Sensors & Transducers, Vol. 168, Issue 4, April 2014, pp. 101-107

Sensors & Transducers

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MEMS Variable Stiffness Spring and Its Application in Fuze

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Received: 24 December 2013 /Accepted: 7 March 2014 /Published: 30 April 2014

Abstract: MEMS processing technology can manufacture any complex structures in a plane, using this point, a variable stiffness design idea for the planar micro-spring is proposed. That is, using one type of structure named contact pairs to achieve stiffness change during the micro-spring's stretching process. Using contact pairs, three types of variable stiffness springs are designed: stiffness increase spring, stiffness decrease spring and stiffness hump spring. Finally, the variable stiffness springs' application for fuze setback arming device is discussed. When the three types of springs are used in setback arming device, the stiffness decrease spring is better than the other two springs from security analysis. Kinematic analysis shows that, if the variable stiffness spring's design is reasonable, the setback arming device not only can effectively solve the safety and reliability issues for rocket fuze, but also applies in small caliber grenade fuze's working environment without changing the setback arming device's size and structure. Analysis result indicate that the setback arming device based on MEMS variable stiffness spring is universal for rocket fuze and small caliber grenade fuze. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Micro-spring, Variable stiffness, Contact pair, Setback arming device, Safety, Reliability.

1. Introduction

In a spring's working process, the relationship between load and deformation of the spring is called characteristic curve. The variable stiffness springs' characteristic curves are nonlinear, these springs' load and deformation have nonlinear relationship, and they can be used in special occasions.

In recent years, variable stiffness springs have been used in macro field as the elastic connections, especially in vehicle suspension systems [1]. The purpose for vehicles using variable stiffness coil springs is that: to ensure the ride comfort. The damping spring's stiffness is expected smaller with a car driving on a flat rod or light load; on the other hand, when a car driving on rough road or overload, the spring with small stiffness can lead to excessive deformation and each section of the spring will fully closed, so that the spring will lost the function of buffer or damping and the car will lost its stability. In conclusion, a car needs one special spring, which has a smaller stiffness when the car in light loading and has a larger stiffness when the car overload. One type of spring whose load and deformation are nonlinear can effectively improve the contradiction between a car's stability and comfort ability. Variable stiffness springs are springs' main development direction in the future.

In MEMS setback arming device, it is also necessary to design variable stiffness micro-spring to improve the fuze's safety and reliability. During fuze service management process, the micro-spring's stiffness should be as rigid as possible, and then the spring's deformation can be as small as possible, so that the mass block moves a short distance and the fuze meet security requirement. During fuze launch process, the micro-spring's stiffness should be flexible, and then the spring's deformation can be large enough to make the mass block's movement in prescribed place and the fuze meet reliability requirement. Currently, there is no information about variable stiffness micro-springs.

2. Design Idea of Variable Stiffness Micro-spring

2.1. Stiffness Change Method for Macro-springs

For coil springs, there are several methods to realize change of spring's stiffness, such as changing spring's pitch, changing spring's mean diameter and changing spring's wire diameter [2-4]. Besides coil springs, disc springs and leaf springs can also change their stiffness during the working process [5, 6].

By analyzing the above springs' stiffness change methods, the following conclusion can be gotten:

1) Using state nonlinear to achieve the change in stiffness. Coil springs achieve variable stiffness by reducing the number of spring's working steps during its deformation process. Essentially, it uses spring's state change to variety spring's stiffness, such as changing the number of working steps or the number of working springs.

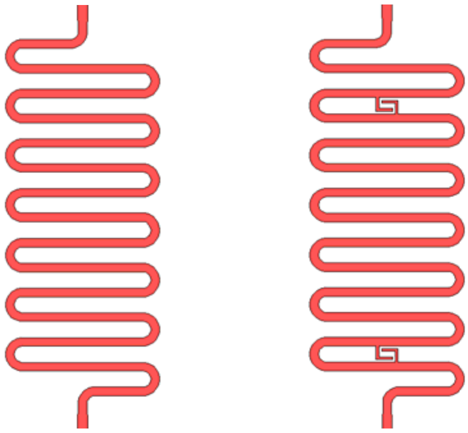
2) Most variable stiffness macro-springs are compression springs. In macro field, spring's stiffness change occurs in the process that the spring is compressed. There is no information about a tension spring achieving its stiffness change.

2.2. Stiffness Change Method for Micro-springs

Now, almost all the micro-springs used in MEMS fuze are tension springs. For this reason, the variable stiffness micro-springs in this paper are tension springs.

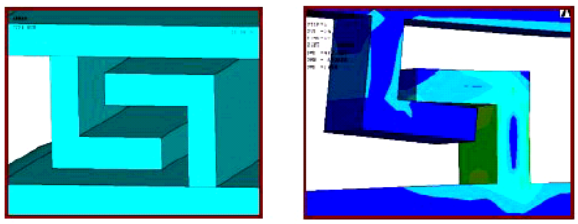
Contact is the main reason that makes structures state nonlinear. For a conical spring, its working steps contact each other during the whole spring is compressed, and this kind of state change make the number of the conical spring's working steps reduce, so that the conical spring's stiffness is variable during working process. Using state nonlinear idea, contact pairs are designed between the two level beams of a linear micro-spring, such as S-shape spring. Fig. 1(a) is S-shape spring, and its characteristic curve is linear, while Fig. 1(b) is S-shape spring with contact pairs and its characteristic curve is nonlinear. Fig. 2(a) is contact pair's partial enlarged drawing, in the course of the micro-spring is stretched, contact pair's state changes from separate to closed (shown in Fig. 2(b)), so that the stiffness of the spring changes from flexible to rigid.

There is need to explain, Fig. 1(b) is just one of variable stiffness micro-springs, and it is mentioned only to illustrate the manner of changing stiffness. Actually, using the idea of contact pair, many more suitable variable stiffness micro-springs can be designed.



(a) (b)

Fig. 1. Linear micro-spring (a), initial variable stiffness micro-spring (b).



(a) (a)

Fig. 2. Two states of contact pair for micro-spring, separate state (a), closed state (b).

3. Three Kinds of Variable Stiffness Micro-springs

MEMS processing technology can manufacture any complex structures in a plane, so contact pairs can be designed in varied forms. Variable stiffness micro-spring can have three kinds of characteristic curve by changing contact pair's number, location or shape. They are stiffness increase spring, stiffness decrease spring and stiffness hump spring, and the three characteristic curves are shown in Fig. 3.

Now, most variable stiffness coil springs are stiffness increase springs, and their characteristic curves are the same with Fig. 3(b). For MEMS variable stiffness springs, they can have many forms, and can be designed in appropriate structure to meet desired characteristic curve depending on their application environment.

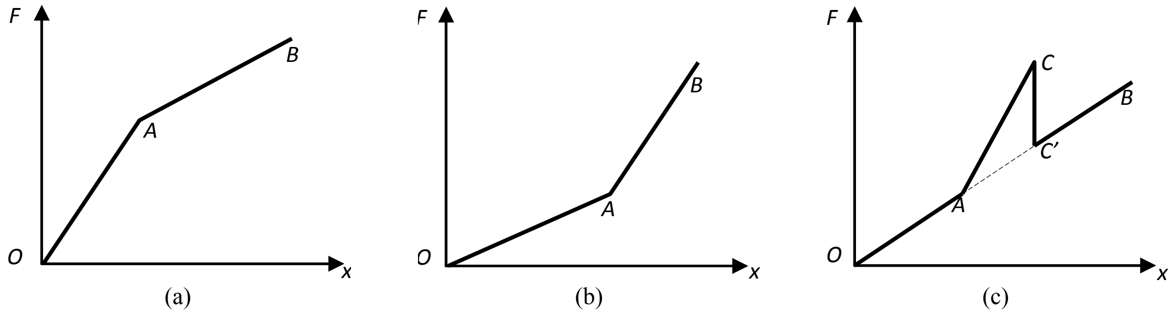


Fig. 3. Variable stiffness micro-spring's three kinds of characteristic curves, stiffness decrease (a); stiffness increase (b); stiffness hump (c).

Fig. 4 is one kind of stiffness decrease micro-spring's schematic. Fig. 4(a) is the micro-spring's nature state, and at this time the spring's characteristic curve is linear. Fig. 4(b) is the micro-spring's outgoing working state, and at this time the spring's characteristic curve is nonlinear.

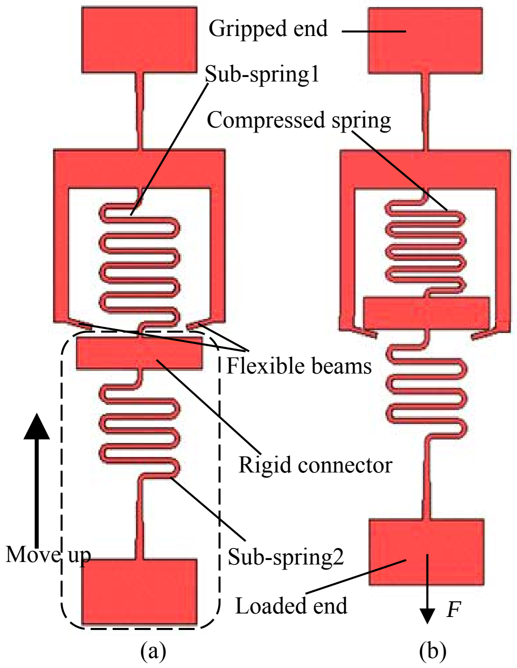


Fig. 4. Stiffness decrease micro-spring, nature state (a); working state (b).

From Fig. 4, we can see the whole spring consists of two sub-springs, two short and flexible beams, and one rigid connector. Before the spring is used in micro systems, the assembler needs to move up the structure enclosed in a dotted box (see Fig. 4(a)) and make the rigid connector snap into the two flexible beams, so that the whole micro-spring has a nonlinear characteristic curve (see Fig. 3(a)). When the spring under outgoing working state, sub-spring1 is not a nature spring but a compressed spring (see Fig. 4(b)). Then impose pulling force F point at loaded end for the whole spring. When *F* is relatively small, sub-spring2 undergoes deformation because the pulling force. Moreover, because of flexible beams' limitation, rigid connector almost doesn't move, so that sub-spring1 is still under compressed state and whose deformation barely changes. Now, the whole spring's stiffness is equal with sub-spring2's stiffness. With the increase of pulling force F, rigid connector escapes from flexible beams, the pulling force imposed on sub-spring1 is equal with sub-spring2'. Actually, the whole spring is the two sub-springs in series, and the stiffness declines. In a conclusion, before and after rigid connector escapes from flexible beams, the spring's number of working steps is not the same, so with the number of working steps increasing, the whole spring's stiffness reduced.

The other kinds of variable stiffness springs are shown in Fig. 5.

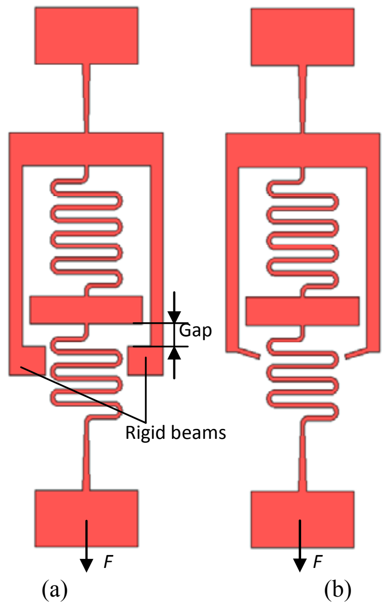


Fig. 5. Two kinds of micro-spring, Stiffness increase spring (a); stiffness hump spring (b).

Fig. 5(a) is stiffness increase micro-spring, whose static beams are rigid, so when the contact pairs consisted by rigid connector and two rigid beams closed each other, they will not separate forever. When spring's deformation is small, contact pairs are separate and the whole spring is equivalent to two sub-springs in series; when deformation reaches a certain value, contact pairs are closed, therefore sub-spring1 don't deform anymore and only sub-spring2 deforms continually.

Fig. 5(b) is stiffness hump micro-spring, whose static beams are flexible, and its contact pairs consist of one rigid connector and two flexible beams. At first, it characteristic curve is same as stiffness increase spring', the difference is that the contact pairs will be separated with the increasing of deformation, so that the two sub-springs deform together again.

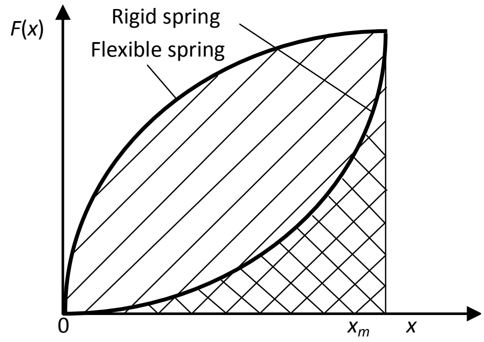


Fig. 6. Rigid and flexible spring's characteristic curves.

4. Application in Fuze Setback Arming Device

4.1. Conflict of Setback Arming Device Between Safety and Reliability

According to GJB373A-1997, only sensing two or more different environment information, fuze can be in arming state. Setback arming device is an important part for fuze safety and arming system, which can make sure that fuze is security under service processing environment, and arming after emission. When fuze is used in the projectile with high shock over loading environment, the difference between emission recoil over loading and dropping impulse loading is distinct, so that the design for setback arming device under above environment is easier. But for rocket projectile, mortar shell or recoilless cannon, whose emission over loading is low, so it is difficult for setback arming device to distinguish emission recoil and accidental dropping over loading. Usually, designers solve the conflict problem by sensing the two over loadings' time of duration. Emission recoil over loading's duration is longer than accidental dropping over loading. Typical macro fuze setback arming devices are: zigzag structure device, interlock card board device and two degree of freedom device, etc. [7, 8].

4.2. Analysis for Variable Stiffness Spring's Characteristic Curves

Generally speaking, variable stiffness springs can be divided into two types: rigid spring and flexible spring, and their characteristic curves are shown if Fig. 6. Now, most variable stiffness macro-springs (e.g. conical spring) are rigid springs. Then flexible spring is a kind of nonlinear elastic device whose slope decreased with the increasing of deformation x, such as disk spring.

For a set of spring-mass system, x_m is spring's maximum deformation, and according to the energy principle, the kinetic energy of mass can be expressed as:

$$\int_0^{x_m} F(x)\,\mathrm{d}\,x = \frac{1}{2} m v_m^{\ 2}, \qquad (1)$$

where F is the spring's resisting force, m is mass' quality, and v_m is mass' maximum velocity.

Equation (1) indicates that the areas of shaded field represent rigid spring and flexible spring's energy (absorbed or stored energy by spring after it deformed). From Fig. 6, the shaped area of flexible spring is bigger than rigid spring, that is flexible spring is superior to rigid spring in absorbing or storing energy, and it means that flexible spring more buffer and vibration isolation than rigid spring.

As this paper mentioned above, in low emission over loading environment, acceleration imposed on setback arming device is high, and its duration is short during accidental dropping; but acceleration imposed on setback arming device is low, and its duration is long during emission. From Fig. 6, for rigid spring, large deformation takes place but spring's resisting force is relatively smaller at beginning; then and small deformation will have a great resisting force when the spring's deformation reaches a certain value. While flexible spring's deformation characteristics is just the opposite. So, we can see, flexible spring's characteristic curve just meets the design need of fuze setback arming device: In the early stage of shock over loading, small deformation with large resisting force will help ensure that setback arming device can't arming under large over loading while short duration circumstance. The slope of resisting force is decreased with the increasing of deformation, it make sure that flexible spring is more favorable at arming than linear spring. Therefore, flexible spring can solve the conflict between safety and reliability.

Springs used in fuze mostly are conical springs or cylindrical coiled springs, and flexible springs are unusual. So, it is difficult for macro fuze to use flexible springs currently.

4.3. Safety Analysis for Variable Stiffness Micro-springs

As shown in Fig. 3, there are three kinds of characteristic curves for variable stiffness micro-springs. Now, linear spring and three variable stiffness springs will be compared about their safety analysis used in fuze setback arming device.

For contrast, the key structural parameters (number of step, thickness, width, etc.) of the linear micro-spring and three kinds of variable stiffness micro-springs (characteristic curves are shown in Fig. 3) are the same, it can make sure that these springs' volumes are basically the same and the compare result is without bias. The four springs' characteristic curves are shown in Fig. 7, and they are defined as followed:

1) Spring1 is a stiffness decrease micro-spring, and its structure maybe like Fig. 4. Part *OA*'s stiffness is k_2, and part *AB*'s stiffness is $k_1 \times k_2/(k_1+k_2)$. Where k_1 is sub-spring1's stiffness, and k_2 is sub-spring2's stiffness.

2) Spring2 is a stiffness increase micro-spring. Part *OA*'s stiffness is $k_1 \times k_2/(k_1+k_2)$, and part *AB*'s stiffness is k_2.

3) Spring3 is a stiffness hump micro-spring. Part *OA*'s stiffness is $k_1 \times k_2/(k_1+k_2)$, part *AC*'s stiffness is k_2 approximately, part *C'B*'s stiffness is $k_1 \times k_2/(k_1+k_2)$ again.

4) Spring 4 is a linear micro-spring, and it consists of two sub-springs and no contact pairs, so its stiffness is $k_1 \times k_2/(k_1+k_2)$ always in the range of elastic deformation.

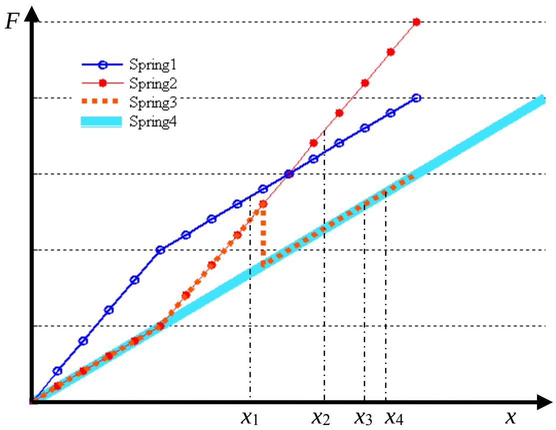


Fig. 7. The maximum deformations of micro-springs.

When a spring-mass system drops down accidentally, and in order to facilitate analysis, assuming that dropping over loading's work converts into micro-spring's elastic potential energy completely. So the four micro-springs obtain the same elastic energy.

Based on above assumption, the four micro-springs' elastic energy are the same at their maximum deformation (the mass' acceleration is zero at the moment). Fig. 7 shows the four micro-springs maximum deformation contour under dropping over loading, where x1 is spring1's maximum deformation, and so on. From Fig. 7, we can get: $x_1 < x_2 < x_3 < x_4$. That means spring1's deformation is minimum among the four micro-springs. Therefore, when fuze setback arming device using the four springs separately meets with accidental dropping, the setback arming device using stiffness decrease micro-spring is most secure, and the device using linear micro-spring is most insecure.

5. Example of Stiffness Decrease Micro-spring Used in Rocket Projectile Fuze

5.1. Principle of MEMS Setback Arming Device

MEMS setback arming device used in small caliber grenade fuze has been studied thoroughly, all kinds of simulation results show that the device will meet the requirements of safety and reliability as long as the linear micro-spring's stiffness is reasonable.

Different from the projectile with high revolution, the distinguish feature is that emission acceleration is smaller and the acceleration's duration is longer.

The MEMS setback arming device using variable stiffness micro-spring is shown in Fig. 8, its composition and working principle is essentially same with MEMS setback arming device of small caliber grenade fuze [9]. The difference is the two devices have different micro-spring. Here, in order to solve the conflict between the safety in security service processing and the reliability in arming for rocket projectile fuze, a variable stiffness micro-spring is used in setback arming device.

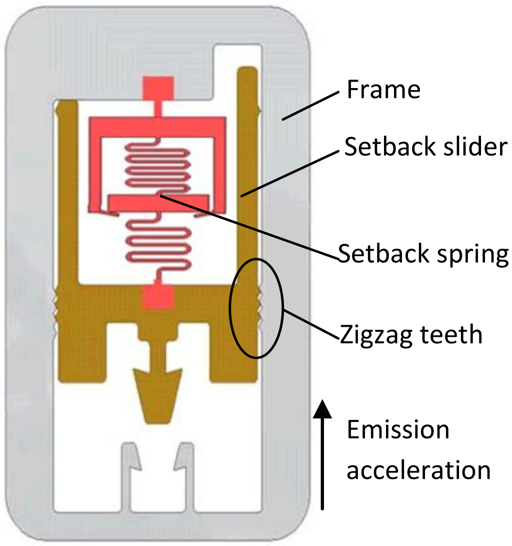


Fig. 8. Setback arming device.

The variable stiffness spring's characteristic curve is shown in Fig. 9. If the spring's deformation is less than 0.1 mm, the stiffness is 60 N/m, and if the spring's deformation is greater than 0.1 mm, the stiffness is 20 N/m.

When the device suffers accidental dropping, setback slider will move downward along zigzag teeth, the friction and collision between teeth will help setback slider move slowly, and at the same time, the spring's stiffness is relatively larger so that the spring's deformation or the slider's displacement will not be noticeable. The duration of accidental dropping over loading is short, so the slider will be pulled back to the initial position by the micro-spring, thus making sure the setback arming device's safety when it suffers accidental dropping. The duration of emission over loading is long, the slider will move downward along zigzag teeth continuously, and the spring's stiffness is relatively smaller when the slider's displacement reaches a certain value, that will be conducive to the spring's deformation.

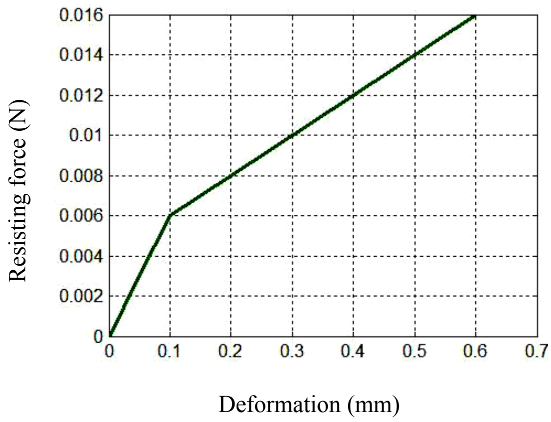


Fig. 9. Characteristic curve of variable stiffness spring.

5.2. Simulation Results

A rocket projectile's mechanical environments are shown in Fig. 10 [10]. Where Fig. 10(a) is emission acceleration curve, and its duration is 50 ms, peak is 100 g; Fig. 10(b) is accidental dropping acceleration curve gotten by projectile dropping to iron from a height of 15 m, and its peak is 12000 g at 230 μs. At first, this paper utilizes the rocket projectile's mechanical environment to a past MEMS setback arming device used in small caliber grenade fuze. The analysis results show that the past MEMS setback arming device is not suited to the new mechanical environment, in other words, the device cannot get arming state reliably. Xiaoxia Wang from Xi'an Institute of Electromechanical Information Technology changed the number of teeth and the linear spring's stiffness, and the simulation results show that the changes in her paper can solve the conflict between safety and reliability for rocket projectile fuze [10]. This paper doesn't change any other structural parameters besides replacing the linear spring to the above stiffness decrease micro-spring.

Imposing rocket projectile emission acceleration for the setback arming device shown in Fig. 8, a curve about setback slider's displacement changing with time can be obtained by kinetics simulation, and the curve is shown in Fig. 11(a). From the curve, the slider can reach the maximum displacement (1.2 mm) when time equals 8.62 ms and it means the device can be in arming state reliably. The simulation result indicates that the setback arming device with variable stiffness micro-spring can meet the requirement of reliability.

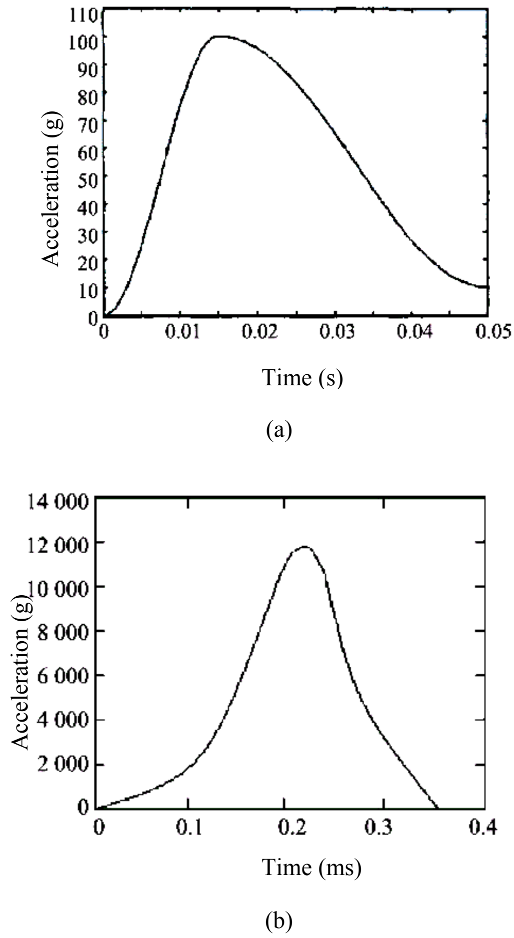
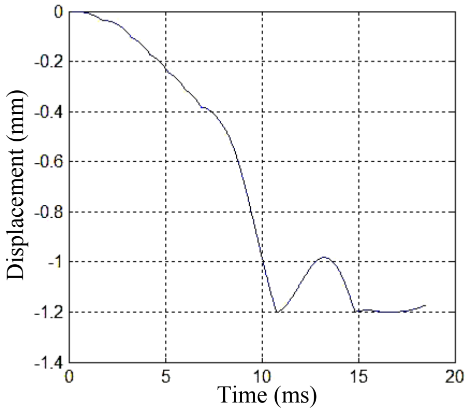


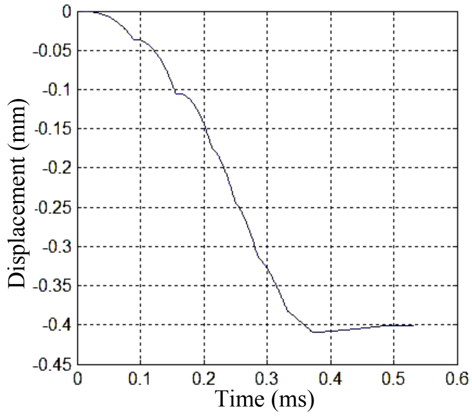
Fig. 10. Emission acceleration curve of a rocket projectile (a); accidental dropping acceleration curve (b).

Then imposing accidental dropping acceleration for the device, and the slider's displacement-time curve is shown in Fig. 11(b). From the curve, the slider's maximum displacement is 0.41 mm when time equals 0.37 ms, then with the disappearance of dropping acceleration, the slider will be pulled back by the micro-spring. The simulation result indicates that the setback arming device with variable stiffness micro-spring can meet the need of safety during security service processing.

In order to verify the versatility of the setback arming device with variable stiffness spring, this paper imposes small caliber grenade emission acceleration for the setback arming device without changing any structural parameters. The mechanical environment can be gotten from ref 9, here no longer repeats. The simulation result is shown in Fig. 12. From the curve, the slider can reach the maximum displacement, and the setback arming device can be in arming state reliably.



(a)



(b)

Fig. 11. The slider's displacement-time curve, under emission acceleration (a); under dropping acceleration (b).

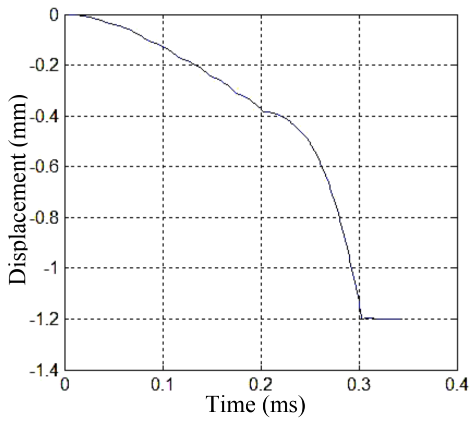


Fig. 12. The slider's displacement-time curve under small caliber grenade emission acceleration.

6. Conclusions

This paper provides an idea of changing stiffness for MEMS planar spring, and designs three kinds of variable stiffness micro-springs, finally discusses the stiffness decrease micro spring's application in fuze. The simulation results show that: the setback arming device with variable stiffness micro-spring can not only effectively solve the conflict between safety and reliability for rocket projectile fuze, but also for small caliber grenade fuze without changing the device's structural parameters.

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