Multi-target Acoustic Localization Algorithm Based on Time-Frequency Transform

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Abstract
Aim at the problem that acoustic passive location technology for multiple supersonic targets is difficult to accurately identify the target when using the method of target passive detection, based on the five element cross array model and the high-speed target shock information, this paper proposes a method of time-frequency transformation to analyze the target acoustic array signals, chooses the appropriate filter parameters to eliminate the false signal and achieve accurately positioning. The experimental of live ammunition results show that this method can effectively improve the accuracy of the target parameter information from the high-acoustic array detection system, which has a certain guiding significance for the measurement of multi-target information.

Key words: Passive Acoustic Detection, Supersonic Target, Time-frequency Transformation, Recognition Information.

1. INTRODUCTION
At present, the measurement of target position information usually adopts the photoelectric test method. But this method will produce interference by changing in flux caused by non target information and affect the parameter measurement of target position information, and the use of acoustic detectors can effectively avoid the above problems. The detection of supersonic targets mainly adopts passive acoustic location technology, and is mainly applied to the measurement of shooting accuracy and empty shoot miss distance and the location of shooter and so on. Based on the rapid development of long-range supersonic precision strike and the limitations of radar early warning, a passive shock sound information detection method is proposed, which is used to detect supersonic weapons and a supplement to radar and infrared detection. In this scheme, the passive acoustic localization of multiple supersonic targets is the key issue in the research.

When the target is flying at supersonic speed, the shock wave is produce by air molecules, its surface is a conical wave front moving with the supersonic target. The shock signal received by the detection system is a pulsed sound signal with short duration (Enflo, 2015; Libal and Spyra, 2014). There are two methods for the passive acoustic localization of the supersonic target (Chen, and Song, 2016; Xiao and Li, 2002), one of the two methods is based on the strength of the shock acoustic pulse signal, and the distance between the target and the microphone is determined by the simple geometric relation. This method is based on the attenuation of sound waves in the air, such as the proposed acoustic measurement method of measuring the empty shoot miss distance of in literature (Xiao and Li, 2002; Li, 2015) and the measurement of the off-target of the tow targets in reference (Zhang and Ma, 2000), has the disadvantage of the distance of the microphone cannot be too large. Another approach is to establish a location model based on time-delay estimation by arranging the sensor array, and the localization model used for low-speed passive acoustic detection is of this type. For the positioning of supersonic targets, in 1970s, David E. Olive in the United States Naval Ordnance Laboratory put forward a mathematical model, which is a algorithm based on the arrival time of the shock and the delay gradient estimation, this algorithm uses more sensor, and the direction is poor. In the practical application, many problems need to be further studied.

Based on the five-element acoustic passive detection array model, this paper studied the principle of five-element cross passive acoustic detection and analyzed the target characteristic of supersonic target, proposed time-frequency transformation method using high-speed target shock information, effectively analyzed multiple supersonic target signal, select the best filter parameters to achieve accurately target acquisition, improve the accuracy of passive acoustic positioning system.

2. PRINCIPLE OF SOUND SENSOR DETECTION
When the target is flying at supersonic speed, the disturbance is too late to propagate due to the belated inertia of the air around the target. As a result, the gas is compressed and the strong disturbance is concentrated, which is mainly reflected in the rapid change of the air pressure. Therefore, the target will produce two kinds of acoustic signals in the process of flight: one shock wave is formed from strong vibration around the air when the...
detection target flying at high speed and the air for intense friction, eddy current, another is generated by the supersonic target (Enflo, 2015).

![Shock signal](image1)

Figure 1. Shock signal

![Sound pressure change at the detector](image2)

Figure 2. The sound pressure change at the detector

Figure 1 shows a schematic diagram of the shock wave generated by the warhead in supersonic flight. Pressure changes of the surrounding air will be affected by the shock wave, the direction of which is perpendicular to the path of the bullet, and finally, it is reflected in the sound pressure, sound field changes (Sen, Seiler, and Srulijes, 2016). Sound pressure detection equipment is placed at the lower end perpendicular to the trajectory of the bullet, it can obtain the sound pressure change information at the time of passage of the object so that the target parameters can be tested. As shown in Figure 2, when there is no target passing, assume that the sound pressure at the acoustic detector is $P_0$, when the target is flying at supersonic speed, the air is compressed and the air pressure is increased due to the passage of the target. The change in pressure is propagated to the acoustic detector at the time $t_0$ and reached its maximum value at time $t_1$. Then the air pressure decreases, and it is to a minimum at time $t_2$. Then it is gradually recovered and returned to the steady state at time $t_3$. Accordingly, the output signal of the sound pressure detector will detected the change of the sound pressure, and output electrical signal, the change trend of which is consistent with the change of sound pressure information. Finally, the relevant information of the target can be obtained through signal processing.

### 3. TARGET CHARACTERISTICS OF ACOUSTIC DETECTION AREA

When single target passes through the detection array, the target can be effectively identified by the design of the acoustic array structure. The traditional method uses threshold voltage, it cannot effectively distinguish the multiple targets. This is because the contribution of the acoustic array is superimposed when the multiple targets are present simultaneously (Li, 2016). The energy of the analog signal output by the detection circuit increases and the energy of the target signal exceeds the threshold voltage, so that only the target signal can be identified, the multi-target signal cannot be effectively identified, as well as the information about the target signal, which cannot process the interference signal and distinguish the effective signal. For a given signal, from the perspective of the frequency domain analysis, it consists of signal phase superposition of some different amplitude and frequency, as shown in the following expression.

$$w(f) = A_1 H(f_1) + A_2 H(f_2) + \cdots + A_n H(f_n)$$  \hspace{1cm} (1)

The $w(f)$ is a analog signal expression when the target through the test array, this signal can be converted to a signal with a frequency of $f_1, f_2, \cdots, f_n$ through the time-frequency conversion. The corresponding amplitude of $A_1, A_2, \cdots, A_n$, the signal can be converted from the time domain analysis to frequency domain analysis.

When multiple detection target signal are generated at the same time, the following expression can be obtained.

$$\begin{bmatrix}
w_1(f) \\
w_2(f) \\
\vdots \\
w_n(f)
\end{bmatrix} = \begin{bmatrix} A_1^1 & A_1^2 & \cdots & A_1^n \\
A_2^1 & A_2^2 & \cdots & A_2^n \\
\vdots & \vdots & \ddots & \vdots \\
A_n^1 & A_n^2 & \cdots & A_n^n
\end{bmatrix} \begin{bmatrix} H(f_1) \\
H(f_2) \\
\vdots \\
H(f_n)
\end{bmatrix}$$  \hspace{1cm} (2)

$w_i(f)$ indicates that there are $i$ target signals; other parameters have the same meaning as the expression (1). Therefore, we can get the multi-target signal characteristics by analyzing the amplitude-frequency characteristic of the signal.
4. FIVE ELEMENT PASSIVE ACOUSTIC LOCALIZATION MODEL

Acoustic localization theory is an acoustic detection method which can calculates the time difference of the target signal to reach N different sensors using the target signal received by the acoustic detector array, and then estimates the azimuth information of the target sound source (Yue, Wang and Zha, 2015). The five-element three-dimensional space acoustic sensor array model is shown in Figure 3.

![Figure 3: The five-element three-dimensional spatial acoustic sensor array model](image)

Assuming that the geometrical size of the target sound source S is far less than the acoustic signal wavelength when the detection distance is very far, the target sound source signal S is regarded as a point sound source, and the radiation form of the sound wave signal can be regarded as a spherical wave. According to the five element acoustic array model, assume the acoustic sensors are P1, P2, P3, P4 and P0 respectively represent four acoustic sensors with the same performance and which are located on the XOY plane. The acoustic sensors P1, P2, P3 and P4 distance from the main sensor P0 are R, azimuth angle is α (0 ≤ α ≤ π), pitch angle is β (0 ≤ β ≤ π/2), the acoustic source distance from the main sensor P0 is h. Through the geometric relationship between the acoustic sensor array and the target, we can obtain the following equations.

\[
\begin{align*}
  r^2 + 2hC\tau_1 - (Cr_1)^2 - 2hr\sin \beta \cos \alpha &= 0 \\
  r^2 + 2hC\tau_2 - (Cr_2)^2 - 2hr\sin \beta \cos \alpha &= 0 \\
  r^2 + 2hC\tau_3 - (Cr_3)^2 - 2hr\sin \beta \cos \alpha &= 0 \\
  r^2 + 2hC\tau_4 - (Cr_4)^2 - 2hr\sin \beta \cos \alpha &= 0
\end{align*}
\]

(3)

From the above formula, the distance of the acoustic source target from the main acoustic sensor can be obtained.

\[
h = \frac{C^2\sum_{i=1}^{4} \tau_i^2 - 4r^2}{2C\sum_{i=1}^{4} \tau_i}
\]

(4)

By figure (3) sort out can be obtained.

\[
\begin{align*}
  4hr\sin \beta \cos \alpha &= 2hC(\tau_1 - \tau_2) - C^2(\tau_1^2 - \tau_2^2) \\
  4hr\sin \beta \cos \alpha &= 2hC(\tau_1 - \tau_3) - C^2(\tau_1^2 - \tau_3^2)
\end{align*}
\]

(5)

By substituting the expression (4) into the expression (5), the azimuth angle α and the pitch angle β of the sound source target can be calculated.

\[
\tan \alpha = \frac{(\tau_2 - \tau_4)(2h - C(\tau_2 + \tau_4))}{(\tau_1 - \tau_3)(2h - C(\tau_1 + \tau_3))}
\]

(6)
The azimuth $\alpha$ and pitch angle $\beta$ of the sound source target can be derived.

\[
\sin \beta = \frac{1}{4hr} \sum_{i=1}^{4} \left[ r^2 + 2hCr_i - Cr_i^2 \right] \cos \left[ \alpha - (i-1)\frac{\pi}{2} \right] 
\]

(7)

The azimuth $\alpha$ and pitch angle $\beta$ of the sound source target can be derived.

\[
\begin{align*}
\alpha & \approx \arctan \left( \frac{r_2 - r_1}{r_1 - r_3} \right) \\
\beta & \approx \arcsin \left( \frac{C}{r} \sqrt{(r_1 - r_2)^2 + (r_2 - r_4)^2} \right)
\end{align*}
\]

(8)

From the formula, in determining the five element acoustic localization model, we only need the accurate detection of delay $\tau_i$ between each acoustic sensor and the main microphone. It can be seen that the accurate identification of the target signal is the key factor for the accurate localization of the five element acoustic array.

5. ANALYSIS OF MULTI TARGET ACOUSTIC DETECTION AND LOCALIZATION

Based on the five source sound localization model, using a high speed data acquisition system to build the platform. Multi target acoustic signal is collected by the sensor, it is shown in Figure 4, when multiple probe targets exist at the same time, the energy of the muzzle shock is the energy of the target shock wave for each detector. There exists a shock wave in each target’s muzzle shock wave at the same time.

Figure 4. Multi target shock signal

Figure 5 shows the single unit target acoustic detection waveform, Figure a is the single target signal waveform, the waveform changes and the theoretical analysis of the signal are consistent. Figure b shows waveform for multiple targets passing through the sound wave detector. From the two pictures, what we can directly observe is that the intensity of two signals is bigger than single signal.

Figure 5. Target shock simulation signal
Two signals above are transformed in frequency domain, and the characteristic of the target frequency domain is obtained as shown in Figure 6.

Figure 6. Signal transform in frequency domain

Figure a is a frequency domain signal of single target signal, it corresponds to a figure in Figure 5, when the target passes through the signal frequency detection array was 100KHz, a high frequency but relatively small amplitude of the signal at the 250–300KHz, the signal for the random interference signal, it will not influence the analysis of signal characteristics. Figure B is corresponding to the above B of the multi target signal spectrum transformation, in the figure, the target signal is at the position of 100KHz, there are two bands of signal a signal strength is bigger, a smaller intensity. When the same two goals passing through, there may be mutual influence caused by the change of pressure, but on the whole, the strength of the signal is bigger than single target signal, and because of the mutual influence, the characteristics of the signal is not only the superposition of single signal effect, in this experiment, the target signal frequency will be slightly increased.

In the quiet environment, the five cross array is built. The layout of the sensor array on a flat ground, the array distance is R=1m, using the acoustic detector of five element cross array as the origin to build a coordinate system, the other four acoustic detector coordinates are (R, 0, 0), (0, R, 0), (-R, 0, 0), (0, -R, 0). Acoustic detection target is rifle bullet shock signal with the 7.62mm, five source cross sensor array sound positioning data acquisition and processing are shown in Table 1-2.

<table>
<thead>
<tr>
<th>Sensor delay</th>
<th>T10(ms)</th>
<th>T20(ms)</th>
<th>T03(ms)</th>
<th>T04(ms)</th>
<th>X-axis X/m</th>
<th>Y-axis Y/m</th>
<th>Height Z/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>-5.09</td>
<td>-1.76</td>
<td>-5.23</td>
<td>-2.34</td>
<td>15.47</td>
<td>6.19</td>
<td>5.03</td>
</tr>
<tr>
<td>Second</td>
<td>-5.10</td>
<td>-1.78</td>
<td>-5.24</td>
<td>-2.35</td>
<td>15.27</td>
<td>6.32</td>
<td>4.60</td>
</tr>
<tr>
<td>Third</td>
<td>-5.08</td>
<td>-1.75</td>
<td>-5.22</td>
<td>-2.35</td>
<td>15.66</td>
<td>6.26</td>
<td>5.21</td>
</tr>
</tbody>
</table>

The set of test target coordinates is (15.8, 6.3, 5), according to the test data, the average value of the target coordinates is (15.47, 6.25, 4.9), the detection of the target horizontal X, vertical coordinate Y and the relative error of height Z are: δx = 0.33m, δy = 0.05m, δz = 0.1m.

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<th>T20(ms)</th>
<th>T03(ms)</th>
<th>T04(ms)</th>
<th>X-axis X/m</th>
<th>Y-axis Y/m</th>
<th>Height Z/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>-5.18</td>
<td>-1.91</td>
<td>-5.28</td>
<td>-2.41</td>
<td>19.09</td>
<td>7.44</td>
<td>5.88</td>
</tr>
<tr>
<td>Second</td>
<td>-5.05</td>
<td>-1.79</td>
<td>-5.20</td>
<td>-2.35</td>
<td>15.97</td>
<td>6.45</td>
<td>4.75</td>
</tr>
<tr>
<td>Third</td>
<td>-5.21</td>
<td>-1.96</td>
<td>-5.31</td>
<td>-2.46</td>
<td>18.82</td>
<td>7.56</td>
<td>4.48</td>
</tr>
</tbody>
</table>

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<tr>
<th>Sensor delay</th>
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<th>T20(ms)</th>
<th>T03(ms)</th>
<th>T04(ms)</th>
<th>X-axis X/m</th>
<th>Y-axis Y/m</th>
<th>Height Z/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>-5.12</td>
<td>-1.87</td>
<td>-5.24</td>
<td>-2.38</td>
<td>17.58</td>
<td>7.22</td>
<td>5.20</td>
</tr>
</tbody>
</table>
The detection targets are two rifle bullet shock signal. Table 2.1 shows the multi target acoustic array data that are detected directly, Table 2.2 shows the test data that through the time-frequency transform, select the appropriate filter parameters to eliminate the different signals, and then we can get delay time of the real target. According to the test data, the average coordinate of the detection target is (17.31, 7.27, 5.29) according to Table 2.2-a. According to Table 2.2-b, the average coordinate of the detection target is (17.26, 7.27, 5.32).

Comparing two groups of experimental data, a accurate coordinate information about target signal can be obtained. As for multiple sound position detection, because sound signals exists multiple target signals, there are always some errors because of false signals, we should set parameters correctly, then the errors can be eliminated by time-frequency transform.

6. CONCLUSIONS

This paper studies five source cross passive acoustic detection array model based on supersonic detection, uses the supersonic multi-target positioning algorithm of high speed shock target information, uses the method of frequency conversion to spectrum analyze the target signal the collected, obtained the frequency characteristics of signals with multiple targets by a single target acoustic array in acoustic array test environment, accurately identifies the target information, achieves effectively poisoning for multiple target signals. The test results show that in the detection of the target signal, the signal collected by the detector is the sum of target signal energy, and it is difficult to distinguish the real target signals, through the target signal time-frequency transformation, multiple signals and false targets can be accurately distinguished. The method lays a foundation for the research and acoustic array analysis on the multi signal in the test environment, which has a certain guidance significance.

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