Influence of the failure effect of MEMS capacitive high g acceleration sensor on the limit range and sensitivity

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Abstract—With the development of MEMS capacitive acceleration sensor to a higher measurement range (tens of thousands of g or even hundreds of thousands of g), the failure of the device microstructure under extreme mechanical impact has become a key factor restricting its performance improvement. Existing research mainly focuses on material stress failure and device structure optimization. Aiming at the failure of micro structure under impact, a simulation model of impact response of micro structure is established in this paper. Based on the existing over stress failure and device structure optimization, the stress failure effect and short-circuit failure effect of MEMS capacitive acceleration sensor under strong impact are proposed, and the influence rules of the two failure mechanisms on the sensor limit range and sensitivity are obtained. At the same time, the optimization design of the key structural parameters of the sensor is discussed.

1. Introduction

In the process of vehicle collision, rocket launch, artillery launch, etc., there will be a large overload.¹ MEMS accelerometer is an extremely important micro sensor, which is used to detect the overload impact signal. It has the characteristics of miniaturization, low cost, mass production, high consistency, ² and is a typical dual-use device. It is widely used in aerospace, satellite, robot, smart fuze, weapon and ammunition. MEMS capacitive acceleration sensor is one of its typical representatives.

Large range MEMS capacitive acceleration sensors have very important research and application value in many fields, especially in the military field. The most typical applications are hard target penetrators.³ ⁴ Many famous companies and research institutions at home and abroad have carried out the research of this type of accelerometer. For example, the ADXL50 accelerometer developed by ADI, the high-g accelerometer developed by ENDEVCO, and the MEMS accelerometer developed by CSEM, crossflow and Motorola for automobiles. In addition, domestic and foreign universities such as UC Berkeley, Stanford, Tsinghua University, and the 13th Ministry of Information Industry all carry out related content.⁵

Therefore, MEMS accelerometer has been mature in many research and applications.⁶ ⁷ However, with the development of MEMS capacitive acceleration sensor to a higher measurement range (tens of thousands of g or even hundreds of thousands of g), the failure of device microstructure under extreme mechanical impact has become a key factor restricting its performance improvement.⁸ The existing related research mainly focuses on the material stress, studies the material failure of micro beam structure under excessive stress,⁹ and alleviates the failure effect through structural optimization design. On this
basis, this paper discussed the stress failure effect and short-circuit effect of a typical MEMS capacitive sensor with multi support beam structure under strong impact. Through the software simulation, the mechanism of the failure effect on the limit range and sensitivity of the sensor is studied, and the optimization method of the related structural parameter design is analyzed. It provides a technical basis for the design of high performance large range MEMS capacitive sensor.

2. Modeling and simulation

2.1 Principle model

In this paper, a typical multi solid support beam MEMS capacitive sensor is studied. Its core structure consists of five parts: fixed electrode, movable electrode, constant voltage source, galvanometer and housing (not planned). As shown in Fig. 1.

![Model of capacitive acceleration sensor](image)

Fig.1. Model of capacitive acceleration sensor

The fixed electrode is in a plane shape and is connected with the sensor shell. The movable electrode is a cantilever structure, which consists of a main structure and eight cantilever beams. The end of the cantilever beam is fixed with the sensor shell. The constant voltage source and the galvanometer are connected with a fixed electrode and a movable electrode. The sensor shell protects and fixes internal components, forming the whole of the sensor.

In the sensor, the fixed electrode acts as one electrode of the micro capacitor and the movable electrode acts as the other. The movable electrode is connected and fixed with the shell through the end of the cantilever beam, so as to maintain a proper space between the movable electrode and the fixed electrode. The movable electrode is a sensitive element of the capacitance sensor, which can convert the overload signal to the movement of its own relative to the fixed electrode, and the movement direction is perpendicular to the surface of the fixed electrode.

The galvanometer is a window for capacitive sensors to output signals. Because the constant voltage source connects the fixed electrode and the movable electrode, the voltage difference between them is constant. When the sensor is impacted by overload signal, the movable electrode will vibrate. Thus, the distance between fixed electrode and movable electrode is changed, and the capacitance of capacitor is changed. When the voltage of the capacitor is constant, the capacitance value of the capacitor changes, and the capacitor is charged and discharged through the galvanometer. The indication of galvanometer is related to the change of capacitance, and the change of capacitance is related to the magnitude of overload impact. There is a correlation between the final ammeter indication and the magnitude of overload impact.

Based on the parameters in Table 1, the model is carried out, and import it into the COMSOL for overload impact simulation. The duration of external overload impact is 30 μs, the amplitude of overload impact is 80000 g, and the waveform of overload impact is square wave. Taking the above model and experimental conditions as research objects, the acceleration impact response process is modeled based on the mechanical constitutive model of linear elastic materials.

In the process of impact response, there are two main failure modes: material failure caused by excessive stress and short circuit failure caused by upper and lower electrode collision contact.

\[
d_{\text{max}} < d \\
\sigma_0 \leq \sigma
\]  

(1)
where $\sigma_0$ is the maximum stress of sensor beam structure, $\sigma$ is the allowable stress limit of sensor material, $d_{\text{max}}$ is the maximum displacement of sensor rebound, and $d$ is the distance between movable electrode and fixed electrode.

### Table 1 Structural parameters of sensor in Fig 2 (unit: $\mu$m)

| Beam width D | Beam length L | Beam spacing C | Beam thicken H |
|--------------|---------------|---------------|---------------|
| 220          | 350           | 500           | 40            |

2.2 Excessive stress failure

After determining the overall structure of the sensor and the beam structure, the beam structural parameters need to be determined. The structure of the sensor is shown in Fig. 2.

![Fig.2. Structure of the sensor](image)

The material of movable electrode is silicon, and the allowable stress limit is 425MPa. The simulation model is established by equivalent principle. When the sensor is impacted by strong overload, only the internal movable electrode is impacted. When the internal movable electrode is impacted by overload, the movable electrode first produces a downward displacement and deviates from the initial position. During the duration of the overload impact, the movable electrode, under the combined action of elasticity, inertia and damping, continues to oscillate at its own resonance frequency. It corresponds to the part with time 0 $\mu$s -35 $\mu$s in Fig. 3 (a). After the overload impact ends, since there is a large elastic force deviating from the initial position at this time, the movable electrode rebounds rapidly, which corresponds to the part with the time of 35 $\mu$s -40 $\mu$s in Fig. 3 (a).

In the whole process of impact, when the movable electrode produces the maximum displacement, the cantilever structure produces the maximum stress. It corresponds to the peak in Fig. 3 (a) when the time is 9 $\mu$s. When the maximum stress reaches the allowable stress limit of the cantilever material, the cantilever material breaks. The movable electrode loses structural integrity and the sensor fails. The displacement and stress of movable electrode are shown in Fig. 3.

![Fig.3. (a) Movable electrode displacement; (b) Movable electrode maximum stress](image)

2.3 Short-circuit failure

When the sensor is impacted by a strong overload, the internal movable electrode oscillates many times under the combined effect of elasticity, inertia and damping. The form of vibration is the same as the failure of excessive stress. When the overload shock disappears, under the action of elasticity and inertia,
the movable electrode rebounds rapidly, corresponding to the part of 35 μs -40 μs in Fig. 4 (a). At this time, the movable electrode produces an upward displacement and is higher than the initial position. The movable electrode is close to the fixed electrode, and the maximum rebound height occurs at the first wave peak after rebound. When the displacement higher than the initial position is greater than or equal to the initial gap between the fixed electrode and the movable electrode, the movable electrode collides with the fixed electrode. The movable electrode collides with the fixed electrode, and the internal capacitance of the sensor is short-circuited. The positive and negative charges carried by the capacitance sensor are neutralized at the moment of collision, which leads to the abnormal operation of the galvanometer. The sensor has a short circuit failure. It is worth noting that under the premise that the internal circuit and the sensor structure are not damaged, the result of short-circuit failure is the abnormal data this time, but the sensor structure and function have not been damaged. The displacement and stress of the movable electrode are shown in Fig. 4.

3. The common law of failure mechanism and parameter optimization design

3.1 The common law of failure mechanism

The short-circuit failure is caused by the rebound of the sensor after being overloaded, and the displacement of the movable electrode rebound exceeds the distance between the movable electrode and the fixed electrode. Therefore, the short circuit failure is closely related to this distance. The distance between the movable electrode and the fixed electrode determines the allowable rebound range of the movable electrode. When the distance between movable electrode and fixed electrode increases, the allowable rebound range of movable electrode also increases. As the distance between movable electrode and fixed electrode decreases, the allowable rebound range of movable electrode also decreases. At the same time, according to Eq. (2), when the distance between the movable electrode and the fixed electrode changes, the capacitance of the sensor also changes. As a result, the limit range and sensitivity of the sensor also change.

$$C = \frac{\varepsilon S}{d}$$ (2)

where C is the sensor capacitance, $\varepsilon$ is the dielectric constant of the media between the plates, S is the positive area of the plates, and $d$ is the distance between the plates.

Figure 5 shows the relationship between the capacitance sensor measurement range and the plate spacing. When other conditions remain unchanged and the plate spacing increases from zero, the sensor measurement range increases first and then remains unchanged.

The reason is: When the distance is in the range of region 1, the sensor measurement range increases continuously with the increase of distance. Because the stress of the cantilever beam has not yet reached the allowable stress limit of the silicon material at this time, the material stress limit is not a limiting
factor of the measurement range. The rebound distance of the sensor is limited by the distance between
the fixed electrode and the movable electrode, so the distance is the main reason. When the distance
increases, the movable electrode allows the rebound displacement range to increase, and the sensor
measurement range also increases. When the space passes through the image inflection point, it enters
the range of region 2. As the distance increases further, the measurement range remains unchanged. This
is because the allowable displacement of movable electrode has reached the maximum value. When the
allowable displacement of the movable electrode reaches the maximum value, the stress at the cantilever
reaches the allowable stress limit of the material, and the sensor fails due to excessive stress. So even if
the distance is further increased, the measurement range remains unchanged. The range in region 2 is
independent of the spacing.

\[ K = \frac{dC}{C} = |C - C_{dx}| = |1 - \frac{d_{dx}}{d + dx}| \] (3)

Where \( K \) is the sensitivity of the sensor, \( C \) is the capacitance of the sensor, \( C_{dx} \) is the change of the
capacitance when the position of the movable electrode changes \( dx \), \( d \) is the distance between the plates,
and \( dx \) is the change of the position of the movable electrode.
Figure 6 shows the relationship between the distance between the sensor plates and the sensitivity. With the increase of plate spacing, the sensitivity of the sensor decreases. There is a negative correlation between the distance and the sensitivity, and they restrict each other. Figure 6 can be divided into two parts:

1) In the range of region 1, the sensitivity decreases with the increase of spacing. Combined with the conclusion of Fig. 6, the sensor measurement range will increase continuously. Therefore, in the region 1, the distance increases, the measurement range increases and the sensitivity decreases. This region is an effective reference region for sensor design;

2) In the range of region 2, combined with the conclusion of Fig. 6, it can be concluded that as the distance increases further, the measurement range remains unchanged and the sensitivity continues to decrease. That is to say, increasing the distance in region 2 cannot change the measurement range, but will reduce the sensitivity. This region belongs to the invalid region of the sensor design reference. When designing the sensor, the spacing between plates should be kept within region 1.

3.2 Parameter optimization design

In order to further improve the indicators of the sensor and obtain the optimal sensor design parameters, it is necessary to carry out the sensor parameter optimization design comparison test and find out the influence law of the cantilever beam width parameters on the indicators of the sensor. In this paper, three tests are designed: keeping other parameters unchanged, changing the width of cantilever beam. The beam width parameters are 190 μm, 220 μm and 250 μm respectively, and the relationship between the maximum range and plate spacing, sensitivity and plate spacing, measurement range and sensitivity is obtained, as shown in Fig. 7.

Fig. 7 In parameter optimization design (a) Maximum range and plate spacing; (b) Sensitivity and plate spacing; (c) Maximum range and sensitivity

In Fig. 7 (a), as the distance between the plates increases, the sensor measurement range increases first and then remains unchanged. And under the same conditions, the cantilever beam width increases, the
measurement range will increase accordingly. Because after the beam width is increased, when the sensor is subjected to the same overload impact, the stress at its cantilever beam will be reduced accordingly. To reach the stress limit of the material, a larger overload shock is required. That is, the sensor needs to withstand a greater overload impact before the stress of the cantilever beam reaches the stress limit of the material, that is, the sensor measurement range increases;

In Fig. 7 (b), as the distance between the plates increases, the sensitivity gradually decreases, but the width of the cantilever beam has a certain effect on the sensitivity. As the width of the cantilever beam decreases, the effective region of the sensor parameter design increases. From this perspective, in order to obtain higher sensitivity, a sensor with a smaller beam width should be selected;

In Fig. 7 (c), at a stage where the sensitivity is small, the sensitivity increases and the sensor measurement range remains unchanged. After the inflection point of the image, as the sensitivity further increases, the sensor measurement range drops rapidly. That is, the sensor measurement range and sensitivity are mutually restricted. The greater the sensitivity, the smaller the measurement range. Comparison of the three can be found, as the width of the beam changes, the beam width of the cantilever beam has an impact on the relationship between the two. As the cantilever beam width increases, the image appears to move up. When the sensitivity remains the same, the larger the beam width, the larger the measurement range.

4. Conclusions
In this paper, the micro structure simulation model of MEMS capacitive sensor is established. Through the research of the simulation model and the optimization design of key design parameters such as electrode spacing and micro beam structure width, the stress failure and short-circuit failure effects of the sensor and two important regions of the sensor design are obtained: Region 1 is the effective region of the design. The main influence factor of the region is the distance. The lower limit is zero and the upper limit depends on the cantilever width. With the increase of the distance, the measurement range increases rapidly and the sensitivity decreases; Region 2 is the invalid region of the design. The main influence factor of the region is the material stress limit. The stress limit depends on the material. At the same time, the interval value in region 2 only has a negative effect. When the distance increases, the measurement range remains unchanged and the sensitivity decreases continuously. So the sensor should be designed to avoid region 2. The simulation model in this paper can provide technical basis for the design of high-performance MEMS capacitive acceleration sensor.

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