Acoustic Vector Sensor and Its Applications
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Abstract

Acoustic wave is a physical field that includes both scale field and vector field. Acoustic Vector Sensor (or called Combined Acoustic Vector Transducer) can pick up the information contained in both pressure and velocity fields, so it makes possible to use much more information. This paper from several sides: principle, structure and possibilities of its future applications, briefly discusses on the Acoustic Vector Sensor (AVS).

1. Introduction

More and more unmanned underwater vehicles (UUV) and autonomous underwater vehicles (AUV) have been developed worldwide. To meet the variant and increasing requirements for the civil and military uses, UUV/AUV still have to be unceasingly improved themselves in maneuverability, endurance, autopilot and so on. But nowadays more important things are that UUV/AUV should be equipped with the new and more powerful sensors to increase their information acquisition, processing, recording, transmission and recognition capabilities. They must more and more deeply discover the nature of undersea environment and objects, so that the sensors should have more frequency bandwidth, more sensitivity and other superior performances to the conventional transducers.

The difficulties are so many restrictions existing in UUV body, such as very limited size and low power. Therefore, besides the functional requirements to be met, the welcome sensors must be light and with low power consumption.

One of the main research directions in Underwater Acoustic Research Institute of HEU (Harbin Engineering University) has been to develop acoustic sensor system for UUV/AUV for many years. Many sensor systems for UUV navigation, positioning, transmission, detection and data acquisition, for instance, long-base, short-base and super-short-base positioning systems, underwater acoustic telecontrol system, data transmission systems, acoustic vision system, 3-D forward looking sonar and so on, have been developed.

Recent years we pay more attention to the acoustic vector sensors (AVS), since its superior performances to the conventional acoustic pressure transducer. AVS may take much more information contained in acoustic field, which are both scale and vector information.

The systems with vector sensors have been developed by many countries in acoustic and underwater acoustic fields. For instance, USA developed AN/SSQ-53 in 1950s, then AN/SSQ-62, DIFAR and SWALLOW system have been built-up. Russian developed RGB-26, CGAC-946, GIA-201, TAPS-8, and B&K company developed an acoustic vector sensor based on bi-receiver principle in 1970s, and so on.

HEU started this work from the beginning of 1990s. First generation of developed system measured acoustic intensity based on bi-transducer method. In 1997, professor Jia of HEU firstly created one-dimension velocity transducer with two accelerometers, which obtained 20dB DOA gain in 10-6300Hz bandwidth[1]. From 1997, HEU started to develop 3D-AVS and related signal processing techniques. The results of lake trial and sea trial show that the developed system with 3D-AVS has good performances in 20Hz-5K bandwidth.

2. Principle

The velocity is a vector and its direction is coincident with the direction of sound propagation. The velocity transducer responds to the velocity projection on its axis, so that its directivity is independent with frequency.

An output of 3D-AVS may be represented by a following column vector:

\[ s(t) = [p(t) \ v_1(t) \ v_2(t) \ v_3(t)]^T \]  \hspace{1cm} (1)

Where \( p(t) \) is pressure and others represent the 3D orthogonal components of particle velocity \( \mathbf{v}(t) \), respectively.

AVS may get a multi-phase space for signal processing: \( \{p\}, \{p^2\}, \{\mathbf{v}\}, \{\mathbf{v}^2\}, \{p\mathbf{v}\}, \{p, p\mathbf{v}\}, \{\mathbf{v}, p\mathbf{v}\} \)
Suppose that the output of AVS is a zero-mean stationary random process, we may have the output spectrum matrix \( [S(f)] \):

\[
[S(f)] = \begin{bmatrix}
S_{pp}(f) & S_{pv_1}(f) & S_{pv_2}(f) & S_{pv_3}(f) \\
S_{pv_1}^*(f) & S_{v_1^v_1}(f) & S_{v_1^v_2}(f) & S_{v_1^v_3}(f) \\
S_{pv_2}^*(f) & S_{v_2^v_1}(f) & S_{v_2^v_2}(f) & S_{v_2^v_3}(f) \\
S_{pv_3}^*(f) & S_{v_3^v_1}(f) & S_{v_3^v_2}(f) & S_{v_3^v_3}(f)
\end{bmatrix}
\]

where \( S_{pp}(f) \) is the pressure autospectrum, which is proportional to the potential energy:

\[
E_p(f) \propto S_{pp}(f)
\]

(2)

\( S_{v_i^v_i}(f), i=1,2,3 \) are the particle velocity autospectra whose sum is proportional to the potential energy:

\[
E_i(f) \propto \sum_{i=1}^{3} S_{v_i^v_i}(f)
\]

(3)

\( S_{pv_i}(f), i=1,2,3 \) are proportional to the sound intensity.

In the matrix, the cross-spectrum components contain a set of phase information \( \Phi_{pv_i} \), from which the information of azimuth \( \Phi \) and elevation \( \Theta \) can be obtained.

The further study indicates the derivatives \( \frac{d\Phi_{pv_i}(f)}{dt}, \frac{d\Theta}{dt} \) are very helpful for signal detection.

Suppose \( y(t) \) represents an output of vector sensor, \( y(t) = s(t) + e(t) \),

where \( s(t) = [p_x(t), v_{1,s}(t), v_{2,s}(t), v_{3,s}(t)] \) represent signal,

\( e(t) = [p_x(t), v_{1,e}(t), v_{2,e}(t), v_{3,e}(t)] \)

represent noise. In the case supposing the noise \( e(t) \) to be an independent, isotropic and white noise plane wave, then the output of AVS is as:

\[
[S_s(f)] = \begin{bmatrix}
S_{pv_i}(f) + N_p & S_{pv_1}(f) & S_{pv_2}(f) & S_{pv_3}(f) \\
S_{pv_1}^*(f) & S_{pv_1}(f) + N_v & S_{v_1^v_2}(f) & S_{v_1^v_3}(f) \\
S_{pv_2}^*(f) & S_{v_2^v_1}(f) & S_{v_2^v_2}(f) & S_{v_2^v_3}(f) \\
S_{pv_3}^*(f) & S_{v_3^v_1}(f) & S_{v_3^v_2}(f) & S_{v_3^v_3}(f)
\end{bmatrix}
\]

(4)

Comparing with equation of \( S_s(f) \), we may find only the diagonal elements may be affected by noise, other elements are only depend on signal. This is a basis for detection of the wake signals.

We also may get the matrix of the coherent coefficients \( [y_s^2(f)] \):

\[
[y_s^2(f)] = \begin{bmatrix}
1 & \gamma_{pv_1}^2(f) & \gamma_{pv_2}^2(f) & \gamma_{pv_3}^2(f) \\
\gamma_{pv_1}^2(f) & 1 & \gamma_{pv_2}^2(f) & \gamma_{pv_3}^2(f) \\
\gamma_{pv_2}^2(f) & \gamma_{pv_2}^2(f) & 1 & \gamma_{pv_3}^2(f) \\
\gamma_{pv_3}^2(f) & \gamma_{pv_3}^2(f) & \gamma_{pv_3}^2(f) & 1
\end{bmatrix}
\]

(5)

We can see matrix of the coherent coefficients only have relation to signal so that the gain of signal to noise ratio of the acoustic energy flow to pressure signal to noise ratio is:

\[
G = 10 \log_{10} \frac{[y_{pv_s}(f)]}{[y_{pv_e}(f)]}
\]

(6)

From above equation, for isotropic acoustic field, \( \gamma_{pv_s}^2(f) \to 0 \), and the coherent signal \( \gamma_{pv_e}^2(f) \to 1 \), then \( G \to \infty \).

3. The structures of AVS

The AVS is composed of the conventional acoustic pressure transducers and the particle velocity sensors. The structure models can be divided into three kinds of models: two-transducers (or two-hydrophones), static sell pressure gradient, and co-vibration sphere model, as seen in Fig. 1.

Depending on the principle and the structure, the model 1 can be used only in narrow frequency band and the sensitivity can not be high. The model 2 and 3 are better structure. In HEU, the model 3 has been implemented since 1997.
As seen in Fig.1, the model 3 implemented in HEU contains three pair piezoelectric accelerometers equipped on three orthogonal axes, respectively, which should have as identical as possible characteristics. The pressure transducer may put outside or inside of the sphere.

The following figure (see Fig.2) shows the directivities of the particle velocity sensors along X and Y direction.

4. Signal processing techniques for AVS

Suppose that the AVS received a signal, which includes the coherent signal and non-coherent noises. From above analysis, it will be very efficient to cancel these isotropic noises. The analysis indicates that in 200-500m deep sea, the noise coherent coefficient may reach to $10^{-3}$ ~ $10^{-4}$, so that for a complete coherent signal, the signal to noise ratio can be 20dB-30dB. The following figures (see Fig.3) show the some results of sea trials:

For canceling the coherent interferences and source positioning, we may use adaptive technology CIES (Coherent Interference Energy Suppress) that created by Underwater Acoustic Research Institute of HEU.

This technique uses the natural dipole directivity (in which the lowest part is lower than the highest
part by about 27 dB) formed by velocity sensors and make it turning and the minimum part points to the coherent interferences, so that it may be canceled.

The method developed in DIFAR system is equivalent to a space filtering. Capon introduced a Minimum Variance Estimation Method that may get more narrow directivity.

In addition, by using the adaptive technique, the directivity of AVS can be sharpened\(^4\). Fig.4 shows processing results on lake trial with this method.

![Fig 4 the result of adaptive directivity sharpening](image)

The reference\(^5\) has proved theoretically the improvement of DOA estimation by AVS without increasing the array aperture: vector sensor removes all bearing ambiguities, even a simple structure of AVS can determine both azimuth and elevation, spatially undersampled spaced array may be employed to increase the resolution performance.

5. **The Conclusions: the possibility for future use of UUV/AUV**

Besides many applications of AVS have been done in past time, we would emphasize the following applications:

- A. Marine noise source positioning and recognition.
- B. In towed array sonar, AVS may easy to solve bearing ambiguities problem.
- C. AVS may compose more compact passive surveillance systems.
- D. AVS can be used in buoy systems.
- E. The size reducing of AVS comparing with traditional pressure array makes it very useful in UUV/AUV applications for passive detection, data acquisition and communication.

6. **Reference**


