A novel MEMS inertial switch with a reinforcing rib structure and electrostatic power assist to prolong the contact time

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Abstract. The MEMS inertial switch is widely used in various industries owing to its advantage of small size, high integration, low power consumption and low costs, especially in the timing of Internet of things, such as toys, handheld devices, accessories and vibration testing. This paper provided a novel inertial switch with a reinforcing rib structure and electrostatic power assist. The designed inertial switch can reduce the complexity of the post-processing circuit and broaden its application prospect. The continuous electrostatic force can extend the contact time of the designed inertia switch before the leakage of electricity ends. The moving electrode with a reinforcing rib structure can effectively restrain the bending of the lower surface of moving electrode caused by residual stress. The array-type fixed electrode can ensure stable contact between the electrodes when the device is sensitive to external shocks. The dynamic displacement-time curve can be simulated by the COMSOL finite element simulation software. The laminated plating process is used to produce the designed inertial switch and the drop hammer acceleration monitoring system is used to test the fabricated device. The results indicate that, compared with the traditional design, the bouncing phenomenon can be prevented and extend the contact time to 336μs.

1. Introduction
In the times of wireless sensor networks and the internet of things (IOT), the status of many things needs to be monitored in real time, such as storage and transportation of goods, toys and car collision [1-2]. In some remote or harsh areas, some devices require continuous vibration detection and transmit the status data to the central control system. In these practical applications, inertial threshold sensor plays a very important role and has a wide range of applications. The micro-accelerometer can accomplish the tasks of these applications well, but it often requires a constant supply of energy, which will lead to large power dissipation and limits its applications together with the difficulty of analog signal processing. Inertia switch is a passive device and outputs pulse signal in the practical applications, which make it better to meet the requirements of the above application environment, especially the vibration detection in the remote unattended harsh environment. However, the rigid contact collisions in traditional designs always lead to very short contact times and rebound phenomena, which makes the subsequent signal processing circuits very complex. The flexible contact electrodes have been designed to extend the
contact time, but the contact time is greatly limited (tens of microseconds) due to the characteristics of the flexible contact structure [3–4]. The designed inertial switch with a reinforcing rib structure and electrostatic power assist can greatly prolong the contact time (hundreds of times) and effectively restrain the bouncing phenomenon.

2. Design and Fabrication

2.1. Design

As shown in figure 1, a type of one-way-trigger inertial switch is proposed in this study. The designed structure consists of three parts: a moving electrode with a reinforcing rib structure, an array structure fixed electrode that is connected to each other through a layout connection, and a pulling electrode with a large surface area. The reinforcing rib structure of the upper surface of the moving electrode can effectively restrain the warping of the electrode produced by the residual stress of the electroplating. The good flatness of electrode surface ensures that the moving electrode and fixed electrode produce as much electrostatic attraction as possible through the parallel structure. The moving electrode is connected by four conjoined snake-like springs and is in a suspended state. The fixed electrode is composed of a contact array structure, which is different from the previous single contact structure [5]. The array structure extends the contact range of the fixed electrode and moving electrode, and can have a certain amount of redundancy under the accidental condition that the lack of flatness of the moving electrode to ensure the most stable contact of the two electrodes. A sufficient micro-gap is designed between the pulling electrode and the fixed electrode, which ensures that the two electrodes can be mutually insulated from each other. The fixed electrode is slightly higher than the pulling electrode, which can ensure the mutual insulation between the moving electrode and pulling electrode when the moving electrode is in contact with the fixed electrode. The method of electroplating growth can make the fixed electrode higher than the pulling electrode to maintain micron-level accuracy and plane consistency. A multi-hole cantilever beam is designed as a barrier-limiting structure above the moving electrode, which can effectively prevent the rebounding phenomena of the moving electrode in the non-sensitive direction in a practical application.

![Figure 1. Schematic of the designed electrostatic force-assisted MEMS inertial switch.](image)
Figure 2. Model of the designed electrostatic force assisted inertia switch.

Figure 2 shows the model of the designed electrostatic force assisted inertia switch, which can be regarded as a spring–mass electrostatic-field-damping system. The equation of dynamic motion control can be described as follows:

\[ m\frac{d^2x}{dt^2} + \beta \frac{dx}{dt} + kx + \frac{\varepsilon AV^2}{2(y - x)^2} + ma(t) = 0 \]  

(1)

where \( m \) is the mass of the moving electrode, \( \beta \) is the damping coefficient, \( k \) is the elastic coefficient, \( \varepsilon \) is the dielectric constant of air, \( A \) is the effective overlap area for the electrostatic force, \( V \) is the voltage between the moving and pulling electrodes, and \( a(t) \) is the time-varying external acceleration. The resistance of the damping system is mainly due to the air damping generated on the moving electrode in the movement process of the moving electrode.

Table 1. The structural dimensions of the designed device.

| Structure         | Structural dimensions | Size(μm) |
|-------------------|-----------------------|----------|
| Moving electrode  | Rectangular side length L | 1810     |
|                   | Mass Thickness m       | 60       |
|                   | Stiffener width a      | 30       |
|                   | Stiffener thickness x   | 15       |
|                   | Suspension gap d       | 10       |
|                   | Stretch across length l | 1040     |
| Snake-like spring | Inner radius r2        | 25       |
|                   | Thickness h            | 15       |
|                   | Width b                | 25       |
| Fixed electrode   | Thickness h1           | 5        |
|                   | Radius R               | 40       |

Table 1 summarizes the main structural dimensions of the designed device of the designed switch. In the design, the moving electrode thickness m is set to be variable, which can be changed through photolithography, lamination, electroplating, or other surface micromachining processes. In the device
structure of the same shape and other parameters, the performance parameters of the device is changed by the preparation of the moving electrode with different thickness.

2.2. Fabrication

2.2. Fabrication

Figure 3. Main manufacturing process of micromechanical inertial: (a) Lead layer, (b) Support layer, (c) Suspended layer, (d) Spring layer, (e) Mass layer, (f) Reinforcing rib layer, (g) Second suspended layer, (h) Barrier layer and (i) Completed structure.

The designed MEMS inertial switch is fabricated by laminated plating process and nickel metal is selected as the structural material. The structure and morphology of the device are determined by lithography, development, and subsequent electroplating processes, and the thickness of each layer is determined by the thickness of the photoresist. The plating bath temperature is 45 °C, the pH value is about 4, and the plating rate is about 0.3µm/min. The composition of the nickel electrolyte is Ni\([\text{NH}_2\text{SO}_3]_2\) (600 g/L), NiCl\(_2\)·6H\(_2\)O (10 g/L), H\(_3\)BO\(_3\) (25 g/L). The main manufacturing process of the designed device is shown in figure 3 and is described as follows:

(a) Lead layer: select the quartz glass as an insulating substrate; sputter Cr/Cu on the substrate as the first seed layer; spin-coat a layer of positive photoresist and transfer graphics; electroplate the fixed electrode and pulling electrode;
(b) Support layer: electroplate the fixed electrode to make the fixed electrode higher than the suction electrode by 1–2µm;
(c) Suspended layer: electroplate the support column to support the spring–mass system and form the air gap between the electrodes;
(d) Spring layer: sputter the second Cr/Cu seed layer on the support layer and plate the conjoined snake-like spring and bottom mass block;
(e) Mass layer: construct the mass block out of a layer of electroplated nickel to make the mass block higher than the height of the spring;
(f) Reinforcing rib layer: construct the stiffener rib structure by electroplating the surface of the mass block to effectively prevent the uneven surface caused by residual stress;
(g) Second suspended layer: electroplate the supporting column to support the multi-hole barrier cantilever beam structure, and form an air gap between the barrier limiting structure and mass block;
(h) Barrier layer: sputter the third Cr/Cu seed layer and electroplate the multi-hole barrier cantilever beam structure;
(i) Release process: remove the photoresist with sodium hydroxide solution, remove the copper seed layer with ammonia and hydrogen peroxide solution, remove nickel seed layer with potassium permanganate solution acetone. The overall structure of the designed device is now obtained.

Figure 4. SEM images of (a) the fabricated device and (b) the designed large flat pulling electrode and array-type fixed electrode and VEECO images of (c) the spring-mass structure and (b) the pulling electrode and fixed electrode.  

Figure 4 displays scanning electron micrograph (SEM) images and VEECO images of the overall structure of the released inertial switch with the electrostatic force assist enhanced contact effect. (a) shows the obtained overall structure of the designed device, which include Pad, Multi-hole crossbeam, Reinforcing rib structure and so on. (b) shows the top view of the array-type fixed electrode and the pulling electrode, which are insulated from each other by the micro-gap. (c) shows the VEECO three-dimensional oblique drawing of the conjoined snake-like spring and partial moving electrode. And (d) shows the pulling electrode and fixed electrode, and it clearly shows that the fixed electrode is slightly higher than the pulling electrode.

3. Simulation results and Experimental results

3.1. Simulation results
As shown in figure 5, a quarter of the finite element model is used as the simulation model because of the design of the MEMS inertial switch as a central symmetrical structure. This simulation model can effectively reduce the requirements for computer memory and other pieces of hardware, and greatly reduce the simulation time. The designed electrostatic force-assisted MEMS inertial switch includes the external acceleration of the half-sine wave, electrostatic force acting on the moving electrode, and elastic restoring force of the spring, which is a multi-physical field coupling problem. The COMSOL simulation software is used to simulate and analyze the dynamic response of the designed structure. The end of the spring, fixed electrode, and pulling electrode are set to a fixed constraint in the model, that is, the degree of freedom is 0. The displacement of the moving electrode can only exist in the Z-direction, and the
displacement in the horizontal direction is set to 0. The free triangulation mesh and sweeping method are used to mesh the mesh. Nickel metal is selected as the structural material of the model because of its excellent mechanical properties. The parameters of the nickel metal are as follows: Young's modulus: 165GPa; density: 8.96g·cm$^{-3}$; Poisson's ratio: 0.31 [6].

![Schematic diagram of finite element simulation model.](image)

**Figure 5.** Schematic diagram of finite element simulation model.

![Dynamic Response curve of the designed device at the acceleration 16g, acceleration 18g, acceleration 18g and 8V, and acceleration 18g and 15V.](image)

**Figure 6.** Dynamic Response curve of the designed device at the acceleration 16g, acceleration 18g, acceleration 18g and 8V, and acceleration 18g and 15V.

Figure 6 shows the dynamic response curve of the designed device in the case of the acceleration 16g, acceleration 18g, acceleration 18g and 8V, and acceleration 18g and 15V. It can be seen from the simulation that the threshold acceleration of the designed structure is 18g when there is no voltage applied. When the applied external acceleration amplitude is 18g, the simulation is also done in the condition of the applied pulling voltage is 8V and 15V, which shows that the contact time is 180μs in
the case of an applied voltage of 8V, and the contact time is pro-longed to 320μs when the applied voltage is 15V.

3.2. Experimental results

The drop hammer system is used to characterize the designed micromechanical inertial switch, and Figure 12 shows the test principle. The acceleration of the drop hammer is detected by the standard accelerometer (ADXL-193, Analog Device Inc.) and the pulse signal generated by the MEMS inertial switch is detected by a multichannel oscilloscope (Agilent 6000 MSO6034A) when the fabricated device is triggered. The standard accelerometer and the inertial switch prepared are mounted on a drop hammer of a standard drop weight system. The fabricated device and standard accelerometer are connected to the external circuit. The inertial switch with a constant voltage source of 3V and current-limiting resistor resistance of 300Ω constitute the circuit. When the drop hammer falls from a certain height and collides with the substrate, a half-sine acceleration will occur on the device. Changing the height of the drop bar and the stiffness of the substrate can change the amplitude and pulse width of the resulting half-sine wave. When the applied external acceleration reaches or exceeds the inertia switch threshold, the inertia switch is turned on and a pulse signal is output.

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Dynamic response results of the fabricated MEMS inertial switch at the acceleration 18g, acceleration 20g, acceleration 18g and 8V, acceleration 18g and 15V.

Figure 7 shows the contrast test results under with and without the applied pulling voltage. Without the pulling voltage, the fabricated device switch on and the contact time is 20.5μs when the applied external acceleration is 18g, which is called the threshold acceleration of the device. The test result shows that the test result is slightly higher than the simulation result, which is due to the deviations from the microfabrication process. In the same condition that without voltage applied and when the applied acceleration is 20g, the device has a rebounding phenomenon and the minimum contact time is 18μs and the maximum contact time is 42μs. The contact time of the device is 192μs when the applied external acceleration is 18g and the applied pulling voltage of 8V. When the applied acceleration is equal to 18g
and the applied voltage is 15V, the contact time of the device is 336μs and there is no rebounding phenomenon. When the applied pulling voltage continues to increase, the air film between the moving electrode and the pulling electrode may be broken down. The experimental results are in good agreement with the simulation results and verify that the designed MEMS inertial switch structure can effectively extend the contact time.

4. Conclusions
An inertial switch with an electrostatic force assist enhanced contact effect was proposed, simulated, and successfully fabricated by laminated plating process. The array-type fixed electrode and moving electrode with a reinforcing rib structure were designed and fabricated, which can ensure stable contact of the two electrodes and restrain the warping of the device caused by residual stress. The whole device is completed by laminated plating process. The test by the dropping hammer system indicates that the contact time of the fabricated inertial switch is about 336μs, which agrees well with the simulated contact time (320μs) in its sensing direction by the finite element COMSOL simulation software. It is demonstrated that the proposed electrostatic force-assisted MEMS inertial with the reinforcing structure is beneficial for extending the contact time.

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