Chapter 8

Echo Characterization in Active Sonar

using Wigner Ville Distribution

Active sonar echo characterization and classification are two new functions added to the repertoire of sonar functions in the recent years. Prior to classification, the received echoes have to be analyzed to extract its features. In this chapter, the potential of Wigner Ville Distribution (WVD) as a base algorithm for echo characterization in active sonars is demonstrated. A novel technique combining WVD with FrFT has been developed to overcome the problem of cross-terms in WVD, thereby representing the active echoes with excellent clarity in the time-frequency map. The under water scenario for active target classification is first explained. The denoising capability of FrFT with multi-component signals is then highlighted, after which, the new implementation scheme combining these two time-frequency methods is explained. As a comparison, computations of Pseudo WVD are also demonstrated. This is followed with the simulation results with single and multiple chirps embedded in noise, along with the results of analyzing recorded underwater data. The ROC curves highlighting the SNR improvements compared to direct WVD implementation are also generated. The chapter is concluded by highlighting the results and discussing the important findings of the new implementation.
8.1 Introduction

Passive classification techniques for extracting the frequencies of machinery and the propeller shafts are widely used in sonars. But active sonar echo characterisation and target classification from the received echoes are two areas where few developments are reported. In active sonar, a signal transmitted from a source is reflected from the target ship. The received signal called the echo is modified in its features like duration, bandwidth, envelope shape etc. Characterising the echo will help in classifying the contact and understanding the medium also. Depending on the different types of targets (surface or submerged) and different aspects of the same target (ahead or behind or along side), the echoes will be different. The first step in contact classification however is echo characterisation. In this chapter, a WVD-based technique for this purpose is discussed and the results are demonstrated. This technique can be used as a pre-processing algorithm for echo characterisation.

Among all time-frequency representations, WVD is the best in terms of achievable time and frequency resolutions [14,15]. However, it is the least used one, mainly because of the problem of cross-terms. Excellent time and frequency resolutions are possible with WVD if the signal has only one component, which is not the practical situation. With multi-component signals and noisy mono-component signals, the WVD representation is distorted by cross-terms, thereby affecting the signal analysis required by the different applications. Many techniques have been proposed to reduce these cross terms namely Pseudo WVD, members of Cohen class etc[14,15]. These techniques have high computational complexity. Also, they achieve the cross-term reduction at the cost of time or frequency resolution or both.

Our aim has been to develop an analysis technique which guarantees good resolution and does not suffer the disturbances of cross-terms. Consequently, one is able to represent chirp signals with an excellent resolution in the time frequency map. One noticeable characteristic of all the cross-term reduction methods mentioned above is that they all modify the WVD equation, which means the reduction process occurs along with the WVD operation. That accounts for the loss of resolutions. But, if we can do the denoising prior to WVD operation, the loss of resolution can be reduced. This is the principal motivation for evolving the WVD-FrFT combo algorithm. Denoising techniques using wavelets are available...
in literature[56,57]. However, from the simulation results on FrFT in chapters 5 and 6, the excellent denoising capabilities of FrFT are demonstrated. Added to that, FrFT is ideal for chirp analysis. Active echoes being chirps mostly, FrFT will be better than WT as a denoising tool. In the sections to follow, the effective utilization of FrFT to recover the high resolution possible in WVD is demonstrated.

8.2 Echo Characterization Scenario in Sonars

As shown in fig.8.1, from the subsequent the subseqeont pings, the beam formed data around the marked regions (in range and bearing, showing detection) are extracted. The new technique is then applied on these beam outputs. Generally, in an active sonar, the transmitted signal will be FM or CW, though the FM is preferred because of its excellent detection capability in reverberation. The proposed algorithm is most effective when FM signals are involved, either linear or non-linear. CW signals can also be analysed with this new method, but existing techniques based on STFT offers acceptable results for the CW signals. In the active sonar, chirp itself is transmitted, hence optimum α is known a priori to the transmitter.

![Tactical Under water Scenario & hypothetical Active sonar display](image)

8.3 Denoising using FrFT

Based on the simulations in Chapter 6, FrFT is applied as a denoising tool with the aim of reducing cross terms occurring in WVD processing. In real situations, multiple chirps may
be present that too embedded in noise. The signal to be analyzed may contain more than one chirp, and these chirps may be overlapping in frequency or time or both. However, each of them will peak in the FrFT output for its corresponding optimum $\alpha$ only.

Extraction and reconstruction of just one of the chirps from the mixture can be achieved by performing an equivalent inverse FrFT on one of the spike components in the FrFT output. A filtering process, which can be performed on the FrFT output, consists of retaining the minimum number of points either side of the chirp component to be extracted and zeroing all values outside this range of the complex FrFT output. An inverse FrFT of equivalent order is applied to the resultant and the real part of its output gives the reconstructed chirp component in the time domain. So, while the chirp is being extracted, denoising also takes place along with it. Also, this denoising method is applicable for both linear as well as non-linear chirps. Simulations to demonstrate this extraction method is given in section 6.2.4 of chapter 6.

8.4 WVD-FrFT Method

As was mentioned earlier, the cross-terms are generated in WVD when more than one chirp is present or when only one chirp is present with additive noise. The filtering procedure performed offers two advantages viz. Multiple chirps can be separated and a noisy chirp can be denoised. The inverse FrFT of the denoised FrFT output, followed by a WVD operation results in a denoised chirp signal. Also, when the signal contains multiple chirps, the WVD of each of them can be obtained without cross terms. Fig.8.2 shows the implementation block diagram for the proposed FrFT-WVD scheme as well as the direct WVD scheme.

In active sonar, the received signal called the echo is modified in its characteristics like duration, bandwidth, envelope shape etc. Depending on the different types of targets (surface or submerged) and different aspects of the same target (ahead or behind or along side), the echoes will be different. As mentioned earlier, the first step in contact classification is echo characterisation. Characterising the echo will help in classifying the contact and understanding the medium also. The WVD-FrFT technique developed in this thesis can be used as a pre-processing algorithm for echo characterisation. Once the echoes are plotted with clarity in the time-frequency map, the differenced in echoes from different targets like echo
bandwidth, shape, slope change, start and end frequencies can be extracted as its characteristics. These characteristics can be then used for target classification. The feature extraction and classification functions have not been attempted in this thesis.

![Image of Implementation Block Diagram](image-url)

**Fig. 8.2 - Implementation Block Diagram**

**8.5 Simulation Results**

The simulations are done on synthetic analytic linear and non-linear chirps, overlapping in time and frequency. They illustrate the potential of this approach in practical applications. All simulations have been done on Matlab. Hilbert transform has been used extensively in the following examples to convert real signals to an analytic form comprising of the positive frequency components of the input signals only.

The developed method is illustrated with three examples. The first simulation is done with a single noisy chirp. In the second simulation, two overlapping noisy chirps are considered, a linear and a hyperbolic chirp. The last simulation has been done with three overlapping chirps. The simulation details are tabulated in table 8.1. Two or more targets being present at same ranges may not happen in general. But in these simulations, cases of two or more chirps overlapping in time and frequency are considered. Such situations are simulated only to demonstrate the efficiency of this new technique, even under such worst
case scenarios. The most common situation is the occurrence of one chirp alone, embedded in noise.

Table 8.1 Simulation Settings

<table>
<thead>
<tr>
<th>Simulation 1</th>
<th>Simulation 2</th>
<th>Simulation 3</th>
<th>Simulation 4</th>
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<tbody>
<tr>
<td>One Noisy Chirp</td>
<td>One Noisy Chirp</td>
<td>Two Noisy Chirps</td>
<td>Two Noisy Chirps</td>
</tr>
<tr>
<td>SNR = -3 dB</td>
<td>SNR = -11 dB</td>
<td>SNR = -9 dB</td>
<td>SNR = -9 dB</td>
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<tr>
<td>Linear FM</td>
<td>Linear FM</td>
<td>a) Linear FM</td>
<td>a) Linear FM</td>
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<tr>
<td>BW = 300 Hz</td>
<td>BW = 300 Hz</td>
<td>BW = 300 Hz</td>
<td>BW = 400 Hz</td>
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<tr>
<td>Duration 128mSec</td>
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<td>Start freq 100 Hz</td>
<td>Start freq 100 Hz</td>
<td>Start freq 400 Hz</td>
<td>Start freq 100 Hz</td>
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<tr>
<td>Up slope</td>
<td>Up slope</td>
<td>Down slope</td>
<td>Upslope</td>
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<tr>
<td>b) Hyperbolic FM</td>
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<td>BW = 300 Hz</td>
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<td>Duration 128mSec</td>
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<td>Start freq 100 Hz</td>
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<td>Up slope</td>
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<tr>
<td>c) Hyperbolic FM</td>
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<td>BW = 300 Hz</td>
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8.5.1 Simulations on a single noisy chirp

For this simulation, a linear chirp of duration 128msec is generated with a sampling frequency of 2 KHz. The signal bandwidth is randomly chosen as 300Hz, with a start frequency of 100Hz. The additive noise is white Gaussian and the signal SNR is -3 dB. Fig.8.3 and 8.4 show the WVD and PWVD of the noisy chirp signal and fig.8.5 shows the WVD of signal denoised using FrFT. The WVD of the signal denoised using FrFT does not suffer from the problem of cross terms whereas the WVD and PWVD plots of noisy signal are totally cluttered with interferences. Fig.8.6, 8.7 and 8.8 show the same outputs for the signal at a lower SNR of -11dB. In this case, the chirp is totally indistinguishable in the WVD and PWVD plots, whereas it is perfectly extracted by the new scheme. FrFT based WVD clearly outperforms direct WVD and PWVD, especially with low SNR signals.
Fig. 8.3 - WVD of Single Chirp (-3dB)

Fig. 8.6 - WVD of Single Chirp (-11dB)

Fig. 8.4 - PWVD of Single Chirp (-3dB)

Fig. 8.7 - PWVD of Single Chirp (-11dB)

Fig. 8.5 - WVD of FrFT Denoised Chirp (-3dB)

Fig. 8.8 - WVD of FrFT Denoised Chirp (-11dB)
8.5.2 Simulations on two different noisy chirps

For this simulation, two overlapping chirps are generated of duration 128 msec with a sampling frequency of 2 KHz. First is a linear chirp with down slope, having a start frequency of 400 Hz and bandwidth 300 Hz. The second is a non-linear chirp having an up slope, with a start frequency of 100 Hz and bandwidth 300 Hz. The additive noise is white Gaussian and the signal SNR is -9 dB. Fig.8.9 and 8.10 show the WVD and PWVD of the noisy chirps. WVD of FrFT denoised signal is shown in fig.8.13. Fig.8.11 and 8.12 show the WVD plots of two individual chirps separately after denoising and filtering using the extraction method explained earlier. The separately obtained WVD outputs, after denoising, are summed to get the denoised, cross term free plot of fig.8.13. The two chirps were hardly discernible in the WVD and PWVD plots. On the other hand, with the new method, two advantages are noteworthy

(i) Cross-terms are cancelled.

(ii) The time-frequency flow of the two chirps are clearly brought out.

![Fig.8.9 - WVD of Two Chirps(-9dB)](image1)

Chirp1: LFM and Chirp2: HFM

![Fig.8.10-PWVD of Two Chirps(-9dB)](image2)
8.5.3 Simulations on Three Different Noisy Chirps

In order to demonstrate that the new method developed here works well with any number of chirps, three overlapping chirps are generated of duration 128msec with a sampling frequency of 2 KHz. First one is a linear chirp with up-slope, having a start frequency of 100 Hz and bandwidth 400 Hz. The second one is a linear chirp having an down slope, with a start frequency of 500 Hz and bandwidth 400 Hz. The third one is a non-linear chirp having an up-slope, with a start frequency of 100 Hz and bandwidth 300 Hz. Fig.8.14 and 8.15 show the WVD and PWVD of the noisy chirps. WVD of FrFT denoised signal is shown in fig.8.19. Fig.8.16, 8.17 and 8.18 show the WVD plots of three chirps separately after denoising and filtering.
Chapter 8

Fig. 8.14 - WVD of Three Chirps (-9dB)

Fig. 8.15 - PWVD of Three Chirps (-9dB)

Fig. 8.16 - WVD of FrFT Denoised Chirp 1 (-9dB)

Fig. 8.17 - WVD of FrFT Denoised Chirp 2 (-9dB)

Fig. 8.18 - WVD of FrFT Denoised Chirp 3 (-9dB)

Fig. 8.19 - The WVD of Denoised Chirps (-9 dB)
8.5.4 Performance Evaluation

The performance analysis of the new technique is done for different SNRs. Fig. 8.20 and 8.21 show the PD vs SNR plot for two different probabilities of false alarms, 0.001 and 0.0001 for a signal with single chirp. Similar curves were obtained for signals with two and three chirps. Montecarlo simulations were done to obtain these performance curves. The performance is remarkable, especially at low SNR values. At PD of 50%, the proposed FrFT-WVD scheme shows an improvement of 5 dB over the conventional WVD scheme.

![Fig. 8.20 - PD vs SNR (PFA=0.0001)](image1)

![Fig. 8.21 - PD vs SNR (PFA=0.001)](image2)


8.5.5 Echo Characterization with Recorded Data

The WVD-FrFT method was applied on real data also with very encouraging results. Fig.8.22 shows the WVD of a recorded active echo. The WVD of the denoise echo is shown in fig.8.23. The bandwidth, start frequency, end frequency and linearity of the FM signal is clearly brought out by the proposed scheme. The new method was applied to recorded underwater biological signal, with similar results (fig.8.24 and 8.25).

Fig.8.22-WVD of Active Sonar Echo

Fig.8.23-WVD of FrFT Denoised Echo
Fig. 8.24 - WVD of Biological Noise

Fig. 8.25 - WVD of FrFT Denoised Biological noise
8.6 Conclusions

Not many works are seen on active target classification in sonars. But it is becoming a mandatory requirement in the new generation sonars. In this thesis, the potential of WVD for echo characterization is explored. Among all time-frequency representations, WVD is the best in terms of achievable time and frequency resolutions. However, it is the least used one, mainly because of the problem of cross-terms. Excellent time and frequency resolutions are possible in WVD if the signal has only one component, which is not the practical situation. With multi-component signals and noisy signals, the WVD representation is distorted by cross-terms, thereby affecting the signal analysis required by the different applications. Many techniques have been developed to reduce these cross terms namely pseudo, smoothed WVD, members of Cohen class etc. But, they all have high computational complexity. Also, they all achieve the cross-term reduction at the cost of time or frequency resolution or both.

Our aim has been to develop an analysis technique which guarantees good resolution and does not suffer the disturbances of cross-terms. A novel method for echo characterization in sonars is developed to identify unknown chirp signals in low signal-to-noise (SNR) environment and represent the signals with excellent clarity as a time frequency representation. This method is based on FrFT denoising, prior to analyzing mono- or multi-component chirps using Wigner Ville Distribution. The method offers excellent rejection capability of cross-terms in the WVD and more robustness against additive white Gaussian noise with pronounced time-frequency resolution. The motivation behind the developed scheme is the inherent ability of FrFT to process chirp signals. The approach is applied on non-linear chirps and CW pulses as well. As a base algorithm for active target classification, the developed WVD-FrFT combination has proved to do an excellent job of echo characterization. The advantages of the developed technique are as follows

- WVD alone has very low MDL (of the order of −5 dB). Developed WVD-FrFT algorithm has an MDL of the order of −12 dB.
- Resolution properties of WVD are achieved with just one FrFT computation done for denoising.
- Method applicable to Chirps as well as CW echoes

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