A Comparative Analysis of Triplet and Vector Sensor Arrays

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Despite their simple geometry, uniform linear arrays suffer from port-starboard ambiguity. Triplet arrays, where a set of three hydrophones is used inplace of a single omni-directional hydrophone, is one possible solution to the problem. An alternative is vector sensor arrays inwhich each hydrophone is replaced with acoustic vector sensor that measures both the acoustic pressure and particle velocity. In this paper, a comparison of triplet and vector sensor arrays from hardware and signal processing perspective is presented.

1 Introduction

Towed arrays are uniform linear arrays (ULA) that consist of several nested sub-arrays of equally separated omni-directional hydrophones. These arrays offer several important advantages compared to other alternative measuring equipment, making them popular for underwater acoustic measurements in bioacoustic, geoacoustic, and oceanographic applications as well as seismic prospecting, naval warfare and underwater communications. A towed array can be extended beyond the region where the acoustic field is dominated by self-noise generated by the towing vessel and can be retracted onto the towing vessel when not operational. Due to the uniform distribution of sensors, relatively simple signal processing algorithms have been developed for tasks such as direction of arrival (DOA) estimation and beamforming [1].

On the downside, towed arrays require bulky drums for storing the array onboard the towing vessel and limit the maneourvability of the vessel when deployed. In addition, conventional signal processing algorithms for ULAs assume that the array is perfectly straight, which is a constaint that is seldomly satisfied in the presence of underwater currents and swells. Despite their simple geometry, uniform linear arrays suffer from port-starboard ambiguity (i.e., one cannot determine whether the target is to the port or starboard of the array). Several modifications to the uniform linear array (such as towing two arrays placed side-by-side, [2]) are utilized to avoid this port-starboard ambiguity associated with towed arrays.

An alternative is to replace each omni-directional hydrophone in the array with a set of three omni-directional hydrophones (i.e., triplets) to form a cardioid response pattern for each triplet element [3]. Since the cardioid's null can electronically be steered, the array can be made to listen to only port or starboard.

Recent advancements in underwater vector sensors capable of measuring the acoustic particle velocity and pressure has increased interest in vector sensor based linear arrays. Vector sensor arrays, also capable of forming cardioid response patterns at each sensor, eliminate the port-starboard ambiguity problem. This paper provides a comparison of triplet and vector sensor arrays.

It should be noted that the derivations presented are based on the assumption that the acoustic wavefield is two dimentional and the acoustic waves are planar. In Section 2 and 3, triplet and vector sensor based arrays are described. A comparison of the two array types is presented in Section 4. Lastly, the concluding remarks are provided in Section 5.

2 Triplet Arrays

A pair of closely spaced hydrophones separated by a distance of a results in a cardioid response at the endfire (see Figure 1) when the measured signals are displaced onto the array axis, provided that the product of the wavenumber of the incident wave and the separation satisfy $ka \leq \pi/2$. Since the cardioid response pattern posesses a null at the opposite side of the peak, the hydrophone pair provides the ability to discrimminate between signals incident from port and starboard. Hence, an array constructed from elements with a cardioid shaped response patterns (rather than omni-directional hydrophones) can eliminate port-starboard ambiguity associated with conventional ULAs. If the array twists by an angle of β, the beampattern gets distorted and an additional hydrophone is necessary to maintain the cardioid response pattern [3]. The steering vector for this case is shown in Eq. (1)

$$\mathbf{d}(k,\psi) = \begin{bmatrix} \exp\left(j\dfrac{ka}{\sqrt{3}}\sin\beta\cos\psi\right) \\ \exp\left(j\dfrac{ka}{\sqrt{3}}\sin(\beta-\gamma)\cos\psi\right) \\ \exp\left(j\dfrac{ka}{\sqrt{3}}\sin(\beta+\gamma)\cos\psi\right) \end{bmatrix}, \qquad (1)$$

where $\gamma = 2\pi/3$ and ψ is the azimuthal steer angle. The optimum filter weight vector that maximizes the signal-to-noise ratio (SNR) for the triplet is given as

$$\mathbf{w} = \begin{bmatrix} \sin\beta & \sin(\beta-\gamma) & \sin(\beta+\gamma) \end{bmatrix}^T. \qquad (2)$$

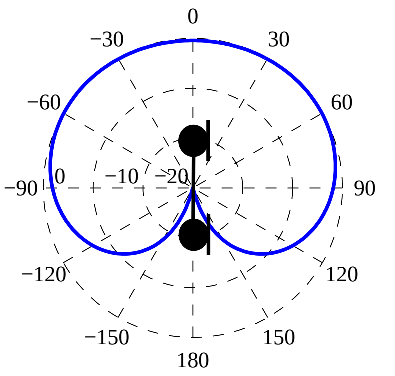

Figure 1: The cardioid response pattern resulting from a pair of omni-directional hydrophones.

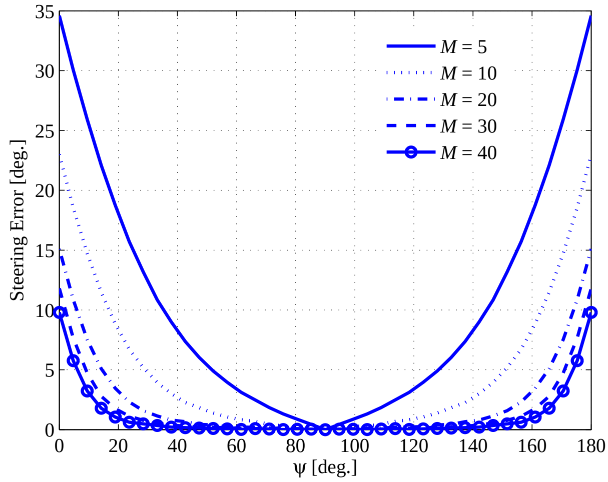

Figure 2: The steering error associated with triplet arrays of M triplets.

Thus, a triplet array is an ULA with a set of three omni-directional hydrophones, each placed at the corners of an equilateral triangle, separated by a distance of d. Beamforming is accomplished in two stages; first, cardioid response patterns are formed at each triplet, and the second stage involves processing the signals measured at the triplets with standard beamforming algorithms used for conventional ULAs.

The port-starboard ambiguity (PSA) associated with the triplet array is computed by Hughes as [3]

$$\text{PSA} \approx \frac{1-\sin\psi}{1+\sin\psi}. \tag{3}$$

The individual cardioid response of each triplet hydrophone is steered either to port or starboard. When the array is steered to a direction other than the broadside, since the response of the individual triplets cannot be steered to intermediate directions, the direction of the maximum beamformer response does not correspond to the steer direction. The steering error is dependent on both the number of triplets of the array and the steer angle, being zero for the broadside and reaching a peak at endfire. The steering error for various array configurations and steer angles are depicted in Figure 2.

3 Vector Sensor Arrays

An acoustic vector sensor consists of sensors capable of measuring the acoustic particle velocity on two orthogonal directions (e.g., along the x- and y-axis) and an omni-directional pressure sensor. The response of a 1-D particle velocity sensor has a dipole shape with a peak response at the primary axis as shown in Figure (3).

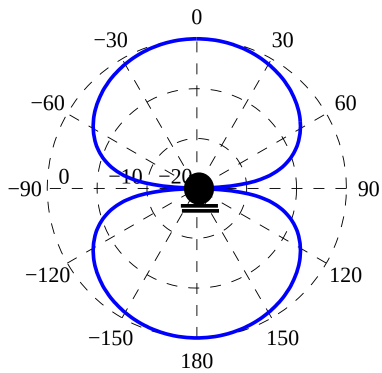

Figure 3: The dipole pattern response of a 1-D velocity sensor.

The response vector of a single acoustic vector sensor is defined as

$$\mathbf{d}(k,\psi) = \begin{bmatrix} \rho c \exp\left(jk\cos\psi\right) \\ \cos\psi \exp\left(jk\cos\psi\right) \\ \sin\psi \exp\left(jk\cos\psi\right) \end{bmatrix}, \tag{4}$$

corresponding the pressure and velocities in the x- and $y-$axes, respectively, and ρc is characteristic impedance. When the filter weight vector is defined as

$$\mathbf{w} = \begin{bmatrix} \frac{1}{\rho c} & \cos\psi & \sin\psi \end{bmatrix}^T, \tag{5}$$

the response pattern of the acoustic vector sensor becomes a cardioid steered towards the DOA of the incident wave.

A vector sensor array consists of several acoustic vector sensors, uniformly separated by a distance of d. Beamforming in a vector sensor array can also be accomplished in two stages; first, beamforming at the sensor level, and next along the ULA [4].

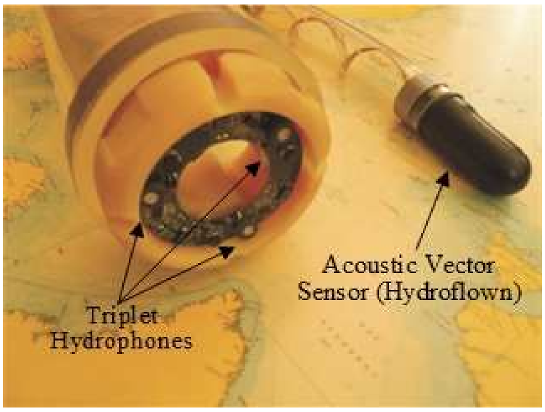

Figure 4: A picture showing a set of triplets used for a triplet array and the Hydroflown, a MEMS based acoustic particle velocity sensor [5] that is used to construct vector sensor arrays.

4 Discussion

It is mentioned in Section 2 that for a given inter-element separation a between the triplet hydrophones, the cardioid response pattern begins to distort as frequency of the incident wave is increased beyond the critical frequency of $f_c = c/4a$. Hence, to improve the upper bound on the working frequency of the array, the inter-element spacing must be reduced. However, this separation cannot be reduced beyond a certain distance due to practical considerations.

It was noted that the cardioid response pattern resulting from a triplet of omni-directional hydrophones can not be steered, which results in a steering error in triplet arrays (see Figure (2)). The steering error is particularly significant for arrays with a small number of elements. The cardioid response pattern associated with a vector sensor can be steered by selecting the appropiate filter weigths, the vector sensor arrays do not suffer from steering errors.

Due to recent developlements in MEMS sensor technology, it is possible to manufacture very compact 3-D acoustic vector sensors. Hence, a vector sensor array typically has a smaller radius compared to a triplet array (see Figure (4), which results in reduced flow noise. Furthermore, since the turbulent flow is circumferentially distributed around the array, the directional particle velocity sensors measurements will be robust to flow noise.

It should be noted that the array processing algorithms discussed here for both triplet arrays and vector sensor arrays are not the only possible or best algorithms, but rather are the most intuitive and straightforward ones. However, a discussion of other possible algorithms and the possible improvements in array performance associated with these algorithms is beyond the scope of this paper.

5 Conclusions

Port-starboard ambiguity is one of the fundamental drawbacks of conventional ULAs. Two array types that eliminate port-starboard ambiguity are discussed and compared in this paper. Instead of equidistant omni-directional hydrophones, a triplet array is constructed from directional sensing elements which consist of hydrophone triplets. Each triplet has a cardioid response pattern that can be steered to either port or starboard, providing port-starboard discrimination. Alternatively, the omni-directional hydrophones can be replaced with vector sensors that measure both pressure and acoustic particle velocity. Vector sensors can also provide a cardioid response at the sensor level.

Compared to triplet arrays, vector sensor arrays do not suffer from steering errors and are more robust in terms of flow noise suppression. The inter-element spacing between the triplet hydrophones is an important design parameter that is determined based on the working frequency of the array as well as practical hardware constraints. Vector sensor arrays can be constructed in much smaller dimensions compared to triplet arrays.

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