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A dynamic collision model for improved over-range protection of cantilever-mass micromechanical accelerometers

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A B S T R A C T

A dynamic collision model is proposed and built to analyze over-range protection of cantilever beam–mass structured micro-accelerometers. The model encloses angular momentum of the seismic mass, squeeze-film air damping, inertial force and supporting force (acting at the cantilever-root) during the collision between the seismic mass and the over-range stopping bumpers. Based on angular momentum balance equation we obtain the relationship among the supporting force F, the collision time duration t and the rotation center c where the bumpers are located. In the best case of $F=0$ which means no supporting force acts on the cantilever, we find the optimal bumper location of c. The accelerometers have been fabricated with the over-range protection design according to the dynamic collision model. Experimental test shows that 5g measure-range accelerometers can endure 9000g acceleration and there is no sign of performance degradation, which well verified the dynamic collision model.

1. Introduction

Since the first silicon accelerometer prototype achieved in 1979 [1], various types of piezoresistive accelerometers have been fabricated using micromachining techniques [2–6]. The devices generally consist of micromachined beams and seismic masses. The sensing principle of the beam–mass structured accelerometer lies in that, when acceleration is applied, the inertial force on the seismic mass makes the beam bending and causes mechanical stress in the beam. In a linear relationship with the acceleration, the stress is sensed with the piezoresistors integrated in the beam. It is deserved to point out that mass production and industrial applications of the piezoresistive accelerometers had not been realized until the over-range protection and damping control were solved in late 1980s [7].

In recent years, accelerometers with ultra-high sensitivity and low measure range are highly demanded for automobiles and consumer electronics [8–10]. These accelerometers should be designed with ultra-thin beams for high sensitivity. Accordingly, the over-range protection becomes much more critical than ever. In these low-g applications, even an ordinary hit would cause an acceleration hundreds of times larger than their nominal measure range.

A static model was built to analyze the over-range protection capacity of the beam–mass structured accelerometer [11], in which the mass is assumed to contact with the stopping bumper (see Fig. 1) after the collision. With the bumper located at the center of the seismic mass, the sensor gains an over-range capacity according to the maximum stress on the beam. However, for those high-sensitivity, low-range, dynamic accelerometers, the mass will no longer keep contact with the bumper but rebound after collision. The traditional static model is not well suited for this situation and a new model considering the dynamic situation should be built to analyze the micromechanical system.

In this article, we model the cantilever beam–mass structured accelerometer with a dynamic collision analysis method. During the collision, squeeze-film air damping, inertial force, supporting force at the beam root and angular momentum of the seismic mass are coupled together. Based on angular momentum balance equation, we obtain the relationships among the supporting force F, the collision time duration t and the rotation center c where the bumpers should be located. In the best case of $F=0$ where no supporting force acts at the cantilever root, we determine the optimal bumper location c. Based on the model, high sensitivity, low-range piezoresistive accelerometers have been designed and fabricated. The testing results show that the 5g-ranged accelerometers can safely endure over 9000g acceleration. This over-range protection capability is much improved compared to the testing results of our previously designed and fabricated 2000g-ranged sensors, where the over-range protection design was based on the traditional static model.

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2. Dynamic collision model for over-range protection

2.1. Modeling

In order to clarify the analysis, we firstly list the symbols in Table 1. The accelerometer developed in this work uses a cantilever beam–mass structure, with the schematic shown in Fig. 1. The sensing structure is sandwiched with a top cap and a bottom cap. The cantilever is designed quite thin for a high sensitivity. The fragile structure is easily damaged with the breakage of the cantilever when the maximum stress on the cantilever exceeds the rapture stress of silicon. To improve the reliability of the system, over-range protection bumpers have been employed to stop the excessive movement of the seismic mass. As shown in Fig. 1, the bumpers in the cavities have a height that is a few microns smaller than the cavity depth so that there is a small gap d_s between the seismic mass and the bumper top. The bumper restricts the displacement of the seismic mass in order that the cantilever is not damaged when the applied acceleration is larger than the nominal measure range of the accelerometer. On the other hand, with the initial cavity depth as d_0, the air in the cavities provides a squeeze-film air damping force on the mass. When a nearly critical damping condition is satisfied, the broadest frequency response band can be reached. Besides, with a low-pass filter-like function, the air damping can effectively depress environmental high-frequency vibration that is a good aid to the over-range protection.

When the acceleration is relatively small and the displacement of the mass at the bumper location is smaller than d_s, the mass can move freely under the inertial force. With increase in the acceleration, the displacement increases until the mass touches the bumpers when the acceleration gets a critical value of a_s. In this case, the momentum caused by the inertial a_s is balanced by the critical bumper-contact force F_s at the cantilever-root and the restrictive bending moment of the beam m_0. With a further increase in the acceleration, the mass will collide with the bumpers and then rebound due to the elastic stiffness of silicon. During the collision, the air damping, the inertial acceleration, the supporting force F at the cantilever-root, the restrictive bending moment m_0 and the force given by the bumpers will have a combined effect on the angular momentum of the mass. If the force F (acting on the cantilever-root) exceeds a critical value, the beam will be broken.

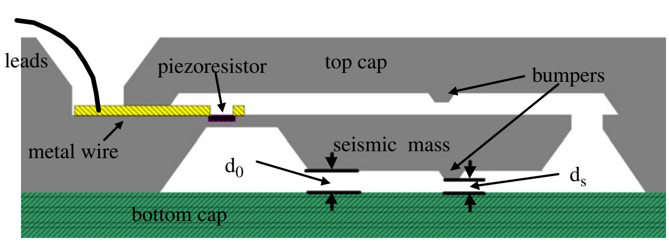

Fig. 1. Schematic of a sandwiched micro-accelerometer, with the squeeze-film air damping cavities and the over-range protection bumpers shown.

When the sensor suffered an over-range acceleration a (a can be several hundreds of times larger than a_s), the mass will heavily impact the bumper and then rebound back. Herein we assume that the deformation of the cantilever beam is the same as that in the static load. Since the restrictive bending moment $m_0 = m a_s L'$, in this case of $a \gg a_s$, the effect of m_0 will be small enough and can be ignored. During the collision process, the following factors will influence the mass angular momentum:

(1) The damping force caused by the squeeze-film air;
(2) The inertial force caused by the acceleration of a;
(3) The supporting force F acting at the cantilever root;
(4) The force given by the bumpers.

In (4) the force given by the bumpers is very difficult to be calculated. In our analysis, we use the point c (where the bumpers are located) as the rotation center. In this case, the force given by the bumpers is located at the rotation center; thus, the angular moment influenced by the factor (4) is null.

2.2. Theoretic analysis

2.2.1. Deformation of the beam–mass structure

Since the seismic mass is much larger than the mass of the cantilever, the inertial force on the cantilever can be ignored. As shown in Fig. 2, the inertial force on the seismic mass is simply treated as a concentrated force $f = ma$ applied at the mass center. The differential equation for the cantilever displacement of $w(x)$ can be expressed as [12,13]

$$-EI_1 w_1''(x') = -f(L' - x') \tag{1}$$

With the boundary condition $w_1(0) = 0, w_1'(0) = 0$, we obtain the cantilever displacement as

$$w_1(x') = \frac{f(3L' - x')}{6EI_1} x'^2 \tag{2}$$

The displacement and the slop of the cantilever at x_1' are

$$w_1(x_1') = \frac{f(3L' - x_1')}{6EI_1} {x_1'}^2 \tag{3}$$

Table 1
Symbols used in the analysis.

Symbol	Definition	Symbol	Definition
A, B, H	Length, width, thickness of the mass	m_0	Restrictive bending moment on the cantilever
a	Applied acceleration	P	Air pressure
a_s	Bumper-contact critical acceleration	s	Mass-center moving distance
c	Location of the bumper	t	Collision time duration
d	Air gap	w_1	Displacement of the cantilever
d_0	Cavity depth	w_2	Displacement of the mass
d_s	Protection gap	$x_1, x_2/x_1', x_2'$	The left and right sides of the mass in the o/o' coordinative system
E	Young's modulus	β	Correction factor of the air damping
F	Supporting force at the cantilever-root	Δl_{air}	Angular momentum change due to air damping
F_s	Bumper-contact critical supporting force	Δl_F	Angular momentum by supporting force
I_1	Inertia moment of the beam	$\Delta l_{inertia}$	Angular momentum change by acceleration
L/L'	Location of the mass center in the o/o' coordinative system	ρ	Material density
l_0/l_1	Angular momentum before/after collision	ω	Angular velocity of the mass