Measure method and signal recognition of projectile explosion position based on acousto-optic combined detection

XUEWEI ZHANG[a,b,*], HANSHAN LI[b]
[a]*School of Mechatronic Engineering, Xi'an Technological University, Xi'an, 710021, China*
[b]*School of Electronic and Information Engineering, Xi'an Technological University, Xi'an, 710021, China*

In order to solve the problem of measuring the explosive position of projectile at the end of the ballistic zone, this paper proposes a method to measure the explosion position of projectile by using acoustic optic combined detection, researches the acoustic signal recognition and time extraction, and designs a compound eye photoelectric detection sensor with a large field of view, which provide a synchronous trigger collection projectile explosion sound signals. we establishes the calculation model of the explosion position of projectile based on the triangular three-element acoustic sensor array, uses the wavelet transform and the improved particle swarm optimization method to realize sound signal filtering and time extraction of projectile explosion. Based on the synchronous collection of the compound eye photoelectric detection sensor, we collect the acoustic signal of projectile explosion and identify the peak value and time of the projectile explosion, and gain the position of projectile explosion. It is verified that the design model and algorithm proposed in this paper are reasonable.

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Keywords: Acoustic sensor, Compound eye photoelectric detection sensor, Projectile explosion, Signal processing

1. Introduction

The projectile explosion position is an important index to measure the damage of ammunition to ground target at the end of the ballistic zone. The main working principle of projectile explosion is that the projectile's fuze control device emits radio waves during the process of projectile falling, the emitted radio waves intersect with the ground target, and the ground target reflects the echo signal of radio waves. The distance between the projectile and the ground target is evaluated by using the time difference between the emitted and received radio waves, when the height value of the fuze loading is meet, the ignition device of the projectile loading is started, and then the projectile exploded [1-2]. Due to the strong dynamic randomness of the ground target in the ballistic terminal zone, the ignition control of the projectile's fuze appears delay phenomenon, which makes the height of the projectile explosion appear a certain random distribution. It is difficult to arrange the ground test equipment for measuring the projectile explosive position at the end of the ballistic zone, especially, the single optical equipment [3-4]. High speed photography or area array camera intersection measurement method is mainly used in the ground test of projectile explosion point height optical imaging equipment. For the optical equipment, it can intuitively obtain the image of the explosion point of the projectile. The actual explosion point height of the projectile can be estimated by using the calibration object with known parameters on the ground [5]. However, the optical equipment is restricted by the background light and optical lens parameters, resulting in poor imaging quality and limited detection area of the optical equipment [6]. It is difficult to capture all the random projectile's explosion information when the drop area is wide. In order to improve the test ability of projectile explosion, a test method of acousto-optic combined detection is introduced. This measure method based on acoustic sensor detection can work all day. According to the mechanism of measuring the projectile explosion position based on acousto-optic combined detection, this paper studies a method of measuring projectile explosion position and a recognition algorithm of projectile explosion sound signal.

2. The measure model of projectile explosion position based on acousto-optic combined detection

This paper uses three acoustic sensor and a compound eye photoelectric detection sensor to form a triangular acoustic array detection and measure system, the layout of acoustic sensors is shown in Fig. 1. In Fig. 1, O is the coordinate origin of measure system, P_1, P_2 and P_3 are three acoustic detection sensors, whose coordinates are $(S/2,0,0)$, $(0,S,0)$ and $(-S/2,0,0)$ respectively, the compound eye photoelectric detection sensor is arranged at point O. Fig. 2 is the design principle of compound eye photoelectric detection sensor. Fig. 2 (a) is the top view of compound eye photoelectric detection sensor, on the hemispherical surface, a plurality of middle lenses are installed to form its detection field of view. Fig.

2 (b) is a schematic diagram of the lens array passing through the central unit lens section. d_1 is the linear distance between adjacent lenses of the compound eye photoelectric detection sensor, r_1 is the radius of curvature of circular curved multi array lens, r_2 is the radius of curvature of each unit lens, d_2 is the thickness of unit lens, ϕ is the aperture of unit lens, $\Delta\theta$ is the angle between adjacent lenses, and it can gain by formula (1) .

$$\Delta\theta = \arctan[(d_1+\phi)/r_1] \qquad (1)$$

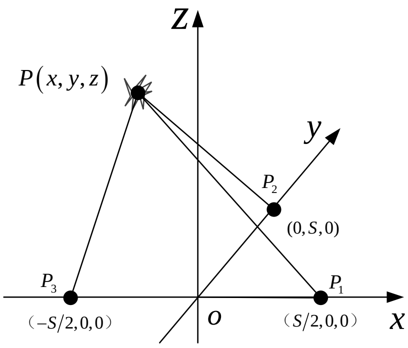
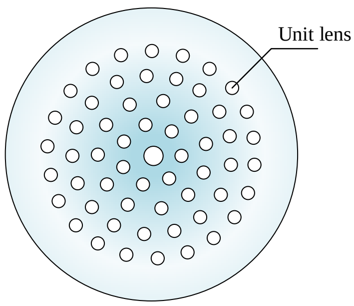
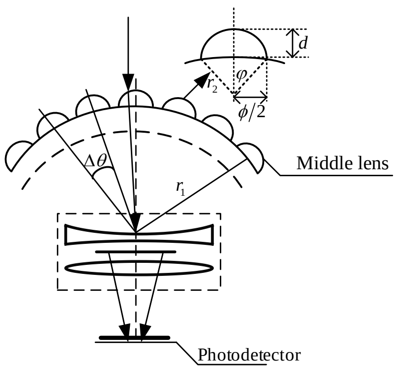


Fig. 1. The layout schematic diagram on three acoustic sensor and compound eye photoelectric detection sensor



(a) The top view of compound eye photoelectric detection sensor



(b) A schematic diagram of the lens array passing through the central unit lens section

Fig. 2. The design principle of compound eye photoelectric detection sensor

For the optical path of compound eye photoelectric detection sensor, a single lens can be regarded as a spherical mirror. According to the optical principle, we use formula (2) to gain the focal length of a single lens.

$$\frac{1}{f'} = \frac{d_2(n_0-1)^2}{n_0 r_1 r_2} + (n_0-1)(\frac{1}{r_2}-\frac{1}{r_1}) \qquad (2)$$

In formula (2), f' is the focal length of a single lens, n_0 is the refractive index of a single middle lens. It is assumed that the number of lens arrays arranged in radial direction is *N*, and the aperture of the unit lens is ϕ, and the number of photosensitive units is ε [7-8]. For the imaging of compound eye photoelectric detection sensor, *M* is its pixels and υ is its pixel width, it can meet the formula (3).

$$\begin{cases} M = N\cdot\upsilon \\ b\cdot\varepsilon = \phi + a \end{cases} \qquad (3)$$

Based on the optical path design of compound eye photoelectric detection sensor, when the projectile explodes in the detection area, the flame signal generated by the projectile explosion enters the optical path of compound eye photoelectric detection sensor. Through optical lens imaging, the photodetector detects the flame signal of the projectile explosion, and after processing, and provide a gather signal for a three acoustic sensor. Assumed that the explosion position of the projectile is $P(x, y, z)$, the time of the flame signal generated by the compound eye photoelectric detection sensor is t_0, t_0 is the starting time of signal acquisition in the acoustic sensor system, usually, $t_0 = 0$, and the time of the projectile explosion signal captured by the three acoustic sensors P_1, P_2 and P_3 is t_1, t_2 and t_3 respectively. According to the sound velocity, the position of projectile explosion and the time-space function of three acoustic sensors are determined, their relation can gain by formula (4).

$$\begin{cases} t_1^2 v_c^{\,2} = \left(x - \frac{1}{2}S\right)^2 + y^2 + z^2 \\ t_2^2 v_c^{\,2} = x^2 + \left(y - S\right)^2 + z^2 \\ t_3^2 v_c^{\,2} = \left(x + \frac{1}{2}S\right)^2 + y^2 + z^2 \end{cases} \qquad (4)$$

Based on formula (4), we can calculate the position of $P(x, y, z)$, the formula (5) is the calculation expression.

$$\begin{cases} x = \dfrac{v_c{}^2\left(t_1{}^2 - t_3{}^2\right)}{-2S} \\ y = \dfrac{v_c{}^2\left(2t_3^2 - 4t_2^2 + 2t_1^2\right) + 3S^2}{8S} \\ z = \dfrac{\sqrt{\dfrac{-25S^4}{16} + \dfrac{v_c{}^2(5t_1^2 + 6t_2^2 + 5t_3^2)}{4} + v_c{}^4\left[\dfrac{-5\left(t_1^4 - t_3^4\right)}{4} + t_1^2 t_2^2 + \dfrac{3t_1^2 t_3^2}{2} - t_2^4 + t_2^2 t_3^2\right]}}{2S} \end{cases} \quad (5)$$

3. Recognition algorithm of projectile explosion acoustic signal

3.1. Signal filtering processing of acoustic sensor

According to the principle of Fig. 1, the output signal of any acoustic sensor is independent, and there is similarity the same projectile explosion sound signal in a triangular acoustic array detection and measure system. It is assumed that the output signal of an acoustic sensor contains projectile explosion acoustic signal and noise signal, we use $f(t)$ to represent their function by formula (6).

$$f(t) = y(t) + s(t) \quad (6)$$

where, $y(t)$ represents the signal of projectile explosion without noise and $s(t)$ represents the noise. The wavelet transform of $f(t)$ is expressed by formula (7).

$$W(a,\tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t) \psi^*\left(\frac{t-\tau}{a}\right) dt \quad (7)$$

In formula (7), a denotes the scale factor, τ denotes the time shift factor, and $\psi^*((t-\tau)/a)$ denotes the conjugate function of the wavelet mother function $\psi(t)$. The value of a is changed in the frequency domain. The signal of projectile explosion is to perform the band-pass filtering of the signal and obtain the frequency localization [9]. $f(t)$ is discretized into $f(n)$.

In the algorithm, n is the discrete point of acoustic signal sampling, and the wavelet scale coefficient $b_{i,j}$ and wavelet coefficient $c_{i,j}$ are obtained by performing orthogonal wavelet decomposition, $b_{i,j} = \sum_n h_1(2j-n) b_{i-1,j}$, $c_{i,j} = \sum_n h_2(2j-n) c_{i-1,j}$, $h_1(n)$ and $h_2(n)$ represent a pair of orthogonal mirror filter banks [10]. $h_1(n)$ is the low-pass filter coefficient, which acts on the signal to obtain the low-frequency smooth profile A_j. $h_2(n)$ is the high-pass filter coefficient, which acts on the signal to obtain the high frequency detail B_j. i is the number of wavelet decomposition levels. The wavelet reconstruction function is expressed by formula (8).

$$e_{j,k} = \sum e_{j+1,n} h_1(j-2n) + \sum c_{i+1,n} h_2(j-2n) \quad (8)$$

Based on the reconstruction function, Daubechies wavelet is used to decompose the projectile explosion signal into six layers. Observe the low frequency smooth profile A_6 and set A_6 to 0. The high frequency component of the projectile explosion signal is obtained by dividing the 1-6 layers of detail into $B_1 - B_6$ reconstruction signal. In order to eliminate the high frequency component of the projectile explosion signal, the wavelet coefficient $w_{i,j}$ of the projectile explosion acoustic signal is divided into two parts [11]. These two parts represent the wavelet coefficients $s_{i,j}$ and $n_{i,j}$ of the projectile explosion acoustic signal respectively. The first part is the wavelet coefficients $s_{i,j}$, representing the projectile signal and the second part is the wavelet coefficients $n_{i,j}$, representing the noise. So, $w_{i,j} = s_{i,j} + n_{i,j}$. The wavelet threshold method is used to remove the noise. It is noteworthy that the Daubechies wavelet basis is selected to decompose the signal into one layer. Consequently, a set of wavelet coefficients $w(i, j)$ is obtained.

We select a fixed threshold function by assuming the threshold value δ. if $|w| > \delta$, the signal characteristics are retained, contrary, if $|w| \le \delta$, the signal characteristics are not considered, and $\delta = 0$. We introduce the unbiased risk threshold rule, the main steps of the algorithm are as follows:

First, let W be a vector whose elements are arranged from small to large by the square W_k of wavelet coefficients $w(i, j)$. k is the number of wavelet coefficients, we obtain a vector $W = [W_1, W_2, \cdots, W_k]$, and it satisfy $W_1 \le W_2 \le \cdots \le W_k$. Secondly, construct the risk vector and calculate the minimum risk value. Suppose F is a risk vector, $F = [F_1, F_2, \cdots, F_k]$, its elements can gain by formula (9).

$$F_m = \sum_{l=1}^{m} W_l / k + (k-2m) + (k-m) W_m \quad (9)$$

In formula (9), $m = 1, 2, \cdots, k$, through the iteration of equation (6), the minimum value F_r is taken as the risk value, and the corresponding W_r is obtained from the subscript r of F_r. And then, we calculate the threshold δ, $\delta = \sqrt{\sigma^2 W_r}$, and make $|w'(i,j) - w(i,j)|$ as small as possible, where, $w'(i,j)$ is the estimated signal and $w(i,j)$ is the original signal. Then, the denoised estimation signal is obtained.

3.2. Recognition and time extraction of projectile explosion acoustic signal based on particle swarm optimization

According to the estimated signal of projectile explosion, the discrete signals of projectile explosion acoustic signal are used as the input layer of particle swarm. The particle swarm is initialized, i.e., ρ particles are generated randomly in the solution space. The positions of the particles are recorded as $L_\rho = \{L_{\rho 1}, z_{\rho 2}, \cdots, z_{\rho\tau}\}$, and the fitness value of each particle is calculated by utilizing the objective function. Then, the particles continuously adjust their positions in the solution space to search for a new solution. In each iteration, each particle is adjusted based on two values [12-13]. First, the optimal position of the particle, i.e., p_{uv}. Second, the optimal position of the whole population, i.e., $p_{\lambda\vartheta}$.

The velocity of each particle is $V_{\rho u} = \{V_{\rho 1}, V_{\rho 2}, \cdots, V_{\rho\tau}\}$, each particle updates its velocity according to formula (10).

$$\begin{cases} V_{\rho v} = \eta V_{\rho v}(t) + a_1 r[p_{\rho v} - z_{\rho v}(t)] + a_2 r[p_{\rho v} - z_{\rho v}(t)] \\ z_{\rho v}(t+1) = z_{\rho v}(t) + V_{\rho v}(t+1) \end{cases} \tag{10}$$

where, $V_{\rho v}(t+1)$ represents the velocity of the ρ-th particle in the v-th dimension at $t+1$ iteration, η denotes the inertia weight, a_1 and a_2 denote the acceleration constant, r denote the random numbers in the interval $(0 \sim 1)$. We set the upper limit on the velocity in order to avoid the high velocity of the particle. When $V_{\rho v}(t+1) > v_{\max}$, we consider $V_{\rho v}(t+1) = v_{\max}$ and when $V_{\rho v}(t+1) < -v_{\max}$, we consider $V_{\rho v}(t+1) = -v_{\max}$.

In order to improve the iterative operation ability of particle velocity update, inertia weight reflects the ability of particles to inherit the previous velocity. A larger weight is conducive to global search, while a smaller weight is more conducive to local search. The particle swarm size is n', the fitness value of particle p_e in the e-th iteration is g_e, the fitness value of the optimal particle is $g_{\max}$ and the average fitness value of the particle swarm is g. If the fitness value is higher than g, g' is obtained by averaging the fitness value again. If the fitness value is lower than that of g, and g' is obtained by averaging the fitness value again [14]. When the fitness value of the particle is close to g, the corresponding results show that the position of particle is close to the global optimization. So, the inertia weight should be smaller to get closer to the global optimization faster. The inertia weight is determined by (11).

$$\eta = \eta_{\min} \times \frac{g_{\max} - g''}{e_e - g'} \tag{11}$$

When the inertia weight is determined, as the initial value of Levenberg- Marquardt, the acoustic signal of projectile explosion is identified according to *LM* algorithm. The improved particle swarm optimization algorithm is used to search the optimal position, and the minimum fitness value μ is calculated, then

$$\mu = \frac{1}{m_1} \sum_{b_1=1}^{m_1} \left| \sum_{b_2=1}^{m_2} (t'_{b_1 b_2} - t''_{b_1 b_2})^2 \right| \tag{12}$$

In formula (12), $t'_{b_1 b_2}$ represents the objective value, $t''_{b_1 b_2}$ represents the calculated value, m_1 denotes the number of training samples, and m_2 represents the number of output nodes [15].

The parameters of particle swarm optimization algorithm are set as follows: the range of velocity of particle is (10-150), the inertia weights $\eta_{\min} = 0.1$, $\eta_{\max} = 0.9$, and $\eta = 0.5$, the acceleration constants are $a_1 = a_2 = 1.15$, read the sample L_ρ [16]. According to the BP algorithm, we calculate the actual output V, and then calculate the error Δ according to formula (11).

If $\Delta < V$, then the result is obtained. Contrary, if $\Delta > V$, the network weights are adjusted. The *LM* calculation method is used to train the network and the actual output V is calculated again. This is again used to check if $\Delta < V$ is satisfied. If $\Delta < V$, the algorithm ends, however, if this condition is not satisfied, we continue the process until the given number of particles are calculated. When the condition is satisfied, the signal time point corresponding to the particle swarm position is the real time t. Based on the particle swarm optimization algorithm, we gain the time value t_1, t_2 and t_3 in a triangular acoustic array detection and measure system.

4. Experiment and analysis

4.1. Experiment methods of testing systems

Based on the recognition and time extraction of projectile explosion acoustic signal, combined with the characteristics of a range test site and the actual projectile proximity test requirements, we carry out the experiment test according to Fig. 1. In the arrangement of the experiment, we choose three high-power acoustic sensors, and its effective detection distance is 100 meters, and the distance of S is 90 meters. The hemispherical field of view of the compound eye photoelectric detector is 105^{o}, which is composed of a long focal length lens array, each sub-lens can effectively detect the fire light with a distance of 150 meters. In the compound eye photoelectric detection sensor, the central distance between two lens is 15 mm, the thickness of unit micro-lens is 4.55 mm, the sub-aperture of unit micro-lens is 10 mm, the radius of curvature of unit micro-lens is 8.66 mm, the radius of curvature of circular curved surface array lens is 51.3 mm, the focal length of the unit lens is 4.8 mm, the transmittance of lens is 0.91, and the number of radially arranged lenses is 13. The number of array photoelectric detection receiver is 5×5, the photosensitive surface area of each unit is 2 mm × 2 mm, the detection blind area is 0.05 mm between two adjacent unit photoelectric detection receiver, the responsiveness of photoelectric detection receiver is 0.1us.

According to the design and testing method of projectile explosion position with three acoustic sensor and compound eye photoelectric detection sensor, the idea of the testing system is shown in Fig. 3.

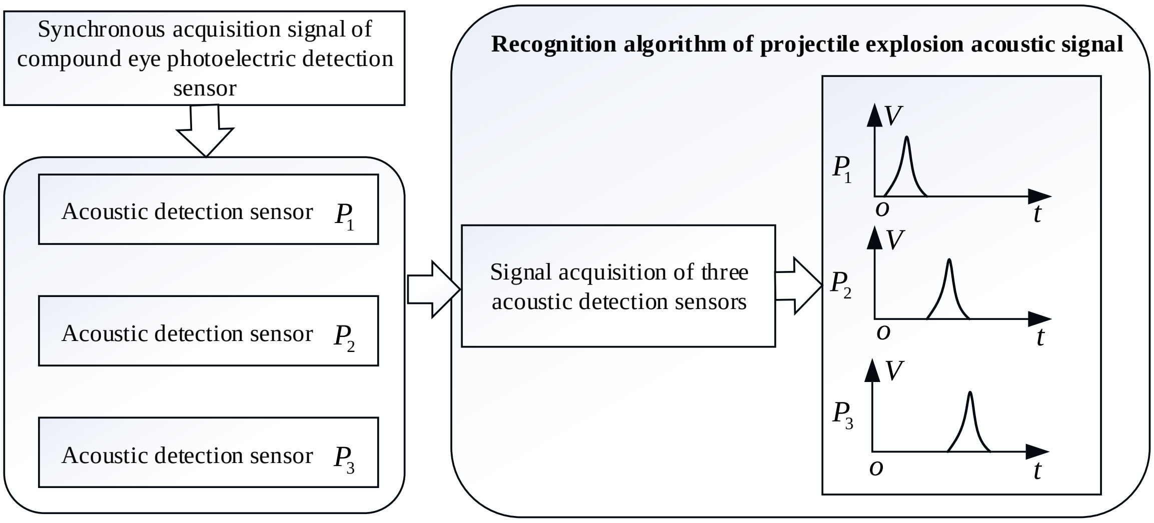


Fig. 3. The idea of the testing system

First, we use compound eye photoelectric detection sensor to capture the fire signal of projectile explosion, and through the processing circuit, provide synchronous acquisition instructions of three acoustic sensors (P_1, P_2, P_3); Second, we uses wavelet transform and the improved particle swarm optimization method to realize sound signal filtering and time extraction of projectile explosion sound signal; At last, we obtain the specific position of the projectile explosion based on formula (4) and (5).

The recognition algorithm of acoustic signal on projectile explosion, the specific processing idea is:

(1) Define the output function $f(t)$ of the acoustic sensor, and use the wavelet transform to process it by formula (7) and (8).

(2) Ensure a fixed threshold function by formula (9) and obtain the denoised estimation signal.

(3) Use the particle swarm optimization algorithm to ensure the time of projectile explosion acoustic signal.

4.2. Data acquisition and processing

According to Part 4.1 and Fig. 1, each acoustic sensor is equipped with an independent acquisition device, the acquisition device is equipped with a fire light synchronous trigger signal input port, and the three acoustic sensors are equipped with a wireless emission module. When the projectile explodes, the fire light signal is obtained by the compound eye photoelectric detection sensor. Under the action of synchronous signal, three acoustic sensors collect their own acoustic signals independently. The collected sound signal is transmitted to the terminal processing computer by the wireless communication module. For the received three-way acoustic sensor signals, the signal filtering processing and the time extraction of projectile explosion are calculated. We gain the time interval between the time projectile explosion position to each acoustic sensor, $\Delta t_1 = t_1 - t_0$,

$\Delta t_2 = t_2 - t_0$, $\Delta t_3 = t_3 - t_0, t_0 = 0$.

Fig. 4 is the original sound signal collected of a projectile explosion, and Fig. 5 shows the signal processed by wavelet filtering, and the corresponding time points t_1, t_2 and t_3 are the corresponding time value points of acoustic sensor. According to formula (6), the position parameter of the current projectile explosion is (-23.62 m, 49.36 m, 32.85 m).

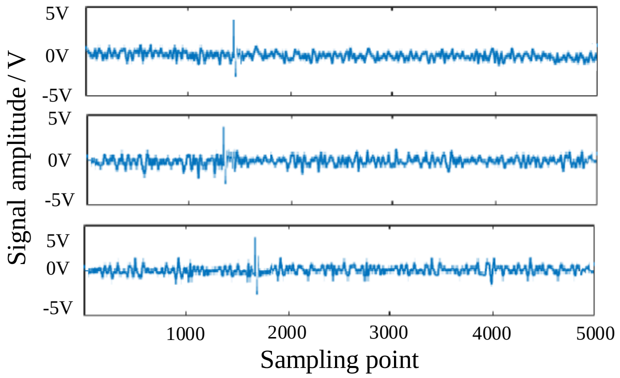


Fig. 4. Original signal of three acoustic sensors

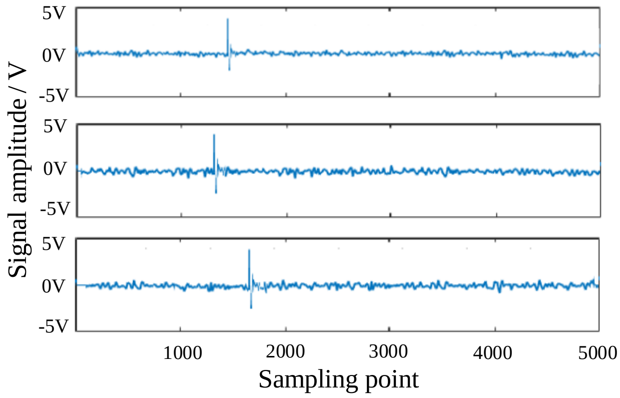


Fig. 5. The output signal by wavelet filtering processing

In order to further verify the correctness of the method proposed in this paper, we conducted multiple sets of experimental tests. According to the test principle and test method, we collected ten projectile explosion signal. After filtering and time extraction, the (V_1, V_2, V_3) is peak voltage of acoustic sensor and (t_1, t_2, t_3) is the time value by time extraction of projectile explosion acoustic signal based on particle swarm optimization in a triangular acoustic array detection and measure system, Table 1 is test data of $P(x, y, z)$.

Table 1. Test data

No.	(V_1, V_2, V_3)	(t_1, t_2, t_3)	$P(x, y, z)$
1	(1762, 4318, 3244)	(0.279, 0.128, 0.186)	(-27.73, 59.28, 14.36)
2	(3318, 3406, 4636)	(0.196, 0.197, 0.119)	(-15.73, 25.82, 11.38)
3	(2416, 2239 4962)	(0.251, 0.262, 0.054)	(-38.47, 11.39, 13.24)
4	(4916, 2506, 2593)	(0.085, 0.235, 0.238)	(31.82, 18.43, 16.42)
5	(3228, 4778, 2485)	(0.201, 0.109, 0.247)	(13.27, 58.38, 14.86)
6	(4152, 4209, 2413)	(0.154, 0.156, 0.251)	(25.42, 46.25, 15.36)
7	(4956, 2187, 2106)	(0.053, 0.326, 0.259)	(41.38, -12.67, 11.57)
8	(4903, 986, 3118)	(0.099, 0.321, 0.196)	(18.36, -16.31, 12.54)
9	(3699, 1718, 4892)	(0.174, 0.287, 0.105)	(-12.38, -5.78, 13.68)
10	(3068, 1509, 4937)	(0.214, 0.302, 0.079)	(-25.42, -8.24, 16.24)

From Table 1, we find that the height of the projectile explosion position is about 9 m to 16 m, and the coverage area is about 90 m × 115 m. Through experiment and test, the measure method and signal recognition of projectile explosion position based on acousto-optic combined detection is verified.

In this paper, the number of sound point sources arranged is relatively small, because of its high power of acoustic sensor, the sound information that can be detected is far. At the same time, the compound eye photoelectric detection sensor is introduced, which effectively solves the problem of synchronously triggering the acoustic sensor with a large field of view, the method proposed provides a new measure for testing the position of the projectile explosion under the large randomly scattered area in the weapon range.

5. Conclusions

This paper analyzes the mechanism of the combination of three acoustic sensor and compound eye photoelectric detection sensor, and establishes the calculation model of explosion position of projectile fuze. From the collected signals characteristics of three acoustic sensors, this paper researches acoustic sensor signal filtering processing method and time extraction of projectile explosion acoustic signal based on particle swarm optimization, and verifies the correctness of the proposed method through experiments, the results find the designed test system and the established model can meet the test requirements. In particular, the compound eye photoelectric detection sensor is introduced as the synchronous acquisition signal source of acoustic array sensor, which effectively simplifies the range test layout and improves the test efficiency. Because acoustic sensors mainly rely on sound propagation to obtain signals, which are inevitably affected by natural wind and other external factors in the actual environment. Therefore, there will be some errors in the measurement data of the test system. The method proposed in this paper provides a basis for subsequent research in the exploration of acoustic sensors.

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*Corresponding author: xueweizhang1986@yeah.net