The attack target location method based on quaternion detection array

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ABSTRACT

The bullet point acoustic detection and location system determines the location of the attack target by receiving and measuring the muzzle shock wave of the attack target and the shock wave generated by the projectile flight. This paper designs an attack target location method based on the quaternion detection array through the analysis of the ballistic wave signal, that is, the location of the attack target is preliminarily determined by the time difference of the muzzle shock wave reaching each sensor, Then, the ballistic trajectory is determined by the time difference between the ballistic shock wave generated during the flight of the projectile and each sensor, and the positioning accuracy is improved through the combination of the two.

Keywords: Quad detector array, attack target, shock wave.

1. INTRODUCTION

The bullet point acoustic detection and positioning system determines the position of the attack target by receiving and measuring the shock wave generated by the muzzle shock wave and the bullet flight. When individual weapons are fired, the high-temperature and high-pressure gunpowder gas in the chamber will suddenly expand and mix with the atmosphere, forming a muzzle shock wave (explosion sound) spread outward at the speed of sound; The high-speed flying warhead will also generate eddy current, shock wave and flight noise due to friction in the air. When the flying speed of the warhead approaches and exceeds the sound speed, the flight noise is more obvious[1-3]. By accurately measuring the time difference between the muzzle shock wave and the ballistic shock wave generated when the projectile flies to each sensor from the prearranged acoustic sensor array, the attack target position, as well as the projectile flight trajectory, flight speed and gun caliber can be accurately calculated. The method proposed in this paper determines the firing point and trajectory vector through the quaternion detection array, and uses the combination of the two methods to locate the attack target, which has good application value[4-5].

2. BALLISTIC WAVE SIGNAL ANALYSIS

The sound field is affected by many factors, such as the acoustic signal (aerodynamic noise) emitted by the projectile during flight, the acoustic signal generated by the explosion of the projectile, the geometric dispersion loss of the signal, environmental noise, etc. Therefore, effectively identifying the gunshot information of the attack target, filtering the background noise, improving the signal-to-noise ratio of the signal, mastering the characteristics of the acoustic signal of the flying projectile and the law of its propagation in the atmosphere are the keys to achieve the accurate location of the attack target shooting point and the calculation of the trajectory direction[6]. Through studying the identification and analysis methods of ballistic shock wave signal and muzzle shock wave signal, the ideal ballistic wave and muzzle shock wave signal can be obtained by using wavelet filter, laying a foundation for further systematic experimental research[7].

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As shown in Figure 1, the experiment uses automatic rifle bullets to sweep over the acoustic sensor at 710 speed. The parallel distance X between the acoustic sensor and the muzzle (shooting point) is about 50, and the ballistic distance Y from the sensor (miss distance) is about 38.2. Assume that the coordinates of the firing point are (x, y) , the coordinates of the sensor (target) are $(0,0)$, and the shock wave generated by the projectile at the point propagates to the target A along the normal direction of the wave front. Then the distance from the shock wave generated by the projectile at the point to the target is d_B , and the distance from the target to the trajectory is R , which is called miss distance (the so-called miss distance refers to the minimum relative distance between the projectile and the target during the encounter). From the geometric relationship:

$$R = d_B \cos \mu \tag{1}$$

However, there are $\sin \mu = 1/Ma$, then

$$R = \frac{d_B \sqrt{Ma^2 - 1}}{Ma} \tag{2}$$

Assuming that the local sound speed is 340 m/s , the difference relationship δt between the arrival time of ballistic shock wave and the arrival time of muzzle shock wave can be approximately calculated by formula (3). Figure 1 is the schematic diagram of shooting point and sensor settings during the experiment.

$$\delta t = \frac{PA}{340} - \left(\frac{PB}{710} + \frac{d_B}{340}\right) \approx \left(\frac{\sqrt{X^2 + R^2}}{340}\right) - \left(\frac{X}{710} + \frac{R}{340}\right) \tag{3}$$

Substitute $X = 50$, $R = 38.2$ into equation (3), then $\delta t = 0.0023s$.

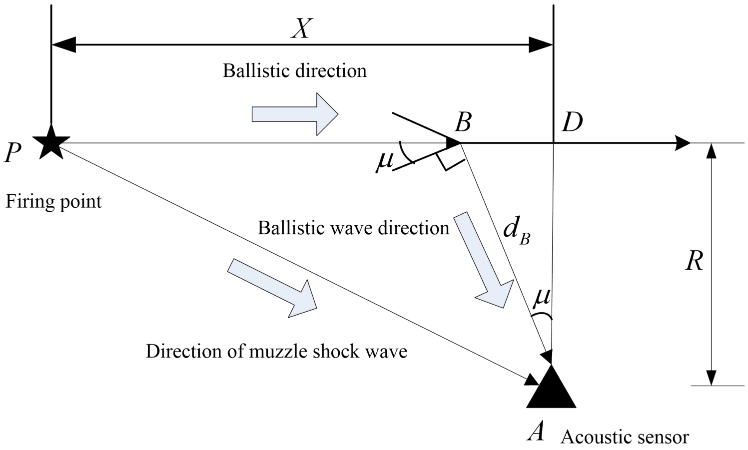

Figure 1. Shooting point and acoustic sensor setting

3. ACOUSTIC DETECTION AND LOCATION ALGORITHM OF ATTACK TARGET

The positioning principle of the attack target acoustic detection system is mainly to locate by measuring the time difference between the muzzle shock wave and the ballistic shock wave reaching each sensor. Two positioning arrays are arranged. The positioning array 1 is used to measure the muzzle shock wave. The location of the attack target is determined by measuring the time difference between the muzzle shock wave and each sensor on the array. Due to the influence of complex factors such as environmental noise, the positioning accuracy is not high, determine the trajectory vector by measuring the time difference between the ballistic shock wave and each sensor on the array with other arrays. The position of the attack target can be detected more accurately by combining the measurement results of array 1 and array 2[8-9].

From the ballistic wave analysis, it can be seen that the muzzle shock wave and the ballistic shock wave can be distinguished. Therefore, the method of combining the fixed firing point with the fixed trajectory can be used to achieve the target location. Because of the complex background noise, the single shooting point will produce large errors. Therefore, a method combining the shooting point and the trajectory is proposed to improve the positioning accuracy.

The fixed firing point is located by measuring the time difference between the muzzle shock wave and each sensor on the sensor array, which belongs to the spatial positioning problem. The positioning array layout adopts the layout of the quaternion detection array, and the trajectory is determined by the sensor array algorithm.

There are two methods to determine the trajectory with sensor arrays: the first method is to determine the trajectory with two or more arrays. Its basic principle is to determine a straight line based on the principle of two points. The coordinates of two points on the trajectory are measured through two positioning arrays, and the trajectory is determined using the coordinates of two points[10]; the second method is to use a sensor array to determine the trajectory direction, and its positioning array uses a quaternion detection array to locate. This method will be described in detail in the following content.

As shown in Figure 2, the detection array consists of acoustic sensors S_1, S_2, S_3, S_4, and installed on four corners of an equilateral tetrahedron, and their coordinates are (x_i, y_i, z_i) $(i = 1,2,3,4)$.

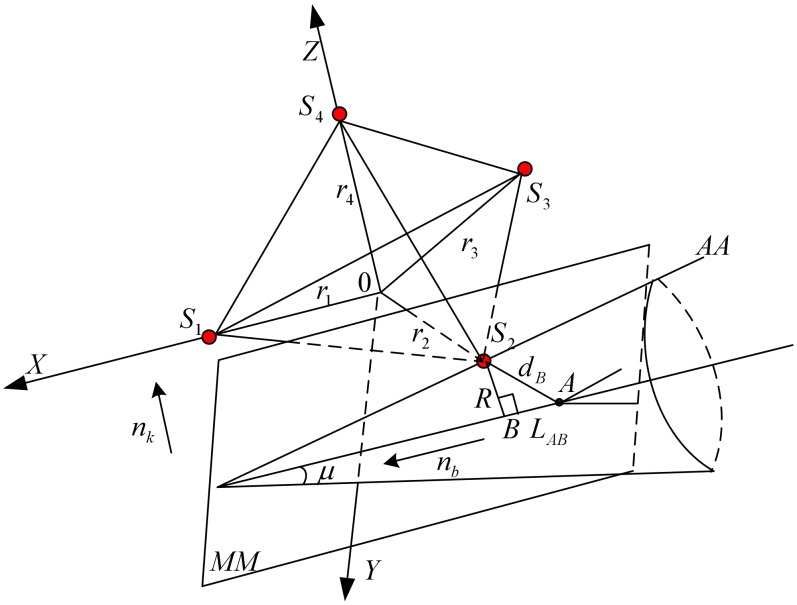

Figure 2. Four element detection array and its coordinate system

The incident direction n_k (unit vector) of the shock wave is calculated by measuring the time difference τ_i of the ballistic shock wave passing through the four sensors.

Let the sensor frame be a regular tetrahedron, and the sensors are distributed on the four vertices of the regular tetrahedron, as shown in Figure 2. At the moment of $t = 0$, the ballistic shock cone AA first meets the sensor, and let the shock wave S_2 generated by the sound source (the sound source point on the trajectory that generates the shock wave) first reach the sensor, which is the unit vector n_k of the propagation direction of the shock wave. A part of the cone is approximately replaced by a axis AA, which is the section MM of the ballistic shock cone including the x.

Set the point S_1 on the axis X, S_4 on the axis Z, where the side length of the regular tetrahedron is 2 length units, then the coordinates of each measuring point are:

$$\begin{cases} S_1(x_1, y_1, z_1) = (\frac{2\sqrt{3}}{3}, 0, 0) \\ S_2(x_2, y_2, z_2) = (-\frac{\sqrt{3}}{3}, 1, 0) \\ S_3(x_3, y_3, z_3) = (-\frac{\sqrt{3}}{3}, -1, 0) \\ S_4(x_4, y_4, z_4) = (0, 0, \frac{2\sqrt{6}}{3}) \end{cases}$$

If the unit vector of the trajectory direction is $n_b = \{n_{bx}, n_{by}, n_{bz}\}$, the steps to solve the trajectory direction are as follows:

(1) The unit vector $n_k = \{n_{kx}, n_{ky}, n_{kz}\}$ that determines the incident direction of the ballistic shock wave.

When $t = 0$, the distance *MM* from each measuring point to the plane is:

$L_i = \vec{r}_{2i} \bullet \vec{n}_k$ (" $\bullet$ " represents the quantity product, $i = 1,3,4$)

The time when the shock wave reaches each measuring point is:

$$\tau_i = L_i / v_k = \vec{r}_{2i} \bullet \vec{n}_k / v_k \tag{4}$$

Where, v_k is the propagation velocity of the plane *MM* (assuming that the plane *MM* travels at the speed of sound, $v_k = c$).

$$\begin{cases} \vec{r}_{12} = \{-\sqrt{3}, 1, 0\} \\ \vec{r}_{32} = \{0, 2, 0\} \\ \vec{r}_{42} = \{-\frac{\sqrt{3}}{3}, 1, -\frac{2\sqrt{6}}{3}\} \end{cases}$$

Let $n' = \vec{n}_k / v_k = \{n'_x, n'_y, n'_z\}$, the equation of direction number n' solved becomes:

$$\begin{vmatrix} -\sqrt{3} & 1 & 0 \\ 0 & 2 & 0 \\ -\frac{\sqrt{3}}{3} & 1 & -\frac{2\sqrt{6}}{3} \end{vmatrix} \cdot \begin{vmatrix} n'_x \\ n'_y \\ n'_z \end{vmatrix} = \begin{vmatrix} \tau_1 \\ \tau_3 \\ \tau_4 \end{vmatrix} \tag{5}$$

Wherein, $\tau_i (i = 1,3,4)$ refers to the time difference when the sound signal of the sound source reaches the sensor S_i and S_2.

Solve the equation to get:

$$\begin{cases} n'_x = \frac{\sqrt{3}}{6}\tau_3 - \frac{\sqrt{3}}{3}\tau_1 \\ n'_y = \frac{1}{2}\tau_3 \\ n'_z = \frac{\sqrt{6}}{12}\tau_3 - \frac{\sqrt{6}}{4}\tau_4 + \frac{\sqrt{6}}{12}\tau_1 \end{cases} \tag{6}$$

Then the unit vector $\vec{n}_k$ of the incident direction of the ballistic shock wave is

$$\vec{n}_k = \frac{n'(n'_x, n'_y, n'_z)}{|n|} \tag{7}$$

(2) Find the coordinates of the sound source point A that generates the shock wave in the trajectory (x_A, y_A, z_A).

The four element detection array can ensure that the signals received by the sensors S_1, S_2, S_3, S_4, and correspond to the signals generated by the same sound source point A, so the time difference can be used to calculate the coordinates of the sound source point. The distance difference between the acoustic signal of the target and the sensor and the velocity c of sound are expressed by r_{i2} $(i = 1,3,4)$, and then:

$$r_{i2} = AS_i - AS_2 = \tau_i \cdot c \qquad (i = 1,3,4)$$

According to the geometric relationship of the model, the following equations can be obtained:

$$\begin{cases} (x_A - x_2)^2 + (y_A - y_2)^2 + (z_A - z_2)^2 = r_2^2 \\ (x_A - x_1)^2 + (y_A - y_1)^2 + (z_A - z_1)^2 = (r_2 + r_{12})^2 \\ (x_A - x_3)^2 + (y_A - y_3)^2 + (z_A - z_3)^2 = (r_2 + r_{32})^2 \\ (x_A - x_4)^2 + (y_A - y_4)^2 + (z_A - z_4)^2 = (r_2 + r_{42})^2 \end{cases} \tag{8}$$

Wherein, r_2 represents the distance from the sound source point A to the sensor S_2.

The coordinates (x_A, y_A, z_A) of the sound source point S_2 can be determined by solving the equations (8).

(3) The unit vector $\vec{n}_b \{n_{bx}, n_{by}, n_{bz}\}$ to determine the trajectory direction.

In order to determine the unit vector $\vec{n}_b \{n_{bx}, n_{by}, n_{bz}\}$ of the trajectory, the direction of the vector from the point P_m to the weapon shooting point is positive. Half cone angle of ballistic shock wave $\mu = \arcsin(1/Ma)$, where Ma is the Mach number of projectile flight.

$$\vec{n}_b \bullet \vec{n}_k = |\vec{n}_b| \cdot |\vec{n}_k| \cdot \cos(\frac{\pi}{2} - \mu) = \sin\mu \tag{9}$$

Among them, $|\vec{n}_k| = 1$, $|\vec{n}_b| = 1$.

The straight line perpendicular S_2 to the trajectory intersects the trajectory line at the point B, and now the point A coordinates are calculated through the point B coordinates (x_B, y_B, z_B), then according to the formula:

$$r_2 = \sqrt{(x_A - x_2)^2 + (y_A - y_2)^2 + (z_A - z_2)^2} \tag{10}$$

Distance between points A and B:

$$L_{AB} = r_2 \sin\mu \tag{11}$$

Since the direction cosine of the unit vector is itself, the point B coordinates (x_B, y_B, z_B) can be obtained as:

$$\begin{cases} x_B = x_A + L_{AB} n_{bx} \\ y_B = y_A + L_{AB} n_{by} \\ z_B = z_A + L_{AB} n_{bz} \end{cases} \tag{12}$$

It can be determined $\overset{\rightarrow}{BS}_2 = \{(x_2 - x_B), (y_2 - y_B), (z_3 - z_B)\}$ by the coordinates of point B , and can be obtained by $\overset{\rightarrow}{BS}_2 \perp \vec{n}_b$

$$(x_2 - x_B) n_{bx} + (y_2 - y_B) n_{by} + (z_2 - z_B) n_{bz} = 0 \tag{13}$$

From the above relationship, we can determine the three equations of the vector n_b:

$$\begin{cases} (x_2 - x_B) \cdot n_{bx} + (y_2 - y_B) \cdot n_{by} + (z_2 - z_B) \cdot n_{bz} = 0 \\ n_{bx} \cdot n_{kx} + n_{by} \cdot n_{ky} + n_{bz} \cdot n_{kz} = \sin \mu \\ n_{bx}^2 + n_{by}^2 + n_{bz}^2 = 1 \end{cases} \tag{14}$$

Thus, the trajectory vector (unit vector) $n_b = (n_{bx}, n_{by}, n_{bz})$.

4. SIMULATION ANALYSIS

A certain type of automatic rifle is used in the experiment, the shooting distance is 100 meters, and the size of the target frame is 520 $mm \times$ 520 mm , install 2 sensors on the same plane on the four sides of the inner side of the target frame. When firing live ammunition, due to the strong signal, a sound barrier (thin iron sheet) is usually added to the sensor. The experimental method is to stick the target paper first, measure the coordinates of the actual impact point from the target paper after the shooting is completed, and then compare the measured actual coordinates with the impact point coordinates calculated using this algorithm displayed by the target reporting system. The measured actual coordinates of the impact point, the impact point coordinates calculated by the target reporting system, and the impact point coordinates calculated by the calculation display system are displayed. Figure 3 shows the signal measured by the instrument in Matlab. It can be seen from Figure 3 that the muzzle shock wave and ballistic shock wave can be distinguished. Figure 3 shows the images of ballistic shock wave and muzzle shock wave measured in the experiment, and the waveforms of ballistic shock wave and muzzle shock wave can be clearly seen. The two images can be segmented according to the difference relation of arrival time.

The left side of Figure 4 and the right side of Figure 4 are respectively the images of ballistic shock wave and muzzle shock wave obtained through time segmentation processing. On the right of Figure 4 and Figure 5 are images of ballistic shock wave and muzzle shock wave obtained through wavelet decomposition and reconstruction. The experiment uses Biorthogonal wavelet (bior6.8) to decompose and reconstruct the original signal, as shown in Figure 4 and Figure 5. The wave period of the ballistic wave N obtained through analysis T =0.000434 (s), the arrival time of the ballistic wave and the arrival time of the muzzle shock wave are respectively t_q =0.50822 (s) and t_s =0.51054 (s).

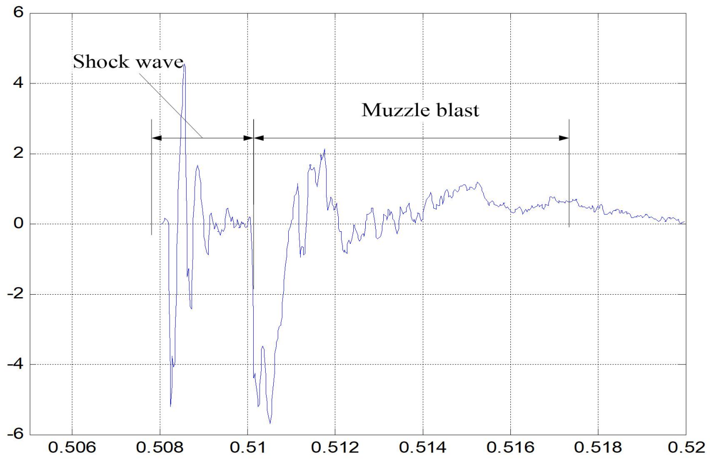

Figure 3. Ballistic shock wave (left) and muzzle shock wave (right) (miss distance 38.2m)

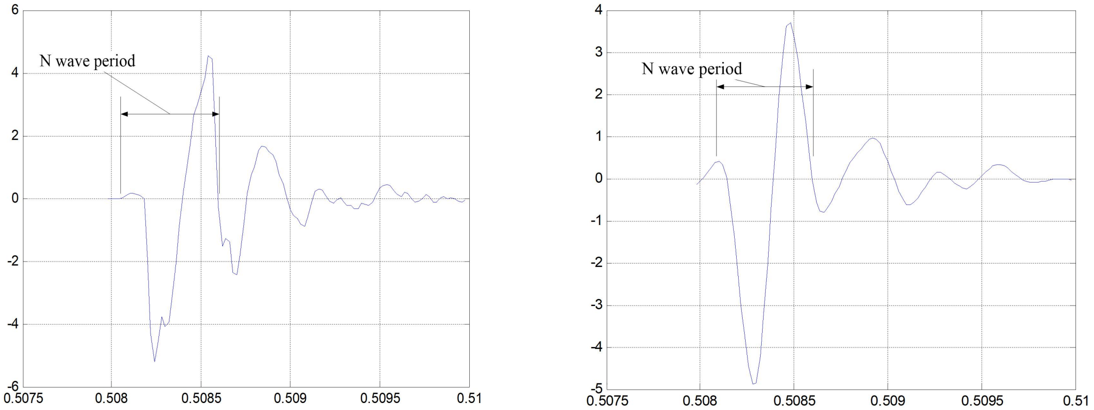

Figure 4. Ballistic shock wave obtained through time separation and filtering

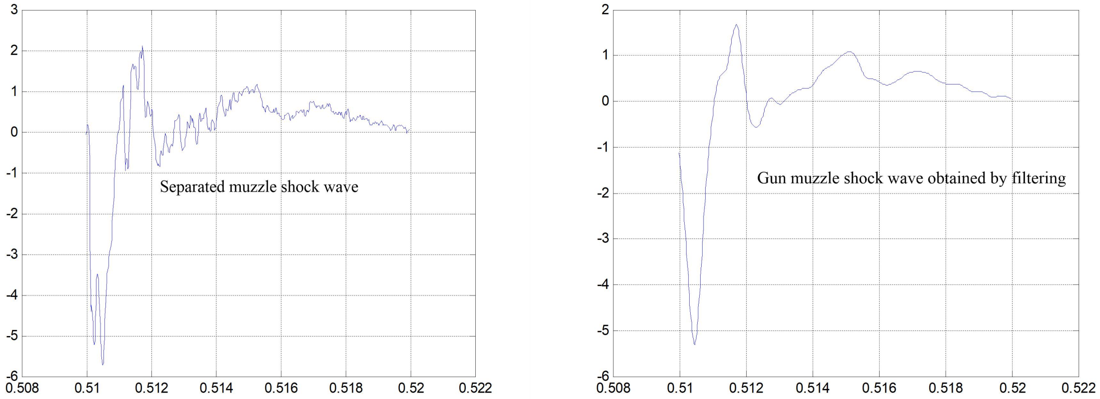

Figure 5. Gun muzzle shock wave after time separation and filtering

5. SUMMARY

By analyzing the actual trajectory wave signal, this paper designs a method combining fixed firing point and fixed trajectory vector to locate the attack target, and gives the design and location algorithm of fixed trajectory vector sensor array. That is to use the time difference between the muzzle shock wave and each sensor to initially determine the position of the attack target, and then use the time difference between the ballistic shock wave generated during the flight of the projectile and each sensor to determine the trajectory. The positioning accuracy is improved through the combination of the two.

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