Study on Passive Acoustic Fuze in Wake Field of Ship with High Precision Recognition for High-Speed Small Target

Xiaohui He 1, 2, *, Zhongle Liu 1, Zhiyong Yuan 1, Ruiqun Su 2

1 School of Ordnance Engineering, Naval University of Engineering, Wuhan, Hubei, China
2 Jiangnan Industries Group Co., Ltd., Xiangtan, Hunan, China

*Corresponding author e-mail: hexh917@163.com

Abstract. It is proposed to adopt a new way against the incoming high-speed small target in the wake field of ship. The passive acoustic fuze composed by a ternary array can detect and receive a large number of signals with characteristic information, among which the intersection process between the incoming target and the acoustic fuze is regarded as the important characteristic information. Through analysis of delay estimation and the delay error according to the characteristics information received from the passive ternary array, such as the distance, the azimuth and the energy envelope, to improve the accuracy of location and azimuth. By means of the modified polynomial least square fitting method to eliminate outliers and interference from signals to improve the sharpness of the curve, to further fit the curve and to eliminate the negative impact from the change of data. An optimal initiation strategy is proposed based on the two above-mentioned aspects. Finally, it proved by tests that the proposed method has a certain value for reference.

1. Introduction

With the development of the underwater offensive weapons, how to improve the ship's countermeasure ability and effectively defend against the high-speed small target has become the focus of the navy's underwater defense [1]. It can be predicted that in the future naval battle, the surface ships of each side will be the object of a high-speed small target of the other side, and the threat will become more and more serious.

The passive ternary array positioning technology based on the time delay is a classic passive positioning method against targets [2-6]. This paper proposes to apply a three-element linear array which is vertically placed in the wake field to locate the incoming high-speed small target and obtain the distance and azimuth information of the incoming target. At the same time, the received radiated noise and other characteristics are used to calculate the energy [7-11], and the modified polynomial least square method is used to fit the curve [7] [8]. The curve filtering method [12] and the method of improving the sharpness of the curve are used to eliminate the interference and outliers, and a relatively smooth bell-like energy envelope curve is obtained [8]. By integration of the obtained information, that is, the distance and the azimuth, an initiation strategy can be given through the solution information of the maximum value of bell-like energy envelope curve [8] [10], which is a scheme to improve the underwater defense ability for ships.
1.1. Background
During attacking a high-speed small target in the wake field of ship, the passive acoustic fuze located in the wake field takes the noise signal received from the incoming high-speed small target to make clear the distance and direction information from the incoming target through the vertical linear array, and also receives an energy signal with bell-like pulse. When a high-speed small target sails closer and closer to the acoustic fuze, the radiated noise signal received from the acoustic fuze is gradually enhanced, and vice versa. When the distance is closest or the energy from the noise signal is the strongest, that is, when the incoming high-speed small target is closest to the acoustic fuze, an optimal initiation time can be given by the acoustic fuze to make the mutilation unit initiate and interfere or mutilate the incoming high-speed small target in the wake filed. The schematic diagram of the process is shown in Figure 1.

Figure 1. Schematic diagram of a ship attacked by an incoming target

2. Working environment and wave-inspection process of the passive acoustic fuze

2.1. Working environment of the passive acoustic fuze
During the sailing process of a ship, cavitation caused by the propeller, the rolling and breaking of sea waves, and the air involved from the waterline form an air curtain belt with a lot of bubbles at the tail of the ship, which is called the wake. The geometrical characteristics of the wake are closely related to the factors, such as the size and speed of ship and the wind speed of the sea surface, moreover, the acoustical characteristics of the wake are also related to these physical phenomena. Under normal circumstances, the length of the wake is about 20 ~ 50 times of the length of the ship, and the length can reach thousands of meters.

The passive acoustic fuze works in the noise of the wake field of ship. When a high-speed small target in the wake field approaches or attacks a ship, the fuze can receive the radiated noise from the incoming target as well.

2.2. Composition of the acoustic fuze
The passive acoustic fuze is composed of an acoustic array (ternary linear array), a processing circuit, a power supply circuit, a cable and other components.

2.3. Wave-inspection flowchart
The wave-inspection flowchart is shown in Figure 2.
After the acoustic fuze receives signal, it starts anti-aliasing filtration to receive signals in the working frequency band, then amplifies the signals by the first stage, after that, it takes signals into two parts, one part carries out broadband filtering so as to eliminate the interference from the anti-aliasing filtration and primary filtration, then amplifies signals by the secondary stage, which makes waveform to meet the requirement of extraction and obtain the information of target; the other part adaptively filters the signals in a selected frequency band, then analyzes the signals in the frequency domain to get interference signal characteristics and to determine whether the interference signal or in the harmonic produced by the interference signal exist or not in the working frequency band. Combining the result from two parts mentioned above and the actual process, it is necessary to eliminate the interference of the harmonic, lastly, judge the data of the extracted waveform, identify the target through the information such as the direction, speed, the closest distance by the acoustic fuze for the movement judgment.

2.4. Passive inspection positioning principle of the ternary linear array
The ternary array is arranged vertically under water, and the adjacent array elements are equidistant. The three array elements on the linear array are used to receive the noise in the wake area and the radiated noise from the incoming high-speed small target at the same time, and the distance and azimuth characteristics of the incoming high-speed small target can be solved through the delay estimation [5] [6] [13]. At the same time, by adjusting the beam shift of the ternary array and improving the signal-to-noise ratio, the ternary array can maximize the spatial gain $10 \lg 3 \text{dB}$ and effectively weaken the interference from other directions, which is beneficial to the inspection of the passing characteristics from the incoming target.

The signals received from two array elements are:

\[ x_1(t) = s_1(t) + n_1(t) \]
\[ x_2(t) = a s_2(t + \tau) + n_2(t) \]

In this equation, \( \tau \) is the time delay, \( x_1(t), x_2(t) \) are the signals received from the array elements 1 and 2, respectively, \( a \) is the constant attenuation factor, and \( n_1(t), n_2(t) \) are the background noise signals, respectively.

The mutual power spectrum method can be used to estimate \( \tau \). Firstly, make the received signals from the array elements 1 and 2 doing the fast Fourier transform, \( X_1(f) \) and \( X_2(f) \) are obtained and then the mutual power spectrum is calculated 

\[ G_{x_1 x_2}(f) = X_1(f)X_2^*(f) \]

In this equation \( f \) is the upper and lower limits of the received frequency, \( f_l \leq f \leq f_h \). The information of \( \tau \) is contained in the phase angle of the mutual power spectrum, and the equation can be obtained as follows:

\[ \phi(f) = 2\pi f \tau = \arctan \left( \frac{\text{Im}(G_{x_1 x_2}(f))}{\text{Re}(G_{x_1 x_2}(f))} \right) \]
To carry on the least square method fitting on $\varphi(f)$ and the optimal estimation of $\tau$ is finally obtained.

$$\hat{\tau} = \frac{1}{2\pi} \sum_{f=f_k}^{f_j} f \varphi(f)$$  \hspace{0.5cm} (4)

If the phase ambiguity occurs on $\varphi(f)$, the mutual power spectrum energy of the signals received from array elements 1 and 2 can be calculated, and the time delay difference can be measured by comparison of the peak search, and then $\hat{\tau}$ is obtained by the least square fitting as per the formula above.

2.5. Delay error analysis

The lower boundary of Cramer-Rao is [15]:

$$\sigma[\Delta(\hat{\tau})] = \left[ 2T^{2\sigma^2} (2\pi f)^2 \sqrt{r(f)^2} \frac{1}{1-r(f)^2} df \right]^{1/2}$$  \hspace{0.5cm} (5)

In the equation, $T$ is the sampling time of data, and $r(f)$ is the coherent spectrum of signals received from the array elements 1 and 2, $r(f)$ is defined as shown in the following equation:

$$r(f) = \frac{K_s(f)}{[K_a(f) + K_m(f)]^{1/2}}$$  \hspace{0.5cm} (6)

If the shapes of $K_a(f)$ and $K_m(f)$ are flat, and set $K_a(f) = S_0$, $K_m(f) = N_0$, $SNR = S_0 / N_0$ as the signal-to-noise ratio of the input, and $f_k \leq f \leq f_j$, therefore:

$$\sigma[\Delta(\hat{\tau})] = \left[ \frac{3}{8\pi^2 T} \frac{1}{SNR} \frac{1}{\sqrt{f_j^3 - f_k^3}} \right]^{1/2}$$  \hspace{0.5cm} (7)

The equation listed above is the delay estimation accuracy of the passive sonar under different signal-to-noise ratio [6] [16] [17].

3. Detection principle of energy method

Use the energy method to carry out the joint inspection, which is beneficial to the acoustic fuze in the detection of the incoming target.

It is supposed that at the time of $t$, the distance between the incoming target and the acoustic fuze is $r$, the horizontal distance is $s$, and the nearest distance between the incoming target and the acoustic fuze is $d$, and $\Delta t$ is at the stationary time, the distance between the incoming target and the acoustic fuze becomes $R$, the horizontal distance $S$, and the velocity of target $V$. Therefore, the following relations can be obtained:

$$r^2 = s^2 + d^2$$  \hspace{0.5cm} (8)

$$R^2 = S^2 + d^2$$  \hspace{0.5cm} (9)

According to the geometric relationship, the following equation can be obtained:

$$S = s - V \Delta t$$  \hspace{0.5cm} (10)

Take Equation (10) into Equation (8) and Equation (9); Equation (8) - Equation (9) = Equation (11):

$$r^2 - R^2 = s^2 - S^2 = V \Delta t (2s - V \Delta t)$$  \hspace{0.5cm} (11)

The relation between $R$ and $r$ actually is the relation between $s$ and $s - V \Delta t$.

According to the above physical model, ignoring the absorption of the medium, the intensity $I(t)$ equation of the radiated noise from the incoming high-speed small target can be established as follows:
\[ I(t) = \frac{I_0}{\sqrt{d^2 + s^2 - V\Delta t(2s - V\Delta t)}} \]  

(12)

In this equation, \( I_0 \) is the radiation intensity at 1m away from the sound source; \( X(k) \) is the envelope of sound pressure, and the sound intensity is \( I(k) = X^2(k) \).

4. Welch spectrum analysis

The smoothing average period method is also called Welch method. This method uses window-adding to obtain smoothing and uses piecewise overlap to obtain average. Therefore, it combines the advantages of average and smoothing as a whole and inevitably has the disadvantages of both, and it is ultimately a compromise method [15].

Set the received signals as:

\[ y_j(t) = y((j-1)K + t) \]
\[ t = 1, \ldots, M \]
\[ j = 1, \ldots, S \]

(13)

...is defined as the data segment at the sequence of \( j \). \( (j-1)K \) is the observation starting point at the sequence of \( j \). The value \( K \) is suggested as \( M/2 \), in this case, \( S = 2M/N \), and the window-adding period diagram of \( y_j(t) \) is calculated as follows:

\[ \hat{\phi}_j(\omega) = \frac{1}{MP} \left| \sum_{t=1}^{M} v(t)y_j(t)e^{-j\omega t} \right|^2 \]  

(14)

In this equation, \( P \) represents the "power" of the time window \( \{v(t)\} \):

\[ P = \frac{1}{M} \sum_{t=1}^{M} |v(t)|^2 \]  

(15)

Welch spectrum estimation can be obtained by averaging the window-adding period diagram for Equation (14):

\[ \hat{\phi}_n(\omega) = \frac{1}{S} \sum_{j=1}^{S} \hat{\phi}_j(\omega) \]  

(16)

5. Elimination of outliers and interference

5.1. Selection of eliminating threshold

The acoustic fuze obtains the incoming target through the characteristic curve, and the processing process of signals can refer to Equation (11). According to Equation (11), the variation distance is related to the velocity of the incoming target, the processing time is related to the horizontal distance from the acoustic fuze at the time of \( t \). Therefore, an appropriate value \( K \) can be selected and the product of the curve value at the previous moment can be used as the elimination threshold at the current moment.

5.2. Curve filtering and sharpness improvement of the curve

In order to improve the sharpness of curve, keep the position of the curve peak constant, and also make the steepness of the wave peak big, a standard line \( g(t) \) should be constructed. The part above the standard line \( f(t) \) should be retained or enhanced, and the part below the standard line should be eliminated or weakened.

The smoothing method is adopted for \( f(t) \) to obtain \( g(t) \). Take the smoothing factor \( h(t) \) as a simple average smoothing factor in order to better reflect the variation characteristics of the curve \( f(t) \).
\[ g(t) = h(t) * f(t) = \frac{1}{2N+1} \sum_{n=-N}^{N} f(t-n) \]  

(17)

Then, the standard line \( g(t) \) subtract from \( f(t) \) is \( z(t) = g(t) - f(t) \). From \( z(t) \), it can be deduced that:

\[
\hat{y}(t) = \begin{cases} 
z(t) & \text{if } z(t) > 0 \\
0 & \text{if } z(t) \leq 0 
\end{cases}
\]  

(18)

Take \( \hat{y}(t) \) multiplied by the magnification \( K \), \( y(t) = K\hat{y}(t) \) can be obtained, \( y(t) \) thus can achieve the purpose of improving the sharpness. 

In the practice of engineering, the ideal sharpness and variation characteristics can be obtained by selecting an appropriate value \( K \) for the envelope curve of the incoming target. Different selections of values \( K \) will lead to different elimination effects. Figure 3, Figure 4 and Figure 5 show the elimination results after selection of different values \( K \). When \( K = 1.3 \), it can be observed from Figure 2 that there is too much elimination, and the threshold tracking speed cannot keep up with the climbing speed through the characteristic curve, which results in elimination beyond limit. When \( K = 2.4 \), it can be observed from Figure 3 that the elimination effect is obvious, the outliers and the interference from pulses are eliminated, and the passing characteristic curve of the incoming target is smooth, which is beneficial to the subsequent processing. When \( K = 4 \), it can be observed from Figure 4 that the threshold of elimination is too high and the effect of elimination is not obvious because the threshold coefficient is too large.

![Figure 3. K=1.3](image1)

![Figure 4. K=2.4](image2)

![Figure 5. K=4](image3)

**5.3. Curve fitting**

The orthogonal polynomial least square method does not require that the fitted function \( y = f(x) \) passes through all points \((x_i, y_i)\), but requires that the residual error \( \delta_i = S^*(x_i) - y_i \) at the given point \( x_i \) should be minimized according to a certain standard. When \( \phi = \text{span}\{\phi_0(x), \phi_1(x), \ldots, \phi_n(x)\} \), a function \( S^*(x_i) \) can be found among them, therefore, the Euclidean norm \( \| \delta \|_2^2 \) is usually used as the measurement standard to minimize the error, the following equation can be obtained.

\[
\| \delta \|_2^2 = \sum_{i=0}^{n} \delta_i^2 = \sum_{i=0}^{n} [S^*(x_i) - y_i]^2
\]

\[
= \min_{S(x) \in \phi} \sum_{i=0}^{n} [S(x_i) - y_i]^2
\]

\[
S(x) = a_0\phi_0(x) + a_1\phi_1(x) + \cdots + a_n\phi_n(x)
\]

(20)
According to the given node \( x_0, x_1, \cdots, x_m \) and weight function \( \rho(x) > 0 \) \((n \leq m)\) with orthogonal weight function is created, which is expressed by a recursive equation \( P_k(x) \), and Equations (21) ~ (23) can be obtained:

\[
P_0(x) = 1
\]
\[
P_i(x) = (x - \alpha_i)P_{i-1}(x) \quad (k = 1, 2, \cdots, n - 1)
\]
\[
P_{k-1}(x) = (x - \alpha_{k+1})P_k(x) - \beta_k P_{k-1}(x)
\]

In this equation, \( P_k(x) \) is a polynomial at \( k \) with the coefficient of the first term as 1. According to the orthogonality of \( P_k(x) \), the following equation can be obtained.

\[
\alpha_{k+1} = \frac{\sum_{i=0}^{m} \omega(x_i)x_iP_k^2(x_i)}{\sum_{i=0}^{m} \omega(x_i)P_k^2(x_i)} = \frac{(xP_k(x), P_k(x))}{(P_k(x), P_k(x))} \quad (k = 0, 1, \cdots, n - 1)
\]

\[
\beta_k = \frac{\sum_{i=0}^{m} \omega(x_i)x_iP_{k-1}^2(x_i)}{\sum_{i=0}^{m} \omega(x_i)P_{k-1}^2(x_i)} = \frac{(P_{k-1}(x), P_k(x))}{(P_{k-1}(x), P_{k-1}(x))} \quad (k = 0, 1, \cdots, n - 1)
\]

According to Equations (21) ~ (25), the corresponding coefficients can be obtained during solving \( P_k(x) \) step by step.

\[
\alpha_{k+1} = \frac{(f, P_k)}{(P_k, P_k)} = \frac{\sum_{i=0}^{m} \omega(x_i)f(x_i)P_k^2(x_i)}{\sum_{i=0}^{m} \omega(x_i)P_k^2(x_i)} \quad (k = 0, 1, \cdots, n - 1)
\]

The fitting curve can be obtained by gradually adding \( a_k^*P_k(x) \) to \( S(x) \).

\[
y = S(x) = a_0^*P_0(x) + a_1^*P_1(x) + \cdots + a_n^*P_n(x)
\]

In the equation, \( n \) can be given in advance or determined according to the error in the calculation process.

6. Initiation timing strategy
Working condition 1: the distance-measurement and azimuth strategy

The distance and azimuth of the incoming target are obtained through the equidistant ternary linear array, and the calculation results are compared with the theoretical solution results. A continuous initiation signal will be given if the incoming target lies in the closest distance and with a maximum azimuth angle error.

Working condition 2: the maximum value estimation strategy for the envelope [10]

When the incoming target passes or approaches the acoustic fuze, the fuze will detect and receive a bell-like signal, which is generally expressed as:

\[
f(t) = \exp(-\alpha(t_0 - t_j)^2)
\]
It can be seen from the above equation that, if $t_x$ can be obtained, the intersection time of the incoming target and the passive acoustic fuze can be estimated (i.e., the closest distance). Take 3 points on the fitting curve of the envelope $[t_0, f(t_0)], [t_1, f(t_1)], [t_2, f(t_2)]$ in Figure 6.

\[
\ln(f(t_0) / f(t_1)) = T^2 (t_1 - t_0)(t_1 + t_0) \\
\ln(f(t_0) / f(t_2)) = T^2 (t_2 - t_0)(t_2 + t_0)
\]  

(29)  
(30)

The following equation can be obtained after sorting:

\[
T^2 = (z_j - z_i) / (t_1 - t_2) \\
z_i = \ln(f(t_0) / f(t_1))(t_1 - t_0) \\
z_j = \ln(f(t_0) / f(t_2))(t_2 - t_0)
\]  

(31)  
(32)  
(33)

After mathematical deduction, the attenuation exponent and the time of maximum value for the envelope can be obtained:

\[
\alpha = (z_j - z_i) / (t_2 - t_1) \\
t_x = 1 / 2(1 + r_2 + \ln((f(t_2) / f(t_1)) / (\alpha(t_2 - t_0)))
\]  

(34)  
(35)

Use the time of the maximum value for the envelope, that is, when the incoming target is the closest to the acoustic fuze, a continuous initiation signal can be given.

Working condition 3: Joint initiation strategy

Joint initiation strategy and priority principle: when the fuze works, if the working condition 1 gives the accurate distance and azimuth, the working condition 1 will be selected; otherwise, the working condition 2 will be selected. In some cases, the working conditions 1 and 2 can be adopted at the same time. The working condition 1 is adopted if the incoming high-speed small target is far away; otherwise, the working condition 2 should be immediately transferred to if the information of distance and azimuth in the ternary array at the working condition 1 appears fuzzy or even fails. The working conditions 1 and 2 also can be used together, that is, which first meets the specified requirements will give the initiation command.

7. Testing Verification

7.1. Dynamic comparison test

The ternary linear array arranged vertically, the spacing between array elements is 5m, the center depth of array element is 18 m, and the depth of the simulated sound source is 18 m, the sound source is 20m from the ternary array in horizontal direction. Simulate the sound source and the radiated noise of the moving incoming high-speed small target, from far to near, then near to far in order to make movement in straight line at V = 40kn, the closest distance from the ternary array is 19m, and the farthest distance is 200m, the test diagram is shown as follows:

Figure 6. Envelope diagram of the bell-like pulse Figure 7. Envelope diagram of the incoming target
Use the method of sound source simulation to carry out tests and study on the real-time distance and azimuth of the high-speed small target, during testing process, there is a certain deviation for the speed of the simulated high-speed small target, and the ternary array also exists certain position fluctuation influenced by the environment, but it is definitely that the deviation is rather big for the simulated moving target if the distance is far away, there is some fluctuation, but with the decrease of the distance, the error between the tested distance and the real distance of the ternary array also decreases; in aspect of the azimuth, the average deviation is about 7.6°, but as the distance approaches, the error becomes bigger and bigger, and the maximum error reaches up to 13.2°. The numerical treatment and prediction are carried out in Figure 7, Figure 8 and Figure 9 as per the collected noise data, which verifies the correctness and effectiveness of the calculation and the initiation strategy.

8. Conclusions
This paper proposes an instantaneous recognition method for the acoustic fuze against the incoming high-speed small target in the wake field of ship; the acoustic fuze recognizes the distance and azimuth information of the incoming high-speed small target by the ternary linear array. Through analysis of the delay estimation and the delay error, the accuracy of the location and direction is improved; by means of eliminating the outliers the interference and the corresponding filtering of signals to improve the sharpness of the curve and fit the curve further, therefore, the negative impact from the change of data can be eliminated. At the same time, the maximum estimation method is adopted based on the characteristics of the signal energy and the bell-like pulse received from the acoustic fuze. The construction and selection of the initiation strategy have been carried out through combining the complementary advantages of the two types of working condition obtained from the acoustic fuze. It is
proved by the testing data that the calculation method and the initiation strategy are effective and correct, having a certain practical engineering value for reference.

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