

Received November 28, 2021, accepted January 4, 2022, date of publication January 11, 2022, date of current version January 18, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3141825

Projectile Explosion Position Parameters Data Fusion Calculation and Measurement Method Based on Distributed Multi-Acoustic Sensor Arrays

HANSHAN LI^{ID} AND XUEWEI ZHANG^{ID}

School of Electronic and Information Engineering, Xi'an Technological University, Xi'an 710021, China

Corresponding author: Hanshan Li (lihanshan269@163.com)

This work was supported in part by the Project of National Natural Science Foundation of China under Grant 62073256, and in part by the Key Science and Technology Program of Shaanxi Province under Grant 2020GY-125.

ABSTRACT In conventional weapon test field, the parameter of projectile explosion position is an important index to measure the control ability and damage efficiency of fuze. Due to the random deviation of gun firing and the difference of detection performance of fuze itself, the projectile explosion position is uncertain and relatively scattered in terminal ballistic, which is easy to miss the projectile explosion information. In order to obtain the parameters of projectile explosion position in large area of in terminal ballistic, this paper constructs a projectile explosion position testing system with distributed multiple acoustic sensor basic arrays, establishes the calculation model of projectile explosion position by a basic array, researches a multi-source data fusion algorithm based on the measurement data of multiple array acoustic basic arrays and gets real projectile explosion coordinates. To improve the measurement accuracy, we use the wavelet transform filtering method to filter the output signal of the acoustic sensors, and propose the time extraction algorithm of the projectile explosion acoustic signal with the wavelet modulus maximum. Through experiment and analysis, we collect the sound signal of the actual projectile explosion and verify the rationality and correctness of the proposed calculation model and algorithm.

INDEX TERMS Projectile explosion position, distributed multi-acoustic sensor basic arrays, multi-source data fusion, wavelet transform, wavelet modulus maximum.

I. INTRODUCTION

In the field of gun and fuze development, the parameter of projectile explosion position is an important index to measure the control ability and damage efficiency of fuze. When the projectile falls in the terminal ballistic area, the fuze that the projectile itself loaded continuously detects the ground target [1], [2]. If the fuze receives the reflected echo energy by the ground target and meet the ignition conditions of detonator of fuze, the projectile will explode and form a warhead fragment group. The fragment group hits the ground target and reaches the purpose of damage target. It is not difficult to find in the terminal ballistic area, there is a certain distance between the projectile explosion position

and the ground target, which reflects the control function of the projectile's own fuze. In addition to the reflection characteristics of the ground target affecting the position of the projectile explosion, there are many factors affecting the specific projectile explosion position [3], [4], for example, the instantaneous vibration of the gun firing the projectile, the velocity of the projectile, the transmitting power of the projectile fuze itself, the angle at which the projectile meets the ground target, the size of the ground target and the its moving velocity, and so on. These factors affect the detection and explosion control accuracy of the projectile's own fuze, it makes the explosion position that the fuze of projectile close the ground is a random state with large dispersion in terminal ballistic area. It is relatively difficult to obtain the position parameters of the projectile explosion. How to measure the explosion position of projectile accurately is an

The associate editor coordinating the review of this manuscript and approving it for publication was Wuliang Yin^{ID}.

important basis for measuring the fuze's performance and effectiveness in artillery system [5]. The test of projectile explosion position is also a difficult problem in current.

About the test of projectile explosion position, most of the current testing methods are focused on the small range of terminal ballistic, which is generally based on the estimation of the theoretical hit area of artillery launch, for example, Wang Yang *et al.* constructed an aerial burst position test model based on passive acoustic location technology by using three three-dimensional array units, and each array unit is composed of five sensors [6]. The direction line intersection of the three acoustic sensor arrays will form a triangle, and the barycenter of the triangle is taken as the target position, they analyze the orientation performance of the three-dimensional array and the positioning performance of the three-dimensional array positioning system. The model established in reference [7] is based on the estimation area of artillery launch theory hitting the ground target, but there are still problems in testing the random explosion position when projectile falling with random uncertainties. Zhifeng Wang *et al.* studied the positioning algorithm of cross array based on five sensors, and analyzed the error of the system [8]; Feng Song *et al.* studied the method of linear solution of projectile burst position coordinate equations and false data elimination based on acoustic detection [9]; In [10], a fast-positioning method for acoustic measurement of burst position coordinates of continuous-fire projectile was studied; In [11], Feng Gao *et al.* proposed a measurement method of multi-projectile burst position based on the acoustic signal propagation characteristics of projectile burst and the time difference of sensor; In [12], Chun Guo *et al.* studied and designed a multi array sound source localization system; and so on. The literatures of the proposed method, to a certain limit within the scope of the condition of the projectile, those testing method can be obtained the explosion position parameters, however, they do not take into account some of the uncertainties that affect the projectile explosion position in an uncertain environment.

This paper focuses on the test requirements of the explosive position of projectile falling in the large area of the terminal ballistic, this paper proposes a new measurement method of projectile explosion position with distributed multiple acoustic sensor basic arrays, establishes the calculation model of projectile explosion position by a basic array, and the main contributions of this work are as follows:

1) A method of using the distributed multi-acoustic sensor basic arrays to establishes the calculation model of projectile explosion position with the large area in terminal ballistic. The proposed test method avoids the influence of many uncertain factors, resulting in large dispersion of projectile explosion and difficult to obtain the position parameters of projectile explosion.

2) To improve the measurement accuracy, we use the wavelet transform filtering method to filter the output signal of the acoustic sensors, and propose the time extraction algorithm of the projectile explosion acoustic signal with the

wavelet modulus maximum. This method avoids the time error when the output signals of two acoustic sensors are not similar.

3) We use multi-source data fusion algorithm based on the measurement data of multiple array acoustic basic arrays, which further improves the reliability of the system and data processing capabilities.

The remainder of this paper is organized as follows. Section II states the design method and principle of distributed multi-acoustic sensor basic arrays and establishes the calculation model of projectile explosion position. Section III introduces the acoustic signal filtering processing and time extraction method of projectile explosion with the wavelet modulus maximum. Section IV presents the multi-source data fusion algorithm based on the measurement data of multiple array acoustic basic arrays. Section V give the theoretical error analysis of the test model. Section VI gives the experimental verification and analysis, Finally, Section VII concludes this paper.

II. CALCULATION METHOD OF PROJECTILE EXPLOSION POSITION BASED ON DISTRIBUTED MULTI-ACOUSTIC SENSOR BASIC ARRAYS

According to the influence factors such as artillery firing, the difference in the detection ability of the projectile's own fuze, and the difference in the characteristics of ground targets, and so on, this paper proposes a new measurement method of projectile explosion position with distributed multiple acoustic sensor basic arrays, as shown in Figure 1.

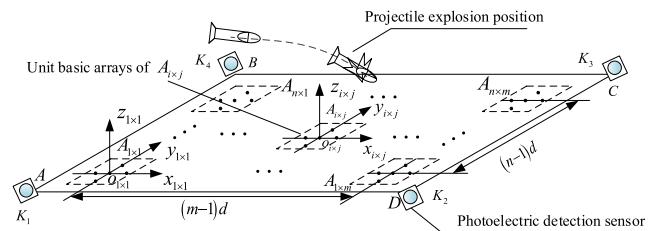


FIGURE 1. The test system of projectile explosion position with distributed multi-acoustic sensor basic arrays.

In Figure 1, $A_{1 \times 1} - A_{n \times m}$ is $n \times m$ unit basic arrays, which constitutes the projectile explosion position test system, each unit basic array is made up of five acoustic sensors, and we denote it as a unit basic array, the distance of central origin coordinates between two adjacent unit basic arrays is denoted as d . $O_{i \times j}$ is the coordinate center unit basic arrays of $A_{i \times j}$. The area ABCD is the flip area of the test system. Four photoelectric detection sensors, K_1 , K_2 , K_3 , and K_4 , were arranged in A, B, C and D positions, in addition, we can also choose the number of photoelectric detection sensors by combining with the actual scope of the test site. And their imaging axes of the lens of photoelectric detection sensors are intersected and can overlay the area ABCD, and form synchronous control acquisition command for $n \times m$ unit basic arrays.

In the test system of projectile explosion position with distributed multiple acoustic sensor basic arrays, the $n \times m$ unit basic arrays are independent of each other and they are all on the same plane. For any unit basic array of $A_{i \times j}$, $O_{i \times j} x_{i \times j} y_{i \times j} z_{i \times j}$ is the spatial coordinate system, $R_{i \times j-g}$ is the th-g acoustic sensor in the coordinate system of $O_{i \times j} x_{i \times j} y_{i \times j} z_{i \times j}$, and, $g = 0, 1, 2, 3, 4$, as shown in Figure 2.

We denote the point $O_{1 \times 1}$ is the original coordinates of the whole testing system, namely, the coordinates of point $O_{1 \times 1}$ is $(0,0,0)$. And then, in the unit basic array of $A_{i \times j}$, the relative center coordinate of $O_{i \times j}$ is $(id, jd, 0)$. Because each unit basic array is independent, we use the coordinate center of each unit basic array as the origin of their coordinate system. In other words, to the unit basic array of $A_{i \times j}$, $O_{i \times j}$ is the coordinate origin in unit basic array of $A_{i \times j}$, we record the relative point $O_{i \times j}$ as $(0, 0, 0)$ in Figure 2, if $P(x_{i,j}, y_{i,j}, z_{i,j})$ is the coordinate of projectile explosion position in the unit basic array of $A_{i \times j}$, and then, the real coordinate of projectile explosion position in whole testing system can gain by formula (1).

$$\begin{cases} x = x_{i,j} + id \\ y = y_{i,j} + jd \\ z = z_{i,j} \end{cases} \quad (1)$$

In order to obtain the coordinate of $(x_{i,j}, y_{i,j}, z_{i,j})$ in the unit basic array of $A_{i \times j}$, according to Figure 2, we arrange five acoustic sensors in the coordinate system of $O_{i \times j} x_{i \times j} y_{i \times j} z_{i \times j}$, and the acoustic sensors of $R_{i \times j-0}$ is located in the origin of coordinates, its relative coordinates are $(0,0,0)$, and then, the relative coordinates of acoustic sensors of $R_{i \times j-1}, R_{i \times j-2}, R_{i \times j-3}$ and $R_{i \times j-4}$ are $(L, 0, 0), (0, L, 0), (-L, 0, 0)$ and $(0, -L, 0)$, respectively.

We define $t_{i \times j-g}$ as the propagation time from the position of projectile explosive to the th-g acoustic sensor, and define $r_{i,j}^g$ as the distance from the position of projectile explosive to the coordinates point of th-g acoustic sensor, $g = 0, 1, 2, 3, 4$, and we can get the projectile explosion coordinates by formula (2) in the coordinate system of $O_{i \times j} x_{i \times j} y_{i \times j} z_{i \times j}$.

$$\begin{cases} x_{i,j}^2 + y_{i,j}^2 + z_{i,j}^2 = (r_{i,j}^0)^2 = (v \cdot t_{i \times j-0})^2 \\ x_{i,j}^2 + (y_{i,j} - L)^2 + z_{i,j}^2 = (r_{i,j}^1)^2 = (v \cdot t_{i \times j-1})^2 \\ (x_{i,j} + L)^2 + y_{i,j}^2 + z_{i,j}^2 = (r_{i,j}^2)^2 = (v \cdot t_{i \times j-2})^2 \\ x_{i,j}^2 + (y_{i,j} + L)^2 + z_{i,j}^2 = (r_{i,j}^3)^2 = (v \cdot t_{i \times j-3})^2 \\ (x_{i,j} - L)^2 + y_{i,j}^2 + z_{i,j}^2 = (r_{i,j}^4)^2 = (v \cdot t_{i \times j-4})^2 \end{cases} \quad (2)$$

In (2), v is the acoustic wave propagation velocity that projectile explosion sound signal [13].

Based on spatial relations of Figure 2, we define $\alpha_{i,j}$ is the azimuth angle of projectile explosion position and the acoustic sensors of $R_{i \times j-0}$, and $\beta_{i,j}$ is the pitch angle. The three-dimensional coordinate system of unit basic array $A_{i \times j}$ is transformed into spherical coordinate system, and the

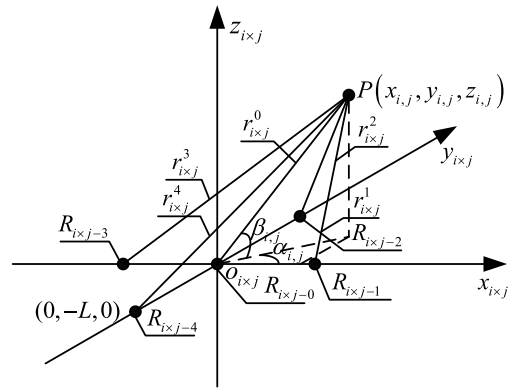


FIGURE 2. The layout diagram of five acoustic sensors in unit basic array $A_{i \times j}$.

formula (3) is the transformation equation.

$$\begin{cases} x_{i,j} = r_{i,j}^0 \sin \alpha_{i,j} \cos \beta_{i,j} \\ y_{i,j} = r_{i,j}^0 \sin \alpha_{i,j} \sin \beta_{i,j} \\ z_{i,j} = r_{i,j}^0 \cos \alpha_{i,j} \end{cases} \quad (3)$$

In (3), the $r_{i,j}^0$, $\alpha_{i,j}$ and $\beta_{i,j}$ can get by formula(4).

$$\begin{cases} \alpha_{i,j} = \arctan \left(\frac{-t_{i \times j-4} - t_{i \times j-2}}{t_{i \times j-3} - t_{i \times j-1}} \right) \\ \beta_{i,j} = \arctan \left(\frac{t_{i \times j-3}^2 - t_{i \times j-1}^2}{t_{i \times j-2}^2 - t_{i \times j-4}^2} \right) \\ r_{i,j}^0 = \frac{2L^2 - (t_{i \times j-1} - t_{i \times j-0})^2 v^2 - (t_{i \times j-3} - t_{i \times j-0})^2 v^2}{2(t_{i \times j-3} + t_{i \times j-1} - 2t_{i \times j-0})v} \end{cases} \quad (4)$$

Based on the synchronous acquisition instruction of the photoelectric detection sensor in the test system of projectile explosion position with distributed multiple acoustic sensor basic arrays, we use the acquisition device to collect the sound signals when the projectile explode in unit basic array of $A_{i \times j}$, and apply the processing algorithm of wavelet modulus maximum to judge the instantaneous time value of projectile explosion, and get the propagation time from the position of projectile explosion to the acoustic sensor, namely, $t_{i \times j-0}, t_{i \times j-1}, t_{i \times j-2}, t_{i \times j-3}$ and $t_{i \times j-4}$. If the sound propagation speed of the projectile explosion is determined, and the parameter of L and d are measured in the test site, we can get the coordinate of $(x_{i,j}, y_{i,j}, z_{i,j})$ in the unit basic array of $A_{i \times j}$, and then, according to formula(1), the position of projectile explosion can be calculated.

III. TIME EXTRACTION METHOD OF PROJECTILE EXPLOSION BASED ON WAVELET TRANSFORM

The acoustic signal that projectile burst is denoted as $f(t)$ with noise, $f(t)$ can be transformed using the wavelet transform by formula (5).

$$W(a, \tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t) \varphi^* \left(\frac{t - \tau}{a} \right) dt \quad (5)$$

In (5), a is scale factor, τ is time-shift factor, $\varphi^*(\frac{t-\tau}{a})$ is conjugate function of wavelet generating function. The signal $f(t)$ is discretized and denoted as $f(k)$, k is the discrete point of signal sampling [14], [15]. If $b_{N,M}$ and $c_{N,M}$ are the wavelet scale coefficients and wavelet coefficients respectively, they can obtain by orthogonal wavelet decomposition. We use formula(6) to achieve the wavelet reconstruction.

$$b_{N,M} = \sum_k b_{N+1,k} H(M-2k) + \sum_k c_{N+1,k} F(M-2k) \quad (6)$$

In (6), $H(M-2k)$ is low-pass filter coefficient, $F(M-2k)$ is high-pass filter coefficient [16].

According to the characteristics of the collected acoustic signal of projectile explosion, the high frequency components can be eliminated by adjusting the scale factor.

Supposing that the obtained signal satisfies $g(t) \in L^2(R)$, and the edge of $g(t)$ under the condition of scale a can be defined as the local mutation point after $g(t)$ is smoothed. The singularity of $g(t)$ at point t_0 can be described by Lipschitz index, ϖ is the Lipschitz index. If e is a non-negative integer, and meet $e \leq \varpi \leq e+1$.

We define Q and e_0 as two constants, and e -order Taylor polynomials, make any $e \leq e_0$, if meet the condition of formula(7),

$$|f(t_0+e) - f(e)| \leq Q|e|^\varpi \quad (7)$$

We call ϖ the Lipschitz index of the output signal $g(t)$ of acoustic sensor in unit basic arrays at t_0 . The higher the order of the derivative of $g(t)$ at t_0 , the larger the corresponding [10]. If the Lipschitz index of $g(t)$ at t_0 is less than 1, namely, $\varpi < 1$, then $g(t)$ exist singular at t_0 .

Assuming that $\varphi(t)$ is a Gaussian function, wavelet has q -order vanishing moment and q -order is differentiable. q is a positive integer and satisfies $\varpi \leq q$. In the neighborhood of t_0 , there is a constant G , which makes wavelet transform of projectile explosion acoustic signal satisfy the relationships of formula (8).

$$|W(a, t)| \leq G(a^\varpi + |t - t_0|^\varpi) \quad (8)$$

It can be seen from (8) that the singular points of the projectile signal are distributed on the modulus extreme value line of the signal wavelet transform, so the Lipschitz index is less than 1, i.e. $\varpi < 1$, and the projectile explosion acoustic mutation signal is a singularity, so the Lipschitz index is more than 0, i.e. $\varpi > 0$. Therefore, the wavelet transform is used to find the singularities of the projectile explosion acoustic signal.

When point t_0 is not a local singular point of the projectile explosion acoustic signal $g(t)$, this point satisfies the relations of formula (9) in its neighborhood.

$$|W(a', t)| \leq |W(a', t_0)| \quad (9)$$

In (9), (a', t_0) is the modulus maxima point of $|W(a, t)|$ at scale a' , $W(a', t_0)$ is the corresponding modulus maximum. The curve connected by modulus maxima points on the scale-time plane (a, t) is modulus maxima line. Through

discrete dyadic wavelet transform, the formula (9) can be changed formula(10).

$$|W_{2^\Delta}(a, t)| \leq H(2^\Delta)^\varpi (1 + |t - t_0|^\varpi) \quad (10)$$

In (10), Δ is a binary scale parameter, while t is a discrete value. If the Lipschitz index ϖ of projectile explosion acoustic signal is greater than 0, the modulus maxima of wavelet increase with the increase of scale Δ . Therefore, the projectile explosion position can be obtained by the singular points of the collected acoustic signal. And the wavelet transform is used for multi-scale analysis of the projectile burst acoustic signal [17]. The singular points are determined by detecting the modulus maxima of the signal. At the same time, the scale a should be selected correctly according to the characteristics of the signal when using discrete wavelet for signal transformation. Assuming that the singular point of the acoustic signal collected by the first acoustic sensor is $t_0(i')$, which is the corresponding time value of the projectile explosion, and $t = t_0(i')$, i' is sampling point where appear modulus maxima points.

IV. MULTI-SOURCE DATA FUSION ALGORITHM BASED ON THE MEASUREMENT DATA OF DISTRIBUTED MULTI-ACOUSTIC SENSOR BASIC ARRAYS

A. REPRESENTATION METHODS OF EXPLOSION POSITION TEST DATA AT UNIT BASIC ARRAY

For any acoustic sensor test equipment, test data will always contain test errors. Errors can be divided into systematic errors and random errors. For the coordinate test of projectile explosion position, the test equipment can be used by controlling method, the sound signal of projectile explosion can be identified by multiple acoustic sensors, and the abnormal data of individual sensors can be eliminated. The error of the testing system can be reduced by strict calibration. The error of projectile explosion position testing system is relatively small relative to random error, so, we assume that the system's test errors are unbiased and the errors are normally distributed.

If $C_{i,j}$ is the observed value of the projectile explosion position coordinates that can obtain by the unit basic array $A_{i \times j}$ and obeys normal distribution. And $C_{i,j}^0$ is its mean value of projectile explosion position coordinates. The standard deviation of unit basic array $A_{i \times j}$ is $\sigma_{i,j}$, which is obtained by the acceptance of shooting range. The probability density function of $C_{i,j}$ is get by formula (11).

$$f(C_{i,j}^0) = \frac{1}{\sigma_{i,j}\sqrt{2\pi}} \exp \left\{ -\frac{(C_{i,j} - C_{i,j}^0)^2}{2\sigma_{i,j}^2} \right\} \quad (11)$$

For the shooting range of projectile explosion position test, in general, the coordinates of projectile explosion position have its theoretical value. The actual explosion position of all targets in a set of tests deviate from the theoretical value, which shows great uncertainty. Therefore, it can hardly provide effective prior information about $C_{i,j}^0$ before test. The test of projectile explosion position is non-repeatable,

one unit basic array can only test one projectile explosion position. $C_{i,j}^s$ is denoted as the test value. $C_{i,j}^0$ is estimated with the observed value $C_{i,j}^s$, by using the traditional point estimation theory. And then, the probability density function of the true value $C_{i,j}^0$ of projectile explosion position can be expressed by formula (13).

$$f(C_{i,j}^0|C_{i,j}^s) = \frac{1}{\sigma_{i,j}\sqrt{2\pi}} \exp\left\{-\frac{C_{i,j}^0 - C_{i,j}^s}{2\sigma_{i,j}^2}\right\} \quad (12)$$

The formula (12) indicates the obtained probability density function of $C_{i,j}^0$ under the condition of the test value $C_{i,j}^s$. It not only contains the information of the actual measured value, but also contains the prior information. However, the traditional data processing method only focus on the actual measured value, without considering the test accuracy of equipment [18]. Therefore, the expression of test data proposed above is more scientific.

According to the viewpoint of probability theory, there must be a probability density distribution function of projectile explosion position under the condition of obtaining evidence, which is expressed by formula (13)

$$f(x, y, z|C_{1,1}, C_{2,1}, \dots, C_{i,j}) \quad (13)$$

The spatial position corresponding to the maximum value of $f(x, y, z|C_{1,1}, C_{2,1}, \dots, C_{i,j})$ is the optimal estimation of the coordinate of projectile explosion position.

The formula (13) is solved based on evidence combination rules. According to the test requirements, the coordinate space set $[x, y, z]$ of the shooting range is denoted as U , which is an infinite set; the observed value $C_{i,j}$ of projectile explosion position obtained by the unit basic array $A_{i \times j}$ is denoted as evidence. The rules of evidence combination require the independence of each other.

When different unit basic arrays detect the same projectile explosion position, assuming that there is no error, all the test data are completely determined by the projectile explosion position in the shooting range. And all the data are completely consistent, that is, these data are not independent of each other. However, objectively, the existence of test errors provides the possibility of independence between each data. The error can be divided into target error, equipment error, environmental error, method error and personnel error from different sources of error. Since the coordinates of projectile explosion obtained by each unit basic array are different, it is generally considered that the errors introduced are not correlated with each other. So, the test data of projectile explosion can be approximated by formula (14).

$$f(x, y, z|C_{1,1}, C_{2,1}, \dots, C_{i,j}) = \frac{f(x, y, z|C_{1,1}) * \dots * f_n(x, y, z|C_{i,j})}{\iiint f(x, y, z|C_{1,1}) * \dots * f_n(x, y, z|C_{i,j}) dx dy dz} \quad (14)$$

Formula (12) shows that each unit basic array has the basis for establishing the conditional probability density distribution of test data of projectile explosion. Therefore,

this also makes it possible to solve formula (14) in specific applications.

B. DATA FUSION OF PROJECTILE EXPLOSION POSITION ON DISTRIBUTED MULTI-ACOUSTIC SENSOR ARRAYS

Because the three-dimensional data of projectile explosion position are independent of each other, the conditional probability of testing data obtained by each unit basic array can be expressed by formula(15).

$$f(x, y, z|x_{i,j}, y_{i,j}, z_{i,j}) = f(x|x_{i,j}) \times f(y|y_{i,j}) \times f(z|z_{i,j}) \left(\frac{\pi}{2} - \theta\right) \quad (15)$$

According to the standard deviation of test, the formula (15) is changed to formula (16).

$$f(x, y, z|x_{i,j}, y_{i,j}, z_{i,j}) = \frac{1}{2\pi \sqrt{2\pi} \sigma_{x_{i,j}} \sigma_{y_{i,j}} \sigma_{z_{i,j}}} \times \exp\left\{-\frac{(x - x_{i,j})^2}{2\sigma_{x_{i,j}}^2} - \frac{(y - y_{i,j})^2}{2\sigma_{y_{i,j}}^2} - \frac{(z - z_{i,j})^2}{2\sigma_{z_{i,j}}^2}\right\} \quad (16)$$

The conditional probability of testing data in $n \times m$ unit basic arrays is

$$f(x, y, z|x_{1,1}, y_{1,1}, z_{1,1} \dots x_{n,m}, y_{n,m}, z_{n,m}) = f(x, y, z|x_{1,1}, y_{1,1}, z_{1,1}) \times \dots \times f(x, y, z|x_{n,m}, y_{n,m}, z_{n,m}) \quad (17)$$

By solving the space coordinate corresponding to the maximum value of formula (17), the actual projectile explosion position $P(x, y, z)$ can be obtained based on the data fusion of projectile explosion position on distributed multi-acoustic sensor array, we use $[x, y, z]$ indicate the fusion calculation results, and then,

$$[x, y, z] = \arg \max_{x,y,z} f(x, y, z|x_{1,1}, y_{1,1}, z_{1,1} \dots x_{n,m}, y_{n,m}, z_{n,m}) \quad (18)$$

V. ERROR ANALYSIS

For the test system of projectile explosion position with distributed multiple acoustic sensor basic arrays, the $n \times m$ unit basic arrays are independent of each other and they are all on the same plane. For the error of the whole system, in addition to the sensitivity difference of the acoustic sensor itself and the distance error between the center origin of each unit basic array, it can be considered that it mainly comes from the measurement error of each unit basic arrays. In order to estimate the error of the test system, in this paper we use single unit basic array to analyze the error of testing system of distributed multiple acoustic sensor basic arrays.

We take the unit basic array $A_{i \times j}$ as an example for error analysis, according to the test principle and method, and the formula (2) – (4), we assume that the time error of each

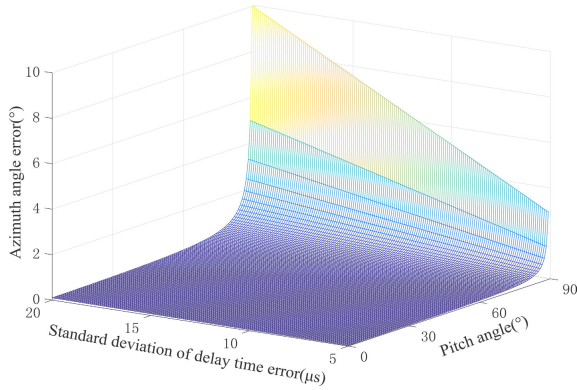


FIGURE 3. The distribution of azimuth angle error with the change of pitch angle and the standard deviation of time delay difference.

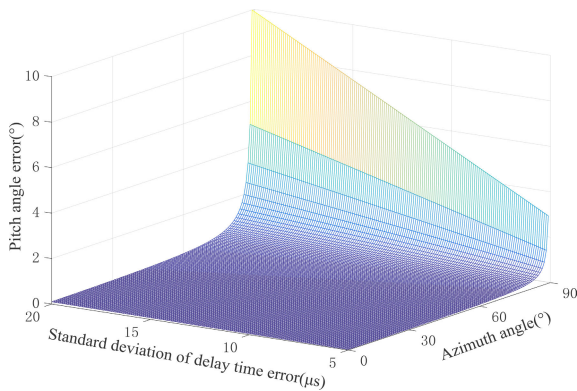


FIGURE 4. The distribution of pitch angle error with the change of azimuth angle and standard deviation of time delay difference.

acoustic sensor is same denoted as σ_τ in the unit basic array $A_{i \times j}$, $\sigma_{\alpha_{i,j}}$ is the azimuth angle error, which can be calculated by formula (19) - (22), as shown at the bottom of the next page.

Similarly, the pitch angle error $\sigma_{\beta_{i,j}}$ can be calculated by formula (19) - (22), (23)–(28), as shown at the bottom of the next page.

Let's set some parameters, such as, $v = 340m/s, L = 1$. When the range of standard deviation of time delay error is $5 \sim 20\mu s$ and the range of pitch angle is $0^\circ \sim 90^\circ$, we calculate the distribution of azimuth angle error, as shown in Figure 3.

It can be seen from Figure 3 that the azimuth angle error increases with the increase of the standard deviation of time delay, and decreases with the increase of the pitch angle. When the time delay error is large and the pitch angle is small, azimuth angle error is increase dramatically. In order to analyze the distribution of pitch angle error, based on the set sound speed and distance parameters between acoustic sensors. If the range of standard deviation of time delay error is $5 \sim 20\mu s$ and the range of azimuth angle is $0^\circ \sim 90^\circ$, we calculate the distribution of pitch angle error, as shown in Figure 4.

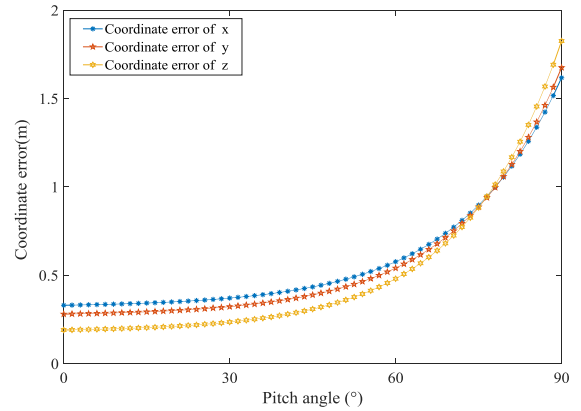


FIGURE 5. The distribution error of projectile explosion position with the change of pitch angle.

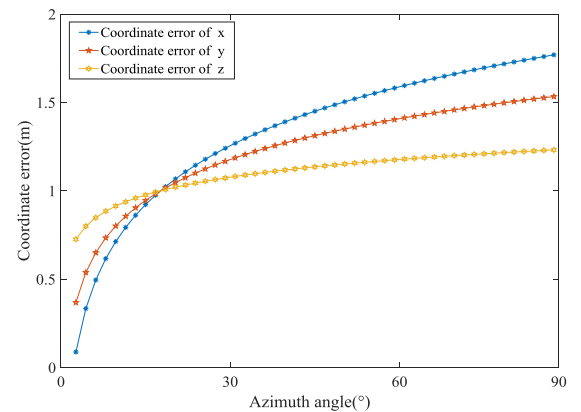


FIGURE 6. The distribution error of projectile explosion position with the change of azimuth angle.

It can be seen from Figure 4 that the distribution of pitch angle error is basically consistent with the azimuth angle error distribution. The pitch angle increases with the increase of the standard deviation of time delay difference and decreases with the increase of the azimuth angle. When the delay error is large, the pitch angle is small, the pitch angle error will increase dramatically.

Based on the formula (4) and the distribution of pitch angle error and azimuth angle error, we analyze the influence of azimuth angle and pitch angle on the projectile explosion position. When the sound speed and distance parameters are the same, the standard deviation of time delay difference in the experiment is $30\mu s$, the height of the projectile explosion position is $20m$, and the x and y coordinate ranges of the explosion position are $-100m \sim 100m$. The distribution trend of the burst position error with the change of azimuth angle and pitch angle is shown in Figure 5 and Figure 6.

It can be seen that when the pitch angle has the maximum error, that is, when the pitch angle is 90° , the minimum errors of x, y and z at the projectile explosion position are about $1.62m, 1.74$ and $1.85m$, respectively. When the azimuth angle has the maximum error, that is, when the azimuth angle is 90° , the maximum errors of x, y and z at the projectile explosion

position are (1.78m, 1.53m, 1.47m). But in the actual test, the test system is affected a lot by other uncertain factors, and the coordinate error of projectile explosion will be slightly larger than the theoretical error.

VI. EXPERIMENT AND ANALYSIS

In order to verify the scientificity of the proposed research method and calculation model, we arranged four unit basic arrays in the shooting range to form an overall test system of projectile explosion position. According to the design ideas and layout of Figure 1, the four unit basic arrays are arranged in test site, and they are denoted as $A_{1 \times 1}$, $A_{1 \times 2}$, $A_{2 \times 1}$ and $A_{2 \times 2}$. The central coordinate $o_{1 \times 1}$ of unit basic array $A_{1 \times 1}$ is the origin of the whole system. And the central coordinates of basic arrays $A_{1 \times 2}$, $A_{2 \times 1}$ and $A_{2 \times 2}$ are denoted as $o_{1 \times 2}$, $o_{2 \times 1}$ and $o_{2 \times 2}$. The distance between $o_{1 \times 1}$ and $o_{1 \times 2}$, $o_{1 \times 1}$ and $o_{2 \times 1}$, $o_{2 \times 1}$ and $o_{2 \times 2}$, $o_{1 \times 2}$ and $o_{2 \times 2}$ are 100m. And the distance between each two acoustic

sensors in one basic array is equal. For example, if the central coordinate $o_{1 \times 1}$ of $A_{1 \times 1}$ is (0, 0, 0), the coordinates of the five acoustic sensors ($R_{1 \times 1-0}$, $R_{1 \times 1-1}$, $R_{1 \times 1-2}$, $R_{1 \times 1-3}$ and $R_{1 \times 1-4}$) in the basic array $A_{1 \times 1}$ are (0, 0, 0), (1.5, 0, 0), (0, 1.5, 0), (-1.5, 0, 0) and (0, -1.5, 0), respectively. According to the coordinate translation, the placement position of acoustic sensors in the other three unit basic arrays is also known.

According to the characteristics and requirements of the test site, in this experiment, we arranged two photoelectric detection sensors at points A and C, and their optical axes were designed and arranged orthogonally. The two photoelectric detection sensor captures the fire light signal of the projectile explosion to form a synchronous acquisition instruction. This experiment can cover 100m × 100m test range. Figure 7 shows the collected original acoustic signal of projectile explosion in unit basic array $A_{1 \times 1}$. Figure 8 is the processing result by wavelet filtering based on Figure 7.

$$\sigma_{\alpha_{i,j}} = \sigma_t \sqrt{\left(\frac{\partial \alpha_{i,j}}{\partial t_{i \times j-1}}\right)^2 + \left(\frac{\partial \alpha_{i,j}}{\partial t_{i \times j-2}}\right)^2 + \left(\frac{\partial \alpha_{i,j}}{\partial t_{i \times j-3}}\right)^2 + \left(\frac{\partial \alpha_{i,j}}{\partial t_{i \times j-4}}\right)^2} \tag{19}$$

$$\frac{\partial \alpha_{i,j}}{\partial t_{i \times j-1}} = -\frac{\partial \alpha_{i,j}}{\partial t_{i \times j-3}} = \frac{1}{1 + \tan^2 \alpha_{i,j}} \cdot \frac{t_{i \times j-2} - t_{i \times j-4}}{(t_{i \times j-3} - t_{i \times j-1})^2} \tag{20}$$

$$\frac{\partial \alpha_{i,j}}{\partial t_{i \times j-2}} = -\frac{\partial \alpha_{i,j}}{\partial t_{i \times j-4}} = \frac{1}{1 + \tan^2 \alpha_{i,j}} \cdot \frac{1}{t_{i \times j-3} - t_{i \times j-1}} \tag{21}$$

$$\begin{aligned} \sigma_{\alpha_{i,j}} &= \frac{\sqrt{2}\sigma_t}{1 + \tan^2 \alpha_{i,j}} \sqrt{\frac{(t_{i \times j-3} - t_{i \times j-1})^2 + (t_{i \times j-2} - t_{i \times j-4})^2}{(t_{i \times j-3} - t_{i \times j-1})^4}} \\ &\approx \frac{\sqrt{2}c}{2L \sin \beta_{i,j}} \sigma_t \end{aligned} \tag{22}$$

$$\sigma_{\beta_{i,j}} = \sigma_t \sqrt{\left(\frac{\partial \beta_{i,j}}{\partial t_{i \times j-1}}\right)^2 + \left(\frac{\partial \beta_{i,j}}{\partial t_{i \times j-2}}\right)^2 + \left(\frac{\partial \beta_{i,j}}{\partial t_{i \times j-3}}\right)^2 + \left(\frac{\partial \beta_{i,j}}{\partial t_{i \times j-4}}\right)^2} \tag{23}$$

$$\frac{\partial \beta_{i,j}}{\partial t_{i \times j-1}} = \frac{1}{1 + \tan^2 \beta_{i,j}} \cdot \frac{-2t_{i \times j-1}}{t_{i \times j-2}^2 - t_{i \times j-4}^2} \tag{24}$$

$$\frac{\partial \beta_{i,j}}{\partial t_{i \times j-3}} = \frac{1}{1 + \tan^2 \beta_{i,j}} \cdot \frac{2t_{i \times j-3}}{t_{i \times j-2}^2 - t_{i \times j-4}^2} \tag{25}$$

$$\frac{\partial \beta_{i,j}}{\partial t_{i \times j-2}} = \frac{1}{1 + \tan^2 \beta_{i,j}} \cdot \frac{-2t_{i \times j-2} (t_{i \times j-3}^2 - t_{i \times j-1}^2)}{(t_{i \times j-2}^2 - t_{i \times j-4}^2)^2} \tag{26}$$

$$\frac{\partial \beta_{i,j}}{\partial t_{i \times j-4}} = \frac{1}{1 + \tan^2 \beta_{i,j}} \cdot \frac{2t_{i \times j-4} (t_{i \times j-3}^2 - t_{i \times j-1}^2)}{(t_{i \times j-2}^2 - t_{i \times j-4}^2)^2} \tag{27}$$

$$\sigma_{\beta_{i,j}} = \frac{2\sigma_t}{1 + \tan^2 \beta_{i,j}} \sqrt{\frac{(t_{i \times j-3}^2 + t_{i \times j-1}^2) (t_{i \times j-2}^2 - t_{i \times j-4}^2)^2 + (t_{i \times j-3}^2 - t_{i \times j-1}^2)^2 (t_{i \times j-2}^2 + t_{i \times j-4}^2)}{(t_{i \times j-2}^2 - t_{i \times j-4}^2)^4}} \approx \frac{c}{L \cos \beta_{i,j}} \sigma_t \tag{28}$$

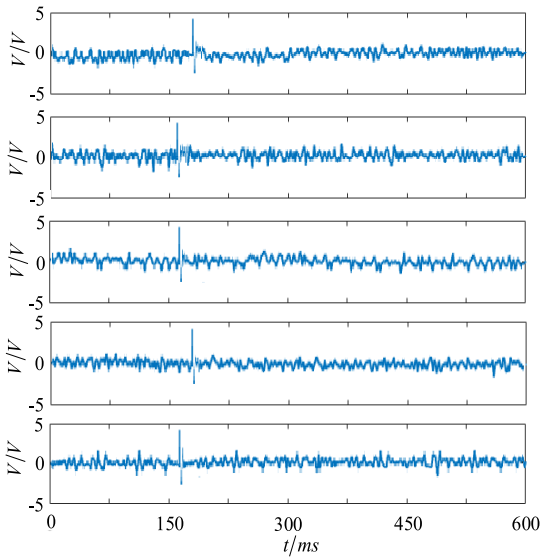


FIGURE 7. The collected original acoustic signal of projectile explosion in unit basic $A_{1 \times 1}$.

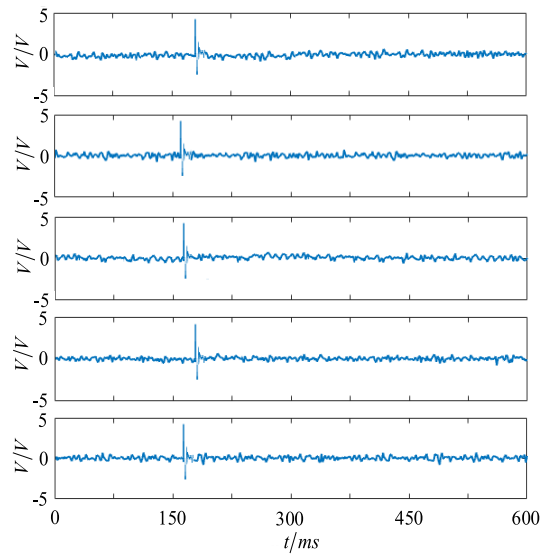


FIGURE 8. The processing result by wavelet filtering based on Figure 7.

According to the time extraction method of the wavelet modulus maximum on the projectile explosion acoustic signal, the time values of each acoustic sensor in the unit basic arrays $A_{1 \times 1}$, and, $t_{1 \times 1-0} = 176ms$, $t_{1 \times 1-1} = 161ms$, $t_{1 \times 1-2} = 163ms$, $t_{1 \times 1-3} = 172ms$, and $t_{1 \times 1-4} = 158ms$, respectively. And the projectile explosion position can be calculated by Formula (4) and Formula (5), the calculation results is $x_{1 \times 1} = 32.12m$, $y_{1 \times 1} = -48.56m$, $z_{1 \times 1} = 13.82$.

In order to further verify the method proposed in this paper, we compared the proposed method with the intersection photography method based on dual area-array cameras. The method proposed used spatial geometric relationship of the dual area-array cameras, image processing technology and

TABLE 1. The test data of projectile explosion position in unit basic array $A_{1 \times 1}$.

	V/V	$t_{1 \times 1}/s$	$(x_{1 \times 1}, y_{1 \times 1}, z_{1 \times 1})$
$R_{1 \times 1-0}$	4.714	0.173	
$R_{1 \times 1-1}$	4.682	0.175	
$R_{1 \times 1-2}$	4.793	0.169	$(-37.71, 42.45, 15.07)$
$R_{1 \times 1-3}$	4.762	0.170	
$R_{1 \times 1-4}$	4.667	0.176	

TABLE 2. The test data of projectile explosion position in unit basic array $A_{1 \times 2}$.

	V/V	$t_{1 \times 2}/s$	$(x_{1 \times 2}, y_{1 \times 2}, z_{1 \times 2})$
$R_{1 \times 2-0}$	0.973	331	
$R_{1 \times 2-1}$	--	--	
$R_{1 \times 2-2}$	0.925	339	--
$R_{1 \times 2-3}$	0.931	337	
$R_{1 \times 2-4}$	--	--	

TABLE 3. The test data of projectile explosion position unit basic array $A_{2 \times 1}$.

	V/V	$t_{2 \times 1}/s$	$(x_{2 \times 1}, y_{2 \times 1}, z_{2 \times 1})$
$R_{2 \times 1-0}$	4.171	0.207	
$R_{2 \times 1-1}$	4.122	0.210	
$R_{2 \times 1-2}$	4.106	0.211	
$R_{2 \times 1-3}$	4.218	0.204	$(-37.64, -57.61, 15.12)$
$R_{2 \times 1-4}$	4.252	0.202	

TABLE 4. The test data of projectile explosion position in unit basic array $A_{2 \times 2}$.

	V/V	$t_{2 \times 2}/s$	$(x_{2 \times 2}, y_{2 \times 2}, z_{2 \times 2})$
$R_{2 \times 2-0}$	0.891	348	
$R_{2 \times 2-1}$	--	--	
$R_{2 \times 2-2}$	0.873	352	--
$R_{2 \times 2-3}$	0.854	355	
$R_{2 \times 2-4}$	--	--	

the actual size of the simulated target to obtain the three-dimensional coordinate of the projectile explosion position. The dual area-array cameras are arranged with 45° pitch angle in central position of test site and the distance between them is 30m. Tables 1 - 4 show the test data of a same projectile explosion acoustic signal in four unit basic arrays.

It can be found that the above data in Table 3 and Table 4 are incomplete, which indicates that the signal

TABLE 5. The comparative test data of projectile explosion position.

	The projectile burst position in basic arrays	The projectile burst position processed by data fusion algorithm of multi-acoustic sensor array	The projectile burst position test by intersection photography method based on dual area-array cameras
$A_{1 \times 1}$	(47.53, 43.84, 16.38)		
$A_{1 \times 2}$	(-52.76, 43.75, 16.14)		
$A_{2 \times 1}$	(47.31, -56.27, 16.17)	(47.29, 43.96, 16.21)	(47.62, 44.09, 16.82)
$A_{2 \times 2}$	(47.43, -56.15, 16.25)		

of some acoustic sensors in unit basic array $A_{1 \times 2}$ and $A_{2 \times 2}$ is weak. Therefore, the unit basic arrays $A_{1 \times 2}$ and $A_{2 \times 2}$ are not used to calculate the projectile explosion position. The unit basic arrays $A_{1 \times 1}$ and $A_{2 \times 1}$ can obtain the complete data. According to the calculation model proposed in this paper, the explosion position coordinates obtained by the unit basic array $A_{1 \times 1}$ and unit basic array $A_{2 \times 1}$ are (-37.71, 42.45, 15.07) and (-37.64, -57.61, 15.12). Combining with formula (1) and the data fusion method of projectile explosion position, the actual coordinate projectile explosion is (-37.67, 42.52, 15.09) calculated by formulas (16), (17) and (18).

It is found through tests that because the projectile explosion position deviates from the center position of the test area, the projectile explosion position is not in the test range of the intersection photography method based on dual area-array cameras. At this time, the intersection photography method based on dual area-array cameras cannot capture the projectile explosion image information and cannot calculate the projectile burst position. However, the projectile explosion position test system with distributed multiple acoustic sensor basic arrays can still capture and calculate the projectile explosion position, which verifies that the test method proposed in this paper can meet the test requirements of large field of view.

In order to further compare and verify, we collected the explosion acoustic signal of another projectile, and processed it according to the calculation model established in this paper. Table 5 is the comparative test data of projectile explosion position.

According to the Table 5, we can find that the average error of the explosion position measured by the proposed method close to the intersection photography method based on dual area-array cameras. Obviously, there is a certain deviation in the result of coordinate calculation, which are mainly due to the acoustic sensor placement error of the test system, the inherent distance measurement error, the time error of signal recognition, etc., which all affect the measurement result. For the intersection photography method. The measurement range is limited by the field of view of the optical lens in intersection photography system. Although this system use the two cameras intersection test method, the effective area

of the intersection is relatively small. This is the reason why it is not easy to capture the explosion of the projectile by the camera method.

This paper researches a distributed multi-acoustic sensor basic arrays to measure the projectile explosion position, through the arrangement of the multi-acoustic sensor basic arrays, which can construct a large-area detection projectile explosion position information, this is also the purpose of this paper. And based on the above experiment, it also fully reflects the scientificity and adaptability of the proposed test method.

VII. CONCLUSION

In order to meet the test requirements of projectile explosion position under the condition of uncertain information, this paper is to explore a new test method of projectile explosion position when projectile falling in a large area and improve the test ability of weapon test system, we constructs a projectile explosion position test system with distributed multiple acoustic sensor basic arrays and establishes the projectile explosion position calculation model in a basic array.

Through the spatial arrangement relationship of multiple array acoustic basic arrays, we calculate the projectile explosion position parameters by translating the center coordinate of each unit basic arrays. Based on coordinate data fusion method of multiple unit basic arrays, we solve the actual projectile explosion position and derive the fusion calculation function of projectile explosion data with multiple unit basic arrays. There are two technical highlights in this paper, first, the calculation method of the projectile explosion position with multiple acoustic sensor basic arrays; second, the data fusion processing method of the projectile explosion position based on multi-source data fusion algorithm.

According to the experiment at specific projectile explosion, the actual coordinates of the projectile explosion height range of 10-25 meters can be obtained in the effective test area of $100m \times 100m$. This result verifies the feasibility and effectiveness of the proposed method. The new method proposed in this paper lays a foundation for further research. At the same time, the theory method of the parameters test of projectile explosion position in large area based on multiple

basic arrays provides a scientific method for the development of various weapons. This also shows that the research in this paper is of great significance.

REFERENCES

- [1] Z. Wang, "Research on mathematical models of damage probability approximate computation of cargo projectile," *J. Syst. Simul.*, vol. 28, no. 6, pp. 1312–1320, 2016.
- [2] E. Kljuno and A. Catovic, "A generalized model for estimation of aerodynamic forces and moments for irregularly shaped bodies," *Defence Technol.*, vol. 15, no. 3, pp. 369–389, Jun. 2019.
- [3] S. Chen, H. Zhang, and X. Xu, "Echo characteristic of planar target in pulsed laser fuze detection," *Acta Armamentarii*, vol. 39, no. 6, pp. 1095–11102, 2018.
- [4] V. A. Banakh, I. A. Razenkov, and I. N. Smalikhov, "Laser echo signal amplification in a turbulent atmosphere," *Appl. Opt.*, vol. 54, no. 24, pp. 7301–7307, 2015.
- [5] H. Li and Z. Lei, "Measurement of space burst location for projectile base on photography," *Opt. Precis. Eng.*, vol. 20, no. 2, pp. 329–336, 2012.
- [6] W. Yang, Z. Hongtao, and J. Chunjia, "A method for locating the impact point of a triangle five element cross hybrid array projectile," *J. Detection control*, vol. 42, no. 4, pp. 92–97, 2020.
- [7] W. Chu, B. Zhang, B. Liu, Z. Gui, and D. Zhao, "An optoelectronic targeting system for measuring the distribution of projectile motion based on the subdivision of a light screen," *Photonics*, vol. 6, no. 4, pp. 126–299, 2019.
- [8] Z. Wang, R. Huang, B. Yang, and Z. Wan, "An acoustic location method for projectile impact point," *Electroacoust. Technol.*, vol. 44, no. 5, pp. 26–29, 2020.
- [9] S. Feng, Y. Zhang, M. Wang, Y. Lu, J. You, and Z. Xi, "Study on time delay estimation technology of burst acoustic signal of continuous projectile," *Comput. Meas. control*, vol. 28, no. 3, pp. 144–147, 2020.
- [10] S. Feng, Y. Zhang, S. Shang, and Y. Lu, "Rapid positioning method for measuring the coordinates of the impact point of successive projectiles," *J. Ordnance Equip. Eng.*, vol. 40, no. 7, pp. 234–237, 2019.
- [11] F. Gao, Y. Sun, S. Zhao, L. Ji, and J. Li, "Study on orientation accuracy of blast point positioning system," *J. Meas. Technol.*, vol. 32, no. 6, pp. 505–511, 2018.
- [12] C. Guo, J. Li, and G. Gao, "Design of a multi array burst point sound source positioning system," *Electron. devices, vo.*, vol. 40, no. 4, pp. 987–993, 2017.
- [13] J. Zheng, B. Zhang, and C. Xiong, "Acoustic location method of projectile impact point based on compound double-arrays," *J. Ballistics*, vol. 28, no. 4, pp. 68–74, 2016.
- [14] Q. Zhang, J. Ding, and W. Zhao, "An adaptive boundary determination method for empirical wavelet transform and its application in wheelset-bearing fault detection in high-speed trains," *Measurement*, vol. 171, Feb. 2021, Art. no. 108746.
- [15] J. M. F. Cervantes, M. T. Ramírez Torres, C. J. Martínez, J. S. M. Ibarra, and C. M. Mejía, "Object detection in aerial navigation using wavelet transform and convolutional neural networks," *Program. Comput. Softw.*, vol. 46, pp. 536–547, Dec. 2020.
- [16] L. Sun, F. Bai, and Y. Wang, "Application of wavelet transform in bullet ultrasonic array," *J. Changchun Univ. Sci. Technol. Natural Sci. Ed.*, vol. 34, no. 1, pp. 96–99, 2011.
- [17] B. Zhang, J. Li, D. Zhao, J. Liu, and Y. Li, "Signal processing of laser screen fragments velocity measurement based on wavelet transform and correlation analysis," *Acta Armamentarii*, vol. 37, no. 3, pp. 489–494, 2016.
- [18] W. Zhu, R. Li, and X. Zhang, "The application of multi-source data fusion to blast target location," *J. Projectiles, Rockets, Missiles Guid.*, vol. 31, no. 6, pp. 203–206, 2011.



HANSHAN LI received the B.S. degree in electronic measurement and instrumentation from Xi'an Shiyou University, Xi'an, China, in 2001, the M.S. degree in testing and measurement techniques and instruments from Xi'an Technological University, Xi'an, in 2004, and the Ph.D. degree in testing and measurement techniques and instruments from Northwestern Polytechnical University, Xi'an, in 2010.

He is currently a Professor and a Ph.D. Supervisor with Xi'an Technological University, where he is engaged in research and development of photoelectricity detection, measurement and control technology, dynamic object test technology, image processing technology, and target damage assessment. He has also published more than 90 articles in academic journals indexed in well-reputed databases, such as Science Citation Index and holds 18 patents, and won more than 17 science and technology progress awards.



XUEWEI ZHANG received the B.S. degree from the Harbin University of Technology, Harbin, China, in 2008, the M.S. degree from the Lanzhou University of Technology, Lanzhou, China, in 2012, and the Ph.D. degree from the Xi'an University of Technology, Xi'an, China, in 2019.

She is currently an Instructor with Xi'an Technological University, Xi'an, where she is engaged in research and development of image processing, photoelectricity detection technology, optical technology, fault diagnosis, and measurement and control techniques. She has also published more than 15 articles in academic journals indexed in well-reputed databases, such as Science Citation Index.

• • •