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Calculation Model of Projectile Explosion Position by Using Acousto-Optic Combination Mechanism

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ABSTRACT In order to accurately calculate the projectile explosion position, this paper takes the five acoustic sensors as a basic array, and proposes a test method for the projectile explosion position based on acousto-optic combination detection of triangular basic array and form acousto-optic combination test system. Combining with the spatial layout of triangular basic array, we derive the calculation model of projectile explosion position parameters of each basic array; use the wavelet transform analysis method to filter the acoustic sensor signal, and utilize the cross-correlation function to establish the time delay estimation processing model of the projectile explosion acoustic signal in the same basic array and obtain the time difference of each sensor in the basic array. According to the basic array acoustic sensor collected signal in experiments, we analyze the distribution characteristics of acoustic signal strength generated by different projectile explosion, and calculate the projectile explosion position. By comparing with the height parameter data collected and processed by high-speed camera, the results show that the measurement accuracy of the proposed method is better than 0.6m in the range of 150m × 150m, which verify the efficiency of the measurement method of projectile explosion position by using acousto-optic combination test mechanism.

INDEX TERMS Five acoustic sensors array, photoelectric detection sensor, projectile explosion position, time delay estimation, triangular basic array, wavelet transform.

I. INTRODUCTION

In the field of weapon test, the projectile explosion position parameters are important indicators. Due to the vibration of gun barrel and the complexity of terrain environment, it is difficult to test the projectile explosion position. The projectile explosion position distribution range is relatively large, so it is impossible to use a single device to test the projectile explosion position parameters in a fixed area [1]–[3]. In particular, with the development of weapons and ammunition technology, artillery firing range is far, the projectile explosion position is difficult to determine, these problems restrict the existing test methods. At present, the test methods of projectile explosion position mainly include photography method and acoustic-electric method. The photography method mainly uses one or more high-speed cameras to capture projectile explosion images. Then the height of the projectile explosion position is calculated by the size of

the calibration object in the images. This method is intuitive, but high-speed camera is limited by the imaging field of view and imaging area of single high-speed camera is small in the long distance. At the same time, at least two high-speed cameras are required to determine the spatial position of the projectile explosion under condition of the intersection. The deficiency of this test method is that the range of overlapping imaging area is relatively limited, the different benchmarks of two high-speed cameras intersection layout can also bring relatively large measurement errors, and the high-speed camera is expensive [4], [5]. The acoustic-electric method mainly adopts the combination of acoustic array sensors. The acoustic signal is generated by the projectile explosion, through the acoustic signal collected by each acoustic sensor and the geometric position of the acoustic sensor, the spatial position of the projectile explosion point is calculated [6], [7]. Acoustic sensors are cheap, its arrangement is simple and convenient, can form any size of the test area, can be applied to a variety of environmental testing, is the ideal means of the current projectile explosion point test [8]–[10]. Feng Song *et al.* studied

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a rapid positioning method for the coordinates of the continuous projectile explosion position. In the process of solving the explosion point of continuous projectile by acoustic measurement equipment, the three-dimensional surface is constructed, and the spatial search algorithm is used to calculate the three-dimensional coordinates of the projectile explosion position [9]. In order to solve the problem that the positioning accuracy of the four-unit cross array passive acoustic positioning algorithm is affected by the target azimuth angle, Wang Yang *et al.* proposed a five-unit cross array algorithm based on the time difference algorithm. They studied the geometric relationship and parameter calculation between five-unit cross array, deduced the formula of target location by spherical coordinate method and least square method, and analyzed the system error [11]. Guo Chun *et al.* analyzed several projectile explosion location methods, obtained the three-dimensional coordinate information of explosion location by acoustic sensor, and established a three-array location method of multi-array probability density [12]. Guo Rong *et al.* studied the wavelet processing algorithm of acoustic sensor signal, analyzed how to select the wavelet function, denoising method and decomposition scale [13]. In the field of conventional weapon test, in order to test the location of the ground projectile explosion all day, Li Dawei *et al.* designed an acoustic sensor explosion position test system constructed by interphone and data acquisition card. The remote device is used to solve the launch control problem of the measurement substation interphone, they studied a time delay estimation method based on explosive energy edge recognition [14]. The acoustic-electric method studied in these references can promote the measurement of projectile explosion point parameters. In order to further improve the parameter accuracy of the projectile explosion position, this paper takes the five acoustic sensors as a basic array, studies a test method for the projectile explosion position based on acousto-optic combination detection of triangular basic array composed by three basic arrays.

The main contribution of this article includes two points:

1) This paper takes the five acoustic sensors as a basic array, and proposes a test method for the projectile explosion position based on acousto-optic combination detection of triangular basic array composed by three basic arrays.

2) The wavelet transform analysis method is used to filter the acoustic signal, and the cross-correlation function method is used to establish the time delay estimation recognition model. Combined with the established projectile explosion position calculation function, the actual coordinates of the projectile explosion position are calculated.

The remainder of this article is organized as follows. Section II introduces the calculation model of the projectile explosion position. Section III analysis the projectile explosion acoustic signal recognition method, and the experimental verification and analysis are provided in Section IV. Finally, Section V concludes this article.

II. CALCULATION MODEL OF THE PROJECTILE EXPLOSION POSITION OF TRIANGULAR BASIC ARRAY

The projectile explosion position test system by using acousto-optic combination test mechanism in this paper is mainly composed of three basic arrays, a photoelectric detection device, signal acquisition and processing module and terminal processing computer. The photoelectric detection device is not only used as the trigger of the test system, but also captures the optical signal of the projectile explosion in a moment as the benchmark for the synchronous acquisition of the acoustic sensors. It provides accurate time information for the test system, and can solve the problem of large amount of data and cumbersome calculation of the traditional acoustic sensors array detection method. In Figure 1, The position of the photoelectric detection device is denoted as o , and the spatial coordinate system $oxyz$ is established with point o as the origin. Points O_1, O_2, O_3 are the bottom center of three basic arrays A, B and C , respectively, and their coordinates are $(0, S, 0), (0, -S, 0), (S, 0, 0)$; S is the distance between each basic array and photoelectric detection device; r_A, r_B and r_C are the distances from point O_1, O_2, O_3 to the projectile explosion position.

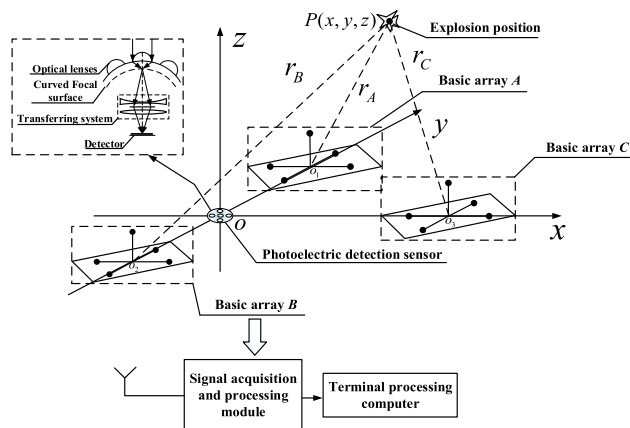
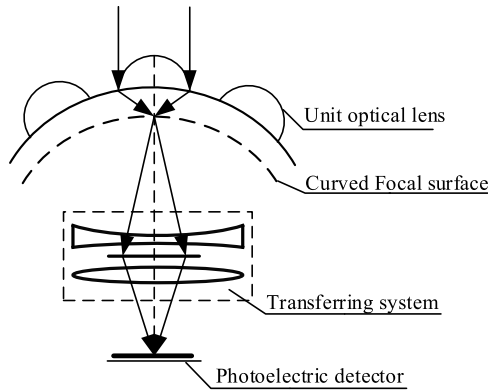


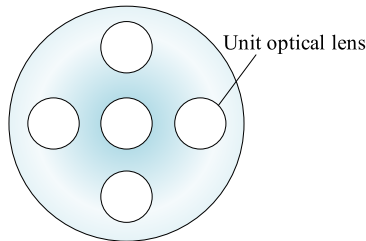
FIGURE 1. The principle of acousto-optic combination test system with three basic arrays.

According to the principle of combination test system with three basic arrays in Figure 1, when the projectile explodes in the specified area, the firelight signal is captured by the photoelectric detection device to trigger the triangular basic array capture the acoustic signal of the projectile explosion; at the same time, according to the spatial layout relationship of the three basic arrays, the time information of the projectile explosion outputted by acoustic sensors is obtained by the signal acquisition and processing module; and then the coordinates of the projectile explosion position can be calculated by the terminal processing computer. In order to improve the detection ability of photoelectric detection device, a full scene compound-eye photoelectric detection device is designed based on the principle of acousto-optic combination detection in this paper, which meets the test requirements of projectile explosion position in a large range.

The schematic diagram of the photoelectric detection device is shown in Figure 2. The detection lens of the photoelectric detection device is composed of five optical lenses. In order to improve the detection distance of the photoelectric detection device, we choose the long focal lens, and the optical lens is evenly distributed around and at the top of the photoelectric detection device to ensure the full range detection to test site.



(a) The structure schematic diagram of optical path of photoelectric detection device



(b) The schematic diagram of hemispherical lens

FIGURE 2. The structure schematic diagram of photoelectric detection device.

According to the optical path structure design of the photoelectric detection device, when the projectile fuse explodes in the landing area, the firelight signal generated by the projectile explosion enters the light path of the compound-eye photoelectric detection device, and then enters the photoelectric detector through the optical lens. The photoelectric detector captures the firelight signal of the projectile explosion, after processing, the firelight signal is used as a synchronous acquisition signal of the test system.

In the test system of the projectile explosion position, the number and layout of acoustic sensors in each basic array are same. Figure 3 shows the detection schematic diagram of basic array A. In order to facilitate the calculation of the projectile explosion position, the bottom center of basic array A is denoted as o_1 , and the spatial coordinate system $o_1x_1y_1z_1$ is established with point o_1 as the origin. The five acoustic sensors in basic array A are distributed in a positive quadrangular pyramid and denoted as N_{A1} , N_{A2} , N_{A3} , N_{A4} and N_{A5} . The height of acoustic sensor N_{A1} is denoted as H ;

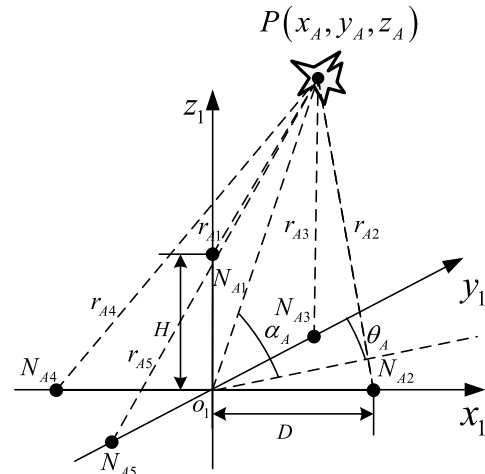


FIGURE 3. The layout schematic diagram of basic array A with five acoustic sensors.

and the distance between the acoustic sensors N_{A2} , N_{A3} , N_{A4} , N_{A5} and point o_1 is denoted as D . The corresponding coordinates of these sensors are denoted as $(0, S, H)$, $(D, S, 0)$, $(0, S + D, 0)$, $(-D, S, 0)$ and $(0, S - D, 0)$, respectively. Similarly, five acoustic sensors of basic array B are denoted as N_{B1} , N_{B2} , N_{B3} , N_{B4} , N_{B5} and the corresponding coordinates are denoted as $(0, -S, H)$, $(D, -S, 0)$, $(0, -S + D, 0)$, $(-D, -S, 0)$, $(0, -S - D, 0)$, respectively. Five acoustic sensors of basic array C are denoted as N_{C1} , N_{C2} , N_{C3} , N_{C4} , N_{C5} and the corresponding coordinates are denoted as $(S, 0, H)$, $(S + D, 0, 0)$, $(S, D, 0)$, $(S - D, 0, 0)$, $(S, -D, 0)$, respectively.

In Figure 3, the coordinate system $o_1x_1y_1z_1$ is the translation of S units along positive direction y axis of coordinate system $oxyz$. Assuming that the projectile explosion position in the coordinate system $o_1x_1y_1z_1$ is $P(x_A, y_A, z_A)$, the distance between the P and each acoustic sensor in the array A is denoted as $r_{A1} - r_{A5}$, and the explosion sound time captured by five acoustic sensors of array A is denoted as t_{A1} , t_{A2} , t_{A3} , t_{A4} and t_{A5} , the time difference of acoustic signal of the projectile explosion from acoustic sensor N_{A1} to acoustic sensor N_{Ai} is $T_{A1i} = t_{Ai} - t_{A1}$, where $i = 2, 3, 4, 5$. Therefore, we can get the space-time function of the projectile explosion position and the five acoustic sensors in array A, as follows:

$$\begin{cases} x_A^2 + y_A^2 + z_A^2 = r_A^2 \\ x_A^2 + y_A^2 + (z_A - H)^2 = r_{A1}^2 = (ct_{A1})^2 \\ (x_A - D)^2 + y_A^2 + z_A^2 = r_{A2}^2 = (ct_{A1} + ct_{A12})^2 \\ x_A^2 + (y_A - D)^2 + z_A^2 = r_{A3}^2 = (ct_{A1} + ct_{A13})^2 \\ (x_A + D)^2 + y_A^2 + z_A^2 = r_{A4}^2 = (ct_{A1} + ct_{A14})^2 \\ x_A^2 + (y_A + D)^2 + z_A^2 = r_{A5}^2 = (ct_{A1} + ct_{A15})^2 \end{cases} \quad (1)$$

In (1), c denotes current sound velocity. According to Figure 2, in coordinate system $o_1x_1y_1z_1$, we denoted the azimuth angle of explosion point P relative to coordinate origin o_1 as θ_A , and the pitch angle is α_A , the distance is r_A ,

the projectile explosion position $P(x_A, y_A, z_A)$ is:

$$\begin{cases} x_A = r_A \sin \theta_A \cos \alpha_A \\ y_A = r_A \sin \theta_A \sin \alpha_A \\ z_A = r_A \cos \theta_A \end{cases} \quad (2)$$

Combining formula (1) and formula (2), we can get:

$$\begin{cases} \theta_A = \arctan \frac{T_{A15} - T_{A13}}{T_{A14} - T_{A12}} \\ \alpha_A = \arctan \left(-\frac{2H\sqrt{(T_{A12} - T_{A14})^2 + (T_{A13} - T_{A15})^2}}{D(T_{A12} + T_{A13} + T_{A14} + T_{A15})} \right) \\ r_A = \frac{(T_{A13} - T_{A12} + T_{A15} - T_{A14})c}{2(T_{A12} - T_{A13} + T_{A14} - T_{A15})} \end{cases} \quad (3)$$

Bring the formula (3) into formula (2), the projectile explosion position P in coordinate system $o_1x_1y_1z_1$ can be solved. Similarly, we established the coordinate system $o_2x_2y_2z_2$ based on the center point o_2 at the bottom of basic array B and the coordinate system $o_3x_3y_3z_3$ based on the center point o_3 at the bottom of basic array C , their parameters can be obtained by formula (4) and (5).

$$\begin{cases} \theta_B = \arctan \frac{T_{B15} - T_{B13}}{T_{B14} - T_{B12}} \\ \alpha_B = \arctan \left(-\frac{2H\sqrt{(T_{B12} - T_{B14})^2 + (T_{B13} - T_{B15})^2}}{D(T_{B12} + T_{B13} + T_{B14} + T_{B15})} \right) \\ r_B = \frac{(T_{B13} - T_{B12} + T_{B15} - T_{B14})c}{2(T_{B12} - T_{B13} + T_{B14} - T_{B15})} \end{cases} \quad (4)$$

$$\begin{cases} \theta_C = \arctan \frac{T_{C15} - T_{C13}}{T_{C14} - T_{C12}} \\ \alpha_C = \arctan \left(-\frac{2H\sqrt{(T_{C12} - T_{C14})^2 + (T_{C13} - T_{C15})^2}}{D(T_{C12} + T_{C13} + T_{C14} + T_{C15})} \right) \\ r_C = \frac{(T_{C13} - T_{C12} + T_{C15} - T_{C14})c}{2(T_{C12} - T_{C13} + T_{C14} - T_{C15})} \end{cases} \quad (5)$$

And then, the coordinate of projectile explosion position in coordinate systems $o_2x_2y_2z_2$ and $o_3x_3y_3z_3$ can be calculated. In coordinate system $oxyz$, $oo_1 = oo_2 = oo_3 = S$, the relative offsets of coordinate systems $o_1x_1y_1z_1$, $o_2x_2y_2z_2$, $o_2x_2y_2z_2$ and coordinate system $oxyz$ are $(0, S, 0)$, $(0, -S, 0)$, and $(S, 0, 0)$, respectively. The coordinate of the projectile explosion position in the coordinate system $o_1x_1y_1z_1$, $o_2x_2y_2z_2$ and $o_3x_3y_3z_3$ also can be calculated. Combined with the relative offset relationship between these three coordinates and coordinate system $oxyz$, the final explosion position $P(x, y, z)$ is determined by calculating the average value, based on formula (6).

$$\begin{cases} x = \frac{x_A + x_B + x_C + S}{3} \\ y = \frac{y_A + y_B + y_C}{3} \\ z = \frac{z_A + z_B + z_C}{3} \end{cases} \quad (6)$$

III. PROJECTILE EXPLOSION ACOUSTIC SIGNAL RECOGNITION METHOD

From formulas (3) - (5), in order to accurately obtain the azimuth θ and pitch α of the projectile explosion position, each basic array needs to calculate the time difference T_{1i} . The target signal of the air explosion position test system is a strong pulse acoustic signal, and the first wave of this signal has a high signal-to-noise ratio. However, the selection of the traditional filter frequency has a slight error, which will filter out the useful acoustic signal or retain the useless signal [15], [16]. And the complexity and accuracy of different time delay estimation methods are different. In order to improve the accuracy of the system, a reasonable delay estimation method must be adopted. Compared with the traditional time delay estimation method, the cross-correlation function method has better comprehensive performance. It has moderate computation, certain anti-interference ability, high delay accuracy and easy real-time processing, and it is a time delay estimation method that is widely used [17], [18]. In this paper, the time-frequency localization of wavelet transform is used to analyze acoustic signals, which improves the shortcomings of traditional analysis methods, and improves the accuracy of time delay estimation combined with cross-correlation function method [19].

In order to filter out the low-frequency noise in the original signal, this paper adopts a method of discrete wavelet transform, and uses its band-pass filtering function and multi-resolution analysis to multi-layer signal processing [20].

The collected acoustic signal is expressed by formula (7).

$$f(t) = x(t) + n(t) \quad (7)$$

In (7), $x(t)$ denotes a pure noise-free acoustic signal, $n(t)$ denotes the noise signal, wavelet transform for acoustic signal $f(t)$:

$$WT(\alpha, \tau) = \frac{1}{\sqrt{\alpha}} \int_{-\infty}^{+\infty} f(t) \psi^* \left(\frac{t - \tau}{\alpha} \right) dt \quad (8)$$

In (8), α denotes the scale factor, τ denotes a time shift factor, $\psi^*(t)$ denotes the conjugate function of the mother scale function $\psi(t)$. Changing the value of α in the frequency domain is equivalent to the signal for band-pass filtering, showing the frequency localization characteristics [21].

The acoustic signal $f(t)$ is discretized to represent $f(n)$, and the scale coefficient $c_{j,k}$ and wavelet coefficient $d_{j,k}$ are obtained by orthogonal wavelet decomposition.

$$\begin{cases} c_{j,k} = \sum_n \bar{h}(2k - n)c_{j-1,n} \\ d_{j,k} = \sum_n \bar{g}(2k - n)c_{j-1,n} \end{cases} \quad (9)$$

In (9), $h(n)$ and $g(n)$ are a pair of orthogonal image filters. $h(n)$ represents the low-pass filter coefficient, acting on the signal can get low frequency smooth profile A_j , $g(n)$ represents a high-pass filter coefficient, acting on the signal can get high-frequency detail part $D_j, j = 1, 2, 3, \dots, n$. j denotes the number of wavelet decomposition layers.

The formula (10) is the wavelet reconstruction function.

$$c_{j,k} = \sum_n c_{j+1,n}h(k - 2n) + \sum_n d_{j+1,n}g(k - 2n) \quad (10)$$

According to the cross-correlation degree of two signals, time difference T can be calculated. The source signal is denoted as $f(t)$, two signals are denoted as $x_1(t)$ and $x_2(t)$, the additive noise signals are denoted as $n_1(t)$ and $n_2(t)$. Assuming that the source signal and the noise signal are stationary random processes with normal distribution and are not correlated with each other, there is:

$$\begin{cases} x_1(t) = f(t) + n_1(t) \\ x_2(t) = af(t - T_{1i}) + n_2(t) \end{cases} \quad (11)$$

In order to make the calculation simple, coefficient $a = 1$, cross-correlation function is $R_{x_1x_2}(\tau) = E[x_1(t)x_2(t + \tau)]$, combined formula (11), and the cross-correlation function can be obtained by formula (12).

$$\begin{aligned} R_{x_1x_2}(\tau) &= E \{ [f(t) + n_1(t)] [f(t - T_{1i} + \tau) + n_2(t + \tau)] \} \\ &= E [f(t)f(t - T_{1i} + \tau)] \\ &= R_{x_1x_2}(\tau - T_{1i}) \end{aligned} \quad (12)$$

In (12), when the cross-correlation function of $x_1(t)$ and $x_2(t)$ reaches the maximum, τ is the delay T_{1i} [22], [23].

IV. TESTING AND EXPERIMENTAL ANALYSIS

According to the test method for the projectile explosion position based on acousto-optic combination detection of triangular basic array proposed in this paper, combined with the requirements of a shooting range test, the windless weather is selected for test. Based on the recorded environmental temperature, the sound velocity c was calculated, $c = 347.8m/s$. The five 0.5-inch MP215 acoustic sensors are selected to form a basic array, and the effective detection distance of each basic array is 100m. According to the layout in Figure 1, three basic arrays and photoelectric detection device are set in the $150m \times 150m$ test site, among it, $s = 50m$, $H = 2m$, $D = 1m$. Each acoustic sensor in the basic arrays has an independent acquisition module. The acquisition module has a synchronous trigger signal input port of the photoelectric detection device. And the three basic arrays have wireless transfer module. When the projectile explodes, the photoelectric detection device captures the firelight signal to trigger the acoustic sensors collecting the acoustic signal. And then, the acoustic signal is transferred to the signal acquisition and processing module by wireless transfer module. In order to meet the test requirements, the signal acquisition and processing module configures a sampling frequency of 2MHz acquisition card to collect the acoustic signal when projectile exploded. Finally, the processed signal is transferred to the terminal processing computer. Based on the received multi-channel acoustic signal, the terminal processing computer extracts the time difference information of the acoustic signal of projectile explosion through signal filtering processing and cross-correlation method. Figure 4 is the original acoustic

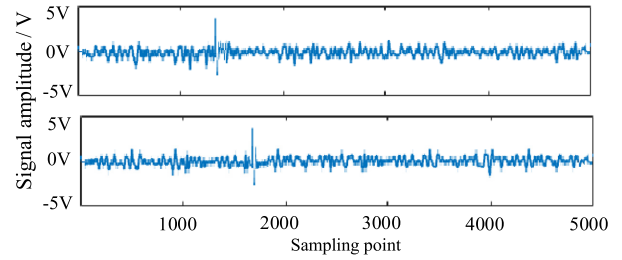


FIGURE 4. Original acoustic signal of projectile explosion in the acoustic sensors N_{A1} and N_{A2} .

signal of a projectile explosion that collected by acoustic sensors N_{A1} and N_{A2} in the basic array A in one experiment.

This paper selects Daubechies wavelet as the orthogonal wavelet base in the signal processing, and the collected signals by the acoustic sensors N_{A1} and N_{A2} are decomposed into six layers. Figure 5 is the result of the processing by wavelet filtering algorithm on the acoustic sensors N_{A1} and N_{A2} .

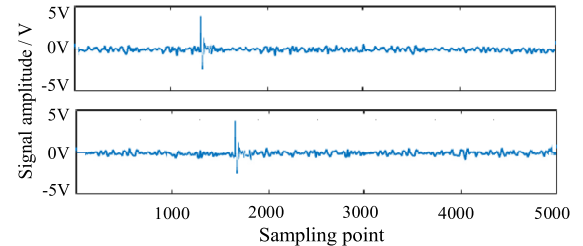


FIGURE 5. The processing result based on wavelet filtering algorithm in the acoustic sensors N_{A1} and N_{A2} .

Similarly, we use wavelet filtering method to process the acoustic signals of projectile explosion that collected by acoustic sensors N_{A3} , N_{A4} , N_{A5} and extract the acoustic signal time value of each acoustic sensor in basic array A , and calculate the relative time delay T_{A1i} of basic array A with plane acoustic sensor and vertex acoustic sensor by cross-correlation function processing algorithms. According to formulas (2) and (3), the projectile explosion position parameters are $x_A = 41.78m$, $y_A = 26.15m$, $z_A = 14.26m$ in basic array A .

In order to further verify the feasibility and accuracy of the acousto-optic combination test system with triangular basic array, we exacts the time value based on the proposed acoustic signal processing algorithms when projectile exploded, record t is the time of projectile explosion, V_s is its peak voltage and V_n is the average noise in three basic array.

Table 1, Table 2 and Table 3 are the peak voltage data of projectile explosion sound signal that are collected by triangular basic array in one experiment.

In Tables 1-3, first of all, the intensity of the output peak voltage is different in each basic array, which is mainly because the distance between the basic arrays is different. Among them, the closer the distance between the basic array and the projectile explosion position, the greater the output voltage signal amplitude in each acoustic sensor. Secondly,

TABLE 1. The output peak voltage data and time in Basic Array A.

| | $t(s)$ | $V_s(mV)$ | $V_n(mV)$ |
|----------|--------|-----------|-----------|
| N_{A1} | 0.1481 | 4268 | 485 |
| N_{A2} | 0.1472 | 4296 | 479 |
| N_{A3} | 0.1511 | 4156 | 487 |
| N_{A4} | 0.1522 | 4094 | 496 |
| N_{A5} | 0.1482 | 4229 | 458 |

TABLE 2. The output peak voltage data and time in basic array B.

| | $t(s)$ | $V_s(mV)$ | $V_n(mV)$ |
|----------|--------|-----------|-----------|
| N_{B1} | 0.2617 | 3721 | 507 |
| N_{B2} | 0.2612 | 3746 | 488 |
| N_{B3} | 0.2600 | 3847 | 496 |
| N_{B4} | 0.2640 | 3672 | 512 |
| N_{B5} | 0.2652 | 3618 | 498 |

TABLE 3. The output peak voltage data and time in basic array C.

| | $t(s)$ | $V_s(mV)$ | $V_n(mV)$ |
|----------|--------|-----------|-----------|
| N_{C1} | 0.0896 | 4917 | 483 |
| N_{C2} | 0.0930 | 4816 | 478 |
| N_{C3} | 0.0897 | 4912 | 492 |
| N_{C4} | 0.0914 | 4842 | 485 |
| N_{C5} | 0.0947 | 4776 | 468 |

the average noise voltage of each basic array is also different, because the basic array is affected by temperature, wind velocity and the characteristics of each acoustic sensor. According to the cross-correlation between the two signals, we can extract the time value of each acoustic sensor from the projectile explosion position to the three basic arrays, and calculate the relative delay of each basic array with the same plane acoustic sensor and the vertex acoustic sensor. Then combined with the position measurement model of the explosion position with basic arrays, the coordinate of the explosion position in each basic array can be calculated. Through the relative offset relationship between each basic array coordinate system and coordinate system, the projectile explosion position in the coordinate system is determined by using the average processing algorithms. Based on the testing principles and calculation methods in this paper, we collected the acoustic signals of four projectile explosions, at the same time, after wavelet filtering processing and time delay estimation algorithm, we can obtain the projectile explosion position by acoustic sensors array A, B and C, as shown in Table 4.

According to the data of Table 4, we calculate the coordinates of projectile explosion position in four experiments, the first projectile exploded at position $P_1(-24.38, 42.64, 15.82)$, the explosion position of the

TABLE 4. Test data of explosion position of triangular basic array.

| No. | Basic array A | Basic array B | Basic array C |
|-----|-------------------------|------------------------|-------------------------|
| 1 | (-24.62, -7.76, 15.54) | (-24.55, 93.99, 15.76) | (-73.97, 42.43, 15.38) |
| 2 | (51.94, 43.53, 10.08) | (51.96, 55.95, 10.07) | (2.64, 6.81, 10.57) |
| 3 | (46.59, -34.29, 13.76) | (46.57, 65.59, 13.78) | (-2.16, 15.08, 13.21) |
| 4 | (-32.22, -85.99, 15.49) | (-32.21, 13.32, 15.14) | (-81.55, -36.14, 15.51) |

second projectile is $P_2(52.18, 6.28, 10, 24)$, the explosion position of the third and fourth projectile are $P_3(46.85, -15.46, 13.57)$ and $P_4(-31.96, -36.27, 15.38)$ respectively.

In order to further verify the accuracy of acousto-optic combination test system with triangular basic array, we set high-speed cameras in the test site to obtain the height information of the projectile explosion position and test four projectile's explosion position. We used the data of high-speed camera to compare with the data of acousto-optic combination test system. Because high-speed cameras can only obtain the height of the projectile explosion, the two-dimensional coordinate data of the projectile explosion in xoy plane can not be accurately determined, so, Table 5 only give the height parameters of high-speed cameras.

TABLE 5. The comparison of test data.

| No. | Acousto-optic combination test system | | | high-speed camera | $\Delta z / m$ |
|-----|---------------------------------------|--------|-------|-------------------|----------------|
| | x/m | y/m | z/m | z/m | |
| 1 | -24.38 | 42.64 | 15.82 | 14.51 | 0.31 |
| 2 | 52.18 | 6.28 | 10.24 | 9.96 | 0.28 |
| 3 | 46.85 | -15.46 | 13.57 | 12.99 | 0.58 |
| 4 | -31.96 | -36.27 | 15.38 | 15.16 | 0.22 |

The results show that acousto-optic combination test system with triangular basic array in this paper can effectively obtain the three dimensional parameters of projectile explosion position. Compared with the projectile explosion height that obtained by high-speed cameras, the average error is better than 0.6m in the range of $150m \times 150m$, which verifies the feasibility and accuracy of acousto-optic combination test system with triangular basic array.

V. CONCLUSION

This paper takes the five acoustic sensors as a basic array, studies a test method for the projectile explosion position based on acousto-optic combination detection of triangular basic array composed by three basic arrays, and form acousto-optic combination test system with triangular basic array. The photoelectric detection sensor is the synchronous acquisition reference source. Combined with the spatial layout relationship of triangular basic array, the calculation model of projectile explosion position parameters of each

basic acoustic array is derived. In order to obtain accurate time delay information, the acoustic signals are filtered and identified, and the projectile explosion position parameters are obtained according to the calculation model established in this paper. The distribution characteristics of acoustic signal intensity of different explosion position are analyzed through specific projectile explosion tests, and the data calculated by proposed method are compared with the data measured by high-speed cameras. The results show that the measurement accuracy of the proposed method is better than 0.6m in the range of 150m × 150m.

The study of this paper provides a comprehensive test and calculation method for the test of the projectile explosion position under the random dispersed. Since these are many random interference factors in the test environment of the shooting range, the acousto-optic combination test system with triangular basic array can be affected. How to obtain the acoustic signal of the actual projectile from various types of interference sources is another key technology. Therefore, this paper lays a foundation for subsequent research on signal estimation, signal evaluation and time delay correction. The acoustic sensor is not affected by the light illumination and can work all-day, it provides a new idea for broadening the photoelectric-based test mechanism and has important value.

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