Narrow-Band Short-Time Frequency-Domain Blind Signal Separation of Passive Sonar Signals

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Abstract. Sonar systems are very important for several military and civil navy applications. Passive sonar signals are susceptible to cross-interference from underwater acoustic sources (targets) present at different directions. In this work, a frequency-domain blind source separation procedure is proposed aiming at reducing cross-interferences, which may arise from adjacent signal source directions. As a consequence, target detection and classification may both be performed on cleaner data and one can expect an overall sonar efficiency improvement. As the underwater acoustic environment is time-varying, time-frequency transformation is performed using short-time windows. Original free of interference sources are estimated using ICA algorithms over narrow-band frequency-domain signals. It is shown that the proposed passive sonar signal processing approach attenuates in more than 10 dB the interference signals measured from two nearby directions and reduces the common background noise level in 7 dB.

Keywords: Passive Sonar, Spectral Analysis, BSS, Convolutive Mixtures, Interference Removal.

1 Introduction

If in a given operational condition exists more than one target to be detected, acoustic signals measured at adjacent directions (bearings) may be corrupted by cross-channel interference, contaminated by a background noise (from underwater acoustic environment) and the self-noise (acoustic signals generated by the own submarine in which the passive sonar system is located). Boths, target detection and classification tasks, may suffer from this interference, which may even provoke errors in important SO (Sonar Operator) decisions.

A narrow-band analysis (DEMON - Demodulation of Envelope Modulation On Noise) [1] is used as a pre-processing step selecting only the frequency band of interest for target characterization. DEMON is performed through Short-time Fast Fourier Transform to deal with the non-stationarity of the passive sonar signals.

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Envisaging cross-channel interference removal, a frequency-domain signal separation procedure is proposed in this paper for a passive sonar system. Original signal source estimation is then performed in frequency-domain using ICA (Independent Component Analysis) over preprocessed signals. Thus, independent components are extracted for each target.

2 Passive Sonar Systems

Passive sonar systems listen to sound radiated by a target using a hydrophone array [2] and detect signals against the background noise, composed by the ambient noise of the sea and the self-noise of the ship. After detection, the target must be identified based on its radiated noise [1]. The system present aural and visual information to the sonar operator, who will use this information to derive his decision, in terms of target identification.

2.1 DEMON Analysis

The DEMON analysis (Demodulation of Envelope Modulation On Noise) is often applied to obtain information about the propulsion of the target [7]. By demodulating the noise produced by cavitation propellers, it is possible to obtain shaft rotation, along with the number of blades and even the number of shafts of the target ship. This extracted information is extremely useful for the identification task [1].

Figure 1 displays the bearing time information obtained from the passive sonar system used in this work. The purpose of the bearing time analysis (beamforming) is to detect the acoustic signals directions of arrival. For that, a Cylindrical Hydrophone Array (CHA) is used in this work, allowing the system to perform omnidirectional surveillance [3].

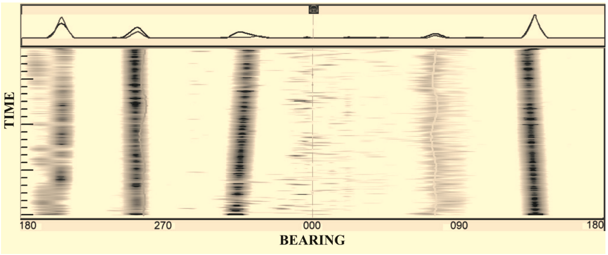


Fig. 1. Bearing time

The broadband noise from a propeller may be amplitude modulated at the blade rate frequency and its harmonics. Typically, target identification is supported by a DEMON analysis [1]. This is a narrow-band analysis that is applied on bearing information and helps the identification of the number of shafts, shaft rotation frequency and the number of blades [4,5]. As they provide a detailed

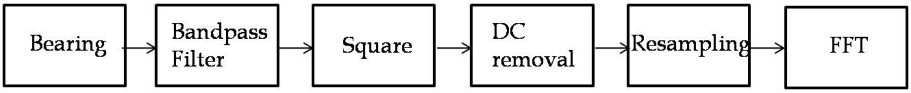


Fig. 2. Blocks diagram of DEMON analysis

knowledge of the threat's radiated noise, narrow-band sonar systems usually show good detection and classification capabilities [1,7].

Figure 2 shows a block diagram for classical DEMON analysis. Acquired time signals are filtered by a bandpass filter, typically between 1 to 10 kHz, which is the frequency band where cavitation is more evident. In sequence, signal is squared as in a traditional demodulation scheme and a TPSW (Two Pass Split Window) algorithm is used to estimate the mean of the background noise [1].

Using TPSW, it is possible to emphasize target signal peaks. Resampling is then performed to reach the band frequency of interest, 0 to 25 Hz, that corresponds to 0 to 1500 rpm. Finally, a Fast Fourier Transform (FFT) [6] is applied for each acquisition, which is 160 second long in this case. As the acoustic signals are time-variant due to modifications on the underwater acoustic scenario, here the FFT algorithm is applied to short lengths of time, which are selected from a moving Hanning-window (approximate length: 500 ms) applied to raw data.

As it has been already mentioned, contamination and interference may occur in neighbour bearings. Interference produces inaccurate peak detection and harmonics poorly definition. The self noise from the submarine may also produce interference in target bearing making it even more difficult the detection procedure.

3 The Proposed Signal Separation Procedure

In this work is proposed a frequency-domain ICA (FD-ICA) method for interference removal in passive sonar systems. As illustrated in Figure 3, DEMON analysis is initially performed over raw-data and frequency information from the three directions are used as inputs for an ICA algorithm, producing the independent (frequency-domain) components. Most of noise and non-relevant signals are eliminated by DEMON, allowing more accurate estimation of the independent components.

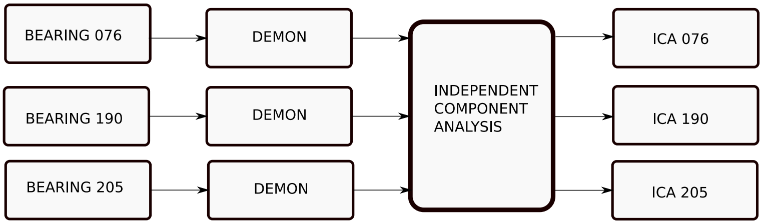


Fig. 3. Interference Removal in frequency domain

A particular characteristic is that DEMON analysis is usually performed over finite time-windows and the frequency components are estimated within these windows. Aiming at reducing the random noise generated in time-frequency transformation, an average spectrum is computed using frequency information from these time-slots.

Frequency-domain ICA (FD-ICA) is closely related to the convolutive mixing model [8], which assumes that the observed signals are generated by delayed versions of the sources. In the frequency-domain, convolutions are reduced to multiplications. A characteristic of FD-ICA is that the mixing matrix is frequency-dependent. In this work, as we are dealing with a narrow frequency band (0 to 25 Hz), for simplification, the mixing matrix is considered invariant in this band.

In ICA algorithms, the order and the amplitude of the estimated components are random parameters and thus different initializations may lead to different scaling factors and ordering [8]. In the proposed approach, ICA algorithms are executed after DEMON estimation at each time window, independent components from a certain direction may appear in different ordering at adjacent time-windows in this sequential procedure. Considering this, the short-time independent components must be reordered and normalized in amplitude. The normalization is performed by converting signal amplitude into dB scale. The reordering procedure is executed by computing the correlation between independent components estimated from adjacent time slots. High correlation indicates that these components are related to the same direction.

In the Section 4, experimental results obtained through the proposed approach are detailed. To estimate the independent components, JADE [10] and the Newton-like [12] algorithms were used. A performance comparison between these algorithms is presented.

3.1 Joint Approximate Diagonalization of Eigenmatrices

JADE (Joint Approximate Diagonalization of Eigenmatrices) [10] refers to one principle of solving the problem of equal eigenvalues of cumulant tensor achieving a diagonalization of the tensor through the eigenvalue decomposition. The tensorial method is used to carry through the independent components analysis. Tensors may be considered as a linear generalization of matrices or operators. The second and fourth order cumulant tensors are used to search for signal independence.

3.2 Multiplicative Newton-Like Algorithm for ICA

A multiplicative ICA algorithm was proposed by Akuzawa and Murata in [12]. Using the kurtosis as cost function, this method applies second-order optimization (through a Newton-like algorithm) in the search for independent components (instead of first-order gradient iterations used in most of ICA algorithms).

This algorithm does not require pre-whitening and thus operates directly over the data. Some experimental results obtained in [13] indicate that Akuzawa's algorithm outperforms classical ICA algorithms such as FastICA [8] and JADE in the presence of Gaussian noise.

4 Experimental Results

Experimental data used in this work comprises signals acquired from a CHA (sample frequency of 31,250 Hz). Initially, DEMON analysis is applied to raw data as a pre-processing. Figure 4 shows typical DEMON displays from three bearings. The horizontal axis represents the rotation scale (in rpm) while the vertical axis corresponds to signal amplitude (in dB). The largest peak amplitude reveals the speed of shaft rotation, while the subsequent harmonics indicate the number of blades.

Two targets are present in this experimental run at directions 190^o and 205^o. As illustrated in Figure 4, the frequency components after DEMON analysis (here DEMON spectrums are composed by 512 frequency bins, spanning from zero up to 1400 RPM) at 190^o target (FA=148 RPM and its multiples) are mixed together with information from the 205^o direction (FB=119 RPM). The same problem exists in the signal measured at bearing 205^o. It was also observed that both signals (190^o and 205^o) are contaminated by a third component (FC=305 RPM), that is the main frequency present at direction 076^o. It is known from the experimental setup that the last bearing (076^o) contains information from the noise radiated by the submarine where the hydrophones array is allocated. It can also be verified that, signal measured at direction 076^o presents interference from target at 205^o (FB).

The proposed narrow-band frequency-domain signal separation procedure was applied to the underwater acoustic signals measured at directions 076^o, 190^o and 205^o. A frequency-time display (demongram) for direction 190^o is provided in Figure 5. It can be depicted that an interference frequency component (FB) is present during the observed interval (from 65 to 85 seconds) in raw data at direction 190^0 (Figure 5-a). Figure 5-b illustrates the frequency-time display for the independent component related to the same direction and it can be observed

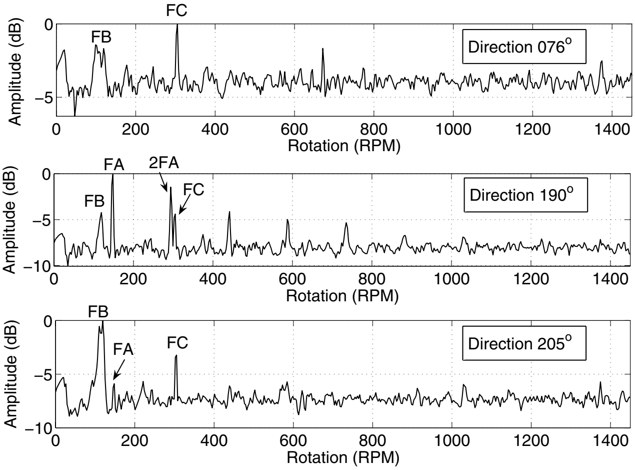
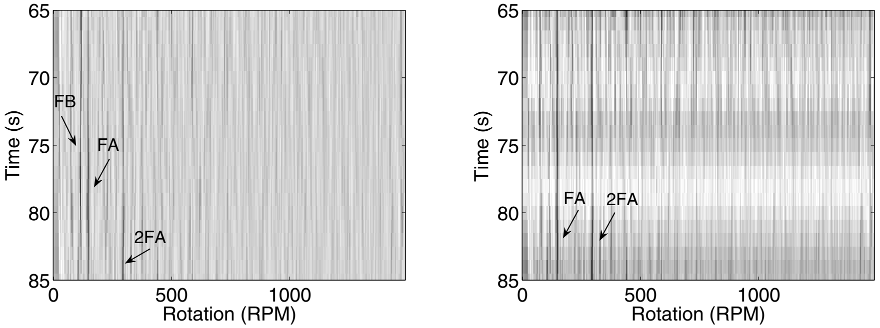


Fig. 4. DEMON analysis for direction 076^o (top), 190^o (middle) and 205^o (bottom)



(a) (b)

Fig. 5. Time-frequency display at direction 190^0 for (a) raw data and (b) short-time frequency-domain independent component

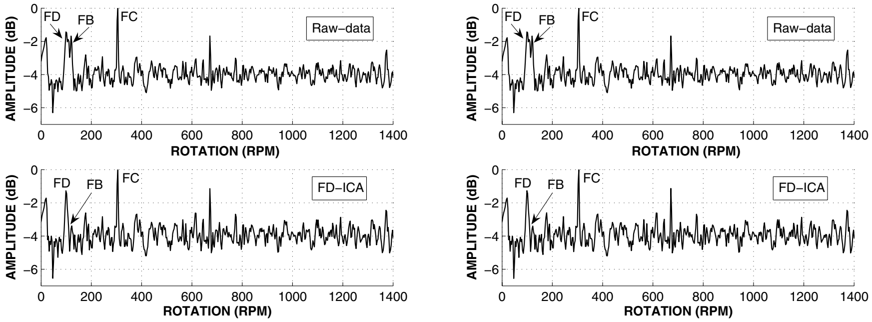


Fig. 6. Separated signals obtained for directions 076^o through JADE (left) and Newton-like (right) algorithms

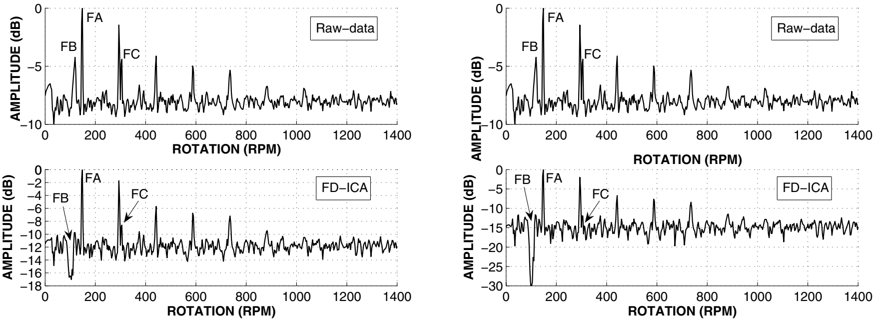


Fig. 7. Separated signals obtained for directions 190^o through JADE (left) and Newton-like (right) algorithms

that the interference is removed and the second harmonic component highlighted as a result of FD-ICA. In this plot, JADE algorithm was applied.

In the classical DEMON processing, the mean amplitude of the frequency components obtained at each short-length time windows is calculated and a

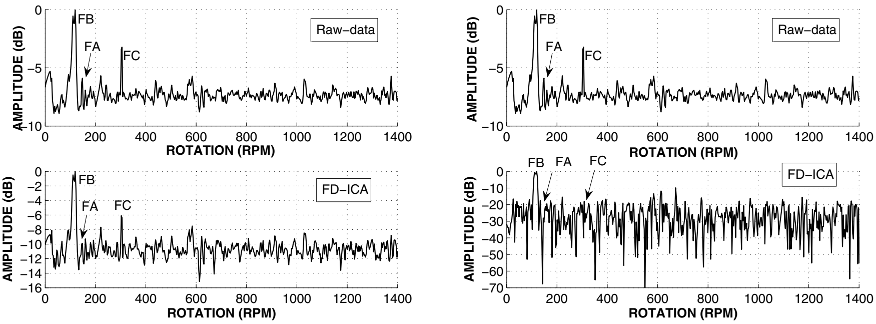


Fig. 8. Separated signals obtained for directions 205^o through JADE (left) and Newton-like (right) algorithms

mean frequency-amplitude plot is generated. The results (considering the mean spectrums) obtained through JADE and the Newton-like algorithms are illustrated in Figures 6, 7 and 8 respectively for directions 076^o, 190^o and 205^o. It can be observed from these Figures that in the independent signals, obtained through both algorithms, the cross-interference was significantly reduced.

For the Newton-like algorithm, it was also observed that the background noise level (which can be estimated from the mean amplitude of the non-relevant frequency components) was more significantly reduced when compared to JADE. For direction 190^o the estimated background noise levels are approximately -8dB (raw-data), -12dB (FD-ICA / JADE) and -15dB (FD-ICA / Newton-like). Considering now direction 205^o, the noise level was reduced from -7dB (raw-data) up to -11dB (FD-ICA / JADE) and -30dB (FD-ICA / Newton-like). The cross-interference peaks were also more severely attenuated at the independent components estimated through the Newton-like algorithm. These results indicates that the independent components estimation through the Newton-like algorithm is more suitable for this application.

5 Conclusions

On passive sonar signals, target identification relies very much on narrow-band frequency-domain information obtained through DEMON analysis. Signals acquired at adjacent directions (bearings) may be corrupted by cross-channel interference from multiple targets. In this work, Frequency-Domain Independent Component Analysis (FD-ICA) was used to reduce this interference. The performance obtained through two ICA algorithms, JADE and Newton-like, were compared and it was observed that the Newton-like method presented better results.

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