Microfluidic inertial switch with delay response characteristics

Weirong Nie\textsuperscript{1,2}, Guowei Liu\textsuperscript{1} and Runduo Zhang\textsuperscript{1}

\textsuperscript{1}School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China
\textsuperscript{2}Science and Technology on Electromechanical Dynamic Control Laboratory, Xi’an, China

E-mail: niewrhappy@163.com

Abstract. This paper proposes an innovation microfluidic inertial switch structure with precise time delay response characteristic, which can be used in the fuze safety and arming system. The switch works on the principle of fluidic inertial force and capillary valve, which makes it sensitive to the unidirection acceleration load and has the ability to recognize the acceleration amplitude. The microfluidic inertial switch has a structure of a J-shaped reservoir, capillary valves, a serpentine delay microchannel and a U-shaped latching microchannel. The acceleration threshold is analyzed theoretically considering the surface tension coefficient of the gas-liquid interface. The delay response time of the switch is studied by finite element simulation based on the Gambit 2.4 and Fluent 6.3 software. The prototype is fabricated by wet etching technology and magnetron sputtering metal technology. Many tests have been done to verify the functions of the switch. The experimental results are matched well to the results of calculation and simulation. When the capillary valve throat widths are 80\,\mu m, 120\,\mu m, 160\,\mu m, the thresholds of the switch are 75.1g, 46.6g, 36.5g. When the switch is loaded with a 75g acceleration load, the delay response is 146.7ms. Finite element simulation and experimental results show that the switch can effectively identify the acceleration threshold, and can achieve a precise delay response under a certain load.

1. Introduction

The micro-inertia switch with time-delay function is a key component to solve the safety problem in the process of weapon launch. Traditional micro-inertia switches usually use a typical "spring-mass-damping" system, and their conduction method is "solid-solid" contact conduction \cite{1-4}, which is prone to low contact pressure, high contact resistance, easy to wear and other disadvantages \cite{5}.

The microfluidic inertial switch is based on "solid-liquid" contact conduction. It adopts the contact conduction switch of conductive liquid and metal electrode, without mechanical moving parts. By designing its micro-channel structure, it can realize the advantages of small size, small contact resistance, high stability, strong anti-electromagnetic interference ability and other advantages \cite{6}. Kwanghyun Yoo \cite{7-8} and others proposed a micro-inertia switch that uses a small amount of mercury as the working fluid. The threshold value of the switch is controlled by a capillary valve. After mercury breaks through the capillary valve, it contacts the electrode to turn on the switch. When the throat width of the capillary valve is 200\,\mu m, the acceleration threshold is 15 g, but the structure does not have a time-delay response characteristic. Shen T \cite{9} designed a self-recovering inertial switch.
based on PDMS and liquid alloy of gallium indium tin. When the inertial force is applied to the switch, the metal droplet moves to the electrode, and the switch is turned on; after the inertial force disappears, the droplet returns to the liquid reservoir. However, gallium indium tin alloy is highly active in air, easily forms a metal oxide film, increases viscosity, and is not conducive to the flow of droplets. Liu Tingting [10] used the electrowetting characteristics of mercury metal droplets to change the acceleration threshold of its microfluidic inertial switch by an external electric field. The larger the applied electric field, the smaller the mercury contact angle. The threshold can be adjusted by changing the magnitude of the electric field. Jiajie Li [11] designed a microfluidic inertial switch based on a J-shaped communicating vessel. The working fluid was sodium chloride solution and the substrate was PDMS. The threshold value of the switch is 92.9g, and the droplets do not flow back into the reservoir after the switch is triggered. However, PDMS material is relatively soft and will affect the shape of the flow channel under high impact overload. Y C Huang [12] proposed a time-delay microfluidic inertial switch based on the capillary valve principle. The working fluid is glycerin. The delay time can be controlled by the angle of the capillary valve and its throat width, and the delay time can reach 4.1 ~ 10.9s. However, its structure cannot achieve accurate time delay, and it will produce jets and droplet separation to affect the stability of the switch's electrical connection.

Through the analysis of the above switches, in order to solve the situation that the delay time of the microfluidic inertial switch is uncontrollable and the droplets are susceptible to separation, this paper designs a microfluidic inertial switch with a delay response characteristic based on a silicon substrate and mercury droplets. The switch designed in this paper is turned off when the acceleration breakthrough threshold is not reached, the acceleration load is delayed after reaching the capillary valve breakthrough threshold, and after an accurate delay time the switch is latching. This article analyzes the working principle and manufacturing method of the switch and theoretically calculates the threshold of the switch. Three different capillary throat widths are designed, and the finite element simulation is performed to determine the theoretical threshold and delay time. Finally, the switch function was verified through experiments.

2. Working principle
The structure of the microfluidic inertial electrical switch with time-delay response is composed of a silicon substrate, a glass cover, and a mercury droplet, as shown in figure 1. The sealing groove, barrier groove and the working microchannel are etched on the silicon substrate. The working microfluidic channel structure includes a J-shaped reservoir, a capillary valve, a serpentine time-delay channel, a U-shaped blocking channel and an air conducting channel, as shown in figure 2-(a). Mercury liquid (31nL) was dripped into the J-shaped reservoir. The UV curing glue is injected into the sealing groove, and the silicon substrate and the glass cover plate are bonded. On the bonding side of the glass cover and the silicon substrate, two pairs of metal electrodes are plated on the glass cover.

In the initial state, the mercury droplets are located in the J-shaped reservoir, which is limited by the two shrinking capillary valves on the left and right sides. When the switch is loaded with the X-axis positive acceleration, the droplet has a tendency to break through the capillary valve and move to the right channel. When the inertial acceleration load is greater than its threshold, the droplet breaks through the capillary valve and moves to the right channel, immersing the first pair of metal electrodes, as shown in figure 2(b). Under the continuous action of inertial load, the droplet enters the serpentine delay channel and continues to move in the delay channel, as shown in figure 2-(c). After a certain time delay, the droplet finally enters the U-shaped latching channel, immerses the second pair of electrodes, and the switch is reliably turned on. After the load disappears, due to the restriction of the capillary valve of the U-shaped lock channel, the liquid droplet remains in the U-shaped lock channel without overflowing, and the switch is latching, as shown in figure 2-(d).
Figure 1. Three-dimensional structure of the switch.

Figure 2. Structure of the Microchannel: (a) Initial state (b) The first pair of electrodes is conducting (c) Delay state of the switch (d) The second pair of electrodes is conducting.

3. Theoretical analysis
In macroscopic fluid flow, capillary forces are small and their effects are generally not considered. However, at the microscale, capillary forces can greatly affect liquid motion, and its role cannot be ignored. Capillary force refers to the pressure difference between the two sides of the "gas-liquid" phase interface caused by the surface tension on the three-phase contact line. Where the surface tension can be expressed as

\[ F_\sigma = \sigma \cdot l_\sigma \]  

(1)

Where \( \sigma \) is the surface tension coefficient of the "gas-liquid" interface; \( l_\sigma \) is the length of the three-phase contact line.

For the microchannels with arbitrary cross-sectional shapes, the calculation formula [13] of capillary force can be expressed as

\[ \Delta p = \sum_{i=1}^{n} \sigma \frac{l_i \cos(\theta_i + \alpha_i)}{A} \]  

(2)

Where \( l_i \) is the contact line length of a side wall surface of the microchannel; \( \theta_i \) is the contact angle of the liquid with the corresponding wall surface; \( \alpha_i \) is the wall surface opening angle; \( A \) is the cross-sectional area.

The structure of the J-shaped liquid reservoir is shown in figure 3, and its cross section is a rectangular cross section. The capillary forces on the left and right liquid interface can be expressed as

\[ \Delta p_1 = p_1 - p_0 = -\sigma \left( \frac{\cos \theta_{sl} + \cos \theta_{sr}}{h} + \frac{2 \cos(\theta_{sl} + \alpha_i)}{w_i} \right) \]  

(3)
where \( h \) is the depth of the microchannel; \( \theta_{nas} \) is the receding contact angle of mercury on the silicon surface; \( \theta_{adv} \) is the advancing contact angle of mercury on the silicon surface; \( \theta_{gda} \) is the receding contact angle of mercury on the glass surface; \( \theta_{gda} \) is the advancing contact angle of mercury on the glass surface; \( \theta_{12} = \min \{ \theta_{nas} + \alpha_2, 180^\circ \} \); \( \alpha_1 \) is the wall shrinking angle of the left shrinking capillary valve, \( \alpha_1 < 0 \); \( \alpha_2 \) is the right wall expansion angle of the right expansion capillary valve, \( \alpha_2 > 0 \).

In the initial stage, due to the restriction of the two left and right shrinking capillary valves, mercury is always kept in the J-shaped liquid reservoir without receiving external load. When the switch is loaded with a positive X-axis acceleration load, mercury gradually has a tendency to break through the right capillary valve. When the acceleration load on the switch is greater than the design threshold, the mercury breaks through the capillary valve and starts to move to the right channel. The theoretical calculation formula for the acceleration threshold can be expressed as

\[
a = \frac{2(P_2 - P_1)}{\pi \rho (R + r)}
\]

Where \( \rho \) is the density of mercury; \( R \) is the radius of the outer circle of the J-shaped reservoir; \( r \) is the radius of the inner circle of the J-shaped reservoir.

4. Numerical simulation

4.1. Numerical method

To investigate the influence of structure parameters to the acceleration threshold and delay response of the micro-fluidic inertial switch, numerical simulation was adopted. Gambit 2.4 is used to build the simulation models and Fluent 6.3 is adopted to simulate the models. The governing equation can be expressed as

\[
\begin{align*}
\frac{\partial (\rho \rho)}{\partial t} + \nabla (\rho V) &= 0 \\
\frac{\partial (\rho u)}{\partial t} + \nabla (\rho V u) &= -\frac{\partial p}{\partial x} + \nabla (\mu \nabla u) + \rho a_x \\
\frac{\partial (\rho v)}{\partial t} + \nabla (\rho V v) &= -\frac{\partial p}{\partial y} + \nabla (\mu \nabla v) + \rho a_y \\
\frac{\partial (\rho w)}{\partial t} + \nabla (\rho V w) &= -\frac{\partial p}{\partial z} + \nabla (\mu \nabla w) + \rho a_z
\end{align*}
\]

Where \( \rho \) is the density of the fluid; \( t \) is the time; \( V \) is the flow speed vector; \( u, v, w \) is the flow speed in x-direction, y-direction and z-direction respectively; \( P \) is the pressure; \( \mu \) is the kinetic
viscosity of the fluid; \( a_x, a_y, a_z \) is the applied acceleration in x-direction, y-direction and z-direction respectively. In simplified situation, y-direction is the sensing direction. \( a_y \) is equal to the loading acceleration, and \( a_x = 0, a_z = 0 \).

VOF (Volume of Fluid) model was adopted to describe the motion of the brine-air interface. The equation of VOF model can be expressed as

\[
\frac{\partial F}{\partial t} + \nabla \cdot VF = 0
\]  

(7)

Where \( F \) is volume factor of the liquid.

Thus, the density and kinetic viscosity in equation (6) can be expressed as

\[
\begin{align*}
\rho &= F \rho_b + (1 - F) \rho_a \\
\mu &= F \mu_b + (1 - F) \mu_a
\end{align*}
\]  

(8)

Where \( \rho_b \) is the brine density; \( \rho_a \) is the air density; \( \mu_b \) is the brine kinetic viscosity; \( \mu_a \) is the air kinetic viscosity.

At the microscale, surface tension effect can’t be ignored. CSF (Continuum Surface Force) model was adopted to describe the surface tension effect. The equation of CSF model can be expressed as

\[
\int \Delta \rho ds = \int \sigma \mathbf{n} \cdot d\mathbf{y} = \nabla F
\]  

(9)

Where \( ds \) is an infinitesimal interfacial area; \( \mathbf{n} \) is the normal direction of the liquid-air interface; \( d\mathbf{y} \) is the infinitesimal change in y-direction.

4.2. Simulation analysis of threshold

According to equation (2), the main factors affecting the capillary force are the throat width of the capillary valve and the wall opening angle. Three simulation models with different structural parameters were set, and the throat width and wall opening angle of the right capillary valve were changed to verify the theoretical calculation formula of the switching threshold. The structural parameters of the three models are shown in table 1. The attribute parameters of the simulation material are shown in table 2.

**Table 1.** Structural parameters.

| Parameter                     | Model 1   | Model 2   | Model 3   |
|-------------------------------|-----------|-----------|-----------|
| Outer circle radius of J-shaped reservoir \( R \) | 600\( \mu m \) | 600\( \mu m \) | 600\( \mu m \) |
| Inner circle radius of J-shaped reservoir \( r \) | 200\( \mu m \) | 200\( \mu m \) | 200\( \mu m \) |
| Throat width of left capillary valve \( w_1 \) | 80\( \mu m \) | 80\( \mu m \) | 80\( \mu m \) |
| Throat width of right capillary valve \( w_2 \) | 80\( \mu m \) | 80\( \mu m \) | 80\( \mu m \) |
| Interface height difference \( H \) | 300\( \mu m \) | 300\( \mu m \) | 300\( \mu m \) |
| Microchannel depth \( h \) | 50\( \mu m \) | 50\( \mu m \) | 50\( \mu m \) |
| Wall Angle of left Shrinking Capillary \( \alpha_1 \) | -28° | -28° | -28° |
| Wall Angle of right Expansion Capillary \( \alpha_2 \) | 28° | 25° | 22° |
| Wall Angle of right Shrinking Capillary \( \alpha_3 \) | -69° | -67° | -63° |
| Wall Angle of left Expansion Capillary \( \alpha_4 \) | 69° | 69° | 69° |
Table 2. Attribute parameters.

| Parameter                  | Value          |
|----------------------------|----------------|
| Mercury density            | 13550 kg/m³    |
| Air density                | 1.225 kg/m³    |
| Mercury viscosity          | 1.52 × 10⁻³pa·s|
| Air viscosity              | 2 × 10⁻⁵pa·s   |
| Mercury surface tension σ  | 0.484 N/m      |
| Forward contact angle of silicon θ_{snA} | 140°          |
| Receding contact angle of silicon θ_{snR} | 130°          |
| Forward contact angle of glass θ_{gsA} | 143°          |
| Receding contact angle of glass θ_{gsR} | 133°          |

The switch of Model 1 was loaded with 75g X-axis positive acceleration load, and the dynamic breakthrough process of the droplet in the J-shaped reservoir was obtained. The simulation result is shown in figure 4. At 0.5ms, the droplet breaks through the right-side shrinking capillary valve; At 1ms, the left and right interfaces of the droplet have the same height; At 2ms, the highest point of the right droplet interface is higher than the height of the expansion capillary valve; At 3.5ms, the droplet continues to move into the right microchannel.

![Figure 4. The process of droplets breaking through the capillary valve.](image)

The “height of right interface-time” curves of the three models under different acceleration loads are shown in figure 5. It can be seen from the figure that under the continuous action of the acceleration load, the right liquid interface continues to rise, indicating that at this time the liquid droplet breaks through the right contraction capillary valve, which is the acceleration threshold of this structure.

![Figure 5. Height of right interface: (a) Model 1 (b) Model 2 (c) Model 3.](image)
Table 3 shows the results of simulation and theoretical acceleration thresholds of the three models. It can be obtained from table 3 that the theoretical threshold calculated by equation (5) and the simulation result have a small error.

| Model | Simulation threshold | Theoretical threshold | error |
|-------|----------------------|-----------------------|-------|
| 1     | 68g                  | 71.2g                 | 4.7%  |
| 2     | 45g                  | 43.7g                 | 2.8%  |
| 3     | 34g                  | 32.9g                 | 3.2%  |

4.3. Simulation analysis of delay characteristics

The structure of the serpentine delay microchannel is shown in figure 6(a), and its structure is composed of multiple units of flow microchannel. The characteristic size parameters of the unit of flow microchannel are shown in figure 6(b). The characteristic size parameters are set as shown in table 4, and the flow time of the droplet in the delay microchannel is simulated and analyzed.

![Figure 6. Structure of delay channel: (a) Serpentine structure (b) Unit of flow microchannel.](image)

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Number of serpentine channel units             | 7     |
| Inner circle radius of serpentine channel $r(\mu m)$ | 110   |
| Width of serpentine channel $w(\mu m)$         | 90    |
| Vertical length of serpentine channel $l(\mu m)$ | 800   |

![Figure 7. Simulation of delay response process.](image)
The switch was loaded with 75g X-axis positive acceleration load, and the movement process of the droplet in the time delay microchannel was obtained. The simulation results are shown in figure 7. At 5ms, the droplet breaks through the right expansion capillary valve, and the first pair of metal electrodes is about to be connected; At 30ms, the droplet is about to completely flow out of the J-shaped reservoir; At 75ms, the droplet moves in the delay microchannel; At 130ms, the interface of the droplet enters the upper side of the U-shaped latching channel, and the second pair of metal electrodes is about to be connected. At 132.5ms, the droplet remains in the J-shaped reservoir. By analyzing the connect-time difference between the first pair of electrodes and the second pair of electrodes, it can be obtained that the delay time of the switch is 125ms.

5. Experiment

5.1. Prototyping

Wet etching was used to etch a microchannel with a depth of 50μm on the surface of a 600μm-thick silicon substrate. Switch prototypes with three sizes of capillary valve throat widths of 80μm, 120μm, and 160μm were processed. The SEM image of microchannel on the processed silicon wafer is shown in the figure 8.

![Figure 8. SEM image of Microchannel.](image)

Magnetron sputtering metal technology was used to electroplate a 200-nm-thick gold electrode on a 1-mm-thick glass plate, and a 50-nm chromium adhesion layer was plated between gold and glass. Remove the gold in the contact part between the electrode and the mercury, leaving chromium as the conductive metal, which can avoid gold and mercury to form gold amalgam to affect the performance of the switch.

A 31nl mercury droplet was produced using a micro-injection pump TJ-2A, which was injected into a J-shaped reservoir and covered with a glass cover. It was observed through an optical microscope that the mercury droplets just filled the J-shaped reservoir without overflowing from the capillary valve. The substrate is fixed in a fixture, a suitable amount of UV curing glue is injected into the sealing groove by a syringe. After the glass cover is placed on the substrate, the substrate is irradiated with a violet light, so that the adhesion side is cured, and a switch prototype is obtained as shown in figure 9.

![Figure 9. Prototype.](image)
5.2. Experiment of threshold measurement

Centrifugation experiments were used to test the static threshold of switch. The centrifugal experiment platform is shown in figure 10. The motor of the rotating plate is controlled by a DC brushless motor controller (WS55-180). The speed is adjusted by the PWM signal output from the Arduino development board controlled by the computer. The switch is fixed on the rotating plate by a fixture, and the direction of the centrifugal force is the same as the sensitive direction of the switch. The second pair of electrodes of the switch is connected in series with the power source and the LED lamp. When the switch is on, the LED lamp lights up.

\[
T = \left(\frac{\pi n}{30}\right)^2 \cdot r
\]

Where \( n \) is the rotating speed of the rotating plate; \( r \) is the eccentricity of the switch installation.

The position of the droplet in the switch and the state of the LED light before and after the experiment are shown in figure 11.

Table 5 shows the results of experimental and theoretical threshold of the three models.
Table 5. Experimental and theoretical threshold.

| Model | Experimental threshold | Theoretical threshold | error |
|-------|-------------------------|-----------------------|-------|
| 1     | 75.1g                   | 71.2g                 | 5.2%  |
| 2     | 46.6g                   | 43.7g                 | 6.2%  |
| 3     | 36.5g                   | 32.9g                 | 9.8%  |

The experimental results show that the error between the actual acceleration threshold and the theoretical acceleration threshold of the switch is not more than 9.8%, which verifies the correctness of the calculation formula of the switch acceleration threshold.

5.3. Experiment of delay response measurement

Based on the centrifugal experiment platform, delay response of the switch is measured by measurement circuit. The experimental platform is shown in figure 12. During centrifugation, the droplet moves in the microchannel. The first pair of metal electrodes and the second pair of metal electrodes are successively immersed by the mercury droplet. The time difference between the two conducting electrodes is measured to obtain the delayed response time of the switch. The conducting time difference between the two pairs of electrodes is measured to obtain the delayed response time of the switch. The measurement circuit is based on the STM32F070 MCU, which can obtain the conducting time difference between the two pairs of electrodes and store it in Flash by two external interrupts, and read it by computer.

![Measuring circuit Inertial switch](image)

**Figure 12.** Delay time measurement platform.

Experimental results show that when the switch is continuously loaded with 75g inertia load, the actual delay time is 144.1ms. The theoretical delay time of the switch obtained through simulation is 125ms, which indicates the theoretical and experimental error was 13.3%. Unlike the ideal smooth state, the silicon substrate still has surface roughness during processing, which affects the flow characteristics of the droplets. Meanwhile, the experiment process is not a dust-free environment, and the dust entering the microchannel will affect the droplet flow characteristics. The analysis shows that the obtained experimental results are in a reasonable range, which verifies the accurate delay response function of the switch under a certain load.

6. Conclusion

This paper proposes a microfluidic inertial electrical switch with time-delay response characteristics, with silicon as the bottom substrate, mercury as the working fluid, and glass as the upper cover. The switch is sensitive to the acceleration load in the positive direction of the X-axis.
When the load is greater than the switching threshold, the droplet moves in the microchannel and the switch is latching after a specific delay time. The surface tension of the droplet at the capillary valve was analyzed, and the theoretical calculation formula of the threshold of the switch is obtained. The principle of the switch was analyzed, and a prototype of the switch was fabricated using wet etching and magnetron sputtering metal technology. The combination of simulation analysis and experiments was used to verify the function of the switch. Experimental results show that when the capillary valve throat width is 80\(\mu m\), 120\(\mu m\), 160\(\mu m\), the thresholds of the switch are 75.1g, 46.6g, 36.5g. The difference between the actual switch threshold and the theoretical threshold does not exceed 9.8\%, which verifies the correctness of the theoretical formula. The actual delay response time of the switch under the inertia load of 75g is 144.1ms and the error from the theoretical delay time is 13.3\%, which verifies the accurate delay characteristics of the switch.

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