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Analysis of bistable inductive micro-switch based on surface micro size effect

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ABSTRACT

The inductive micro-switch can not only induce an external acceleration, but also be controlled by the external acceleration to realize a trigger action. It is an integrative device of a sensor and an actuator. However, little work has been done to develop a comprehensive model to accurately analyze the micro size effect during micro-switch contact process. So its malfunctions related to “fail-to-closure” and “transient-closure” result in low reliability and weak anti-jamming capability. A bistable inductive micro-switch is presented based on nano electro-mechanical system (NEMS) technology and micro size effect. And the sine-model is used to describe the rough contact surface of the micro-switch. Micro size forces such as the Casimir force and van der Waals (vdW) force are analyzed in detail using the principles of vacuum energy and the Wigner–Seitz micro-continuum media. The vdW force includes the repulsive force. The simulation results of the Casimir force varied with the gap are obtained, which is compared with the relative experimental result. The dynamic equation of the bistable inductive micro-switch is established. Dynamic simulation results are shown to be in agreement with experimental results. The threshold acceleration is 6.8 g, and the response time is 17.5 μs.

1. Introduction

Based on the NEMS technology [1,2], an inductive micro-switch can not only induce an external acceleration, but also be controlled by the external acceleration to realize a trigger action. When external acceleration is less than the threshold acceleration, the micro-switch maintains its Off-state. While when the external acceleration reaches to the threshold value, the micro-switch is triggered quickly to realize its On-state automatically, and then the external circuit is switched on.

The inductive micro-switch is an integrative device consisting of a sensor and an actuator. It is small, simple, low-cost, highly sensitive and fast responsive. Based on these characteristics, the inductive micro-switch is applied widely in the triggering field, such as in the automotive air restraint system, space probe callback system, fairing firing separation system, crashworthy data protection system of portable computer etc. Z. Jian et al. [3] designed a micro-switch with a post-bucking structure for the airbag restraint system. However, their micro-switch beam is too fragile making it too difficult to assemble. Alexander et al. [4] designed a dual-mass-spring micro-switch, which used an inductive mass to induct the external acceleration. That design had a “fail-to-closure” problem so that before the external acceleration reached to the threshold acceleration, the inductive mass would strike the fixed electrode and then induce a premature On-state. Therefore, the system's reliability was very low. Yang et al. [5] designed a snake-shape beam micro-switch. In that design when the external acceleration reached to the threshold acceleration, an inductive mass striked the fixed electrode to realize the trigger action. But the elastic force pulled the inductive mass quickly back to the Off-state. Therefore, this micro-switch could not realize a stable contact, and the external circuit could not maintain a stable On-state. It had a problem of “transient-closure” clearly. D. Yan et al. [6] analyzed the plastic deformation in the micro-switch contact area. Esquivel [7] analyzed the Casimir force in the micro-switch. Ongkodjojo et al. [8] designed a micro-switch for health care applications. However, the micro-switch could not precisely and reliably control the external circuit to switch.

Little work has been done to develop a comprehensive model to accurately analyze the micro size force during the micro-switch contact process. Therefore, current inductive micro-switches lack stability in the Off-state or On-state, and cannot trigger accurately at the threshold acceleration. Malfunction of the existing inductive micro-switch, i.e., “fail-to-closure” and “transient-closure”, results in low reliability and weak anti-jamming capability.

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Nomenclature

E	(effective) work potential
E_0	exergy
E_{00}	energy of a system
K	Kelvin temperature scale
S	entropy
T	temperature or Celsius temperature scale
W	effective work

In this paper, we present an inductive micro-switch with a bistable structure based on the adhesive effect. A sine-model is used to describe the rough contact surface of the micro-switch. Micro size forces such as the Casimir force and van der Waals (vdW) force are analyzed in detail using the principles of vacuum energy and the Wigner–Seitz micro-continuum media. In the Off-state, a "double-snap-back" phenomenon is discovered. It is shown that the proposed micro-switch can be accurately controlled to realize the trigger action. Due to the bistable structure, the micro-switch has strong antijamming capability and high reliability. The dynamic simulation results indicate that the threshold acceleration is 6.8 g, and the response time is 17.5 μs.

Recent adhesive behavior studies focused on adhesive energy and elastic energy [1,2] cannot accurately analyze micro adhesive behavior. There is no consensus on the reason resulted in the adhesive energy yet. Therefore, in this paper we use the micro size force to analyze the adhesive effect. The importance of the Casimir and vdW forces is currently well recognized. Some researchers think that the Casimir force is the extension of the vdW force [9]. But other researchers think that the Casimir force differs from the vdW force [10]. Current researches assume that the Casimir force and vdW force are both the attraction (long range force) [11], which are not in agreement with the engineering phenomenon [12,13]. When two slices are brought into contact and adhere to each other, they cannot attract each other forever. At the balance point, the attraction force equals to the repulsive force, then adhesion stops [14]. In this paper, we believe in that the Casimir force differs from the vdW force. Based on the Wigner–Seitz micro-continuum media principle, we analyze the repulsive part of the vdW force (short range force) to realize the micro-switch bistable structure.

2. Inductive micro-switch with bistable structure

Fig. 1 shows a silicon inductive micro-switch with a bistable structure. Both of the lower surface of the inertial mass, 4, and the upper surface of the bottom cover, 3, are deposited by gold to form electrodes and connect with an external circuit. F_e is the electrostatic force between the moveable electrode, 6, and the fixed electrode, 8, and F_k is the elastic force of beam, 5. F_c and F_f are the Casimir force and vdW force between the mass, 4, and the top cover, 1, respectively. Since the tip, 6, and fixed electrode, 8, do not contact the model shown in Fig. 1, the switch is in the Off-state.

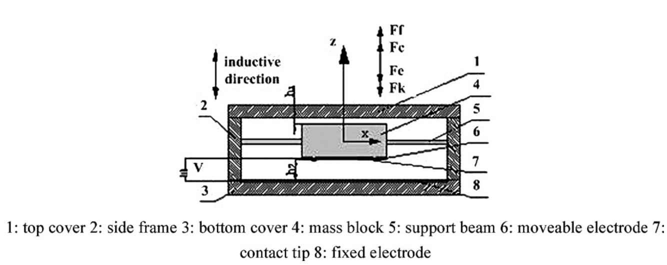

Fig. 1. Inductive switch with bistable structure in Off-state. 1: top cover 2: side frame 3: bottom cover 4: mass block 5: support beam 6: moveable electrode 7: contact tip 8: fixed electrode.

In the Off-state, the distance, h_1, is less than 1 μm. F_f and F_c are micro size forces. According to the micro size effect, F_f and F_c lead the mass, 4, to adhere to the top cover, 1. This is the first stable state, realized when the external acceleration is less than the threshold acceleration, i.e., $F_c + F_f > F_e + F_k + F_{m.}$ Here, F_m is the inertia force caused by the external acceleration. Micro size forces, F_c and F_f, can ensure the mass block, 4, does not move down to avoid "fail-on-closure" malfunction.

When the external acceleration reaches to the threshold acceleration, i.e., $F_c + F_f < F_e + F_k + F_m$, the mass block, 4, moves down and strikes at the bottom cover, 3, quickly, bringing the tip, 7, in contact with the fixed electrode, 8. In that case, the micro-switch is in the On-state, and the external circuit switches on. This is another stable state. The distance between the moveable electrode, 6, and fixed electrode, 8, is less than 1 μm. According to the micro size effect, F_c and F_f exist between the moveable electrode, 6, and the fixed electrode, 8, which can ensure the mass block, 4, is closely adhered to the bottom cover, 3. Even if there is an external interferential acceleration, a_d, the mass block, 4, remains in a stable contact model and cannot be separated from the bottom cover, 3. This stable contact practically avoids the "transient-closure" malfunction.

Based on the analysis above, we find that the micro size Casimir and vdW forces are the key forces for the micro-switch to realize the stable On-state and Off-state. The studies of elastic force F_k and electrostatic force F_e had been formulated before. In the following, we analyze F_c and F_f in detail.

3. The micro size force

3.1. Casimir force

Philip Ball [15] discovers that vacuum energy appears in the form of particles that forms or disappears ceaselessly in the form of particulates. Generally, the vacuum is filled with particulates with various wave lengths. Long waves are excluded, but other waves induce an attraction, which makes two thin slices stay closely attached to each other. The attraction is inverse proportion to the gap between the slices, i.e., the closer the slices, the greater the attraction. This effect is called the Casimir effect, and the attraction is known as the Casimir force. The surface roughness has an effect on Casimir force at small separations [16]. In addition, in the presence of Casimir force and electrostatic force, the pull-in characteristics of electromechanical switches will also be affected, which is also called the influence of self-affine surface roughness [17,18]. According to the theory of the vacuum energy [19], the Casimir force for two smooth parallel plates is,

$$F_0 = \frac{-\varepsilon\hbar c\pi^2}{240h^4} \tag{1}$$

where ε is the dielectric constant, $\hbar$ the reduced Planck's constant, c the speed of light, h the gap. A micro-switch is typically manufactured by the micro fabrication technology, such as lithography, etching, deposition, bonding and so on. Surfaces of the mass block, 4, the top cover, 1, and electrodes 6, 8 shown in Fig. 1, although may be considered smooth in a macroscopic scale, are rough in the microscopic scale. According to Hariri's result [20], contact between two rough surfaces can be simulated with a smooth–rough contact model. As shown in Fig. 1, we assume that the inner surface of the top cover, 1, is smooth, and the top surface of the mass block, 4, is rough. We have modeled this rough surface by the following sine distribution (also shown in Fig. 2):

$$h(x,y) = A\left[\sin\ \left(\frac{2\pi x}{T}\right) + \sin\ \left(\frac{2\pi y}{T}\right)\right] \tag{2}$$