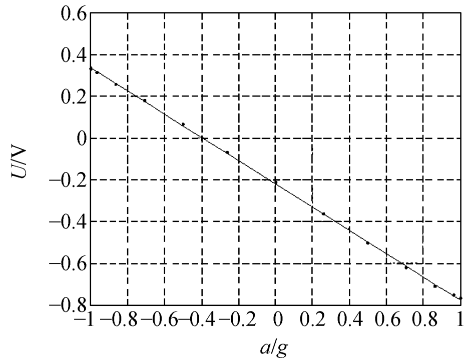

Fig. 7 Output fitting curve of accelerometer

6 Conclusions

In this research, a theoretical analysis of electromechanical coupling characteristics for force-balanced vacuum microelectronic accelerometer is achieved and a test system is established. The analysis results show that the linearity and sensitivity of the vacuum microelectronic accelerometer can be improved by increasing deflection voltage. According to the experimental results, when the deflection voltage and the emission voltage are 5.478 V and 1.953 V respectively, the accelerometer has a sensitivity of 557 mV/g and a non-linearity of 0.95%. Moreover, in order to obtain better dynamic characteristics, the damping ratio of the system should be adjusted by modulating the preload deflection voltage applied on the deflection electrodes. But affected by the pull-in, the optimum preload deflection voltage need to be analyzed, which be the next working in the future.

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