

## Research and Design on Trigger System Based on Acoustic Delay Correlation Filtering

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*Received: 22 December 2013 /Accepted: 22 January 2014 /Published: 31 January 2014*

**Abstract:** In the exterior trajectory test, there usually needs a muzzle or a gun muzzle trigger system to be used as start signal for other measuring device, the customary trigger systems include off-target, infrared and acoustic detection system. But inherent echo reflection of the acoustic detection system makes the original signal of sound trigger submerged in various echo interference for bursts and shooting in a closed room, so that it can't produce accurate trigger. In order to solve this defect, this paper analyzed the mathematical model based on acoustic delay correlation filtering in detail, then put forward the constraint condition with minimum path for delay correlation filtering. In this constraint condition, delay correlation filtering can do de-noising operation accurately. In order to verify accuracy and actual performance of the model, a MEMS sound sensor was used to implement mathematical model onto project, experimental results show that this system can filter out the every path sound bounce echoes of muzzle shock wave signal and produce the desired trigger signal accurately. Copyright © 2014 IFSA Publishing, S. L.

**Keywords:** MEMS acoustic sensor, Muzzle shock wave, Delay correlation filtering.

### 1. Introduction

In the test of light weapons, it usually use a muzzle or a gun muzzle trigger system as start signal for other measuring device, at present the muzzle customary trigger systems include off target line (also called net target) detection systems, infrared detection system, sky screen, light Screens, Coil Target, acoustic systems, etc. [1]. On this basis, other measuring devices can test the bullet velocity, flight attitude, spatial coordinates and bullet intensity when this signal was used as the system signal [2].

Traditional off target line detection generates the trigger signal by breaking the target line when bullets are flying. This method belongs to contactless capturing device and has a high detecting reliability.

The limitation is that the measurement depends on the fact that it must contact with the flying bullet, which will influence bullet speed, flight stance, and then will lead to different state when the bullet passes through the two inconsistent respectively. Because of low manufacturing precision of the target aircraft, it is difficult to ensure those two target planes are coincident and perpendicular to flight path of bullet. Infrared detection system, sky screen, light Screens, Coil Target, acoustic systems are all belong to non-contact detection systems. Although these detection systems avoid the drawback of contact detection systems, they still have some shortcomings. Infrared detection system is a method which extracts light signal generated by muzzle; it is the most extensive method at present, the detection accuracy is high, but it can't detect bullet if gunpowder is not used to push.

The sky screen and light screen are influenced by sunlight, glare, place, and the types of gun. Coil target is easily affect to strong electromagnetic radiation interference, so it does not work normally, and it is difficult to achieve parallel, concentric and perpendicular to bullet flight path in two target surface. Therefore, when the bullet passes along the center of the coil target, there will be some offset, and its consistency is poor for work state of the two targets [3]. In view of the high-decibel sound field intensity of gunfire, muzzle acoustic signal has been applied as the original physical applications for non-contact trigger for a long time, but muzzle acoustic signal has the features such as reflection, attenuation which is similar to the common signal. The original signal of muzzle sound trigger will be submerged in various echo interference for bursts and firing in a closed room, so that it can't produce accurate trigger signal, which is a major drawback of the acoustic trigger system.

In order to solve this problem, to further optimize the acoustic detection system, this system adopts the delay correlation theory, using high-performance MEMS acoustic sensor as acoustic detection sensors, also using two sound detectors to overcome secondary false triggering caused by ground bounce noise [4], it will improve the reliability of system triggers signal, and enhance the accuracy and the uniqueness of trigger signal in bursts and firing in a closed room.

## 2. Characteristic Analysis of Muzzle Acoustical Wave Signal

According to some theory of intermediate trajectory, during bullet launch, it will first ignite a little sensitive gunpowder in primer detonating cap, and go through a series of the spread of fire system to strengthen ignition capability, so it increases casings' internal pressure, the bullet will break away from casings and squeeze into rifled part when it reaches a certain pressure. Then the bullet will be push-off under the effect of high temperature, high pressure gas. When bullet is out of muzzle, it will discharge the blowout from muzzle and form a muzzle shock wave signal [5].

The bullet will produce three acoustic signals when it is pushed out of the muzzle, shown in Fig. 1.

When the bullet is pushed out of muzzle, the muzzle shock wave will be formed, and bullet will fly with supersonic speed when it gets out of muzzle, the head and tail of the bullet will compress air to produce two shock wave, this wave become to bullet head wave and bullet tail wave, and they become muzzle shock wave, in fact it's the sound generated by explosion of gunpowder in muzzle, also the shot acoustically. Its frequency mainly focused on a range from 4 kHz to 20 kHz, the muzzle shock wave signal is approximately a spherical wave which is the main trigger energy of acoustic trigger system [6, 7].

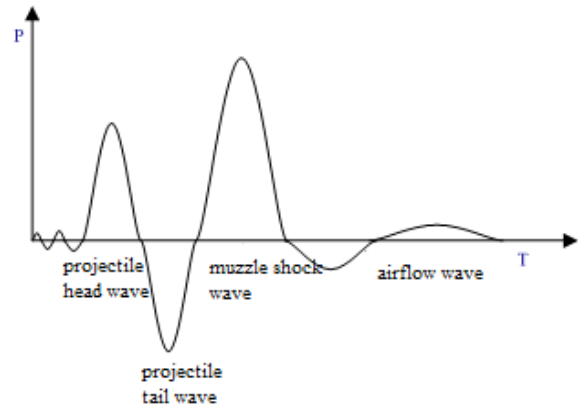


Fig. 1. Muzzle acoustic signals.

Because there are high temperature and pressure and the air in gun barrel is released suddenly, impacting the flow at gunpoint, the flow outside of muzzle will back-flow again, forming a muzzle sound field after expending rapidly and noise signal with different frequencies and little amplitudes around muzzle [8]. It will cause false triggering because of glitch generated by the sound trigger system.

## 3. Model Building of the Muzzle Acoustic Trigger System

Transmission of muzzle acoustic signal has a significant wave characteristic, including reflection [9], diffraction and interference characteristics, etc. In view of such a characteristic of muzzle acoustic wave signal, although there are no obstacles in the transmission path, when muzzle acoustic signals transmit with the velocity from the shooter to the acoustic sensors, the acoustic sensor can receive muzzle acoustic wave generated by the ground bounce. When there is an obstacle between the shooter and the acoustic sensors, according to wave's characteristics of refraction and attenuation, the acoustic sensors receives the reflected wave again with the similar or less amplitude [10]. So these reflected signals will bring misuse to the system.

For a typical sound trigger field shown in Fig. 2. Point A is the position of the gunpoint or muzzle, point B is the position of the received signal for acoustic sensor received signal. In general, the blast wave will transmit from A to B, from reflecting surface M and N to B, so that point B will receive repeated muzzle acoustic wave signal, that can interfere original acoustic wave signal seriously, then it will be triggered by mistake.

When the right of line AB is extended to C and the acoustic sensor set up, if the muzzle acoustic signal received at point B at this moment is delayed some time (delay time is the distance/velocity between B and C), and making correlation filter operations with the muzzle acoustic signal received at

point C, it will filter out the noise of other reflective surfaces, especially in an indoor closed environment [11]. When the system is in this situation, the ground bounce noise and multipath interference signal are main muzzle interference signals, and the two primary sound trigger systems can effectively filter out these two noise signals and generate an accurate trigger signal.

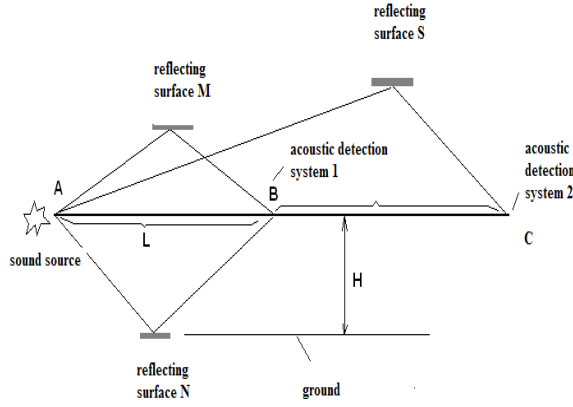


Fig. 2. Model of acoustic trigger system (the principle of delay autocorrelation).

Assuming mathematical model of the received muzzle acoustic signal by acoustic detection system 1 at point B and 2 at point C respectively is:

$$f_1(n) = \alpha_1 s_1(n - \tau_1) + \nu_1(n), \quad (1)$$

$$f_2(n) = \alpha_2 s_2(n - \tau_2) + \nu_2(n), \quad (2)$$

where  $\alpha$  is the wave transmission attenuation factor,  $s_1(n)$  and  $s_2(n)$  are effective acoustic signals,  $\tau_1$  and  $\tau_2$  are transmission time when the muzzle acoustic signal is transmitted to the MEMS acoustic Sensor 1 and Sensor 2,  $\tau$  is the time difference between MEMS acoustic Sensor 1 and Sensor 2, because  $\tau'$  is the time difference when the rebound effect acoustic signal from N reflective surface gets to MEMS acoustic Sensor 1 and Sensor 2,  $\nu_1(n)$  and  $\nu_2(n)$  are weighted sum of all noise signals, including environmental noise signal and interfering noise from each path in transmission process of the muzzle acoustic signal, and these noise signal are unrelated.

Correlation function between muzzle acoustic signal  $f_1(n)$  and  $f_2(n)$  is:

$$R_{12}(\tau) = E(f_1(n)f_2(n - \tau)) \quad (3)$$

Substituting formula (1) and formula (2) into Equation (3) can get formula (4):

$$\begin{aligned} R_{12}(\tau) &= E(f_1(n)f_2(n - \tau)) \\ &= \alpha_1 \alpha_2 E(s_1(n - \tau_1)s_2(n - \tau_2 - \tau)) \\ &\quad + \alpha_1 E(s_1(n - \tau_1)\nu_2(n - \tau)) \\ &\quad + \alpha_2 E(s_2(n - \tau_2 - \tau)\nu_1(n)) \\ &\quad + E(\nu_1(n)\nu_2(n - \tau)) \end{aligned} \quad (4)$$

Since the signal and noise are uncorrelated, and assuming the average value of noise is zero, then according to the nature of the correlation function, it can get formula (5):

$$\begin{aligned} R_{12}(\tau) &= \alpha_1 \alpha_2 E(s_1(n - \tau_1)s_2(n - \tau_2 - \tau)) \\ &= \alpha_1 \alpha_2 R_s(\tau - (\tau_1 - \tau_2)) \end{aligned} \quad (5)$$

Making a analysis of formula (5), assuming two microphones have a very good consistency, and there are no attenuation in the sound source signal after transmitting, when  $\tau = \tau_1 - \tau_2 = R / C \ll \tau'$ , the correlation function has a maximum value, it can change the time difference  $\tau$  detected by MEMS acoustic Sensor 1 and Sensor 2 by adjusting the distance between the two acoustic sensors, then the correlation function  $R_{12}(\tau) = \alpha_1 \alpha_2 R_s(\tau - (\tau_1 - \tau_2))$  generates maximum value, so it can accurately extract muzzle target sound signal from noise signal.

#### 4. Minimum Path Constraints of Delay Correlation Filtering

Muzzle acoustic signals exists not only the attenuation of sound intensity, but also multiple direction of transmission. Since sounds during the transmission will encounter various obstacles, there will appear acoustic multipath interference phenomena, in these transmission lines, straight line can best make detector early get more realistic target sound signal. In a variety of reflection paths, ground bounce noise generated by ground reflection is the main noise. Although there is attenuation in the course of sound signal transmission, when the rebound noise enters the detection system again, its amplitude is close to the muzzle shock wave signal [12]. If the time difference between muzzle shock wave received by the two detector and ground bounce signals is equal, the delay correlation operation can not eliminate ground bounce noise interference eventually and it will still cause secondary false triggering [13].

Assuming the height between sound source and two detectors is H, the distance between sound source and detector 1 is L, the distance between the two detectors is R, the shortest time are  $t_1, t_2$  when sounds are linearly transmitted to MEMS acoustic Sensor 1 and Sensor 2, the shortest time is  $t_3$  for ground bounce arrive to MEMS acoustic Sensor 1, the shortest time is  $t_4$  for ground bounce arrive to MEMS

acoustic Sensor 2, sound wave transmission rate is  $C$  in air.

Times when sound waves are transmitted in different path to the two detectors are:

$$\begin{cases} t_1 = \frac{L}{C} \\ t_2 = \frac{L+R}{C} \\ t_3 = 2 \frac{\sqrt{(\frac{L}{2})^2 + H^2}}{C} \\ t_4 = 2 \frac{\sqrt{(\frac{L+R}{2})^2 + H^2}}{C} \end{cases} \quad (6)$$

To completely eliminate ground bounce noise caused by the phenomenon of secondary false triggering, time difference from different paths of sound wave reach to the detector must demand  $t_4 - t_2 \neq t_3 - t_1$ , namely:

$$\begin{aligned} 2 \frac{\sqrt{(\frac{L+R}{2})^2 + H^2}}{C} - \frac{L+R}{C} &\neq 2 \frac{\sqrt{(\frac{L}{2})^2 + H^2}}{C} - \frac{L}{C} \\ \sqrt{(\frac{L+R}{2})^2 + H^2} - \sqrt{(\frac{L}{2})^2 + H^2} - \frac{R}{2} &\neq 0 \end{aligned} \quad (7)$$

To solve the formula (7), it will get the relation among  $L$ ,  $H$ ,  $R$ , as follows:

$$\frac{9}{16} R^2 + \frac{3}{4} LR \neq H^2 \quad (8)$$

In the field test environment, the distance  $L$ , the height  $H$  between detector and sound source, and the distance between the two detectors are all uncertain. So it must rely on actual test conditions, the detection condition is as formula (8). Under this condition, the delay correlation theory can be applied to eliminate ground bounce interference.

After the above theoretical analysis, before the field test, demarcating the acoustic detection system, defining the distance  $L$ , the height  $H$  between detector and sound source, and the distance  $R$  between two acquisition systems with same parameters, so that delay time  $\tau$  can be determined. MEMS acoustic Sensor 1 collect muzzle signal, then do self-correlation operation with MEMS acoustic Sensor 2 after a certain delay, this delay time makes the correlation function to obtain the maximum value. Target signal is extracted by effective signal, also eliminate ground bounce noise and other noise in the space field, then to ensure the reliability and accuracy for acoustic detection signal.

## 5. The Implementation of Delay Correlation Filtering System

System structure block is shown in Fig. 3, the MEMS Sensor 1 and Sensor 2 are placed in measuring table, the two sensors and sound source are keeping at the same line. The acoustic detection subsystem uses high integrity, high sensitivity MEMS acoustic sensors to detect muzzle shock wave signals. This system uses ADMP404 omnidirectional microphone of ANALOG DEVICES, the sensor consists of a MEMS micro-capacitive sensors, micro-integrated switching circuit (amplifier), tune and RF anti-noise circuit. MEMS micro-capacitance pole section contains silicon diaphragm and silicon backplane that is used to receive sound, silicon diaphragm can directly transmit received audio signal through MEMS micro-capacitance sensor to microchip, the microchip can change and amplify high impedance audio level signals to a low-resistance, while via filtering with RF anti-noise circuit, the output signal will complete "sound-electricity" conversion [14]. ADMP404 omnidirectional acoustic sensor has the wideband frequency response between 100 Hz to 15 kHz, it can provide collection for high-fidelity natural sound.

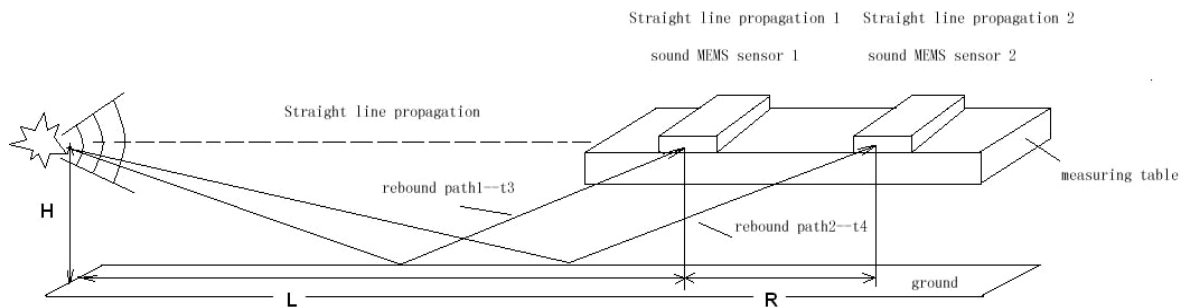


Fig. 3. Application model of delay correlation filter system.

In the system model, muzzle and acoustic detection system are in the same horizontal line, and the height is  $H$ . When the sound signal is generated, it is transmitted in straight line to MEMS acoustic

Sensor 1 and acoustic Sensor 2 within time  $t_1$  and  $t_2$ , and it will be bounced back again to the two MEMS acoustic sensors by the ground. Although the acoustic signal exist attenuation during the communication

process, when the rebound noise enters the detection system, its amplitude is close to muzzle shock signal's amplitude. If the system just uses one acoustic detection equipment to produce the starting signal, it will cause the secondary trigger and false triggering. In order to solve this problem, the system uses two MEMS acoustic sensor which parameters are same to collect muzzle shock wave signal [15]. When the signal passes data processing circuit, using muzzle shock wave signal with appropriate delay collected by first MEMS acoustic sensor to make self-correlation operation with second MEMS acoustic sensor. So it can generate accurate trigger signal for the subsequent test equipment.

In a closed test environment, the target sound signal, in a straight line and by ground bounce transmission paths, will reach to MEMS acoustic Sensor 1 and Sensor 2 after each shot, the acoustic

signal is collected by two acoustic sensor which have a time difference, that is  $\tau = R/C$ . According to delay correlation theory, the two MEMS acoustic sensors will collect the muzzle signal twice at least, the first time is straight line travel time of the target signal generated by muzzle shock wave; the second time is produced because of the ground bounce. For the same acoustic sensor, there is a delay between the two received acoustic signals in time.

In order to achieve accurate MEMS sensor sound-electrical conversion and filter chamber air backflow caused by the low frequency interference, the system uses a processing circuit, as shown in Fig. 4, composed by the signal acquisition module, signal front-end processing module, the signal correlation filtering and signal transmission module.

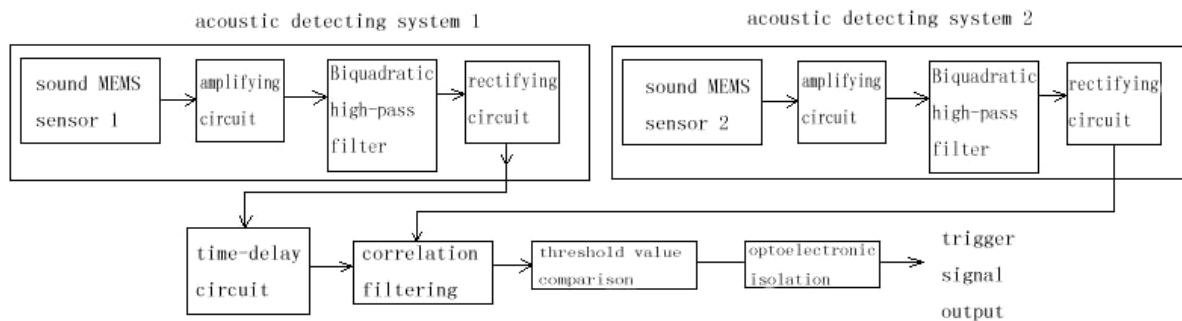


Fig. 4. Processing circuit.

MEMS sensor will transform the collected muzzle sound signal into electrical signal, this electrical signal has a part of dc, so it is necessary to filter it by a capacitance and do zero processing. Although there is a micro-integration acoustic sensor in conversion circuit (amplifier), the signal out of sensor is weak, it needs to use an amplifier circuit to amplify signal to certain amplitude. In order to filter low frequency acoustic signal (about dozens Hz), it needs to adopt biquadratic high-pass filter for processing. Because the collected sound waves signals have positive and negative value, a full wave shaping circuit should be used to turn negative voltage signal 180° and make the acoustic signal a positive voltage signal. Using a threshold comparison circuit to process the analog voice signal and convert it into digital pulse. According to the delay related theory, the target acoustic signal collected from MEMS acoustic sensor 1 will be delayed in time  $\tau = \tau_1 - \tau_2 = R/C$ , making correlation processing with acoustic signal (collected by sound MEMS Sensor 2), filtering rebound noise signal and noise signal, then it will receive an exact trigger signal [16]. Isolated from a high-speed optical coupling device, it will be beginning work signal for the each test equipment.

## 6. Experimental Analysis

In order to verify the specific function of delay correlation filtering system, this paper analyzed the algorithm of combining experimental environment simulation. the muzzle shock wave signal generated by the gun is belong to the shape of point-source explosion, in general, when the physical size of the sound source is much smaller than the acoustic wave length, or the distance between collection point and sound source point is very far, the sound source can be regarded as a point, that is point source [17]. This assumption is completely applicative to the muzzle. The acoustic wave is spherical wave which spread from the point source with surface dilatation, in other word, regarding the point source as the center, the acoustic wave's phase in same spherical surface are equal [18, 19]. The wave equation of spherical wave is:

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2}$$

$$\Rightarrow \frac{\partial^2 (rp)}{\partial r^2} = \frac{1}{c^2} \frac{\partial^2 (rp)}{\partial t^2} \quad (9)$$

We can use  $P(r, t)$  to describe harmonic spherical wave transmitted from center of sphere to outside:



$$p(r, t) = \frac{P_o}{r} \cos(\omega t - kr) \quad (10)$$

Shown in Fig. 5, the wave characteristics of the sound waves is clearly described in Matlab simulation, it exhibits the characteristics of harmonic oscillation what is common to the wave, and it also have reflection and diffraction properties.

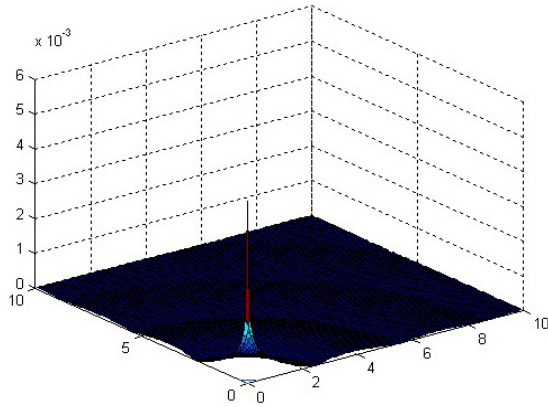


Fig. 5. The simulation for the volatility of sound field.

Fig. 6 exhibits waveform from a relatively empty area outdoor experiment, the actual muzzle acoustic signal has already done the process those are rectifier and high-pass filter, in the exterior trajectory test environment, the muzzle original signal's amplitude is close to ground bounce noise. In the case of bullet repeatedly firing, they are difficult to distinguish. If in a closed indoor environment, muzzle acoustic signals not only have ground bounce noise, but will suffer from the walls and interior equipment bounce noise.

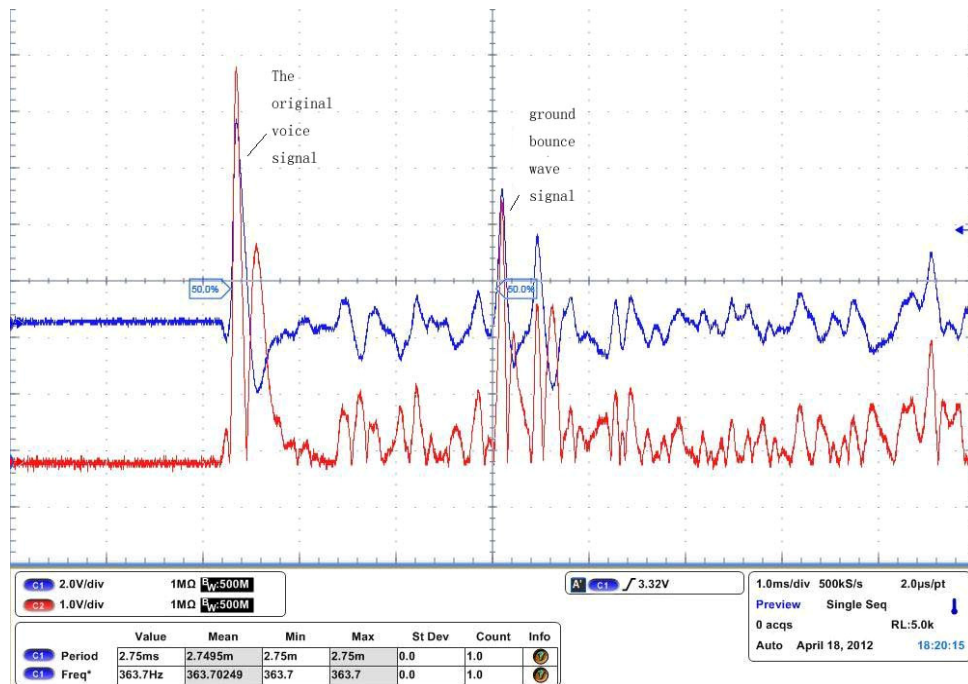


Fig. 6. Sound detection signal with ground bounce noise.

## 7. Analysis of Circuit Simulation

Experimental condition includes two states, one state is 1, it has a reflective surface  $N$  (ground), using Multisim to do simulation. According to the minimum path constraints for delay correlation filtering, the variables are shown as follow: state 1:  $L$  is 1.7 m,  $R$  is 1.7 m,  $\tau$  is 5 m, reflective surface is  $N$ , the distance for reflective surface  $N$  is 1.2 m; state 2:  $L$  is 1.7 m,  $R$  is 1.7 m,  $\tau$  is 5 m, reflective surface is  $N$  and  $M$ , the distance for reflective surface  $N$  is 1.2 m, for  $M$  is 2 m.

The simulation principle is shown in Fig.7, in the simulation, using three EXPONENTIAL\_VOLTAGE as the imitation of muzzle shock wave. Changing the parameters of the signal source can reasonably construct muzzle shock signal waveform, meanwhile, using the thermal noise device to simulate the environmental noise generated by the real device.

In Fig. 8, SENSOR1 is the output waveform of the Sensor 1, SENSOR1\_DELAY is the analog waveform after a time delay  $\tau$  of Sensor 1, SENSOR2\_REALTIME is the muzzle blast received by Sensor 2, including the noise signal of the reflective surface, SENSOR1\_DELAY and SENSOR2\_REALTIME do a multiplication operation, then it realize correlation filter, the result is RESULT signal, the simulation results are shown in Fig. 8 and Fig. 9. The noise generated by  $N$  reflecting surface has been filtered out when it multiply with SENSOR1\_DELAY signal, the noise generated by the reflecting surface also has been filtered out when it multiply with SENSOR1\_DELAY signal, it's visible, RESULT signal make the bounce noise reduce.

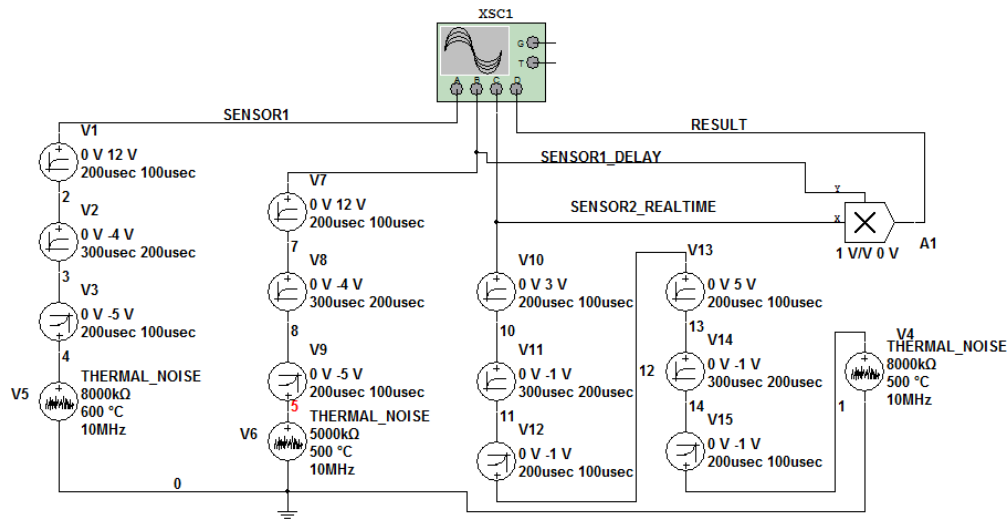


Fig. 7. Simulation for circuit principle.

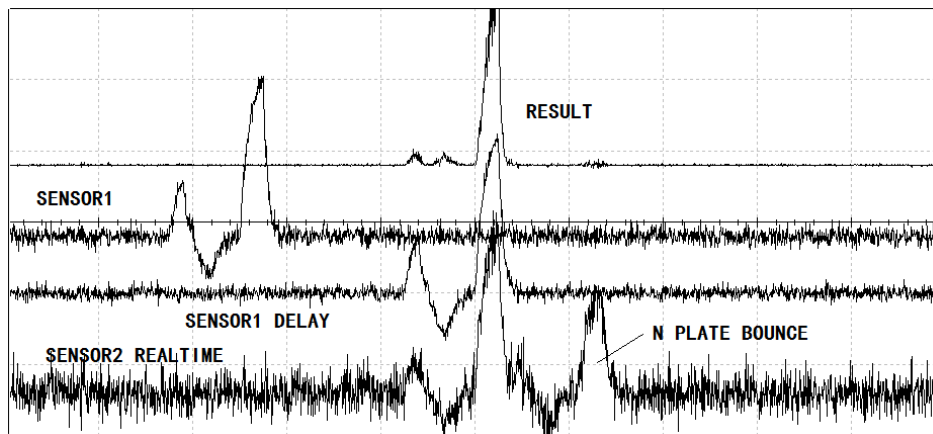


Fig. 8. Multisim simulation result for state 1.

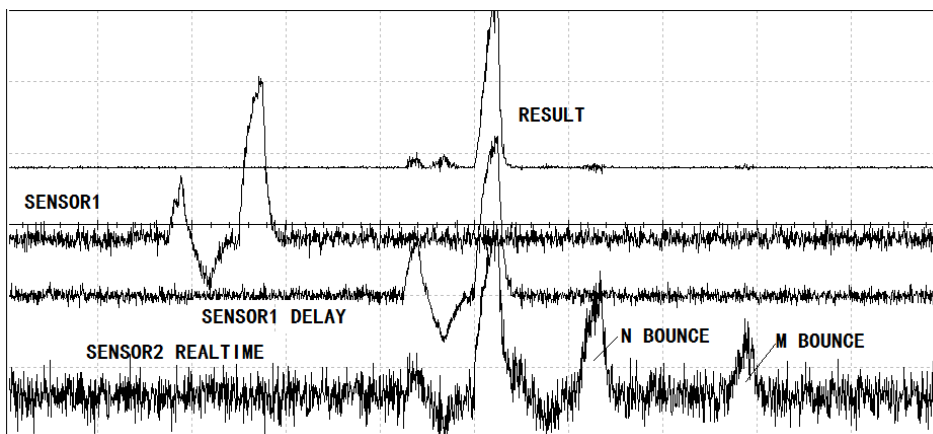


Fig. 9. Multisim simulation result for state 2.

In order to verify the simulation results, in the experiment, using the MEMS acoustic sensor based on the infrastructure of the Fig. 3 to test the shock wave signal, the results wave is shown in Fig. 10. In the figure, the Channel 4 is Sensor 1 signal, Channel 2 is

the Sensor 1 delayed signal, Channel 1 is Sensor 2 real time signal, Channel 3 is a result signal, the simulation is consistent with Fig. 8 and Fig. 9.

According to the formula (8), the above three test condition parameters meet the requirements,

therefore, in acoustic detection System 2, time difference between collected shock chamber mouth wave signal and ground bounce noise signal must be greater than that from acoustic detection System 1. When delay correlation processing is applied, ground bounce noise and other path rebound will be effectively filter out. As shown in Fig. 10, in sound detection System 1 (Channel 4) trigger signal delay time was set in 4.4 ms and it generates pulse width adjustable time delay signal (Channel 2), then it is used to make correlation operation with trigger signal from acoustic detection System 2 (Channel 1), then the accurate trigger signal (passage 3) is obtained.

Through the analysis to experimental results, when system test conditions meet the formula (8), adopting delay correlation method can effectively eliminate noises from rebound muzzle signal which generates repeated mistake trigger, and this method is easy to realize, in the practice engineering application, it has a high practical value.

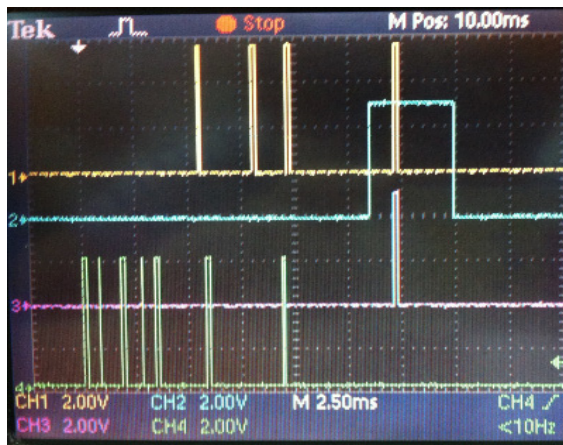


Fig. 10. The acoustic signals after processed by the delay correlation.

Through the analysis to experimental results, when system test conditions meet the formula (8), adopting delay correlation method can effectively eliminate noises from rebound muzzle signal which generates repeated mistake trigger, and this method is easy to realize, in the practice engineering application, it has a high practical value.

## 8. Conclusions

His paper analyzed the muzzle acoustic signals, and studied the characteristics of the shock chamber mouth wave. The problem of echo noise caused by sound trigger system was analyzed in detail. The delay correlation filtering algorithm is adopted to sound trigger system mathematical modeling, and the paper put forward the minimum delay correlation filtering path constraint conditions. In order to verify the feasibility of the system, the related sound trigger system was designed. The analysis and experiments show that in the case of a rebound wave interference,

when the three conditions of a system working parameters meet certain requirements, using the theory of delay processing shock chamber mouth wave signal can effectively eliminate the influence of the multipath interference of trigger system. It is proved that it has a certain value in the improvement of the reliability of the trigger system.

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