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MEMS-based Low-g Inertial Switch

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Abstract: In this paper, a novel MEMS-based switch is designed and characterized for the purpose of sensing the low g acceleration and output on-off signa1. The switch consists of an annular proof-mass suspended by helix spring that is fixed to the pedestal which located in center and connected with the bottom glass cover. The characteristic of the helix spring decides that the switch can sense the weak signal. The dynamic modeling of the design is obtained using finite element method (FEM) in the commercial code ANSYS. To verify the sensitivity and the reliability of the switch, the impact process is simulated, and the response time is calculated. The results show that the response time is short enough, the helix spring presents elastic deformation, and the switch can be used time after time. The modal analysis of the switch is carried out using finite element method in the case of constrained model, the inherent frequencies and mode shapes of the first 4 order modes are obtained respectively, and the analysis result gives a reference for switch design and us. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: MEMS, Inertial switch, Dynamic analysis, Finite element method, Mode analysis.

1. Introduction

The immense success of micro-electronics technology led to a miniature revolution in many fields since the 1950s, prompting the birth and vigorous development of Micro System technology. The feature of MEMS is multi-interdisciplinary, it combines with the technology of microelectronics and the precision machining, integrates such functions as micro-mechanism, sensor signal processing and control, and has the info acquisition, processing, execution, etc. The development of MEMS has a revolutionary influence on science and technology and communities. MEMS inertial switch, the product of combination of mechanics and electricity, which was also known as the g-value or threshold switch, is the MEMS actuators provided the action of switch closure to be sensitive to change in acceleration. The features, e.g., high efficiency, rapid response, accuracy, high reuse frequencies and reliability, make the MEMS inertial switch employed in a wide variety of applications such as automobile airbag deployment systems, vibration alarm systems, etc.

The United States, at the turn of the century, reported a kind of MEMS inertial switch [1] which sense the changes of unidirectional acceleration, and its inertia hammer whose top constraints by the thermodynamic or electromagnetic force to ensure that the inertia hammer does not move downward in non-working status. When the switch entails work, the circuit supplies power and thermodynamic or electromagnetic force removes the constraints of inertia hammer which is stuck in the right place at the bottom after the downward movement, the bottom of cantilever beam distorts under inertia hammer, and connects circuits. A passive universal inertia switch [2], which is of normal open, instantaneous action, and non-locking of inertial threshold and able to be coupled with fuse circuits, was proposed by Robinson, *et al.* in patent in 2002. Micro-inertia switches that Greywall *et al.* proposed adopted that the structure of loop mass supported on helical spring in patent in 2006 [3]. By adjusting voltage to regulate acceleration threshold, threshold adjustable acceleration switch of Korea high-tech research institute utilized inertial and resultant force of electrostatic forces caused by the inside electrode voltage [4].

MEMS inertial switch has several advantages:

1) MEMS inertial switch has super-mini size. Compared with traditional inertia switch, the size dwindles over several times to make room for extending other functions

2) The strong anti-jamming ability to MEMS inertial switch. Especially the ammunitions use under the adverse circumstances, subjected to these interferences such as electromagnetism in the flight. Compared with solid-state electronic switch, MEMS inertial switch is able to ensure connection or disconnection in physics; and contrasts with the acceleration sensor, simple is the structure to MEMS inertial switch which dose not require tracking measurement variation at all times.

3) The features of MEMS technology itself determine MEMS inertial switch, which can be rapidly perceptual to such signal that acceleration is less than 5 g but not to traditional one, to capture weak signals sensitively.

4) The process of each of components has a good consistency and no assembly. Compared with traditional process methods, no matter whether DRIE or LIGA ones, it has a good consistency, and avoid the problems that distributed switch threshold caused by assembly errors, leaving that the safety and reliability of the switch can be greatly enhanced.

5) Wide response angle and reliable solution to the problem of uneasy fire in the present of large projectile and target hit by large touch angle.

6) The anti-overloaded performance is good which ultimately holds up to 100000 g overload.

7) Light weight, and the single parts materials – using silicon or nickel; Cost would reduce to quite low by the means of micro-silicon and LIGA had the mass production been put into.

2. Structure

The designed low g switch is a glass-silicon-glass sandwich. To describe the structure layer definitely, the top and bottom flat is not shown herein, the middle structure layer is the heart of the device, it consists of an annular proof-mass suspended by helix spring that is fixed to the pedestal which located in center and connected with the bottom glass cover as shown in Fig. 1. The designed switch should sense low g, so the stiffness of the spring must small enough, and the helix spring can be competent. The annular proof-mass is a movable electrode, and the frame is a fixed electrode. Between the two electrodes, there is a gap, the gap separates movable electrode and fixed electrode thereby keeping the switch in the open state. As the system accelerates, the annular proof-mass will leave from its initial position and move towards the fixed electrode. If the acceleration is not high enough, the annular proof-mass will go near by the fixed electrode (but not contact) and soon is pulled to its home position again with the tension of the helix spring increasing. In contrast, when the absolute value of acceleration along a particular direction exceeds a certain threshold value, the annular proof-mass cannot be re-balanced and then contacts with the fixed electrode, the inertial switch changes its state. Because of the peculiarly annular structure, the inertial switch reacts the same threshold acceleration along any direction in the x-y plane, and reacts in a substantially analogous fashion to equal levels of acceleration and deceleration.

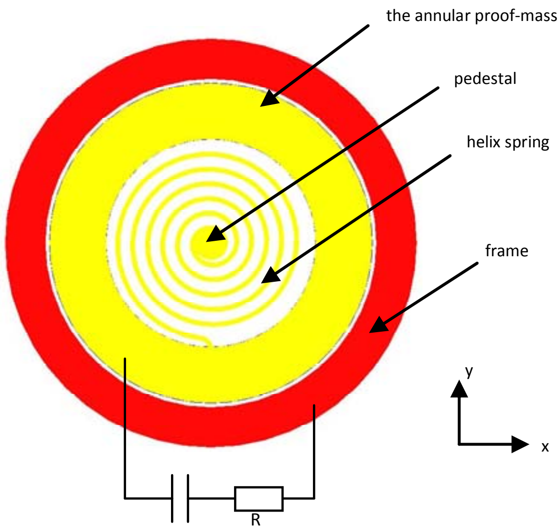


Fig. 1. Front view of switch device.

3. Dynamic Analysis of the Switch

The primary purpose of this switch is to change its state when sensing the threshold acceleration, requiring an understanding of the dynamic process of the annular proof-mass. In this section the movement process is simulated and analyzed, and the frequency and mode shapes of the switch are studied with the FEM based on ANSYS software.

3.1. The Working Principle

The working principle of MEMS inertial switch is the same as traditional. The whole structure consists of cantilever beam, mass, movable and fixed electrodes. Force situation is shown in Fig. 2.

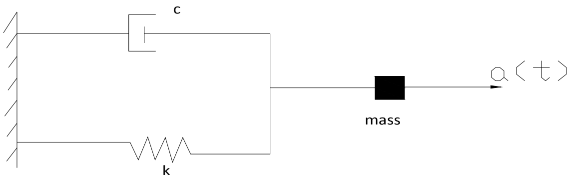


Fig. 2. A simplified model for the low g switch.

In the moving process, the dynamic equilibrium equation of movement is

$$m\ddot{x} + c\dot{x} + kx = ma(t)\,, \qquad (1)$$

where x is the moving distance of the sensing mass, m is the effective mass, c is the damping coefficient, k is the equivalent stiffness of the four serpentine flexures and a(t) is the externally load. The external load a(t) is not an invariable force, it changes by time.

3.2. Instantaneous Dynamics Simulation

To simplify the calculation process, the pedestal is ignored in Fig. 3, because it connects with the substrate die, it is replaced with constraining the root of the helix spring. Material and the dimensions of the fabricated structures are given in Table 1.

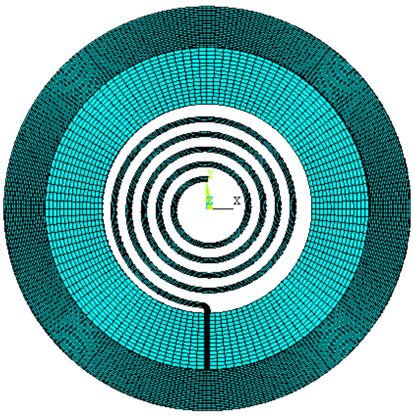
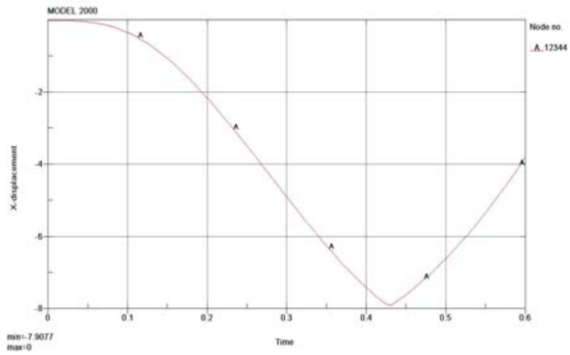


Fig. 3. The simplified finite element model.

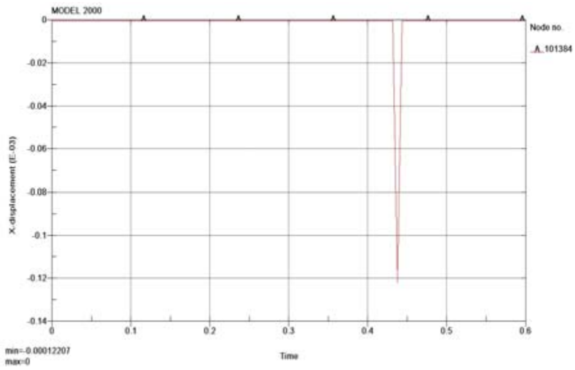
Table 1. Material and geometrical parameters of the switch.

Parameter	Value	Unit
Width of the sensing mass	700	[μm]
Thickness of the sensing mass	60	[μm]
The gap between sensing mass and fix electrode	8	[μm]
Width of helix spring	60	[μm]
Thickness of helix spring	60	[μm]
Young's modulus of the silicon	1.67e11	[N/m^2]
Poisson' ratio of the silicon	0.3	
Density of the silicon	2300	[Kg/m^3]

When the annular proof-mass accepted the acceleration from the positive x direction, it moves towards the negative x direction. Fig. 4 (a) shows the displacement of the sensing mass under the external force 20 g. Node 12344 is selected to represent the sensing mass, the displacement of the annular proof-mass increases along with time adding, at about 0.46 ms, the annular proof-mass impacted with the fixed electrode and the displacement along the negative x direction reached the maximum 7.9077 μm, which is bigger than the gap size 7.9 μm, it illustrates that when the sensing mass impact with the fixed electrode, the fixed electrode exhibits the elastic distortion.



(a) The motion of the sensing mass under the external force 20 g.



(b) The motion of the fixed electrode during the impact.

(c) Contour of von-mises stress during impact moment.

Fig. 4. The dynamics simulation of the switch.

Fig. 4(b) shows the displacement of the fixed electrode during the impact, the node 101384 that belongs to the fixed electrode is corresponding with the node 12344 in the sensing mass. At about 0.46 µs, the fixed electrode receive the impact, the maximal displacement of the fixed electrode along the negative y direction reach to 0.12 µm that means the sensing mass will move together with the fixed electrode along a small distance, the contact time is ensured by this small distance. Fig. 4(c) is a von-mises stress contour of the structure. The von-mises stress of the structure reached the maximum at about the impact moment, because the annular proof-mass makes the helix spring straining extremely. The maximum stress occurs in the helix spring, the value is 5.99 MPa, much less than the yield strength of the silicon, it illustrates that the helix spring presents elastic deformation, and the switch can be used time after time.

3.3. Modal Simulation of the Switch

Some applications need switch that has good dynamic performance. The modal analysis of the switch is carried out using finite element method in the case of constrained model. Through the analysis, the inherent frequencies and mode shapes of the first 4 order modes are obtained respectively. The first frequency is 304.408 Hz, the switch turns round the z axes (Fig. 5), the second frequency is 358.717 Hz, the switch turns round the x axes (Fig. 6), the third frequency is 363.22 Hz, the switch turns round the y axes (Fig. 7), the fourth frequency is 425.465 Hz, the switch oscillate along the z axes (Fig. 8). The last results that the mode shapes and natural frequencies by simulation are shown in Table 2.

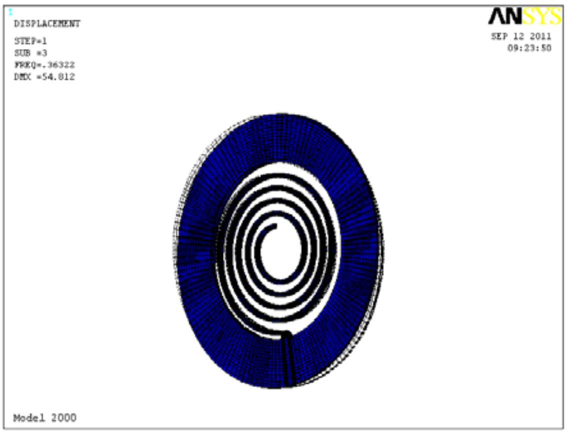


Fig. 5. The 1st order mode shape (f1=304.408 Hz).

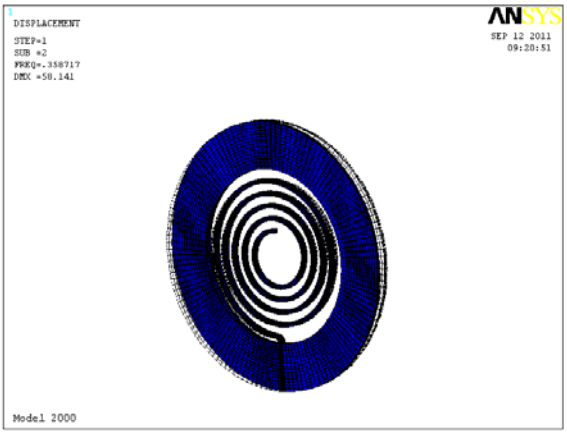


Fig. 6. The 2nd order mode shape (f2=358.717 Hz).

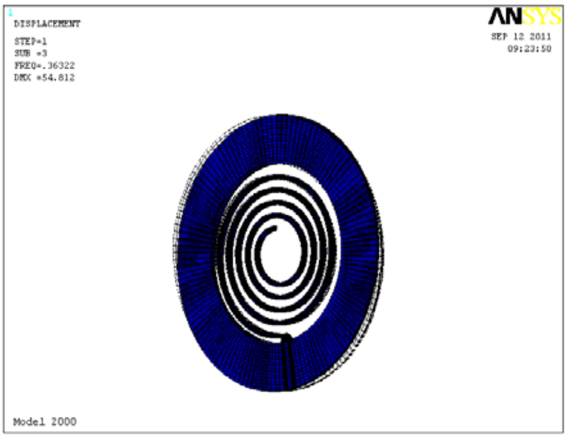


Fig. 7. The 3rd order mode shape (f3=363.22 Hz).

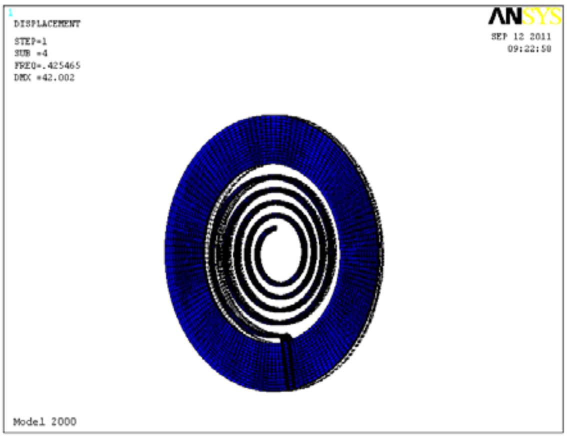


Fig. 8. The 4th order mode shape (f4= 425.465 Hz).

Table 2. The inherent frequencies of the first 4 order modes

Mode	f5	f6	f7	f8
Inherent frequencies	788.44 Hz	825.46 Hz	3301.4 Hz	4059.6 Hz

4. Conclusions

This paper proposes an omni-directional MEMS switch which can sense the weak signal, low g acceleration. It has the same sensitivity in different axes. The motion of the annular proof-mass is analyzed by dynamic simulation under the 20 g threshold acceleration, the simulation results show that the response time is 0.46 ms, it illustrates that the response time is short enough. The von-mises stress of the structure is calculate, the maximum stress occurs in the helix spring, the value is 5.99 MPa, much less than the yield strength of the silicon, it illustrates that the switch can be used time after time. The modal analysis of the switch is carried out using finite element method in the case of constrained model. The inherent frequencies and mode shapes of the first 4 order modes are obtained respectively, and the results will offer the reference for design and use.

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