Reduction of self-noise effects in onboard acoustic receivers of vessels using spectral subtraction

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The engine noise as well as turbulence, cavitation etc. created by the propellers generate immense acoustic noise in the vicinity of the vessels and the onboard acoustic receivers or other observation systems will essentially pickup these near-field noise to a greater extent from their immediate surroundings. This will introduce a major challenge in effective listening of signals of interest that are camouflaged by the noise ambience. This paper discusses a method, based on spectral subtraction, for reducing the effect of these slowly varying noise field created by engines or propellers in the surroundings of acoustic receivers. Spectral subtraction is a technique used to retrieve the power spectrum of a non-stationary signal of interest in a stationary noise field by subtracting an estimate of noise spectrum from a time series of the spectral observations. The noise spectrum is estimated in advance to the actual communication or observation, i.e. while the signal of interest is absent or silent. During consecutive iterations of the process, it will adapt to the spectral shifts that may have occurred in the noise field. The method can be used with acoustic receiver front ends as a preconditioning stage for improving the overall signal quality.

1 Introduction

Commercial, military and research as well as other observational platforms are pervasive in the oceans. These vessels as well as platforms operating round the clock contribute heavily to the overall background noise spectrum of the ocean soundscape, especially in coastal zones and continental shelves [1]. Measurement data reveals that there exists a clear and distinctive dependency on shipping activities and the levels of underwater noise. It has been proposed that the global average of the ambient noise due to shipping traffic is mostly connected with three fundamental features of global shipping namely mean source level, tonnage of individual ship and an estimate of total number of ships, and two environmental parameters, the absorption coefficient and critical angle [2]. Commercial shipping fleet is continually growing in several orders of magnitude in tonnage, hull size, drafts and propeller size and is becoming the dominant contributor of the underwater noise [2]. Despite the best efforts to make the engines and associated machineries more and more silent, the rise in shipping activity overturns all these achievements so far.

Due to the astonishing penetration range, in comparison to other modalities of radiated energy, almost all of the underwater systems built for communication, telemetry, tracking, remote sensing and mapping relies on acoustic signals for their operation. But the acoustic channel is severely polluted by a large number of sources, all occupying the band limited spectrum; it is often very difficult for signals to get through. The strident noise of the own platform, the vessel and its structure, usually referred to as self-noise, is the main source of the near field noise. This powerful near field noise generated in the immediate vicinity of the receiver, with often too high sound levels, can camouflage the interesting phenomena occurring in far fields. Due to the cumulative exposure of *signals of interest* to machinery and propulsion noise, they become hardly tangible. Though several mechanical design modifications have been made in the past with the hydrophones and their installation mechanisms, trying to mitigate the coupling of the self-noise, its effects could not be alleviated completely. Hence, active noise control techniques need to be incorporated in the onboard acoustic receiver to culminate the tangibility of the target signals.

In this paper, a method based on spectral subtraction is proposed to reduce the effect of ambient noise, especially the stationary self-noise, in onboard acoustic receivers. Spectral subtraction proposed by S.F. Boll [3, 4], is one of the earliest and popular noise reduction techniques. The noise is assumed to be stationary or slowly varying, additive and uncorrelated with the signal of interest. In such a scenario, the original signal spectrum can be extracted by subtracting an estimate of the spectral magnitude of the noise, obtained under no signal condition. The signal is then computed by taking inverse Discrete Fourier Transform. The method is rather simple and computationally efficient and can be used for online signal enhancement applications.

2 Acoustic Ship Noise

Powered vessels produce multiple genre of interfering hydro-acoustic noise; most significant contributing factors being propeller action, propulsion machinery and auxiliaries (diesel engines, electric motors, gear trains, pumps, generators, etc.), and motion of the ship through the water or flow over the hull. In the scenario of a single ship under consideration, the overall hull area and the bearing of the ship determines the directivity of noise propagation in the horizontal sonic plane and while ship densities are considered, the acoustic signals is often treated as a superimposed noise field, as it is assumed to be averaged out. The propeller action creates severe amount of water turbulence, vortex and cavitation [5]. The low pressure gradients created by the swirling of the propeller blades results in voids and vapor bubbles because of the abrupt decrease in the flow pressure. The bubbles eventually flow into the downstream and collapse at the high-pressure region and generate shockwaves that leads to intense babbling noise field both broadband (~1MHz) and tonal, due to the modulation by blade-passage frequencies and their harmonics [6]. Apart from the turbulence and other disturbances, most of ship-radiated noise power credits to the broadband and tonal components [5].

2.1 Self-Noise

Self-noise received by the ships onboard sonar or communication receivers, contributing to the overall noise interfering with the signals of interest. The immense strength of this near field noise can hide most of the interesting signals well below the recognition level. The scenario is depicted in Figure 1.

Some of the sources of self-noise are:

Thermal self-noise:- generated by the electronic circuitry and hydrophones due to thermo-electronic agitation.

Platform self-noise:- is a combination of several components acting together, like the noise emanated from the platform itself which is then picked up by the hydrophones directly or indirectly, the vibrations coupled directly to the transducer through the mountings, the hydrodynamic anomalies formed around the hydrophone and the electronic interferences induced in the receiver circuitry by the heavy electrical equipment onboard [5,7,8].

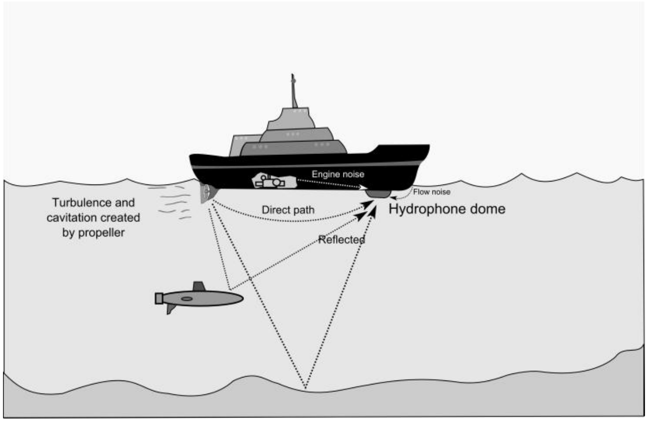


Figure 1: The Sources of Ship Self Noise

Stationary signals arising from rotating machinery generally contain a complex spectrum of frequencies. The rotating parts in the machinery generate fundamental tones and its harmonics. While the ship is cruising at slow speeds, the ambient noise will be prominent and as it catches up the speed, low frequency components become more powerful. At the normal and higher cruising speeds propeller and flow noise dominates the spectrum [5]. Altogether the self-noise and ambient noise components create a more or less stationary noise field over shorter duration, as the noise spectrum does not change substantially, near the densely populated shipping channels.

2.2 Effect of self-noise on underwater acoustic receivers

Information gathered by an acoustic receiver in the absence of real interesting signals can be regarded as self-noise, originally a collective sum of all noise signals and which in turn defines the ambient noise floor. The self-noise level in an acoustic receiver can be described by the equation:

$$SNL = SNL_{1K} - 20\log\left(\frac{\mathrm{f}}{1000}\right) \quad (1)$$

where, SNL_{1K} is the self-noise spectral level at 1KHz and is standardized as $60 - 80$ dB re 1μPa/$\sqrt{\mathrm{Hz}}$ with several measurements[5,7].

Signal to Noise Ratio (SNR) is generally used for characterizing the performance of an acoustic receiver. The SNR of an acoustic receiver can be written explicitly for a passive system

$$SNR = SL + DI - TL - NL \quad (2)$$

where SL is the source level, TL is the transmission loss, NL is the noise level (contributed by ambient noise AN and self-noise SN) and DI is the directivity index. In case of an active sonar unit, an additional term is added to describe the reflected energy, the target strength, TS

$$SNR = SL - 2TL + TS - NL + DI \quad (3)$$

Additionally the receiver reverberation and self-noise can be included in the model, such that,

$$SNR = [SL - 2TL + TS] - \{NR + (NL_0 - DI_R)\} \quad (4)$$

where NR is the reverberation level, NL_0 is the sum of ambient and self noise and DI_R is the directivity index.

As indicated by the Eqn. (4), the self-noise level has direct influence in determining the SNR in an underwater acoustic receiver. Thus, any reduction in the self-noise before it is received by the hydrophones or after the signal acquisition can effectively improve the performance of the receiver. The spectral subtraction method can be used for reducing the effect of stationary additive noise in the captured signals by an acoustic receiver, hence improving the SNR.

3 Spectral Subtraction

When the signal spectrum is superimposed by a noise spectrum additively, it can be safely assumed that the spectrum of the collected signal is a linear sum of the signal spectrum and the noise spectrum. Spectral subtraction technique, a method of subtracting an estimated average noise spectrum from the noisy signal spectrum and restoring the power or magnitude spectrum of a signal observed in additive noise, can be used to enhance a target signal corrupted by self-noise. When self-noise $\mathrm{L}_0(\mathrm{n})$ is additive to the target signal $x(n)$, the noisy signal $y(n)$ can be written as,

$$y(n) = x(n) + L_0(n), \quad for\ 0 \le n \le N-1 \quad (5)$$

where n is the time index and N is the total number of samples under consideration. The objective of target signal enhancement is to find the enhanced target signal $\hat{x}(n)$ from the observed $y(n)$, with the assumption that $L_0(n)$ is uncorrelated with $x(n)$.

3.1 Algorithm

Initially, the input signal $y(n)$ is segmented into K segments of uniform length. The time-domain signals can be transformed to the frequency-domain as,

$$Y_k(\omega) = X_k(\omega) + L_{0_k}(\omega), \quad for\ 0 \le k \le K-1 \quad (6)$$

where k is the segment index, $\mathrm{Y_k}(\omega)$, $\mathrm{X_k}(\omega)$ and $\mathrm{L_{0_k}}(\omega)$ are the short-time DFT magnitudes taken of $y(n)$, $x(n)$, and $\mathrm{L}_0(\mathrm{n})$ respectively. Spectral subtraction is given as,

$$|\mathrm{X_k}(\omega)|^{\mathrm{a}} = |\mathrm{Y_k}(\omega)|^{\mathrm{a}} - |\mathrm{L_{0_k}}(\omega)|^{\mathrm{a}} \quad (7)$$

the DFT magnitudes are raised to a power a where, a=1 corresponds to magnitude spectral subtraction, a=2 corresponds to power spectrum subtraction. If an estimate of the self-noise spectrum $\hat{L}_{0_k}$ (that is self-noise) can be obtained, then an approximation of interested signal $\hat{X}_k$ can be obtained from

$$\hat{X}_k = Y_K(\omega) - \hat{L}_{0_k}(\omega) \quad (8)$$

The noise magnitude spectrum $\hat{L}_{0_k}(\omega)$ can be estimated as a running average of those signal blocks determined to be primarily noise alone. The average noise magnitude spectrum is then subtracted from the magnitude spectrum of the incoming signal discarding the negative differences to avoid undesirable spectral excursions in the output. The modified magnitude spectrum is further supplemented with the phase spectrum for generating modified spectrum and the output signal is recovered via an inverse FFT.

4 Implementation

In underwater acoustic receivers, the noise spectrum can be estimated from the signal for a period when no interested signal is present in the input signal. Since spectral subtraction algorithm requires an estimation of average self-noise spectrum, the estimation of the self-noise spectrum is usually performed during the absence of interested signal. The detection is made according to the evidence provided by the measurements, i.e. a particular feature of the signal is observed or not in a specific interval. Signal activity detectors are used for this purpose [9]. The noise is assumed to be short-term stationary or a slowly varying process, and that the self-noise spectrum does not change significantly between the update periods, so that self-noise from interested signal frames can be removed by making use of noise from signal free frames. The block diagram of the technique is illustrated in Figure 2.

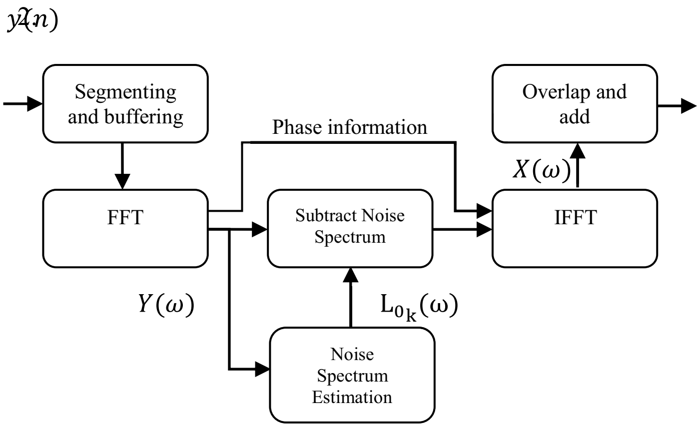


Figure 2. Block diagram of Spectral Subtraction algorithm

5 Results and Discussions

The specific objective of the proposed approach is to reduce the effect of self-noise, during the collection of ocean noise data. The noise floor of the acoustic measurements is often too high due to the presence of the intense acoustic field generated by the propulsion of the ship. The engine, cavitation, machinery and flow noises are almost stationary or have slow variations in their patterns. The proposed method of spectral subtraction can reduce the effect of background noise present in the hydrophone measurements up to formidable levels and hence improves the signal quality considerably.

Figure 3(a) shows a time domain plot of a composite signal containing stationary engine noise and non-stationary Dolphin call and 3(b) shows the spectrogram plot of the same. Figure 3(c) and 3(d) reveals the self-noise estimated during no signal activities and its spectrum while figure 3(e) and 3(f) shows the extracted signals using spectral subtraction. Now the Dolphin call is clearly observable and the effect of background noise is feeble.

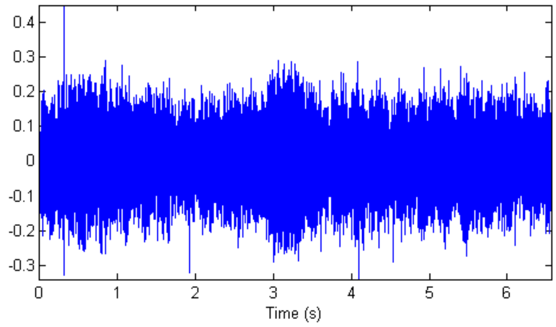
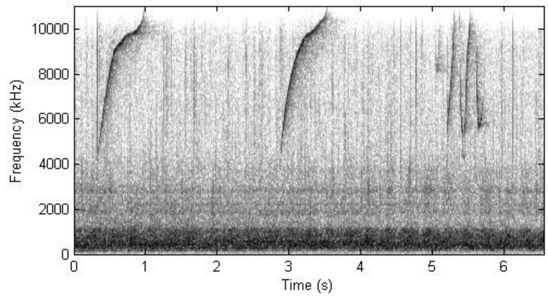


Figure 3(a) The observed noisy signal contains engine noise and a dolphin call



3(b) The spectrogram of the observation

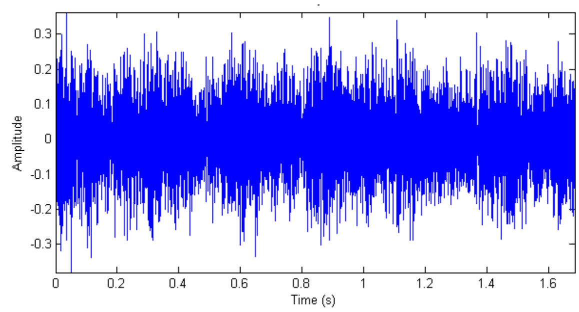
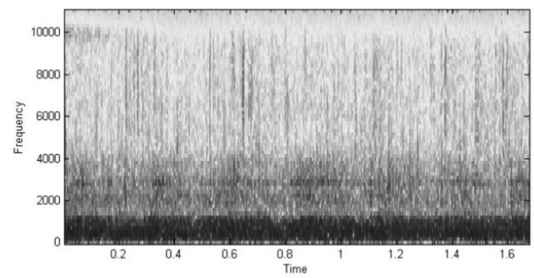
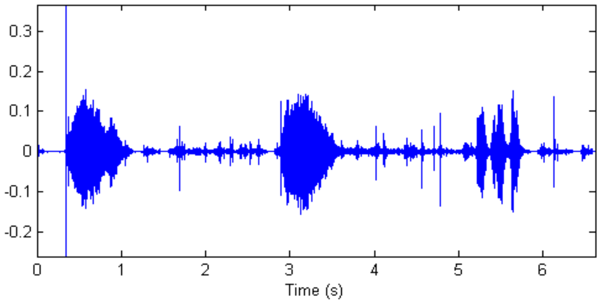


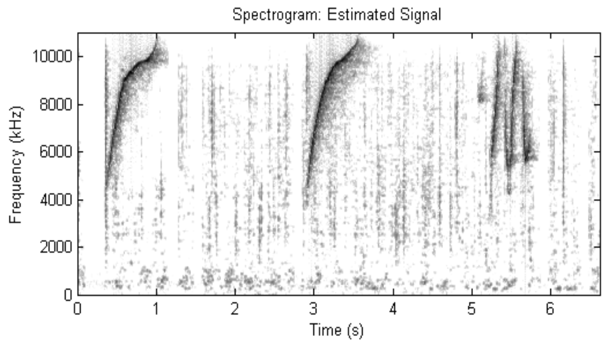
Figure 3(c) Observed signal containing engine noise only



3(d) The spectrogram of the noise signal

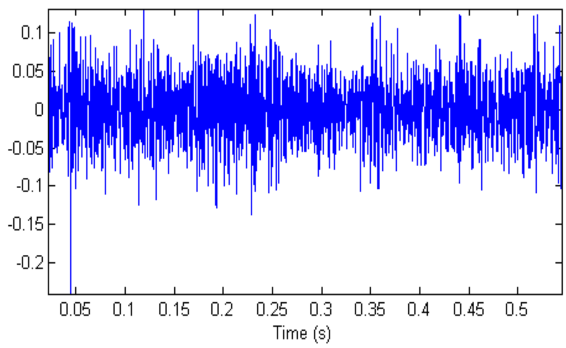


3(e) The retrieved Dolphin call

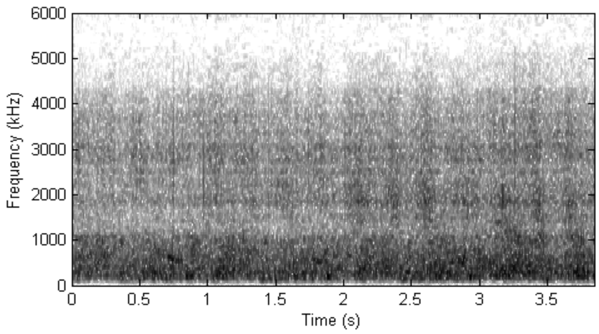


3(f) The spectrogram of the retrieved Dolphin call

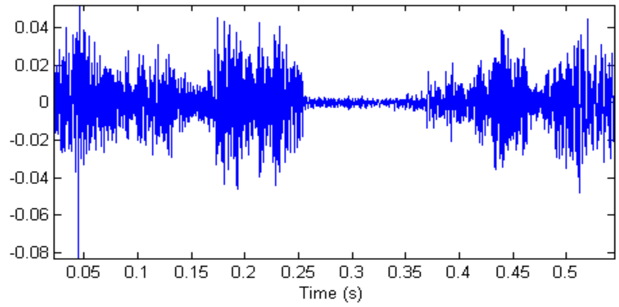
During surveillance operations, the surveillance systems typically look for their signature propeller beats. But they are normally camouflaged by the ships own self-noise. In the second experiment, the propeller beats were extracted from the noisy observations. Figure 4(a) and 4(b) shows the noisy observations in which the turbine noise is hidden. Both in time domain representation and spectrogram there is no observable clues of any propeller action. In the estimated signal, the propeller beats are clearly observable.



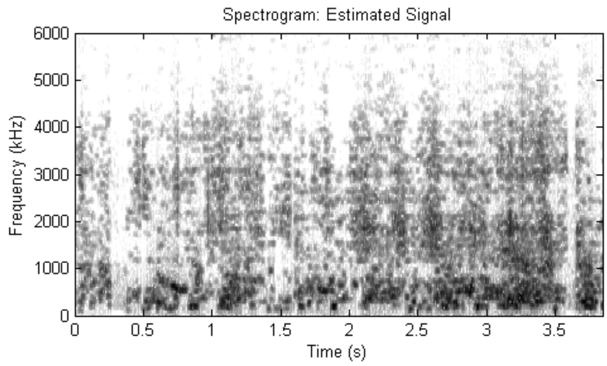
4(a) Noisy observations with hidden propeller beats



4(b) The spectrogram of the observation



4(c) The revealed propeller beats



4(d) The spectrogram of the revealed propeller beats

As described, the spectral components of the self-noise is a function of ship speed and the spectral estimates of the noise spectrum need to be updated periodically in a cyclic manner or gated by spectral shifts. In this evaluation only short time frames are taken such that there is not much variation in the noise spectrum.

As mentioned the process sometimes estimates negative-value for the short-time magnitude spectrum. These values are set to zero to ensure non-negative magnitude spectrum. But this non-linear processing creates small peaks in the spectrum. While it is reproduced in time domain it is appear as noise termed *'musical noise'* . Non-linear spectral subtraction can be employed for avoiding such erroneous estimations.

6 Conclusions

Shipping is a major source of acoustic noise in the global ocean, and due to the exponential increase in shipping activities during last few decades the acoustic medium became chaotic in the vicinity of shipping channels. The self-noise, emanating from the propeller action, engine and other auxiliaries of own ship carrying the acoustic receiver, is the most dominant noise. For the effective utilization of the noisy acoustic channel, the self-noise should be brought under control. The spectral subtraction method is one of the most widely used noise reduction algorithms in the domain of speech processing due to its simplicity and computational accuracy. In this paper, the possibility of utilizing spectral subtraction to mitigate the effect of self-noise has been investigated. Results of such studies were promising and technique can be easily adapted for the real time noise reduction application. The adaptive noise spectrum estimation techniques in conjunction with statistical methods like

Independent Component Analysis (ICA), can be incorporated for improving the performance of the system.

Acknowledgments

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