Micromachined Accelerometer with Frame Structure

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Abstract. A novel differential capacitive accelerometer with a frame-mass structure is presented in the paper. The equivalent circuit model of the accelerometer is simulated with the software SPICE. The accelerometer with the frame-mass can increase the effectual static capacitance. The micro-accelerometer, with the size of 2800×3000×60µm, the static capacitance of 3.618pf, and the inertial mass of 0.14mg, can be implemented in closed-loop system efficiently, and endure overload of 5000g or above. Through the systematic simulation, the accelerometer with the sensitivity of 75mv/g, the full-scale range of 0~±50g and the system bandwidth of 10 KHz, is supplied with the voltage of 18V.

1. Introduction
At present, micro-machined accelerometers are widely applied in many kinds of inertial navigation system as well as the center of the vibration examination system for their small size, low cost and low power consumption [1]. To further improve the performance, typically, electrostatic force feedback is used to increase the bandwidth, linearity and dynamic range of the sensor [2]. Traditional micro accelerometer can be used in hybrid-integrated accelerometer system. For example, our group has designed a hybrid-integrated micro-accelerometer with self-test function, which sensitivity is 18mV/g and frequency bandwidth is 1 KHz [3]; and the University of Michigan has reported a hybrid silicon-on-glass accelerometer with a measured sensitivity of 40mV/g [4]. But those structures generally have too small capacitance and are too weighty to be implemented in hybrid-integrated closed-loop system.

The novel structure presented in this paper can be efficiently implemented in closed-loop system by increasing its static capacitance and reducing its mass. The micro-accelerometer can achieved a high sensitivity, wide bandwidth, and good linearity.

2. Device Design
The structure of the accelerometer is shown as Figure 1. The frame-mass structure with comb electrodes is suspended by two folded beams and anchored to the glass substrate. The movable electrodes and the fixed electrodes form a pair of sensing capacitance and a pair of driving capacitance. There are 60 pairs of comb fingers attached to the mass. Among them, 7 pairs of fingers act as the sensing fingers and the rest are designed as driving fingers.

When the structure is applied an acceleration, the proof mass with the movable electrodes moves. When it moves closer to one side of the fixed electrodes, the capacitance between the movable electrodes and the fixed electrodes increases. At the same time, the movable electrodes move away from the other side of the fixed electrodes, and the capacitance between them decreases. The readout circuit can detect the change of the differential capacitance.
In order to estimate the performance of the accelerometer and provide parameters for the closed-loop simulation, we implemented the static, modal and the stress analysis of the structure with the FEM (Finite Element Method) software ANSYS.

When the acceleration of $1g$ is applied to the structure at the sensitive direction, the displacement of the proof mass is $2.94 \times 10^{-9} m/g$, in other words, the mechanical sensitivity of the accelerometer is $2.94 \times 10^{-9} m/g$. In the modal analysis, we obtained the first vibration mode and second vibration mode, as shown in Figure 2. The resonant frequencies of them are 9.3 KHz and 20 KHz. When the accelerations of 5000g at different directions are applied to the structure, the maximal stress of the structure is $1.78 \times 10^8 Pa$. Thus we obtained that the overload immunity of the structure is more than 5000g.

3. System Simulation

Through the simulation with the software ANSYS, some parameters of the micro accelerometer have been obtained for the SPICE model. With the software SPICE, the performances of the whole closed-loop system are simulated and the parameters of the accelerometer are achieved.

3.1. Closed-loop system design

The accelerometer can be modelled by a second-order mass-damper-spring system, as shown in Figure 3 [5,6]. $M$, the mass of the frame-mass, $K$, the constant of the effective spring of the folded-beams, and $D$, the system damping coefficient are the three factors that affect the characteristics of the micro-accelerometer.

Using Newton’s second law, the accelerometer model can be described by the following equations.

$$M \frac{d^2x}{dt^2} + D \frac{dx}{dt} + Kx = ma$$

(1)
where $a$ is the external acceleration, $x$ is the proof mass’s displacement.

Using the software SPICE, we created the equivalent circuit model of the open-loop system of the accelerometer, as shown in Figure 4. The function of it is shown as (2), where $u$ is the value of the voltage on the capacitance $C_1$.

$$C \frac{d^2(R_1 C_1 u)}{dt^2} + G \frac{d(R_1 C_1 u)}{dt} + \frac{1}{R_1^2 C_1} (R_1 C_1 u) = I_{\text{EXT}}$$

The form of function (1) and (2) is entirely identical, thus we can use the electrical parameters to simulate the mechanical parameters. The corresponding relationship of them is shown in Table 1.

| Mechanical parameter | Electrical parameter |
|----------------------|----------------------|
| $M$                  | $C$                  |
| $D$                  | $G$                  |
| $K$                  | $1/(R_1^2 C_1)$      |
| $X(t)$               | $R_1 C_1 u$          |
| $F_{\text{EXT}}(ma)$ | $I_{\text{EXT}}$     |

By applying the feedback voltage to the movable electrodes, the voltage between the movable electrodes and the two sides of the fixed electrodes is changed, thus two electrostatic forces will be generated on the mass, which can maintain a negative, linear feedback relationship [7].

The closed-loop system equivalent circuit of the accelerometer is shown in Figure 5. Compared with the open-loop system equivalent circuit, a feedback resistance $R_2$ has been added to obtain a feedback current. Choosing the resistance properly can make the value of the current the same as the feedback force.
3.2. Simulation and results

Figure 6 shows the curves of the value of the voltage on the capacitance $C_1$, which are proportional to the displacement of the open-loop system and the closed-loop system under the same load of 1g. The curves show that the displacement of the open-loop system is much greater than that of the closed-loop system, in other words, the proof mass works steadily around the balance position with the electrostatic force in closed-loop system.

Through the simulation of the whole closed-loop system, the value of the sensitivity, 75mv/g, is obtained, shown in Figure 7. The full-scale range of the accelerometer is ±50g and the full-scale output voltage is ±3.75v.

Figure 5. The equivalent circuit of closed-loop system.

Figure 6. Displacement curves of open-loop system and closed-loop system.

Figure 7. System sensitivity curve.
The harmonic analysis in the research is to investigate the amplitude-frequency characteristic of the system. The amplitude-frequency characteristic of the closed-loop system is shown in Figure 8. The curve indicates that the bandwidth of the system is 10 kHz.

![Figure 8. Amplitude vs frequency response curve.](image)

4. Conclusion
An accelerometer with the frame-mass structure has been designed. Since its static capacitance is larger and the proof mass is lighter, the structure can be implemented in closed-loop hybrid-integrated micro-accelerometer efficiently. The overload immunity of the structure is more than 5000g. Through the system simulation, the sensitivity of the accelerometer is 75mv/g and the bandwidth is 10 kHz.

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