Simulation and Experimental Research on Underwater Target
HBT Interference Positioning Method

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Abstract. To realize the positioning of underwater sound sources, a target positioning method based on acoustic field HBT interference is proposed. The precision of HBT interferometric target locating principle is verified by simulation under different parameters. The positioning effect is simulation analyzed at different frequencies with multiple sound sources. The results show that the position of the sound source can be found accurately by this method for single frequency source and multiple sources. At the same time, the positioning experiment in lake is carried out. The results verify the correctness of HBT positioning method and realize the orientation of single and multiple frequencies with the level of 180 dB which the distance of the sound source is 59 meters.

1. Introduction

With the rapid growth of China’s economy and the improvement of China’s comprehensive national strength, national defense security measures need to be strengthened accordingly. Nowadays, sonar equipments use underwater acoustic sensor array to detect corresponding targets. However, when the target acoustic signal is transmitted over a long distance in sea water, the effective signal is very weak, and its energy attenuation and waveform change are very large, which causes great inconvenience to signal detection and subsequent analysis. Therefore, it is of great significance for China’s marine safety to study the detection of long-range signals[1-2].

At present, the main passive acoustic source positioning methods can be divided into three categories: time different of arrival (TDOA), target motion analysis (TMA) and matched-field processing (MFP). The passive positioning method based on TDOA[3-4] can achieve high accuracy in short-range positioning, but it is difficult to achieve long-range accurate positioning due to the increase of time delay and difficulty in extracting distance information. TMA is a mature remote passive positioning method at present[5-6]. Its key technology is to utilize the dynamic information of the target, but this algorithm has a large amount of computation. MFP makes full use of all available information in underwater acoustic source, ocean channel and hydrophone array. It has good prospects for low-frequency and long-range target localization, but it still has a large amount of calculation and depends strongly on environmental parameters[7].

In this paper, a target positioning method based on Hanbury Brown-Twiss (HBT) interferometry is proposed. This method not only has small size and strong anti-interference ability, but also can locate single-frequency and multi-source. The correctness of the method is proved by simulation and lake water experiment.
2. Positioning principle

2.1. HBT interference principle

The second-order interference phenomenon of light was first proposed by R. Hanbury Brown and R. Twiss in 1956. They designed a new type of interferometer of light intensity for measuring the diameter of star Angle, namely the HBT interference device. The experimental schematic diagram of the HBT experiment in the visible band in the modern laboratory is shown in Fig.1. The light field from a thermal light source S passes through a 50:50 beam splitting prism BS and is divided into two beams, which are respectively entered into the point detector D1 and D2, and then the intensity correlation measurement is carried out for the signals measured by D1 and D2. Usually, the position of one detector is fixed, such as D1 is fixed, that is, \( x_1 \) is not changed, and then the other detector D2 is scanned to obtain the correlation between the intensity values of the two detectors, that is, the HBT value. Namely, to get the relationship between the correlation function and the relative positions of the two detectors, \( x_1 \) and \( x_2 \).

\[
G^{(2)}(x_1, x_2) = \frac{\langle I(x_1)I(x_2) \rangle}{\langle I(x_1) \rangle \langle I(x_2) \rangle} = \frac{\langle I(r_1, t_1)I(r_2, t_2) \rangle}{\langle I(r_1, t_1) \rangle \langle I(r_2, t_2) \rangle}
\]  

When the relative distance between two detectors is zero, the correlation function is the maximum. As the distance between the two detectors D1 and D2 increases, the value of the correlation function gradually decreases and eventually tends to a constant.

2.2. HBT interference positioning in underwater acoustic field

Sound field is similar to light field, both of which have the property of fluctuation. As shown in Fig.2, the sensor \( M_i \) represents the position of the underwater acoustic sensor array. The sound source \( S' \) is the position where the sound source may appear. Taking one of the sensors as the origin to establish a coordinate system. Suppose there is an underwater sound source \( S \), whose coordinates are \((X, Y)\), and the signal is transmitted to the sensor array. 

\[
g^{(2)} = \frac{\langle I(x_1)I(x_2) \rangle}{\langle I(x_1) \rangle \langle I(x_2) \rangle} = \frac{\langle I(r_1, t_1)I(r_2, t_2) \rangle}{\langle I(r_1, t_1) \rangle \langle I(r_2, t_2) \rangle}
\]
The sound source travels in the form of spherical waves, so its amplitude will decrease inversely with distance $r$, thus, the signal $P_i$ received by the sensor can be represented as:

$$P_i = N_i + \frac{A_i}{r_i} \cos \left[ \omega_i (t - \frac{r_i}{v}) + \phi_i \right]$$

(3)

Where, $N_i$ represents the environmental noise, the $A_i$ represents the amplitude of sound source emission, $r_i$ represents the linear distance between the sensor $M_i$ and the sound source $S$, the $\omega_i$ indicates the angular frequency of the sound source received by the sensor. The $v$ represents the speed in water.

The distance from the sound source to the sensor is different, and the time to reach the sensor is different. Therefore, the time delay $\Delta T_{ij}$ of the signal received by the sensor is represented as:

$$\Delta T_{ij} = \frac{r_i - r_j}{v}$$

(4)

Where $r_i$ and $r_j$ are the distances from the sound source position $S$ to the two sensors respectively.

Calculate the normalized HBT correlation function according to the time delay, in order to find the position where the time delay between the signals received by the sensor is zero, therefore, one of the signals is time-compensated to calculate the correlation function, and the HBT correlation function $C(\Delta T_{ij})$ is obtained as follows:

$$C(\Delta T_{ij}) = \frac{\langle P_i(t) \bullet P_j(t + \Delta T_{ij}) \rangle}{\langle P_i(t) \rangle \bullet \langle P_j(t) \rangle}$$

(5)

Where $P_i$ represents the signal received by the $i$th sensor, and $P_j$ represents the signal received by the $j$th sensor.

Assuming that the sound source position is the actual sound source positioning, and the correlation function is the maximum value. The delay $\Delta T$ is defined by:

$$\Delta T = \frac{R_1 - R_2}{v}$$

(6)

The maximum correlation function $C_{\text{max}}$ is:

$$C_{\text{max}} = \frac{\langle P_i(t) \bullet P_j(t + \Delta T) \rangle}{\langle P_i(t) \rangle \bullet \langle P_j(t) \rangle}$$

(7)

In this way, the HBT correlation function is calculated for all points in the range where the sound source may occur. The position of the largest correlation function can accurately find the positioning of the sound source.

3. Simulation analysis

Passive sonars receive signals transmitted from seawater and needs to judge its properties and measurement parameters. Therefore, the positioning analysis is carried out for different environmental parameters. The number of different frequencies and the number of different sound sources are analyzed.
3.1. Number of different frequencies
Target signals received by hydrophones are mainly from the radiated noise of ships. There are many kinds of machines in submarines. The frequency spectrum of these noises is continuous in the low frequency range, but sometimes the line spectrum will appear. Therefore, the number of frequency components also has a great impact on localization. In the actual environment, the sound source frequency component is complex, generally not a single, and the simulation analysis is performed on the case where the sound source has a single to multiple frequency components. Table 1 shows the different frequency components of the sound source and their corresponding positioning results. Fig. 3 is the simulation diagram of sound source positioning under three conditions.

Table 1. Source frequency components and positioning results

| Number | Target positioning | Frequency component | Simulation results |
|--------|--------------------|---------------------|-------------------|
| a      | (5000, 300)        | 500Hz               | (5025, 300)       |
| b      | (5000, 300)        | 500Hz, 477Hz        | (5000, 300)       |
| c      | (5000, 300)        | 500Hz, 322Hz        | (5000, 300)       |

Fig. 3 (a) is positioned as (5025, 300), and Fig. 3 (b) and (c) are positioned as (5000, 300). The position of sound source can also be found for a single frequency component, but there is a certain error in positioning, and there are many interference fringes in other positions. Comparing Fig. 3(b) with 3(c), when the interval between frequency components is large, the bright fringes are more obvious, and the other interference bright fringes are less, the more accurate the positioning is.

3.2. Number of different sound sources
Considering the complex marine environment, there may be two similar sound sources, such as reflections caused by fishes or reefs. It is assumed here that the frequency components received by the two sound sources are 510Hz, 170Hz, 65Hz, and 500Hz, 177Hz, 61Hz, respectively. Five triangular arrays are selected here for remote positioning. The position coordinates of the three small arrays are (0, 0), (0, -10), (0, -190), (0, -1200), (2, -1205), (0, 1010), (0, 1000), (2, 995). The position coordinates of the two large arrays are (0, -880), (0, -920), (20, 940), (0, 520), (0, 480), (20, 460), in meters. As shown in Fig. 4, the simulation results of positioning of two sound sources are shown.

Figure 4. Two sound source simulation results
As shown in Fig. 4(a), the positioning results are (4050, 300) and (3950, 300), as shown in Fig. 4(b), the positioning results are (5075, 320) and (4875, 280). When the sound source position is 4000 meters and 5000 meters, five triangular arrays can be used to accurately locate multiple sound sources. However, since the frequency components of the two sound sources are very similar, the similar influence of the sound source signals will cause positioning errors, but the results are basically consistent with the actual sound source positioning.

4. Lake positioning experiment
In order to verify the correctness of this principle in underwater positioning, the target positioning experiment in lake is carried out. In the actual lake environment, the ship can only be fixed in one direction, so only the underwater sound source orientation experiment is completed.

4.1. The experimental scheme
Three sensor orientation experiments are designed, and the experimental scheme is shown in Fig. 5. The experiment is carried out in a 500m × 500m water area. The signal amplifier is connected to the transducer as the sound source for signal output. A hydrophone array composed of three hydroacoustic sensors is used to conduct directional experiments on sound sources, and change the frequency number of sound source to conduct directional experiment.

![Figure 5. Lake water experiment program](image)

4.2. Experiments on the Number of Different Frequencies
Experiments are carried out on different frequency components of the sound source. A coordinate system is established as shown in Fig. 5. The position coordinates of the three hydrophones are (0, 0), (-0.25, 0), (-0.48, 0). When the coordinate of the sound source is (59, 0), the different frequency components are analyzed.

1) Single Frequency Pulse Wave
When the transducer transmits a pulse signal with a frequency component of 8 kHz, the sampling waveform and orientation results are shown in Fig. 6. The final test results show that the orientation direction is (59, 1.5), the orientation error is 2.5% per meter, and there are not many bright fringes. So even if the frequency component of the signal transmitted by the transducer is single, the sound source can be orientated, which is consistent with the simulation results.
(2) Dual-frequency pulse wave

When the frequency components transmitted by the transducer are 8kHz and 19kHz, the sampling waveform and orientation results are shown in Fig. 7. The result of the final test is (59, -1) and the orientation error is 1.7%. When the difference between the two frequency components becomes larger, the bright fringes of the correlation function are more obvious, and the error is reduced compared with the single-frequency sound source signal.

5. Conclusion

The HBT interference theory in optical measurement is applied to underwater acoustic field, and a target positioning method based on HBT interference in underwater acoustic field is proposed. The simulation analysis is carried out under different frequency components and multiple sound sources of the sound source. The simulation results show that the method can realize single-frequency and multiple sound source localization. The lake water positioning experiment was carried out, and the lake water experiment realized the orientation under single frequency and multi-frequency conditions at 59 meters. The experimental results were consistent with the simulation results.

Acknowledgments

This project is supported by National Natural Science Foundation of China (Grant No.51805154), State Key Laboratory of Precision Measuring Technology and Instruments (pilab1805&1708), Key Project of Educational Commission of Hubei Province of China (D20131407), and Special Fund in the Public interest of General Administration of Quality Supervision Inspection and Quarantine of P.R.China (201310004).

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