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WAVENUMBER-FREQUENCY ANALYSIS IN UNDERWATER ACOUSTIC ARRAYS

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Abstract

Underwater acoustic sensor arrays are affected by self noise from a large number of different sources. Effective remedial action requires the identification of the relative importance of these various sources. Spectra derived from Fourier transforms of single element time series or beam time series have been found to be inadequate in separating the sources of noise. Transforming the data to the wavenumber domain offers one method of data presentation that can solve this problem. This technique provides a graphical representation of acoustic data known as k-Omega plots or k-space plots. The paper explains the generation methodology and illustrates the interpretation of the plot. This method is applied to an example of underwater acoustic data from an array of piezo-electric sensors. The paper further discusses the benefits of the method within the analysis task and some limitations.

INTRODUCTION

The aim of this paper is to explore the usage of a particular analysis technique in underwater acoustics. The fundamental problem is the diagnosis of the dominant sources of noise and vibration in an array of hydrophones to enable effective improvement in design and implementation. In particular the diagnosis needs to separate the energy from vibration within the array from acoustic energy propagating in the water. One observation is that the noises from various sources have different speeds of propagation, such that a mathematical technique that can exploit this has the potential for separation of the sources. This can be achieved by transforming the hydrophone time-series data to the wave-number versus frequency domain.

UNDERWATER NOISE AND VIBRATION

One solution to the problem of achieving a long acoustic aperture in underwater acoustics is to tow a long array of acoustic sensors behind a ship. This array consists of a long tube containing hydrophones, electrical cables, strain cables and fluid A short section of such a towed array is illustrated in figure 1.

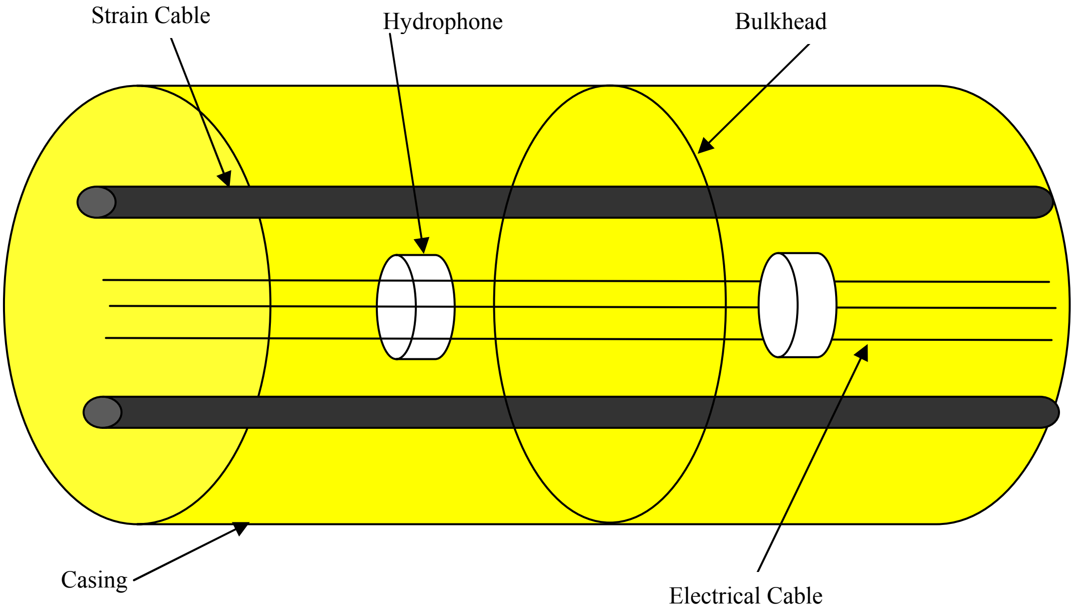

Figure 1 – Schematic of an underwater towed acoustic array

Towed arrays are subject to noise from a variety of mechanisms, as shown in figure 2:

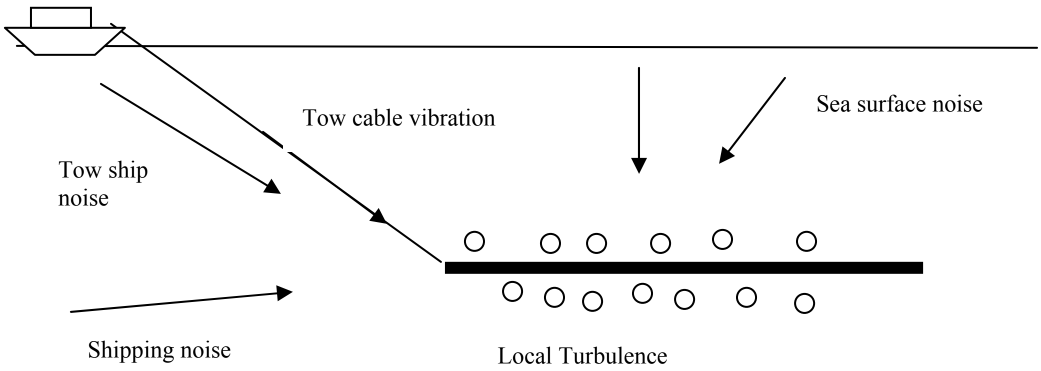

Figure 1 – Underwater noise mechanisms affecting towed arrays

Some of these noise mechanisms, such as sea surface noise, are external to the array and towing ship whereas others are internal or under the control of the towing ship. In order to maximise performance of the array; the aim is to minimise those noise mechanisms directly associated with the array and towing ship such that the performance is solely limited by the external noise.

Gathering underwater acoustic data at sea is a time-consuming and expensive activity. The weather in many regions of the North East Atlantic is often characterised by high wind speeds, with consequential large waves, generating high levels of broadband noise. Hence it is not always possible to gather data in low noise conditions. However the ideal system would be limited by ambient noise in all sea conditions. Thus an analysis technique with the facility to separate external generated noise from self noise has the potential to enable gathering of data to examine array performance under commonly observed sea conditions.

WAVENUMBER-FREQUENCY ANALYSIS

Fourier Techniques

Transforming individual hydrophone or beam time-series data into the frequency domain using Fourier transform techniques is the most obvious analysis method as it enables discrimination between high and low frequency effects and also between broadband and narrowband processes. However, Fourier transforms of beam or hydrophone data do not discriminate between acoustic energy propagating in the water from those propagating in the array.

Derivation of a wave-number versus frequency (κ-ω) plot

The underlying technique for wavenumber-frequency analysis is a two-dimensional Fourier transform. The first dimension is a conventional transformation from an individual hydrophone time- series to the frequency domain. The second dimension transforms the regularly spaced simultaneous measurements from the spatial domain to the wavenumber domain. This method is expressed mathematically in Equation 1:

$$F(k,\omega) = \iint f(x,t)\exp(i\omega t)\exp(ikx)dtdx \quad (1)$$

Note that wave-number. k, can be defined to be either $2\pi/\lambda$ or $1/\lambda$. In this paper it is defined as $1/\lambda$.

The main features of the technique are schematically represented in Figure3:

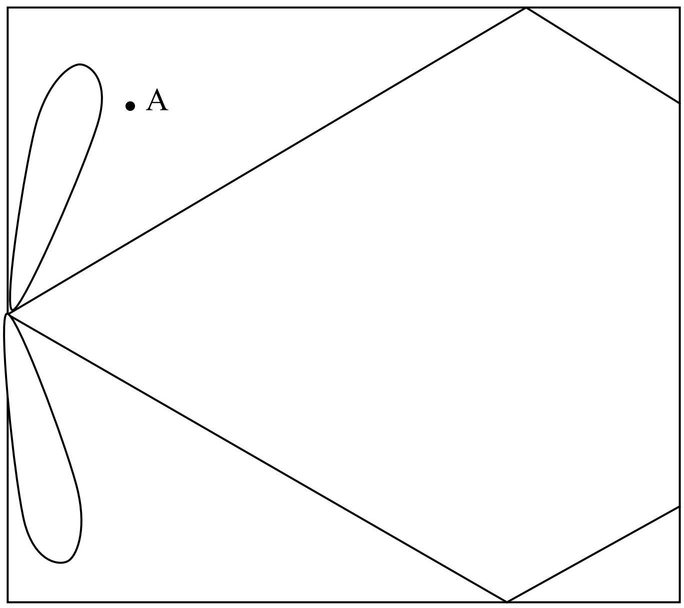

Figure 3 – Wavenumber-frequency plot schematic

If we assign the 'distance' parameter associated with the ordinate to be the distance between successive crests of a plane wave we have nothing more than the wavelength for that wave. More importantly though, this means that the equi-spaced bins of the ordinate will indicate coherence when the wavelength is a whole multiple of the bin 'separation' distance, i.e. the hydrophone spacing in an array. So we see that 1/d is can be made to be $1/\lambda$ or wavenumber 'k'. The phrase 'can be made to be' is used deliberately. This means we set the number of points along the ordinate to match the number (and spacing) of the hydrophones in the line array, this way plot directly represents the physical array.

The black lines therefore represent energy propagating along the array at 1540ms-1, which is a typical speed of sound in water. The upper line represents forward propagation direction and by convention the lower black line represents backward propagation at the same speed.

An example of the application of this technique to real acoustic data is shown in Figure 4:

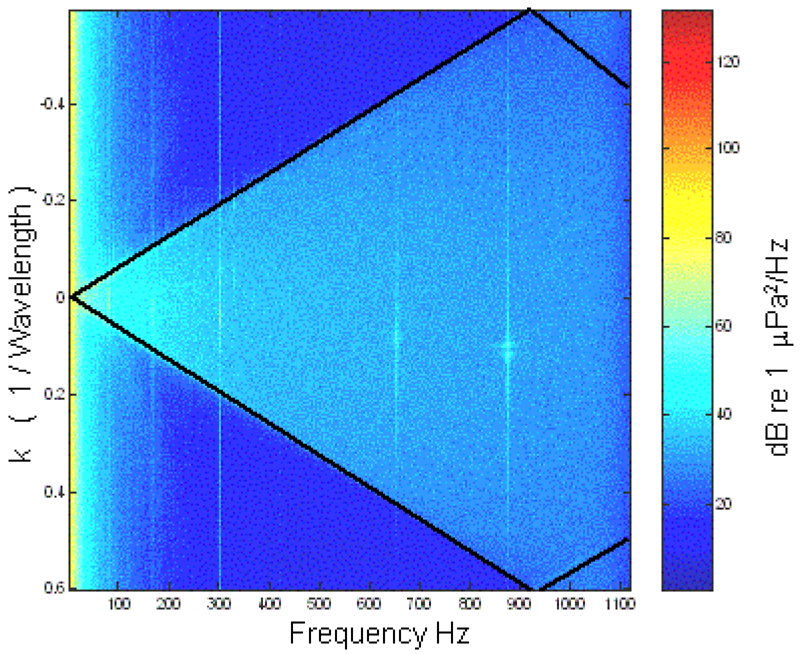

Figure 4 – Example of a wavenumber-frequency plot

The following observations can be made from Figure 4:

- there is more energy inside the acoustic region bounded by the black lines than outside (the largely blue regions). This indicates that the array was being dominated by noise propagating in the water rather than vibration along the cable.
- There is an increase in the pressure level as frequency is reduced below about 200Hz. This is true across all wave-numbers, inside or outside the acoustic region. The lack of dependence on wavenumber

indicates that the noise is being generated locally at the hydrophones rather than propagating in the water or along the array structure. Hence the most likely cause is local uncorrelated turbulence.

- There are some narrowband tones that are also independent of wavenumber, indicating that they are not due to a noise source in the water. They could be due to electrical interference in the system.
- There is no strong source of broadband noise in a particular direction either inside or outside the acoustic region. Hence the towing ship is not seen to be a significant cause of interference. Furthermore there are no significant contributions from vibration along the tow cable.

In this particular example it is possible to conclude that the system design has achieved the aim of reducing broadband self-nose sufficiently to render the external noise sources the dominant cause of noise in the array above 100Hz. The tonal artefacts could be a significant source of narrowband interference. Hence the focus of any improvement strategy should be towards very low frequency noise and tonal artefacts.

DISCUSSION

The separation of the noise propagating in the water from the locally generated turbulent noise is of particular benefit in the assessment of this type of system. This leaves the question as to whether it remains worthwhile attempting to gather acoustic data from a towed array under low ambient noise conditions. Gathering such data often requires long sea transit to areas with a lower likelihood of inclement weather. Hence there would be substantial cost savings if this were to be confidently regarded as unnecessary. In essence, this question equates to apprehension as to whether there is a possibility that reliance on this technique for the assessment of the self-noise of a towed array would lead to a failure to measure a significant cause of self-noise.

CONCLUSIONS

Application of wavenumber-frequency analysis to the underwater acoustic towed array problem has been shown to be a useful analysis tool. We have demonstrated that the technique has achieved the aim of separating the various causes of noise. In particular we have demonstrated separation between controllable self-noise and uncontrollable ambient noise. However there is an underlying concern that a reliance on this technique in combination with data gathered in high ambient noise conditions might be insufficient.