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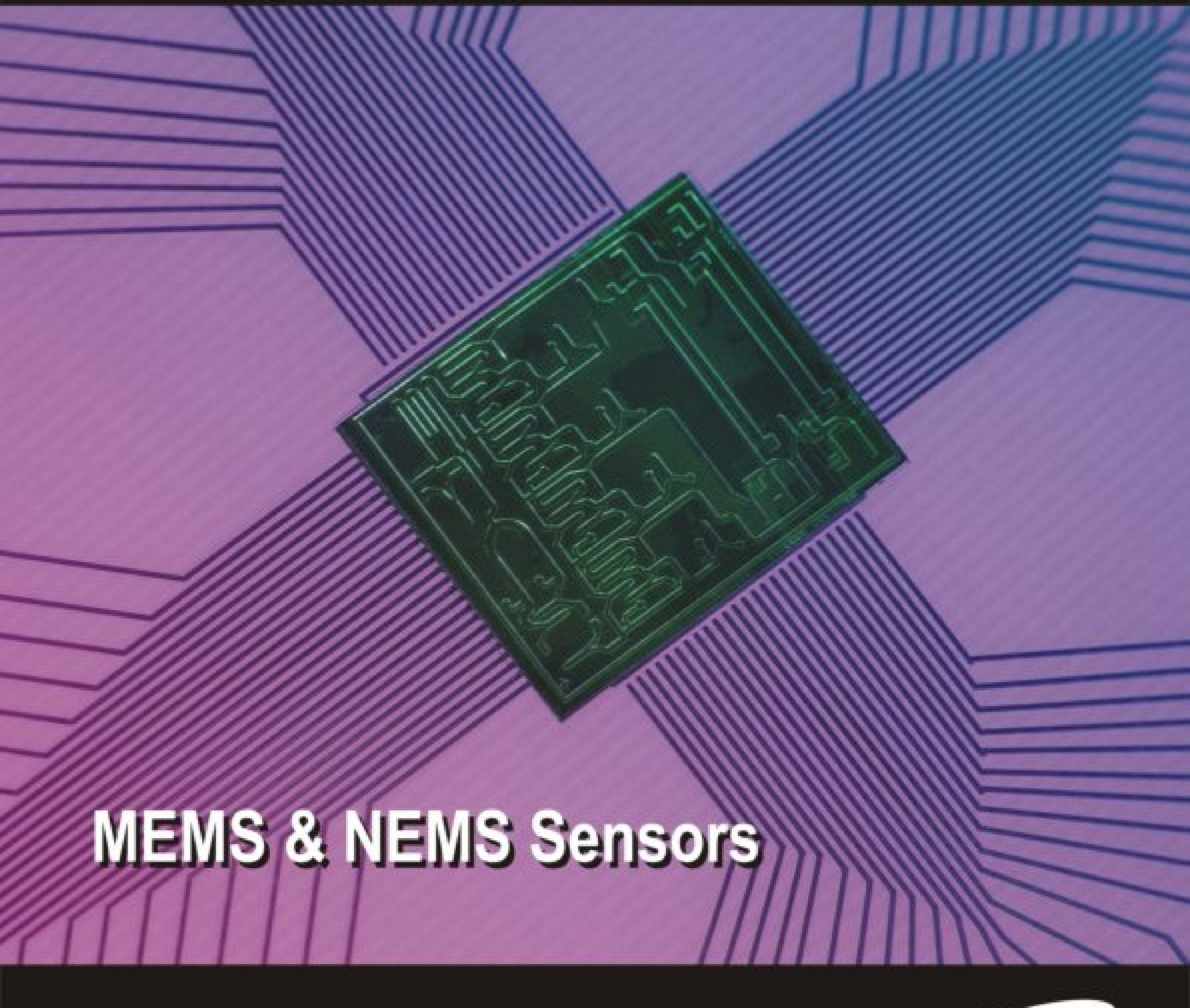

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Shock Resistance of MEMS Capacitive Accelerometers

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Abstract: With deeper research of silicon micro accelerometer, and its wider applications in the commercial fields such as drilling, consumer electronics, automotive industry, and in special military field, the device’s shock resistance has been an urgent issue. The paper presents a theoretical approach of the micro structure's shock response, and focuses on the finite element impact dynamic simulation considering the contact effects of stoppers. A kind of MEMS capacitive accelerometers are designed and fabricated. Failure types due to different shock circumstances are investigated, and experimental estimation of the micro-structure's three-orientation shock resistibility is analyzed, using Hopkinson Pressure Bar (HPB) apparatus. Results indicate that beams' stiffness and stoppers' areas are the key factors to determine the shock resistance, and pulse duration also plays a critical role in the shock effects of micro-machined structures. *Copyright © 2012 IFSA.*

Keywords: MEMS accelerometer, Shock resistance, Impact simulation, HPB, Failure analysis.

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1. Introduction

MEMS (Micro-electromechanical Systems) sensors are more robust to shock due to its small mass, high aspect ratio and good frequency response. As MEMS technology has been widely applied in various fields, including drilling, consumer electronics, automotive airbag and harsh military environments, sensors’ resistance to shock has become a crucial issue. The shock amplitude during fabrication, deployment, or operation, could be as high as 5,000 g-10,000 g [1] with tens of microseconds to several milliseconds duration time. Till now, multiple methods have been applied to address MEMS device reliability at every step of device design and development. Srikar and Stephen obtained the time-domain criteria to distinguish between the impulse, resonant and quasistatic responses of MEMS structures to shock loads [2]. Stefano investigated the effect of accidental drops on a polysilicon MEMS accelerometer within macro-scale and meso-scale finite element approach [3]. D. M. Tanner et al. performed shock experiments on a surface micro machined engine, and studied the susceptibility of MEMS device to shock [4]. More extensive experiments on various MEMS sensors and flight tests on artillery projectiles are presented in T. G. Brown's report [5].

The survivability of MEMS accelerometer under high-g environment mainly includes two aspects: the integrity of micro structure and the sensor's performance change after enduring shock events. The paper analyses the shock reliability of a kind of comb-finger accelerometers' micro structure. Through theoretical approach and finite element analysis, the accelerometer's shock response of deformation and stress concentration is investigated, considering the contact effects of stoppers. HPB shock experiments are performed to determine the typical failure modes and to obtain an experimental estimation of MEMS accelerometers' structure due to performance change in different shock environments. Beneficial suggestions are concluded to improve the shock resistibility of MEMS sensors.

2. Design and Fabrication of MEMS Accelerometers

The MEMS accelerometer investigated is a kind of gap sensing differential capacitance transducer. Considering a comb-finger silicon micro-machined accelerometer developed by our research group [6], the sensing element shown in Fig. 1, mainly consists of movable mass, multi-fingers, spring beams and overload stoppers. The proof mass is a kind of frames with comb-fingers stretched from either side as the movable pole of the differential capacitor pair. The mass is attached to the Pyrex 7740# glass substrate by one clamped–clamped beam and four folded beams. The fixed comb fingers are anchored directly on the glass in a staggered layout with the movable comb to constitute two differential capacitors. The overload stoppers are composed of several small silicon cylinders in x direction, while stoppers are also placed in y direction. Table 1 shows the typical structure parameters of the tested accelerometer.

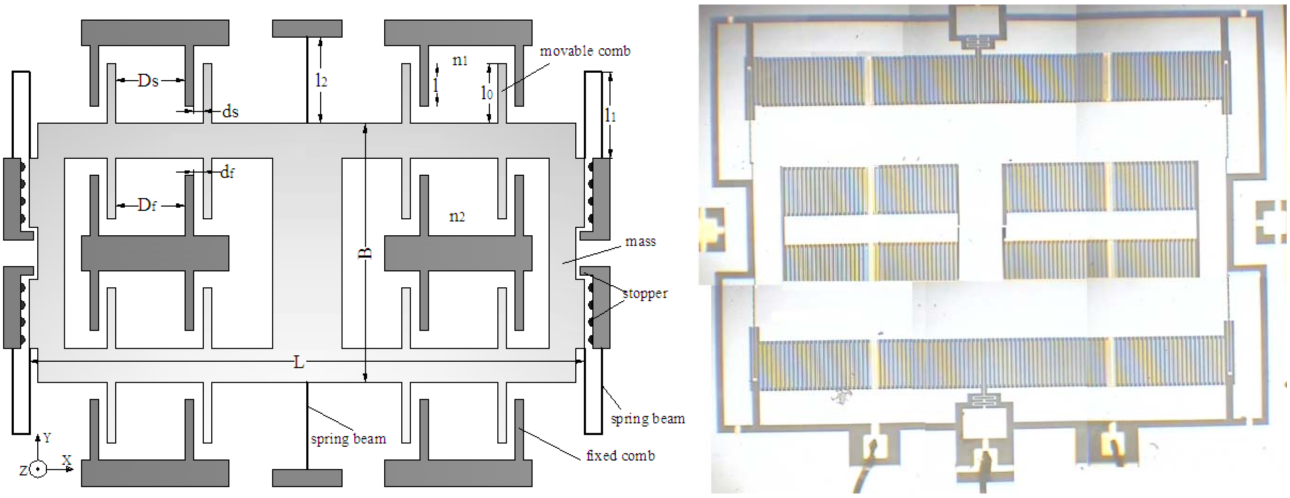


Fig. 1. Simplified sketch and micrograph of the MEMS accelerometer's structure.

Table 1. Structure parameters of the accelerometer.

Items	Values	Items	Values
Sensitive mass	570 µg	Stoppers' areas of x-axis	1800 μm^2
Stiffness of the x direction	158 N/m	Distance between stopper and mass	2 µm
Stiffness of the y direction	4478 N/m	Stoppers' areas of y-axis	600 μm^2
Stiffness of the z direction	14430 N/m	Distance between stopper and mass	2 µm

The accelerometer is fabricated by SOG (silicon on glass) MEMS technology including metal sputtering, RIE and ICP etching, wafer bonding and so on (Fig. 2). It's packaged in a 10-pin LCC ceramic shell. Differential capacitance changes due to external acceleration input, and the capacitance detection circuit converts the change to DC voltage V_d linearly in a wide bandwidth. A PID conventional controller is applied to form a closed serve loop. The movable mass is driven back by the electrostatic force generator when capacitance change is detected. Fig. 3 gives an outline of the measuring and controlling system.

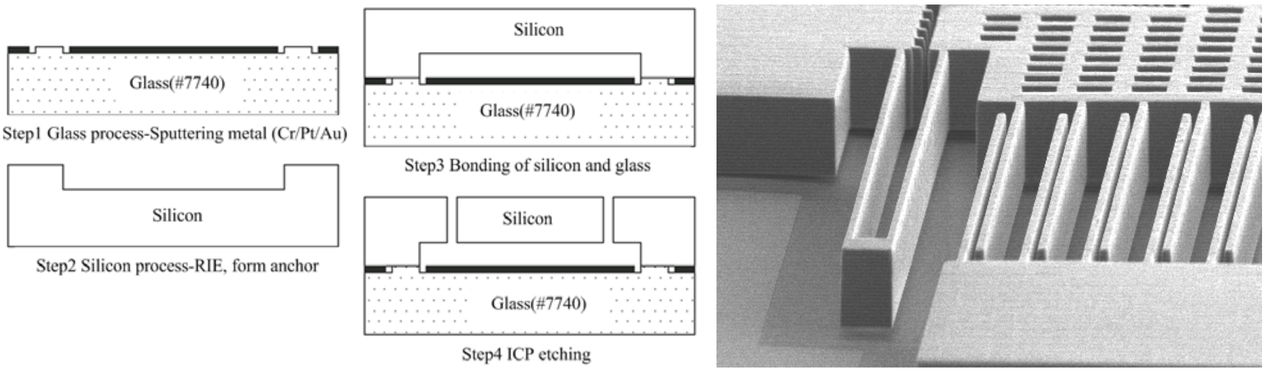


Fig. 2. Fabrication technology and SEM photo of the structure.

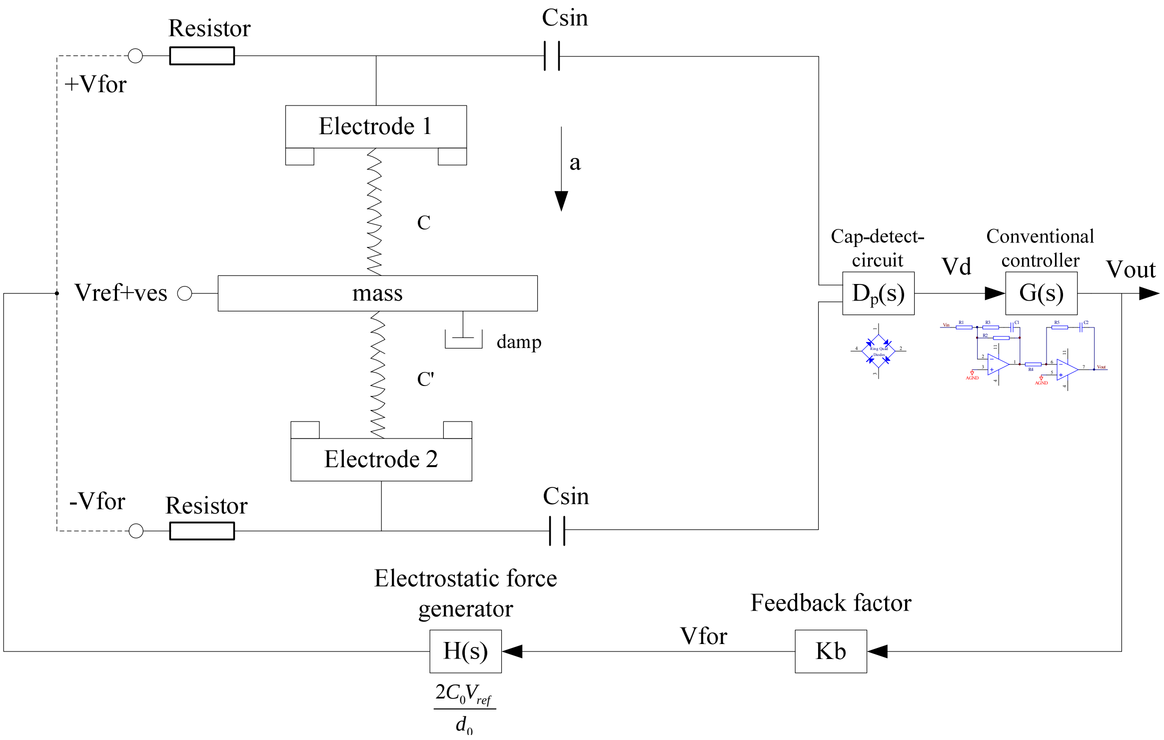


Fig. 3. Sketch of the measuring and controlling circuit.

3. Theoretical Approach of Shock Response

Theoretical approach gives a brief mind of what happens due to shock. Some assumptions are made here to simplify the modeling process: (i) the package transmits the shock load to the substrate directly without damping; (ii) the acceleration is transferred to the proof mass through the spring beams [7]; (iii) the irregular shock pulse induced is approximated by a half-sine waveform which could be expressed as follow.

$$a(t)=\begin{cases} a_p \sin(\frac{\pi}{\tau}t) & 0\le t\le \tau \\ 0 & \tau \le t \end{cases} = a_p \sin(\frac{\pi}{\tau}t)u(t) + a_p \sin[\frac{\pi}{\tau}(t-\tau)]u(t-\tau) \tag{1}$$

where a_p is the amplitude of the shock, τ is the effective pulse width of the waveform, $u(t)$ is the unit step signal.

The accelerometer unpowered could be modeled as a second order system of mass-damp-spring. Using Laplace and inverse Laplace transform to solve the differential equation (2), the displacement response of the mass to the shock pulse [8] could be calculated as equation (3), in which k denotes the mechanical stiffness, m indicates the proof mass, $\zeta = c/2\sqrt{mk}$ indicates the damping ratio of the system, and $w_n = \sqrt{k/m}$ denotes the non-damping natural frequency of the micro structure.

$$m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx(t) = ma(t) \tag{2}$$

$$x(t) = L^{-1}[\frac{(s+2\zeta w_n)x_0 + \dot{x}_0 + w_n^2 L[\xi(t)]}{s^2 + 2\zeta w_n s + w_n^2}] = \begin{cases} R(t) & 0 \le t \le \tau \\ R(t) + R(t-\tau) & \tau \le t \end{cases} \tag{3}$$

For different damping conditions, $R(t)$ is given by

$$\begin{aligned} \zeta < 1, R(t) = a_p \frac{\pi}{\tau}[\alpha \cos(\frac{\pi}{\tau}t) + \beta \frac{\tau}{\pi}\sin(\frac{\pi}{\tau}t) + \ldots \\ \ldots + e^{-\zeta w_n t}(\chi \cos(w_n\sqrt{1-\zeta^2}t) + \frac{\delta - \chi\zeta w_n}{w_n\sqrt{1-\zeta^2}}\sin(w_n\sqrt{1-\zeta^2}t))] \end{aligned}, \tag{4}$$

$$\zeta = 1, R(t) = a_p \frac{\pi}{\tau}[\alpha \cos(\frac{\pi}{\tau}t) + \beta\frac{\tau}{\pi}\sin(\frac{\pi}{\tau}t) + e^{-w_n t}(\chi + (\delta - \chi w_n)t)], \tag{5}$$

$$\zeta > 1, R(t) = a_p \frac{\pi}{\tau}[\alpha\cos(\frac{\pi}{\tau}t) + \beta\frac{\tau}{\pi}\sin(\frac{\pi}{\tau}t) + \eta e^{-(\zeta - \sqrt{\zeta^2 - 1})w_n t} + \lambda e^{-(\zeta + \sqrt{\zeta^2-1})w_n t}], \tag{6}$$

where coefficients $\alpha, \beta, \chi, \delta, \eta, \lambda$ are expressed as follow.

$$\begin{gathered} \alpha = \frac{-2\zeta w_n}{(\pi^2/\tau^2 - w_n^2)^2 + 4\zeta^2 w_n^2 \pi^2/\tau^2}, \beta = \frac{w_n^2 - \pi^2/\tau^2}{(\pi^2/\tau^2 - w_n^2)^2 + 4\zeta^2 w_n^2\pi^2/\tau^2} \\ \chi = \frac{2\zeta w_n}{(\pi^2/\tau^2 - w_n^2)^2 + 4\zeta^2 w_n^2\pi^2/\tau^2}, \delta = \frac{4\zeta^2 w_n^2 - w_n^2 + \pi^2/\tau^2}{(\pi^2/\tau^2 - w_n^2)^2 + 4\zeta^2 w_n^2 \pi^2/\tau^2} \\ \eta = \frac{-\chi w_n(\zeta - \sqrt{\zeta^2-1}) - \delta}{2w_n\sqrt{\zeta^2-1}}, \lambda = \frac{\chi w_n(\zeta + \sqrt{\zeta^2-1}) - \delta}{2w_n\sqrt{\zeta^2-1}} \end{gathered} \tag{7}$$

Equations (3)-(7) express the deformation of sensor's micro structure under the acceleration shock. As shown in above Fig. 1, the accelerometer is supported by 6 parallel beams, and the stiffness of x direction could be calculated by $k_x = 48EI_z/l^3$. The tested accelerometer is designed to be an under damping system with $\zeta < 1$. The mechanical parameters could be tested by electrometric methods referred to our previous work [9]. Fig. 4 shows that the displacement response follows the input waveform, and different damping circumstances influence the oscillation after the induced shock pulse.

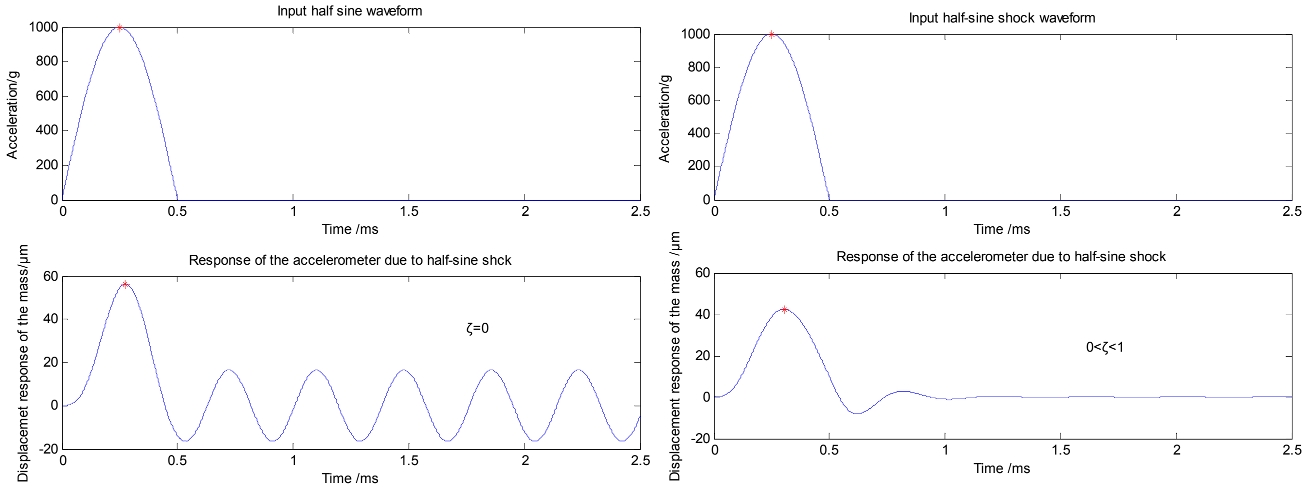


Fig. 4. Response of the accelerometer due to half-sine shock under different damping circumstances

Fig. 5 shows the theoretical approach of shock response spectrum. The displacement represents the maximum deformation of the spring beams, which could indicate the maximum stress distribution of the structure to a certain extent. From the shock response spectrum, it could be concluded that damping could efficiently reduce the deformation to a short duration shock pulse less than 2 ms, as damping is a kind of energy consumption components. For long duration pulse, the sensor responses quasistatically, and the device simply tracks the applied load. Fig. 6 gives the maximum displacement respect to duration time in different damping conditions. It indicates that pulse width plays a critical role in the dynamic shock response of MEMS accelerometers' structure. For under damping system, there is a peak point which should be avoided by adjusting the structure's natural frequency.

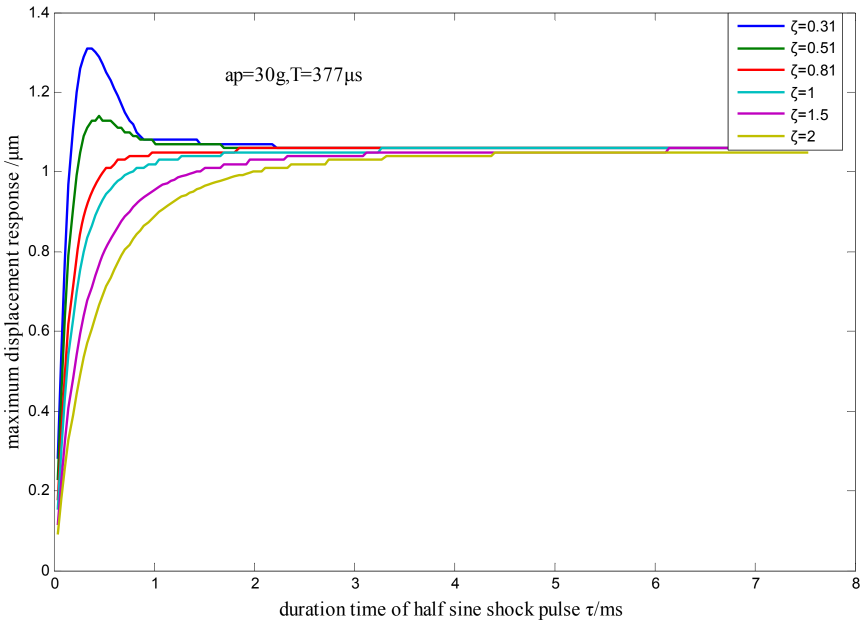


Fig. 5. Accelerometer's shock response spectrum.

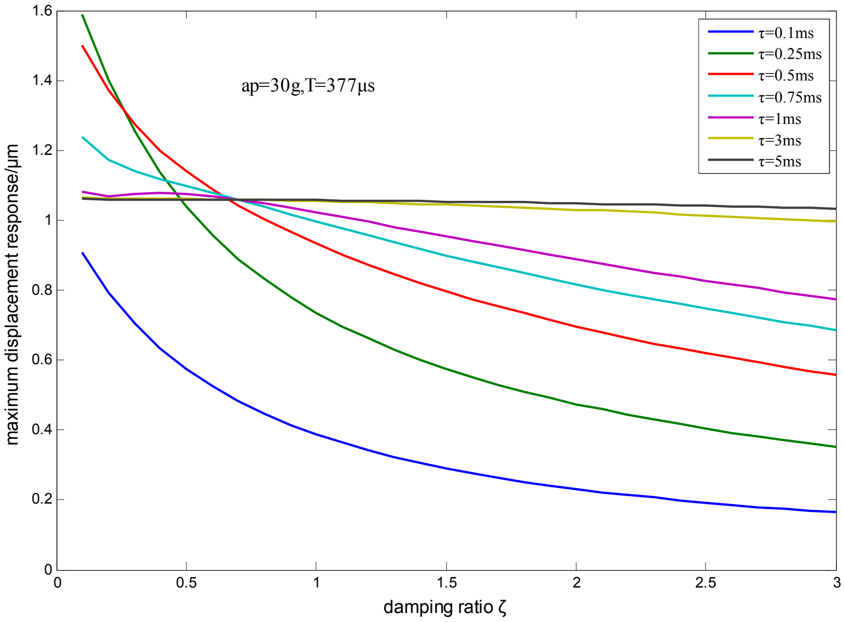


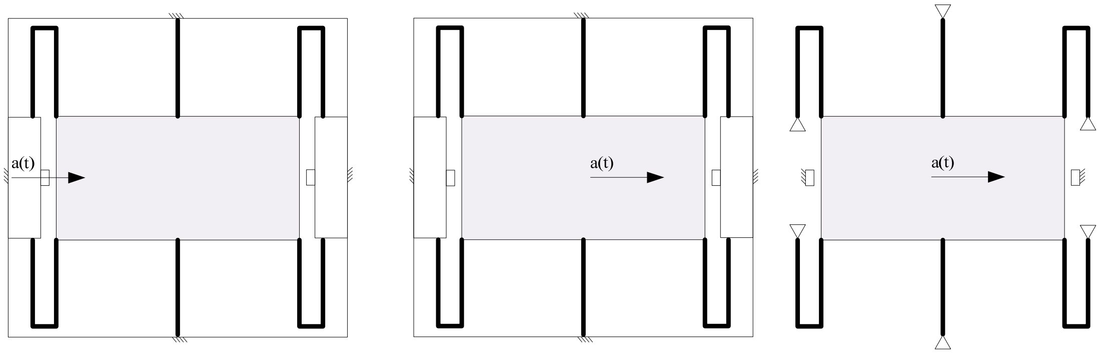
Fig. 6. Maximum displacement respect to duration time of the accelerometer.

In fact, for over range shock accelerations, the displacement of proof mass would exceed the minimum stopper gap. The stopper could limit the free motion while on the other hand, impact force on the contact surface of stoppers may bring other stress concentration problems. More approximate theory model should take contact into consideration.

4. FEA Simulation

4.1. Static Analysis

By assuming the accelerometer's structure with a gravity acceleration of 30 g (1 g=9.8 m/s^2), 3D finite element simulations have been performed using ANSYS 10.0. Fig. 7 shows three conditions of constraints and loads, and Fig. 7(c) has the largest margin, which is applied in the following simulation.



(a) (b) (c)

Fig. 7. Different simulation conditions of constraints and loads.

The maximum von Mises stress is found at the connection part of the clamped-clamped beam due to the largest deformation (Fig. 8). Detailed results show that the deformation and stress are proportional to the acceleration amplitude almost linearly in the static analysis. The proof mass would touch the stoppers in x direction within a 45 g shock acceleration input.

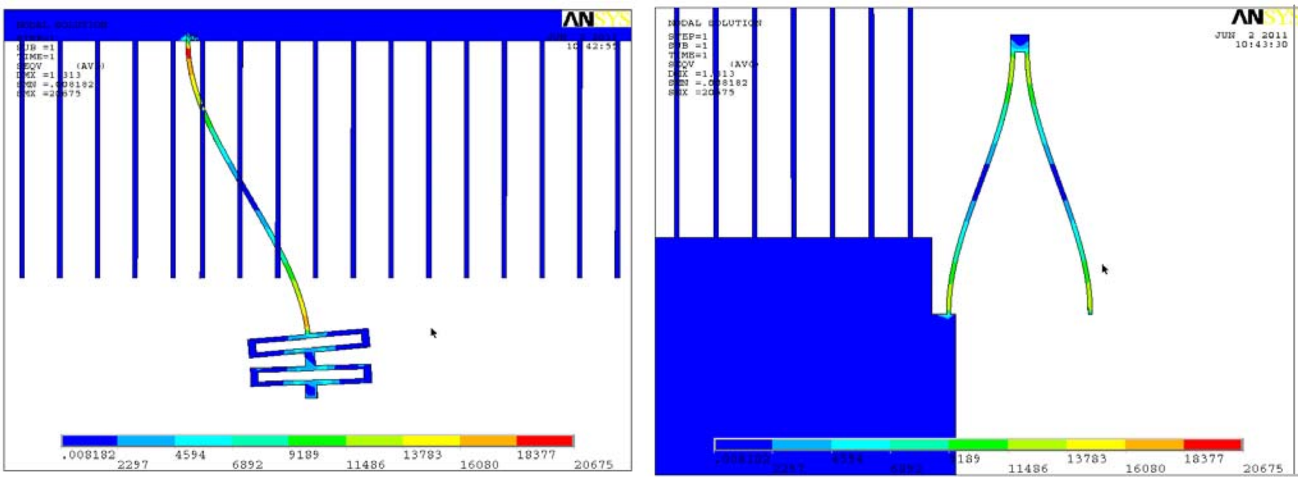
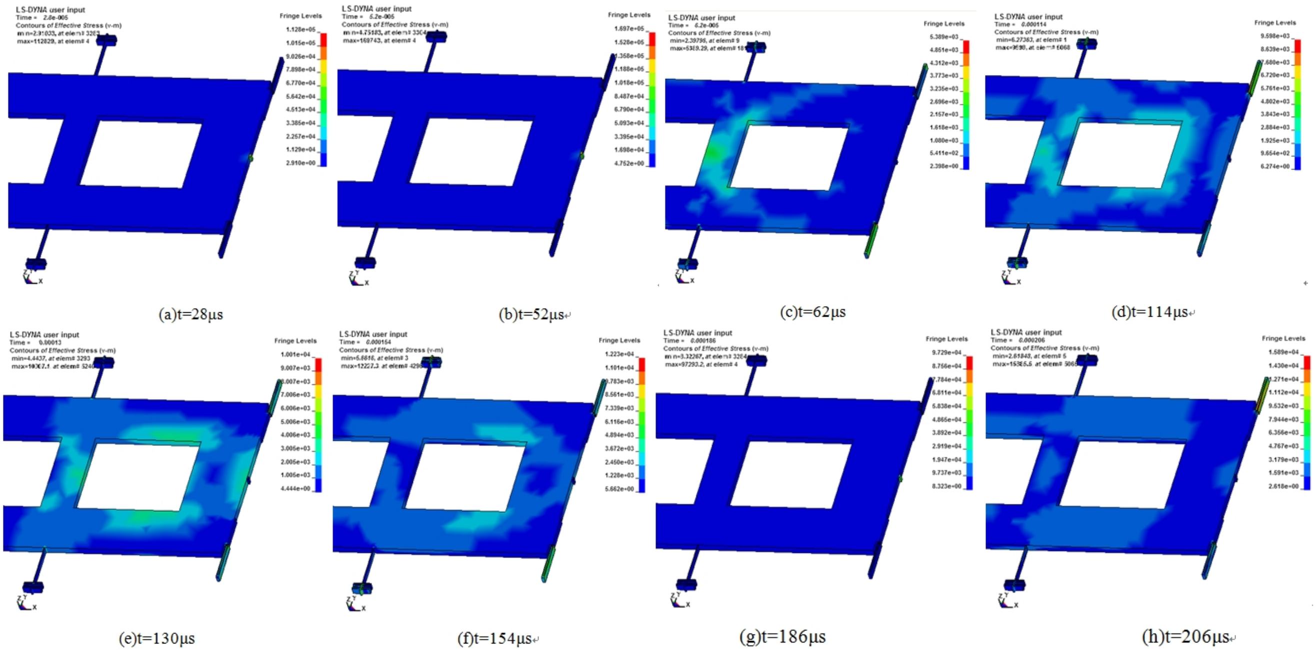


Fig. 8. Static analysis by ANSYS (deformation magnified, unit: g, µm, s).

4.2. Dynamic Impact Analysis

For shock accelerations greater than 45 g, considering the contact effects of stoppers, dynamic FEA simulation using ANSYS/LS-DYNA is applied to calculate the structure's deformation and stress distribution under various shock amplitudes and pulse width. Fig. 9 briefly shows the stress distribution at different time under 4000 g, 200 µs shock. Both the spring beams and stoppers become fragile under the combined effects of shock inertial force and contact force. The maximum stress appears on the stoppers at t=88 µs.



(a)t=28µs (b)t=52µs (c)t=62µs (d)t=114µs

(e)t=130µs (f)t=154µs (g)t=186µs (h)t=206µs

Fig. 9. Stress distribution of the micro structure at different time.

Fig. 10 is the simulated deformation of the mass, and it shows that x-direction stopper and the mass have collided with each other 9 times in 200 μs, as the distance between them is 2 μm. The first contact happens at 27-28 μs, with a velocity of 0.172 m/s. By setting x=2 μm, the theoretical first contact time is 28-29 μs and the velocity is 0.199 m/s solved from equation (3). The frequent contacts between the micro structure and stoppers would cause stress concentration on the contact surface. Fig. 11 gives a comparison between the maximum stress concentration elements in clamped-clamped beams and x-direction stoppers. It could be seen that the stoppers endure more harsh impact than the beams (more than 10 times larger).

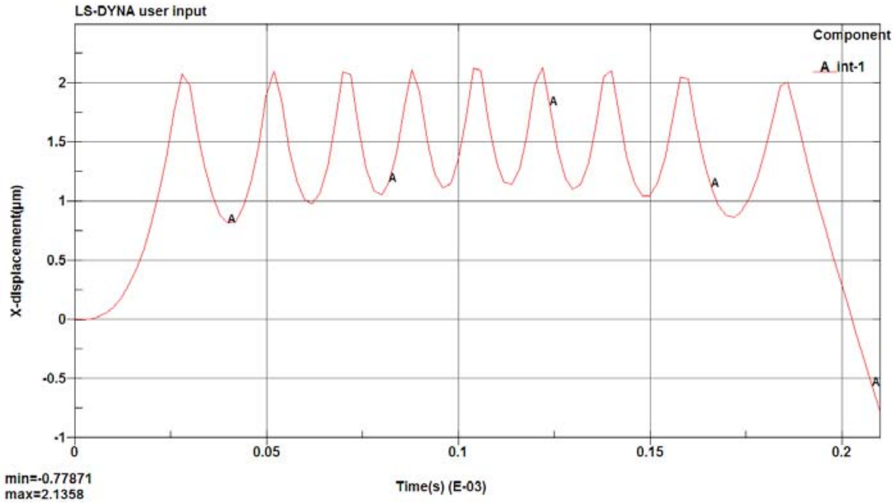


Fig. 10. X displacement of the movable mass within the shock pulse.

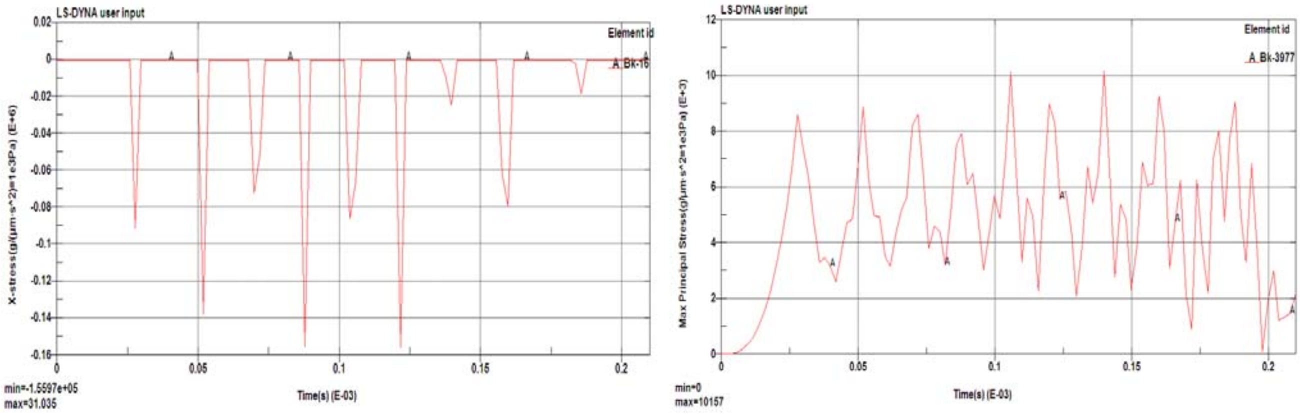


Fig. 11. Time response curve of the stress distribution on stoppers (left) and beams (right).

5. Shock Experiments and Analysis

5.1. Shock Experiments

Based on the above analysis, a modified Hopkinson pressure bar (HPB) is used to load MEMS accelerometers at various shock accelerations (Fig. 12). With the adjustment of gas pressure values and energy absorb cushions made of foamed aluminum, the incident pulse could generate approximate semi sinusoidal accelerations ranging from 10^4 to 10^5 m/s^2, and the pulse width could be expanded to more than 300 μs. The packaged accelerometer is mounted on a designed mechanical fixture. A high-g piezoelectric accelerometer is also attached to measure the experienced shock acceleration curve. Typical shock acceleration curve with 200 kS/s sample rates is shown in Fig. 13. The wave oscillation is due to stress relaxation of the crystal inside the piezoelectric sensor after high-frequency dynamic shock.

Shock experiments of 66 MEMS accelerometers' structures have been carried out individually in three orthogonal orientations, shown in Table 2. Micro images of the sensor structure are observed. Functionality of the accelerometers including the scale factor, zero-bias, capacitance and impedance between different poles has been measured both before and after the shock test.

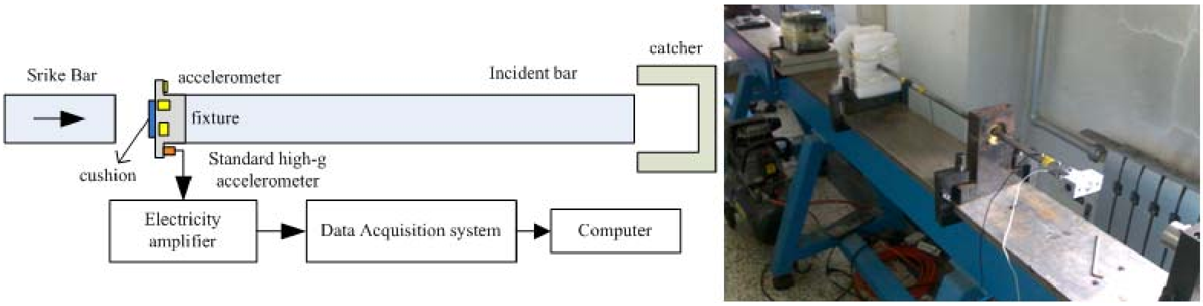


Fig. 12. The block diagram and photo of the HPB apparatus.

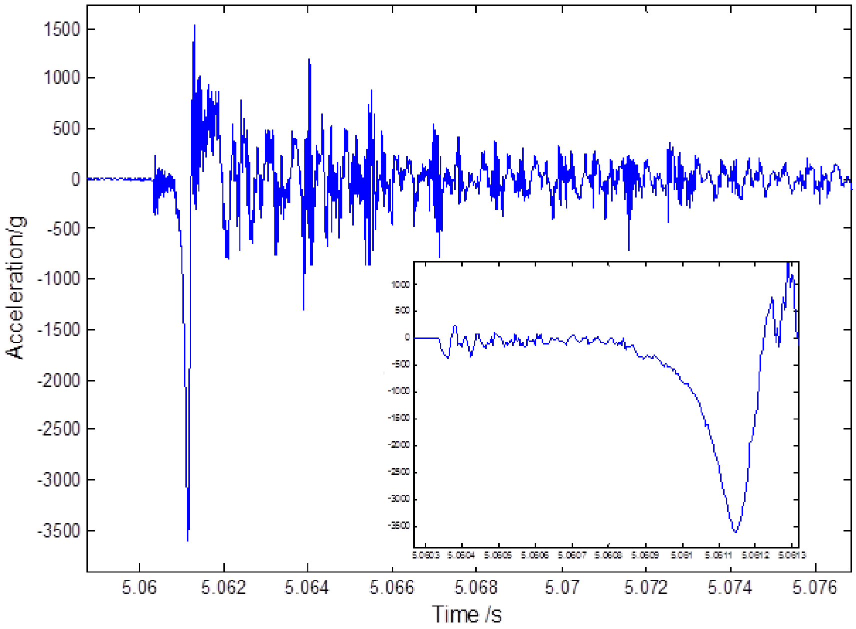


Fig. 13. Typical shock acceleration curve.

Table 2. Number of MEMS accelerometers tested at different shock level.

Level	**x-direction**	**y-direction**	**z-direction**
< 1,000 g	2	1	3
1,000 g-5,000 g	9	10	9
5,000 g-7,000 g	5	4	1
7,000 g-10,000 g	2	3	2
> 10,000 g	7	6	2
Total samples	25	24	17

5.2. Failure Analysis

Failure of the micro structure after HPB shock experiments has been observed in different parts of the accelerometers, such as spring beams, stoppers, proof mass, peripheral frames and so on, while the comb fingers, bonding pads and die package shell are rather robust to shock. Several micro images of typical failure modes are shown in Fig. 14. Failure types on the spring beams appear as deformation, cracks, partial pitting, fracture of several beams and complete fracture of total beams. Failures of the stoppers are shown as cracks, pitting, collapse, partially damaged and totally damaged. Failures of the peripheral frames are classified into pitting, cracks and fractures. Pitting of the proof mass on the contact area with the stoppers has also been observed.

Typically more than 2 failure types could appear under one shot, and some failure types are specific to a particular shock direction and amplitude range, while some of them always occur in company with each other. A full discussion of the results and failure analysis in three orientations respect to various amplitudes and pulse width are shown as follow.

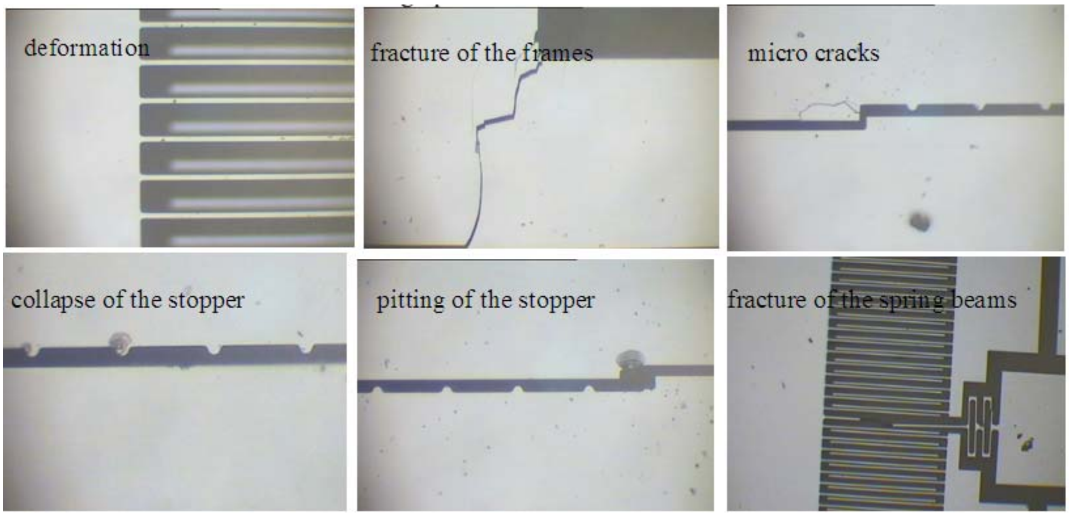


Fig. 14. Micro images of different failure modes.

5.2.1. X-direction Results

All tested accelerometers have exhibited no damage at shock levels less than 1,000 g in x direction. Micro cracks and fractures of the peripheral frames appear under 1469 g, 360 μs; 2964 g, 390 μs and 4489 g, 360 μs shock levels. At 2106 g, 330 μs shock action, cracks have been found on the buffer structure of the clamped-clamped beams which doesn't affect the practical function of the beams. Long duration shock pulse could lead to deformation of the spring beams, observed at the load of 2330 g, 875 μs.

Severe failure types have occurred in the 14 tested specimens at shock levels more than 6000 g, such as fractures of 3-4 spring beams (7145 g, 300 μs; 7244 g, 335 μs; 7754 g, 269 μs) and large deformation of the beams (6179 g, 300 μs) in z direction. As the proof mass would twist under continued shock impact after it has touched the x-direction stoppers, both the stoppers in x and y direction have been found damaged. Fractures of partial beams reduce the support force of the proof mass, which could result in large deformation in z-direction.

5.2.2. Y-direction Results

No failures happen at shock levels less than 5,000 g in y-direction. Failures only occur at the y-direction stoppers including micro cracks, pitting and collapse, when the shock amplitude is ranged from 5,000 g to 7,000 g. Two folded beams have fractured on the tested micro structure at 7244 g, 335μs shock.

Experiment results show that the tested accelerometer could resist larger shock impact in y direction. It's mainly determined by the mechanical stiffness. The stiffer the beams are, the less deformation would occur under high-g shock.

5.2.3. Z-direction Results

The micro structure is weakest in z-direction as it has no stopper to limit the motion. Spring beams begin to fracture at the shock level of 3000g, and shock amplitudes more than 4,000g would lead to complete fractures of total beams. In fact, k_z is much bigger than k_x as shown in Table 1, but overload stoppers are designed in x-direction. Comparison of the experimental results between x and z direction indicates that the stopper is a critical factor in the shock reliability of MEMS sensors. Stoppers could limit the deformation of the micro structure and transmit the induced shock energy partially, which could reduce and share responsibility for the stress concentration in the micro structures.

5.3. Experimental Estimation

Sensors are supposed to function normally with little performance change after enduring shock events. On the basis of the influence on the open-loop performance of the accelerometer, failure types could be classified into three levels: 1. almost normal, the accelerometer could practically work as usual; 2. partially available, the performance has changed but the device could still operate; 3. totally damaged, the device could not be used any more. Level 1 consists of failures of the stoppers and frames. Level 2 includes the small deformation and fractures of several spring beams, which would affect the accelerometer's scale factor and zero bias. Level 3 happens as the proof mass falls off from the glass substrate due to the complete fractures of total beams.

According to the above classification, experimental estimation of the three-orientation shock resistibility of the MEMS accelerometers' micro structure is shown in Fig. 15 in detail. The area surrounded by the green line, the longitudinal and horizontal axis gives a safe range of shock amplitudes and pulse width. Long duration pulse would allow low shock amplitudes as the fracture stress criteria is concerned with the energy induced to a certain extent. The image at the bottom right corner gives an experimental evaluation of the shock reliability in three directions. Results show that the accelerometer could resist about 4,000-5,000 g shock in x direction, 6,000-7,000 g shock in y direction, and 3000 g in z direction. The three orientation shock resistibility is about 3,000 g, 300-400 μs with little performance change.

6. Conclusions

Comparison of the results of different directions indicates that micro structure's spring stiffness and stoppers' areas are the key factors to determine the shock resistance. Both the pulse duration and damping ratio play critical roles in the shock effects of micro-machined structures. Research also shows that MEMS sensors have advantages of better shock resistance. Prospective research should pay attention to the contact effects between micro structures due to shock. The paper provides meaningful guides to improve the shock reliability of MEMS accelerometers. The research methods mentioned may also be applied to estimate the shock reliability of other MEMS device.

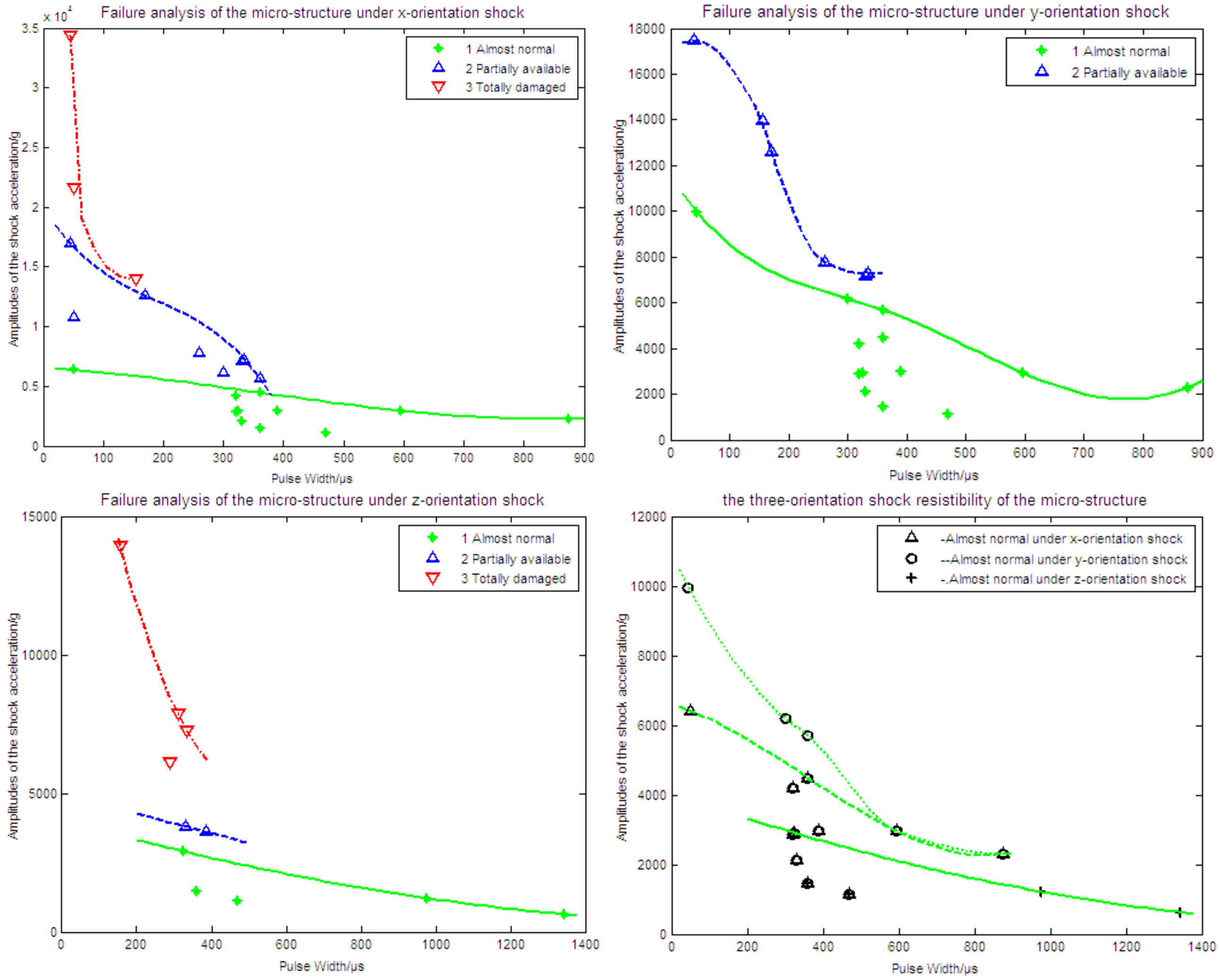


Fig. 15. Experiment estimation of the three-orientation shock resistibility.

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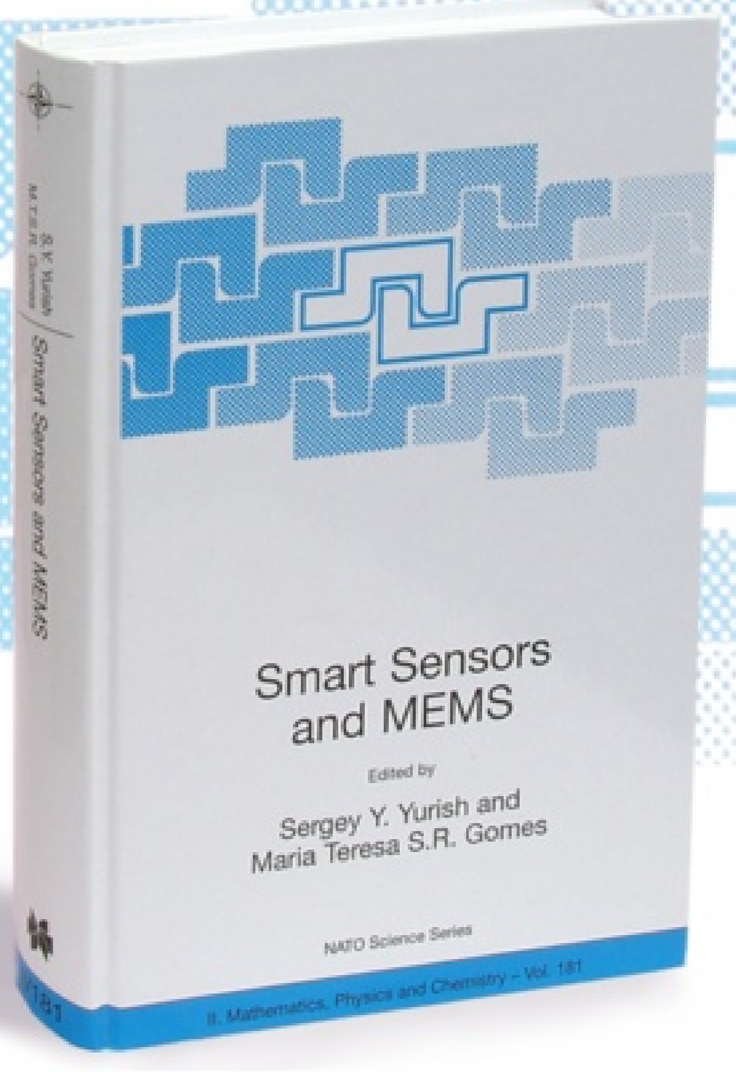
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