In-situ Non-acoustic Noise Measurement System for Towed Hydrophone Array

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I. Introduction

A linear array of hydrophones towed by a ship finds applications in underwater target detection as well as in seismic surveys. Currently research is going on for the development of thin line towed arrays for fitment on submarines and Autonomous Underwater Vehicles (AUV) [1], [2]. The virtues of such an array are large aperture at low frequency of operation, hence long detection ranges, and the substantial reduction of platform noise as compared to a ship mounted hydrophone array. Apart from the ambient sea noise, other sources of noise are vibrational energy coupled to the hydrophone array through the tow cable (cable strum noise as well as those due to platform motion) and the flow noise resulting from turbulent boundary layer pressure fluctuations. The vibrational noise can be controlled by Vibration Isolation Module (VIM), compliant hydrophone suspension, acceleration compensation for the hydrophone etc. Control of flow noise, which is a dominant noise source, demands special design techniques for the hydrophone and its housing [3]. Vibrational noise and flow noise are both predominant non-acoustic noise sources in a towed array. They propagate at velocities much less than the velocity of acoustic waves in water.

Frequency-wavenumber (f-κ) analysis exploits the velocity differences and provides a tool for analyzing relative power of acoustic and non-acoustic noise contributions on the towed array [4], [5], [6] . Since, non-acoustic noise levels vary widely depending on the array construction and dimensions, towing conditions as well as ocean scenarios, there is a need for a tool to estimate the absolute, rather than relative, levels of non-acoustic noise in a given towed array at a specified towing speed. This would facilitate the comparison of performances of several towed array designs and estimate non-acoustic noise levels arising from such designs. Estimation of non-acoustic noise levels would help in pinpointing the causes of performance degradation of towed array sonar systems and take steps to address them. Responding to this need, a non-acoustic noise level estimation system was developed, which is the theme of this paper.

The system described in this paper is intended as an in-situ non-acoustic noise level measurement tool, which affords the flexibility in use, while the array is being towed for its intended purpose. Frequency-wavenumber analysis, which have been used for separating non-acoustic and acoustic noise components can reliably estimate non-acoustic power relative to acoustic power. It has certain drawbacks when attempt is made to estimate absolute powers of the noise components. These are discussed in section II. If we introduce intentional acoustic source (reference signal) this drawback can be eliminated. The principle of this novel idea is discussed in section III. Application of this principle entails use of f-κ analyses on two sets of array data, i.e. with and without reference signal. The measurement system described in section IV eliminates this two step process by restricting the reference signal to a tonal and introducing Adaptive Line Enhancer (ALE) preprocessing whose outputs are tapped for f-κ analysis. The in-situ non-acoustic noise power estimation system was tested on a thin line towed array in a towing trial experiment conducted in a lake. Section V describes the experimental validation of the system and section VI gives the conclusions

II. Frequency-Wavenumber Analysis

The frequency wavenumber analysis is a wave filter, which filters both in frequency and spatial domain simultaneously [6]. Given an incident plane wave of frequency f and arrival of angle θ, its spatial frequency, or wavenumber , as seen along the axis of the array is $\kappa = (2\pi fd/c)\sin\theta$, where d is the inter element spacing in the array and c is the speed of the wave. Let $\{x_m(i)\}$ denote the time series from the m^{th} hydrophone, where $0 \le m \le M-1$ and i is the time index of the sampled data. The time series from each sensor is segmented into blocks, and the discrete Fourier transform (DFT) coefficients $X_m(k)$ are computed, where k is the frequency index. Now the equation

$$B(k,\kappa) = \sum_{m}^{M-1} w_m X_m(k) \exp^{j2\pi m f_k \frac{d}{c}\sin\theta} \tag{1}$$

is the basis for the frequency wavenumber analysis. Here, κ is the wavenumber, $f_k = \frac{kf_s}{N}$ for sampling frequency f_s and FFT length N and w_m is some window function. A plot of $|B(k,\kappa)|^2$ with wavenumber as abscissa and frequency as the ordinate separates into two non-overlapping regions [6]. Fig. 1 shows a typical frequency wavenumber grid. The shaded area of the grid is the non-acoustic region, in which no waterborne acoustic signal can lie. The fundamental assumption behind the statement is that the acoustic noise travels with a speed around $1500\ m/s$, while the non-acoustic noise travels with

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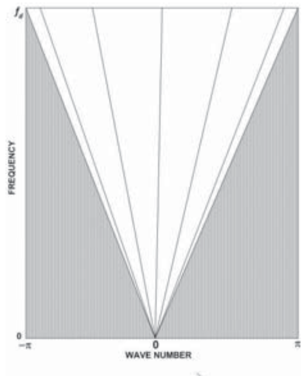

Fig. 1. Frequency Wavenumber Grid

very low speed. The ratio of integrated power in non-shaded area to that in shaded area gives ratio of acoustic power to non-acoustic power, r_1. Specifically, if $x_j(n)$ is the received signal on j^{th} sensor of the array,

$$x_j(n) = u_j(n) + v_j(n) \tag{2}$$

where $u_j(n)$ and $v_j(n)$ are the acoustic and non-acoustic part of the signal, respectively. The acoustic power (P_u) to non-acoustic power (P_v) ratio, estimated by f-κ analysis is

$$r_1 = \frac{P_u}{P_v} \tag{3}$$

If the absolute value of power in non-acoustic noise is to be estimated using f-κ analysis alone, one needs to apply a filter in f-κ domain and apply two inverse Fourier transforms. But, this method has got the inherent spectral leakage problem associated with finite length FFT. A novel measurement methodology suggested below mitigate this problem.

III. Principle of the Measurement

The key to solving the above problems in measuring absolute levels of non-acoustic noise is to introduce an intentional acoustic source, which we call the reference signal. The signal received on j^{th} sensor of the towed array is denoted by

$$\tilde{x}_j(n) = s_j(n) + u_j(n) + v_j(n) \tag{4}$$

where,$s_j(n)$ is the reference signal and let P_s be corresponding power. Therefore, the ratio of acoustic to non-acoustic power, which can be measured through f-κ analysis on the sensor array measurements with reference signal, can be written as

$$r_2 = \frac{P_s + P_u}{P_v} \tag{5}$$

From (3) and (5),

$$P_v = \frac{P_s}{(r_2 - r_1)} \tag{6}$$

Now, (6) can be used to estimate the non-acoustic noise power, if r_1, r_2 and P_s are estimated. The terms r_1 and r_2 are obtained through f-κ analysis. The easiest method to estimate

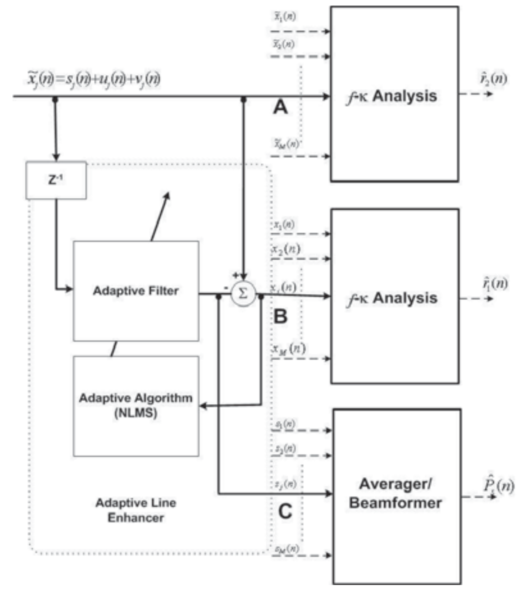

Fig. 2. System Diagram

P_s is to apply a transmission loss model. In this case the accuracy of the estimate of P_s will highly depend on the model. A better method of estimating P_s is by subtracting the average power of all the array sensors without reference signal from the average power with reference signal. For an M sensor array with N time samples, the estimate is

$$\hat{P}_s = \frac{1}{NM}\left(\sum_{m=1}^{M}\sum_{j=1}^{N}\tilde{x}_j^2(n) - \sum_{m=1}^{M}\sum_{j=1}^{N}x_j^2(n)\right) \tag{7}$$

Application of this principle calls for f-κ analyzes on two sets of array data - one without reference signal and another with the reference signal.

IV. In-situ Measurement System

The system diagram is shown in Fig. 2. In order to design a non-acoustic noise level measurement system based on on the above principle, following issue has to be addressed. The towed array sensor data collection in sequential steps with and without reference signal are to be combined into a single step. If the reference signal chosen is monotone signal from a continuous source, this could be achieved by feeding each sensor output to an adaptive line enhancer (ALE). Here, the tonal line canceled output (branch B in Fig. 2) gives a situation akin to (2). Branch A in Fig. 2 is a situation similar to (4), which estimates the acoustic to non-acoustic power ratio from the sensor data. The delayed sensor data is also fed to adaptive filter, which uses NLMS algorithm to estimate the tonal line canceled output. The line enhancer output (branch C in Fig. 2) would contain only reference signal, subject to adaptive filter convergence. Hence this output from each associated sensor ALE, gives input for estimation of $\hat{P}_s$.

The system estimates $\hat{r}_1$ and $\hat{r}_2$ through f-κ analysis of raw array data and reference signal suppressed array data respectively (refer Fig. 2). In order to filter out the reference signal, the system applies an ALE IIR filter [7] on every sensor output. Though, the reference signal frequency is known, there could be Doppler shift, when received on the array. Hence, an ALE with its self tuning characteristics is used to automatically lock to the reference signal. $\hat{P}_s$ can be estimated accurately from the magnitude and phase compensated ALE output s_j in Fig. 2. The power can be estimated from the single channel data or from the beamformer output, since the reference signal direction is known.

V. Experimental Evaluation

The in-situ measurement technique described above has been evaluated using a Digital Thin Line Array (DTLA) system [1] intended for AUV-based sensing applications. The DTLA was 10m long and 10.5mm in diameter with a tow cable of length 12m and diameter 8.5mm. There were 11 acoustic sensing elements with an inter-element spacing of 0.75m corresponding to half wavelength at 1 kHz. The very small diameter of the array makes it vulnerable to flow induced noise when towed using an AUV as there is very less separation between the sensors and the turbulent layer. This may result in a strong coupling of the flow induced noise thus limiting the performance of DTLA in underwater sensing applications. It was therefore necessary to evaluate how the non-acoustic noise would impact the performance of DTLA at different tow speeds. Current practices of measuring the flow noise over a hydrophone involve allowing the hydrophone to free fall through water or towing the hydrophone through water with a boat. Allowing the hydrophone to free fall through water limits the speeds at which the noise measurements may be taken to the terminal velocity of the hydrophone. Another approach is to use a hydro acoustic tunnel. Also, when towing the hydrophone through water with a boat, noise from the boat and/or the towlines adversely affects the measurement. Therefore, an approach, which produces a reduced amount of unwanted noise and allows the measurement of the flow noise at variety of flow speeds was adopted. The experimental set up used was as follows.

A hydraulic winch was mounted on a barge. The winch was run by a hydraulic power pack and it was powered by a generator which was mounted on the shore to avoid any noise propagating from it and interfering with the measurement system. The array was towed behind a dinghy and the Data Acquisition System (DAS), which is powered by battery, was secured inside the dinghy. The dinghy was then attached to the winch drum through a rope which pulled the dinghy. The transmission of reference signal from a far field source was at a frequency of 1 KHz, throughout the motion of the dinghy. The experimental scenario is shown in Fig. 3. The experiment was repeated for speeds varying from 2 to 5 knots.

The power spectrum of single channel is shown in Fig. 4 and Fig. 5 before and after removing the reference signal respectively. A snapshot of the result of f-κ analysis of the data for various speeds is shown in Fig.6 and Fig.7 with and without the reference signal. In all the images in Fig.6 and Fig.7, the intensity vary from 0 (blue) to 60 (red) and the acoustic cone is shown in green color. In Fig.6, it can be seen that the peak is observed at 1 KHz and wavenumber corresponding to an angle of arrival 120 deg. This is because the transmitter is kept around 120 deg to the array horizontal axis. Also, there are some more brightened area, other than the that corresponding to 120 deg. This is possibly reflections from the lake bottom. The corresponding marking is completely vanished in Fig.7.

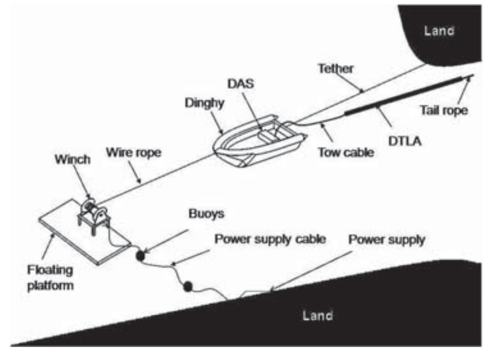

Fig. 3. Schematic of the Experimental Setup

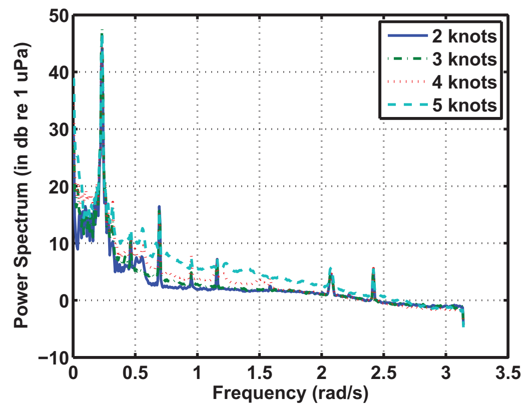

Fig. 4. Power Spectrum of a Single Sensor for various speeds (Branch C of Fig.2)

The amount of non-acoustic power, which is contributed mostly by the flow noise is shown against various speeds in Fig. 8.

VI. Conclusions

Frequency wave number analysis is a standard tool to separate acoustic and non-acoustic noise in underwater towed array sonar. In order to measure absolute levels of the noise components, the paper proposes introduction of a reference acoustic signal source for the in-situ noise level measurement system based on this principle, It also introduces ALE preprocessing followed by f-κ analysis on its outputs. The measurement system was evaluated on Digital Thin Line Array

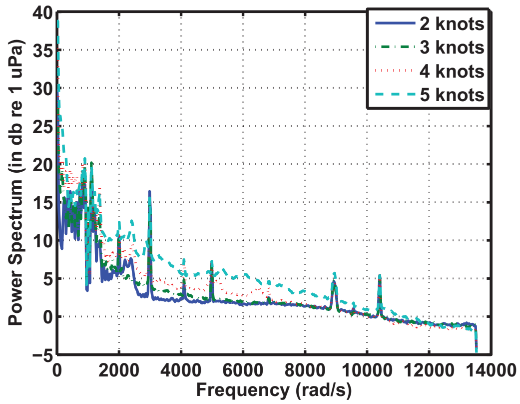

Fig. 5. Power Spectrum of a Single Sensor for various speeds after removing the reference signal (Branch B of Fig.2)

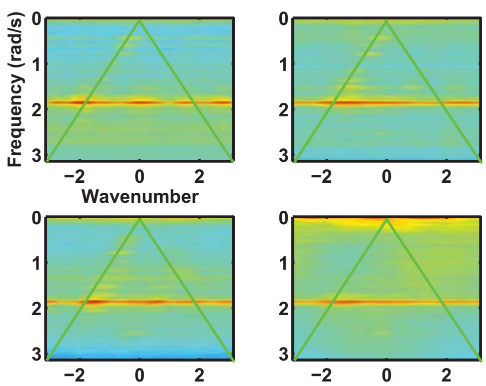

Fig. 6. *f*-κ Analysis result (top left - 2 knots, top right - 3knots, bottom left - 4 knots, bottom right - 5 knots)

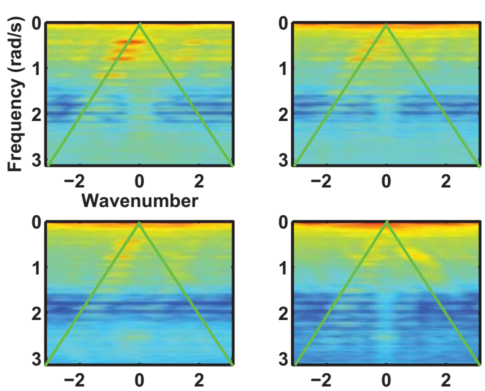

Fig. 7. *f*-κ Analysis result After removing the reference signal(top left - 2 knots, top right - 3knots, bottom left - 4 knots, bottom right - 5 knots)

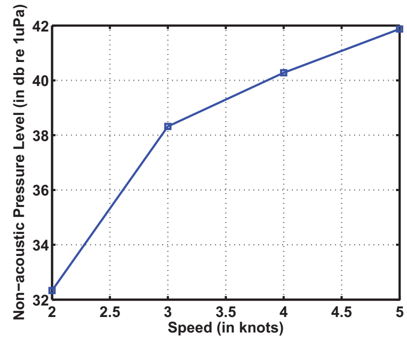

Fig. 8. Amount of Non-acoustic Noise Pressure Level (in db)

(DTLA).

The approach can be extended to the case, where the reference signal frequency is unknown and also it is continuously drifting. In such cases, the automatic frequency identification and tracking method suggested in [8], [9] can be used to estimate the signal power $\hat{P}_s$ and the ratio $\hat{r}_2$. This method is useful, especially when own ship emanated tonal is used as the reference.

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