Experimental Study on a Target Direction Finding Algorithm for Gas Leakage Detection in Underwater Structures

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Abstract. Aiming at the application scenarios of underwater structure gas leakage detection in marine oil and gas development process, the power spectrum characteristics of underwater structure gas leakage radiation noise are analyzed. An new target direction finding algorithm is proposed, and the gas leakage detection-finding software is designed. Then, the test platform is built to complete the experimental study of underwater structure gas leak detection. The test results show that the new target direction finding algorithm used in this paper is compared with the conventional beam forming algorithm. The difference between the maximum beam energy value and the sub-maximum value is bigger, indicates that the target's resolving power is strong, which effectively improves the detection capability of gas leakage targets in underwater structures.

Keywords: passive sonar; direction finding algorithm; underwater structure; gas leakage detection.

1. Introduction
In the development of marine oil and gas resources, various underwater structures are deployed on the seafloor for the exploitation and transportation of marine oil and gas. When gas leakage occur in these underwater structures, combustible gas of up to tens or even hundreds of megapascals will be ejected from the leak at high speed, which will seriously threaten the safety of personnel and facilities and endanger the marine environment. At present, the technical methods for gas leakage detection and location of underwater structures mainly include mass balance method, pressure distribution method, negative pressure wave detection method, etc. [1] These methods have different detection principles. They judge whether gas leakage occurs by detecting whether the inflow and outflow quality of the pipeline is balanced, whether the internal pressure distribution of the underwater structure is abnormal, and whether a strong pressure wave is generated in the fluid medium [2]. Although they can effectively detect the occurrence of gas leakage, there are disadvantages such as the inability to accurately locate the leak point, the need to pre-install sensors in the underwater structure, or the high cost of the detection system. In addition to the above methods, sonar technology can also be used to detect gas leakage in underwater structures, which can be specifically divided into active sonar detection technology and passive sonar detection technology.
When a gas leakage occurs in an underwater structure, the high-pressure gas jetted from the leak point will form bubbles in the nearby waters, and the leak point will produce radiation noise with a sound source level much higher than the environmental background and certain characteristics. Active sonar detection technology uses image sonar to detect whether there is a bubble group in the target area to determine whether there is a leakage [3]; and the passive sonar detection technology uses whether the radiation noise intensity is stronger than the background noise to determine whether there is a leakage. Compared with other detection methods, the sonar detection technology is an external inspection method. It does not need to install the measuring equipment on the measured object in advance, and only needs to deploy the sonar array in the detection area, which has the advantages of easy expansion and easy installation. In addition, compared to active sonar, passive sonar does not generate acoustic signals to interfere with other acoustic equipment used in the oil production, and passive sonar systems have lower power consumption and longer lifespan [4]. At present, there are some mature products abroad that use passive sonar technology to detect gas leaks in underwater structures. Such as the Norwegian NAXYS company, the Italian Co.L. Mar company, the British Neptune Oceanographics company, and the Swiss Weatherford company, all of them have related products [5]. There are only some theoretical studies in this area in domestic, and no relevant products have appeared in the market. This paper first studies the power spectrum characteristics of the radiated noise from the gas leakage of underwater structures, then proposes an gas leakage target direction finding algorithm, which divides broadband noise into multiple sub-bands in the frequency domain, performs constant beamwidth beamforming on each sub-band, and then coherent accumulates multiple beams processed by the sub-bands to improve the detection ability of low noise targets.

2. Gas leakage noise characteristics

2.1. Signal acquisition environment
The experiment site is Lake F in Yuxi City. The hydrophone is placed about 10m outside the dock. An air compressor with a rated pressure of 18Mpa is used to generate high-pressure gas for simulating gas leakage, and a gas leakage simulator is designed to simulate the state of an underwater structure when gas leakage occurs. The air compressor and the gas leakage simulator are connected by a high-pressure air pipe. In the experiment, the distance between the air compressor and the dock exceeds 100m, and the ship must carry the gas leakage simulator away from the shore for more than 100m, and the total length of the high-pressure air pipe exceeds 200 meters. The pressure display in reducing valve at the leakage point can only reach 10Mpa, on account of long-distance transmission.

2.2. Gas leakage simulator
When a real gas pipeline leaks, it basically occurs at the joints of the pipelines, and the pipeline itself is rarely damaged. This paper has designed gas leakage simulator. As shown in Figure 1, the upper and lower pipelines have a diameter of 100mm (the real submarine oil and gas pipeline is usually 400–1000mm in diameter). One end of the pipeline has a gas source connector, one end of the pipeline is closed, and the other flange connection is used between the two pipes. The closing surface of the flange is filled with a rubber sealing ring, and there is a screw hole on the flange. The two pipes are fastened and closed with screws.

In the experiment, a 4mm leakage aperture was cut out on the sealing ring. When the channel was filled with high-pressure gas, the gas was ejected from the leakage aperture, which simulated gas leakage at the joint of the gas pipeline.
Figure 1. Gas leakage simulator

Figure 2 shows the usage scenario of the gas leakage simulator. In the picture, the air source connector is connected to the high-pressure gas cylinder through the rubber gas pipe, and it is actually connected to the air compressor in the experiment.

Figure 2. Usage scenario of gas leakage simulator

2.3. Statistical analysis of gas leakage noise

A hydrophone was used to collect gas leakage noise, and an ADC (Analog to Digital Conversion) with a sampling rate of 100 kHz and a sampling accuracy of 16bit was used to sample the analog signal of the hydrophone. The analog signal passes through a 2 kHz-20 kHz band pass filter before entering the ADC. Figure 3 shows the normalized power spectrum of radiated noise during gas leakage. An air compressor is used to generate a 10Mpa high-pressure gas at a water depth of 30m and a distance of 100m from the hydrophone. The high-pressure gas is released from a 4mm leakage aperture in gas leakage simulator. Figure 3 is the result of collecting five times signals and every signal duration of 5s, respectively calculating the power spectrum five times and averaging all. The references [6-10] shows that the gas leakage spectrum characteristics are closely related to the leakage point pressure and the leakage point aperture: when the leakage pressure increases, the entire spectrum moves to the high frequency direction, and the noise source level increases at the same time; the leakage point aperture increases When it is large, the entire spectrum moves in the low frequency direction.

Figure 3. Gas leakage radiation noise normalized power spectrum (statistical average)
2.4. Analysis of the transient characteristics of gas leakage noise

In the experiment, the whole continuous gas leakage time is 120s-500s. In many short continuous time periods (20s-60s), the gas leakage noise has a strong energy line spectrum, but it cannot be maintained stably during the entire gas leakage period. The analysis shows that it is caused by the instability of the test equipment. The high-pressure air pipe between the air compressor and the gas leakage simulator is too long to maintain stable pressure at outlet. In addition, the air compressor cannot maintain a constant pressure for a long time, and the pressure gradually decreases over time, and the decrease process is not absolutely linear. Therefore, although the gas leakage noise has an obvious line spectrum, it cannot be maintained at the same frequency point, and the amplitude is relatively random.

Figure 4 shows the power spectrum of a signal with a total duration of 20s. Each small image in the figure corresponds to a 5s time-domain sampling signal. In the figure, a strong line spectrum appears near 27 kHz.

![Figure 4. Gas leakage radiation noise normalized power spectrum](image)

3. Algorithm design

As shown in Figure 5, the radiated noise generated by gas leakage is a broadband signal. Aiming at this feature, this paper proposes a beamforming algorithm for gas leakage target detection, which divides the wideband signal into different sub-bands after DFT transformation, constrains the beam width of different frequency bands, keeps it constant, and processes multiple frequency bands. The coherent accumulation of multiple beams improves the output signal-to-noise ratio of beamforming, that is, the ability to detect low-noise targets.

The main lobe width of conventional broadband beam formation varies with frequency. Only when the target is in the direction of the beam, can the power spectrum of each frequency remain unchanged. With constant beamwidth beamforming, as long as the target is located in the main lobe, it can ensure that the power spectrum in its working frequency band is not distorted [11].

There are basically three types of constant response beamforming methods: The first type of method is to use the relationship between the beam pattern and frequency and aperture, according to a reference frequency beam weight vector, and use an analytical method to obtain other frequency beam weight vectors in the working frequency band; The second type of method is a numerical method, which designs beams with expected response for each design frequency, so that the beam response in the working frequency band is close to the expected beam response; The third type of method is a broadband beamforming method based on focus transformation. According to the idea of broadband spatial spectrum estimation, the data on different frequency sub-bands are transformed to a reference frequency through a transformation matrix. This method only requires an array, and the calculation amount is small, and it can effectively overcome signal cancellation and process multipath signals [12]. The specific method of low-noise target detection beamforming algorithm is:

Step 1: Perform DFT on the M channel signal \( X_m(t) \) collected by the sonar array element to obtain its frequency domain data \( DFT[X_m(t)] \), divide \( DFT[X_m(t)] \) into multiple sub-bands, each sub-band meets the narrowband condition, and each sub-band takes the center frequency, that is, the center frequency of the jth sub-band is \( f_j \).

Step 2: Construct amplitude beam control window function vector \( w_{M\times1} \), focus matrix \( T(f_j) \), spatial steering vector matrix \( A(f_j, \theta) \), where \( \theta \) is the beam direction. Expand vector \( w_{M\times1} \) into \( M \times K \) dimensions Matrix \( w \times 1_{1\times K} \), where \( K \) is the index of \( \theta \). Take the product of the focus matrix \( T(f_j) \)
and the spatial steering vector matrix \( A(f_j, \theta) \) and take the Hadamard product with \( w \times 1_{1 \times K} \) to obtain \((w \times 1) \odot T(f_j) A(f_j, \theta)\);

Transpose \((w \times 1) \odot T(f_j) A(f_j, \theta)\) and multiply \(DFT[X_m(t)]\) and integrate with frequency \( f \), and the space detection output \( y(\theta_k) \) is obtained.

\[
y(\theta_k) = \left[(w \times 1) \odot T(f_j) A(f_j, \theta) \right]^T \times DFT[X_m(t)] df
\]

\( w_{M \times 1} \) is the amplitude beam control window function vector. In this paper, the sidelobe level of the constrained beam is constant, and it is designed as a Chebyshev window function of -30dB sidelobe level;

\( T(f_j) \) is the focus matrix. The focus matrix focuses data on different frequency sub-bands to a reference frequency through transformation without changing the content of the signal. The broadband beamforming method based on focus transformation obtains constant beamwidth response beamforming. In order to achieve the goal of constant beamwidth, the focus matrix should satisfy the following equation [13].

\[
T(f_j) A(f_j) = A(f_0), j = 1, \ldots, J
\]

\( f_j \) is any frequency in the bandwidth, and \( f_0 \) is the reference frequency, that is, the focus frequency. If \( T^H(f_j) T(f_j) = I \), that is, the focus matrix \( T(f_j) \) is the chief matrix, and the focus gain can take the maximum value 1. The focus transformation will not change the signal-to-noise ratio of the array output, nor will it affect the statistical characteristics of the noise signal. The acquisition of the best focus matrix is the process of solving the optimization problem under constraints.

\[
\begin{cases}
\min \| A(f_0, \theta) - T(f_j) A(f_j, \theta) \|_F^2, j = 1,2,K,J \\
T^H(f_j) T(f_j) = I
\end{cases}
\]

Solving the above equation, we can get:

\[
T(f_j) = V(f_j) U^H(f_j), j = 1, \ldots, J
\]

\( U^H(f_j) \) is a matrix composed of the left singular vectors of the matrix \( A(f_j, \theta) \), and \( V(f_j) \) is a matrix composed of the right singular vectors of the matrix \( A^H(f_0, \theta) \).

\( A(f_j, \theta) \) is the space steering vector matrix, the expression is:

\[
A(f_j, \theta) = [a(f_j, \theta), a(f_j, \theta), \ldots, a(f_j, \theta)]
\]

\[
a(f_j, \theta_k) = \begin{bmatrix}
\exp(-i \frac{2 \pi f_j \sin \theta_k}{c} \frac{M-1}{2}) \\
\exp(-i \frac{2 \pi f_j \sin \theta_k}{c} \frac{M-3}{2}) \\
\vdots \\
\exp(+i \frac{2 \pi f_j \sin \theta_k}{c} \frac{M-1}{2})
\end{bmatrix}
\]

4. Lake experiment and software design

4.1. Experiment program

The internal pressure of the underwater structure for offshore oil and gas exploitation is about a few MPa to tens of MPa, and the highest working pressure is even more than 100 MPa. In the lake experiment, due to the limitations of air compressor pressure, the real leakage of oil and gas pipelines cannot be fully simulated. According to the discussion in Section 2 above, the higher the gas leak pressure, the stronger
the radiated noise source level and the higher the frequency of the center of the spectrum, which is more conducive to the working conditions of the passive sonar. Therefore, the test results can be extended to the real oil and gas production environment.

The experiment site is Lake F. Figure 5 shows the placement position of the sonar array and the gas leakage simulator during the lake experiment. First, the sonar array is placed at a predetermined position to 30m underwater with fix direction. After that, the ship carries and gas leakage simulator, takes the placement point of the array A as the coordinate origin, and the true north is 0° direction, and sails to (300m, 38°), (200m, 14°), (100m, 26°) three positions, at a depth of 30m, release high pressure gas of 10Mpa.

Figure 5. Experiment program

Figure 6 shows the hydrophone array, which consists of 24 array elements arranged at equal intervals of 0.075m to form a line array. Figure 7 shows the overall structure of the sonar array. The two hydrophone arrays (line arrays) A and B are respectively fixed to the two ends of the overall frame structure. The center spacing is 20m. The two line arrays form a passive dual-array system used to locate the target. Figure 8 shows the deployment scene of the sonar array. Figure 9 shows the bubble group formed on the water surface when gas leakage simulator releases high-pressure gas underwater.

Figure 6. Hydrophone array

Figure 7. Sonar array structure

Figure 8. Deployment scene of the sonar array
4.2. Algorithm verification

In order to verify the performance of the algorithm proposed in this article, the conventional beamforming algorithm (CBF algorithm, specifically using digital interpolation beamforming) is used as the object of comparison. Taking into account the sonar array processing frequency corresponding to the element spacing, the signal is subjected to digital low-pass filtering with a cut-off frequency of 15kHz before data processing.

In the experiment, the only variable is the position of the gas leakage simulator. All other operating conditions remain unchanged, only the algorithm is switched between algorithm mentioned in this article and the CBF algorithm in the software.

In the experiment, there is only an effective target the gas leakage noise. Due to the natural directivity of the line array, the background noise is enhanced in the 0° direction. For the scenario of a single effective target, except for the real target, in most cases, the sub-maximum beam energy is located at the side lobe of the target or 0° direction. The difference between the maximum value and the sub-maximum value of the beam energy can judge the quality of the beamforming algorithm.

For ease of description, "LNBF" (Leaking noise Beam Forming) is used to refer to the algorithm proposed in this article. The $\Delta E_{\text{LNBF}}$ represents the difference between the maximum value and the sub-maximum value of the beam energy obtained when the algorithm is used to detect the target. In the same way, $\Delta E_{\text{CBF}}$ represents the result of CBF algorithm.

In the experiment, the line arrays A and B have the same function and are used for direction finding. The linear array A is selected as the research object below. Figure 10 shows the beam pattern comparison of the CBF algorithm (dashed line) and the LNBF algorithm (solid line), when the gas leakage point is located at an azimuth of 38° and a distance of 300m. As shown in the figure, $\Delta E_{\text{LNBF}} = 10\, \text{dB}$, $\Delta E_{\text{CBF}} = 5\, \text{dB}$.

Figure 11 shows the beam pattern comparison of the CBF algorithm (dashed line) and the LNBF algorithm (solid line), when the gas leakage point is located at an azimuth of 14° and a distance of 200m. As shown in the figure, $\Delta E_{\text{LNBF}} = 25\, \text{dB}$, $\Delta E_{\text{CBF}} = 12\, \text{dB}$.
Figure 11. Direction finding algorithm comparison at 200m/14°

Figure 12 shows the beam pattern comparison of the CBF algorithm (dashed line) and the LNBF algorithm (solid line), when the gas leakage point is located at an azimuth of 26° and a distance of 100m. As shown in the figure, $\Delta E_{LNBF} = 40\text{dB}$, $\Delta E_{CBF} = 14\text{dB}$.

Figure 12. Direction finding algorithm comparison at 100m/26°

Table 1 is a comparison table of beam energy between the CBF algorithm and the LNBF algorithm at different distances. The LNBF algorithm has a stronger ability to detect the target direction at all distances than the CBF algorithm. Due to the limitation of pipeline length in the test, the maximum distance was only tested to 300m. According to Table 1, it is not difficult to infer that when the distance exceeds 300m, at a certain distance, when the $\Delta E_{CBF}$ becomes "0", It means that the real target cannot be distinguished from background, and at this time the $\Delta E_{LNBF}$ is greater than "0", and there is still a certain resolution ability.

| Energy Difference | 300m | 200m | 100m |
|-------------------|------|------|------|
| $\Delta E_{CBF}$(dB) | 5    | 12   | 14   |
| $\Delta E_{LNBF}$(dB) | 10   | 25   | 40   |

4.3. Software design

LabVIEW platform was used to design the direction-finding software for underwater structure gas leakage, and the software implements two direction-finding algorithms of CBF and LNBF. LabVIEW is a software development platform for measurement and control engineering launched by NI (National Instruments). It has various encapsulated digital signal processing functions, including FFT, FIR/IIR filtering, etc. LabVIEW can even directly call MATLAB source code through MATH-SCRIPT. These features enable engineers to focus on algorithm development, rather than the software design, greatly improves development efficiency.
Figure 13 is a screenshot of the main interface of the software. In the figure, area "1" is the parameter configuration area, which is used to configure the relevant parameters of the array and acoustic signal processing. Area "2" is the time domain waveform display area, and the left side is the time domain waveform of all array elements. The right side is the single-array element time domain waveform, you can freely select the element you want to observe through the drop-down menu above the display area. Area "3" is the beam pattern display area, you can freely select the CBF algorithm or the LNBF algorithm by pressing the button in the upper left corner of the software. Area "4" is the frequency spectrum display area, which displays the frequency spectrum of the time domain signal of the corresponding single-array element in area "2". Area "5" is the software operation status monitoring area, which displays the process data of the key software processing flow, including the buffer queue length, data communication status, operation time and other parameters.

5. Conclusion
Aiming at the application scenarios of underwater structure gas leakage detection in the process of offshore oil and gas development, this paper first studies the power spectrum characteristics of the radiation noise of underwater structure gas leakage, and then proposes a beamforming algorithm for underwater structure gas leakage detection, using LabVIEW Platform design The underwater structure gas leakage direction-finding software has implement the direction finding algorithm. The experiment program was designed and the test platform was built to complete the experiment study on underwater structure gas leakage detection. Experiments have shown that for the scenario of a single gas leakage point, the gas leakage point maintains the same sound source level. Compared with the CBF algorithm, the direction finding algorithm used in this paper has a larger difference between the maximum and sub-maximum energy value of beamforming, which shows that the ability to distinguish the target is strong, which effectively improves the detection ability of the leaking target, and has a certain engineering application and promotion prospect.

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