A Microcantilever-based Piezoresistive High g MEMS Accelerometer

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The high g MEMS accelerometer with range from 50,000g to 200,000g is one of the key components applied to armament tests and projectile fuse systems. This paper develops a silicon microcantilever piezoresistive MEMS high g accelerometer based on the micromachining technology. The sizes of the mcrocantilever, the packaging technology and the projectile penetration test are described. Meanwhile, utilizing the shock response model with no damping of the microcantilever, some important mutual restriction relations are discussed systematically, such as among the resonance frequencies of the microstructure and the packaging body and the vibration frequency of the measured acceleration shock pulse, between the resonance frequency of the microstructure and the sampling frequency of measuring system. Then some practical principles are put forward which should be useful during developing a novel high g accelerometer applied to high g shock environments. The projectile penetration test result indicates that the high g accelerometer and measuring system can measure an acceleration signal more than 70,000g accurately. At the same time, it validates the importance of the systematical considerations during the development of a high g accelerometer.

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NOMENCLATURE

L = length of the microcantilever
B = width of the microcantilever
H = thickness of the microcantilever
$a(t)$ = acceleration of the tested body
m = equivalent mass of the microcantilever
k = rigidity of the microcantilever
$x(t)$ = displacement of the m
ω_n = resonance frequency of the microcantilever
ω = frequency of the acceleration shock pulse
t_m = peak time of the shock response of microcantilever

1. Introduction

After the first silicon piezoresistive cantilever accelerometer prototype developed by Roylance and Angell[1], the studies on the piezoresistive MEMS accelerometers have had a great progress. There are still coming forth many piezoresistive MEMS accelerometers with different microstructures and various ranges. These microstructures which can sense a high g (acceleration of gravity) acceleration range from several thousands of g to hundreds thousands of g are in the ascendant, such as the double-clamped beam designed by H.Seidel et al[2], the double-beam with island and five-beam with double-island developed by M.Bao et al[3], I-beam with double proof masses developed by Ebdevco[4], the single crystalline silicon membrane single cantilever with no proof mass invented by Alberta corporation[5], the double cantilevers surrounded by a curved overload protection microstructure proposed by Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences[6] and so on. These data also introduced the packaging and testing technologies involved in the development of a high g accelerometer. However, few investigations have been done on the relationships among the microstructure, packaging and testing. From the view of a system, this paper focuses on researching into the mystery underlying the microstructure, packaging and testing of a silicon microcantilever piezoresistive MEMS high g accelerometer. We put forward the conditions which the microstructure and packaging of the accelerometer applied to high g shock environment must meet. In addition, the design, packaging and testing of a silicon microcantilever piezoresistive MEMS high g accelerometer are discussed.

2. Characteristics of the Microcantilever

2.1 Shock Mechanical Model of the Microcantilever

Usually, a high g acceleration signal is a shock pulse closed to a semi-sine wave. Its pulse width τ is short to millisecond or dozens of microsecond. We can consider that the frequency of the shock pulse satisfy the formula $\omega = \pi / \tau$. Obviously, let $\tau = 10\,\mu$s, then the frequency of the shock pulse may be more than 314KHz. During the high g acceleration test, the damping effect is inappreciable to the peak response of the microcantilever. At the same time, although subjected to high g shock, the deformation of the microcantilever is still marginal. So the damping (include structural damping and squeeze film damping) effects may be neglected. Then the shock mechanical model of the microcantilever can be described as a vibrating system of mass-spring with no damping. The structure of the microcantilever is shown in Fig.1 and its shock mechanical model is shown in Fig.2.

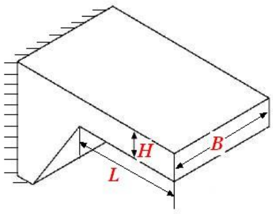


Fig.1 Structure of the microcantilever

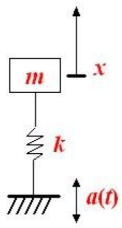


Fig.2 Shock mechanical model of the microcantilever

According to the knowledge of vibration, the shock dynamical equation of the microcantilever is

$$mx''(t) + kx(t) = ma(t) \qquad (1)$$

or

$$x''(t) + \omega_n^2 x(t) = a(t) \qquad (2)$$

2.2 Shock Response Characteristic of the Microcantilever

In order to investigate the shock response characteristic of the microcantilever, suppose that there is a semi-sine wave acceleration shock pulse shown as equation (3) acting on the microcantilever,

$$a = \begin{cases} a_o \sin \omega t & (0<t<\frac{\pi}{\omega}) \\ 0 & (\text{other}) \end{cases} \qquad (3)$$

During the acting period of the shock pulse, we can obtain the response of the microcantilever as the following equation

$$x(t) = \frac{a_o}{k} \cdot \frac{1}{1-(\omega/\omega_n)^2}\left(\sin \omega t - \frac{\omega}{\omega_n}\sin \omega_n t\right),\ p<0.5\left(1+\frac{\omega_n}{\omega}\right) \qquad (4)$$

What we are interest in is the peak value of the response. It is evidently that only when $\omega_n > \omega$, viz., the resonance frequency of the microcantilever must be more than 314KHz, the frequency of the acceleration shock pulse, a peak value of the response can be achieved during the acting period of the acceleration shock pulse. Then this brings a great challenge for packaging. From equation (4), we can obtain the time when the response reaches to its peak is

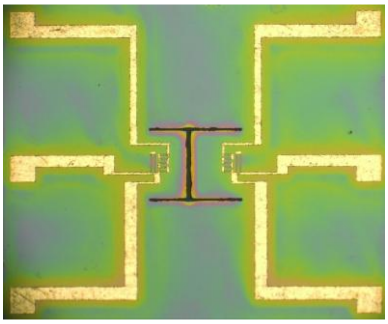
$$t_m = \frac{2p\pi}{\omega_n + \omega}, \quad (p = 1, 2, \cdots) \qquad (5)$$

here, only when $p = 1$, t_m has actual signification.

Let $\omega_n = \omega$, then $t_m = 0.01$ ms at least, this is a challenge f or the amplifier, collector and memory of the measuring system.

2.3 Structure of the Microcantilever

In this paper, we select a most simple structure, a single crystalline silicon single-cantilever with no proof mass, as the sensor's sensing structure, which achieved by micromachining technology. The fabrication procedures are not presented here because many similar processes can be available from many reported papers. Fig.3 presents the SEM images of the sensor chip with two microcantilevers. Sizes of *L-B-H* are: the left one, 290μm -500μm -100μm, the right, 390μm -500μm -100μm.



(a) Top view

(a) Back view

Fig.3 SEM images of the sensor chip

In practice, we just use the right microcantilever. Of course we can utilize the left one to assemble another accelerometer with different range. Under the static acceleration of 200,000g, the ANSYS simulation results show that the strain is 266μ, satisfying the strength requirement; and the resonance frequency is 609KHz, about double times of 314KH, which guarantees a peak response can be obtained during the acting period of the acceleration shock pulse.

3. Characteristics of the Accelerometer

3.1 Packaging

Packaging is another very important point which looks simple, but actually, it is a key technology, especially, for a high g shock environment. On one hand, the packaging body must protect the sensor chip and circuit keysets mounting in and have a good overload capacity. On the other hand, because the whole motion of the accelerometer is generally controlled by the lowest vibration frequency of the assembly, the packaging body must have a greater resonance frequency than the one of the microcantilever[7]. Only in that way can the microcantilever sense the acceleration signal of the measured body accurately. The material parameters adopted in the packaging body are showing in Table.1.

Name	Material	Young' modulus (GPa)	Poisson's ration	Density (kg/m^3)
Case	Stainless steel	206	0.3	7900
Chip	Silicon	131	0.28	2330
Circuit keysets	Epoxy-based FR4	16	0.3	1800
Adhensive	Epoxy-based FR4	16	0.3	1800

Table. 1 Material parameters adopted in packaging body

The packaged accelerometer is shown in Fig.4.

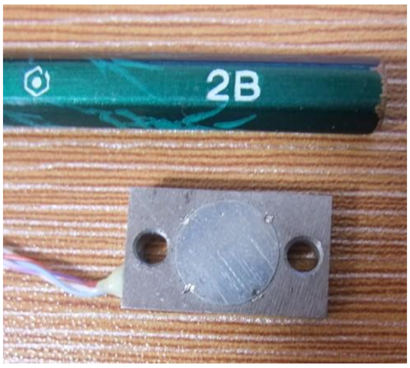


Fig.4 A packaged sensor

The sizes of the packaged sensor are 19.5mm×11.5mm×4mm.

3.2 Projectile Penetration Test

In order to evaluate the performance of the accelerometer, a projectile penetration experiment has been done utilizing a certain type cannon. The diameter of the projectile is φ62mm, the weight 3.6kg. The impact velocity of the projectile is about 600m/s. The target plate is C40 reinforced concrete with a diameter of φ1.8m and thickness of 1m. The testing projectile and the penetrated target are shown in Fig.5.

(a) Testing projectile

(b) Penetrated target

Fig.5 Testing projectile and penetrated target

From Section 2.2 and 2.3, we know that during the acting period of the acceleration shock pulse, the time when achieve the peak response is about 0.0068ms. Integrating the sampling theorem, the sampling frequency of the measuring system ought to be more than 300KHz. So it is enough for a sampling frequency of 300KHz to the measuring system. It is noted that the accelerometer, amplifier, memory and power source must be mounted in the projectile strongly. Especially, the coupling stiffness must be enough between the sensor and the projectile.

3.3 Results and Discussion

After the projectile penetration experiment, recover the projectile and derive the measured data from the memory through the data interface of the measuring system. By data processing, we obtain the acceleration time history measured by the accelerometer. The result is shown in Fig.6.

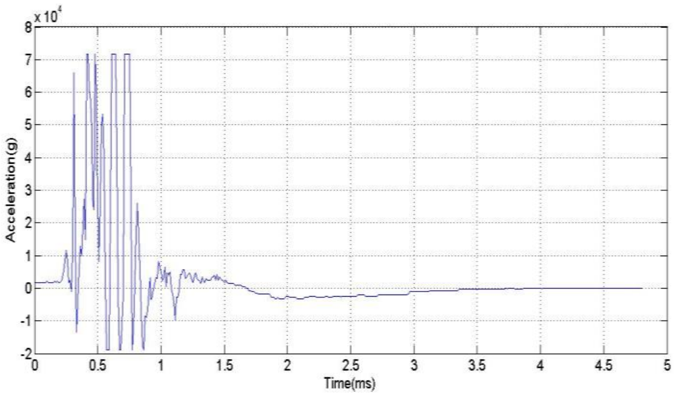


Fig.6 Acceleration time history

Theoretically, there is only one acceleration shock pulse during the course of the projectile penetration. But from Fig.6, we can clearly find that there are 10 times of shock pulses during the acceleration time history. The reason resulted in this phenomena primarily is the anisotropism of the concrete material. Just because of the anisotropism, the resistance reacting on the projectile is not a constant; certainly, the acceleration will change with the resistance. The acceleration time history also indicates that the time of the penetration is about 0.65ms. So the average pulse width of each acceleration shock pulse is about 0.065ms, further, the frequency of the shock pulse is 48.33KHz. This proves that the 300KHz of sampling frequency of measuring system is scientific.

Now, using equation (5), we can exactly determine the peak time of the shock response of microcantilever is 0.00956ms. Moreover, the peak acceleration of the penetration projectile is more than 73,000g and the actual peak time is 0.0325ms, shorter than the theoretical value. This result is doubtless and correct because of the presence of the actual damping effects acting on the microcantilever.

4. Conclusions

Based on the systematical considerations of microstructure design and packaging and test, a silicon microcantilever piezoresistive MEMS high g accelerometer has been developed. During this project, some very important conclusions are achieved.

(1) An accelerometer which used to measure a high g acceleration shock pulse must possess these characteristics: the lowest resonance frequency of the packaging body is higher than the one of the microstructure; the resonance frequency of microstructure is higher than the vibration frequency of the acceleration shock pulse.

(2) The sampling frequency of the high g measuring system is greatly correlated to the resonance frequency of microstructure of the sensor and the vibration frequency of the acceleration shock pulse. Usually, a sampling frequency more than 300KHz can accomplish majority of high g shock measurements.

(3) Theoretically, as long as the pulse width of the measured acceleration shock pulse is not shorter than 10μs, the accelerometer and the measuring system which we developed can be used to measure a acceleration shock not more than 200,000g accurately. The projectile penetration test result indicates that it can measure an acceleration signal more than 70,000g.

But some important works need us to do in the future such as a higher velocity projectile penetration tests, sensor calibrating, industrialization, and so on.

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