Chapter 10

Summary and Conclusions

A brief summary of the research work conducted and the important conclusions thereon are highlighted in this chapter. The scope for further work in this field as an extension of the present study has also been discussed.
10.1 Summary of the Work and the Important Conclusions

Sonar signal processing comprises of a large number of signal processing algorithms for implementing functions such as Target Detection, Localisation, Classification, Tracking and Parameter estimation. Current implementations of these functions rely on conventional techniques largely based on Fourier Techniques, primarily meant for stationary signals. Interestingly enough, the signals received by the sonar sensors are often non-stationary and hence processing methods capable of handling the non-stationarity will definitely fare better than Fourier transform based methods. The present dissertation has addressed this aspect in detail.

Time-frequency methods (TFMs) are known as one of the best DSP tools for non-stationary signal processing, with which one can analyze signals in time and frequency domains simultaneously. But, other than STFT, TFMs have been largely limited to academic research because of the complexity of the algorithms and the limitations of computing power. With the availability of fast processors, many applications of TFMs have been reported in the fields of speech and image processing and biomedical applications, but not many in sonar processing. A structured effort, to fill these lacunae by exploring the potential of TFMs in sonar applications, is the net outcome of this thesis. To this end, four TFMs have been explored in detail viz. Wavelet Transform, Fractional Fourier Transform, Wigner Ville Distribution and Ambiguity Function and their potential in implementing five major sonar functions has been demonstrated with very promising results. What has been conclusively brought out in this thesis, is that there is no “one best TFM” for all applications, but there is “one best TFM” for each application. Accordingly, the TFM has to be adapted and tailored in many ways in order to develop specific algorithms for each of the applications. Main achievements of the thesis are as follows:

10.1.1 Improved target detection in Active Sonar using FrFT

It is well known that the optimum detector for active sonar detection is matched filtering. Direct time-domain implementation of matched filtering is hardware intensive and so many practical systems are realized using a fast method of implementation called heterodyne correlator. This simplification is achieved, by making narrow-band assumptions about the
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reduced signal. In the present method, Fractional Fourier Transform (FrFT) has been applied to active sonar processing, as viable alternative to the well known FFT based approach and an algorithm has been developed to achieve improved matched filter based detection performance. The motivation behind this development is the ability of FrFT to process non-stationary signals like chirp signals better than the conventional Fourier Transform. FrFT is a parameterized transform with parameter $\alpha$, related to the chirp rate. Many active sonar systems choose to transmit chirp signals for better detection in the presence of reverberation. Accordingly, FrFT if used instead of FFT in the correlation receiver, has great potential by utilizing the a priori knowledge of the optimal $\alpha$ of the transmitted waveform. This has been demonstrated in the simulations in Chapter 5, wherein a 3 dB improvement has been achieved in the detection performances at different SNRs and with moving targets. Estimation of target speeds is also achieved at the same accuracy as the FFT method. These improvements have been obtained with no additional implementation cost.

10.1.2 Excellent Parameter Estimation in Intercept Sonar using FrFT

Detection of chirp pulses with varying parameters is required in many applications like the intercept sonar, where transmissions from other platforms, can be chirps, among other types of waveforms. The application of FrFT for chirp parameter estimation in intercept has been explored extensively in Chapter 6. The chirp parameters to be estimated are bandwidth, start frequency, duration and onset time of echo. A notable outcome of the thesis is a novel parameter estimation procedure, by which these chirp parameters are calculated systematically from the two primary estimates, namely optimum $\alpha$ and FrFT peak position. The developed search algorithm can estimate the optimum $\alpha$ of unknown chirps to an accuracy of 3 digits. Estimation of multiple Chirps overlapping in time as well as frequency is possible. The method performs very well, even when processing length does not match with the echo length. The algorithm does not require any reconstruction algorithm as in the conventional STFT method. Another advantage is its capability to differentiate linear and hyperbolic chirps, while detecting them. Also, from the performance comparison of FrFT detector with FFT and Energy detectors, in the presence of white Gaussian noise as well as 1/f noise, it is demonstrated that estimation of Chirp parameters up to $-27$ dB SNR is possible.
with the developed method which is 11dB over FFT detector and over 23 dB over Energy
detector. The developed FrFT based estimation procedure is straight forward and outperforms
the presently used FFT method on many scores. Only overhead is the additional
computational load required for the ‘optimum α’ search.

10.1.3 Better and Fast Transient Detection in Passive Sonar

using Lifting Based Wavepacket Transform

Quieting techniques used in the newest classes of submarines of the world’s navies have
greatly reduced the narrowband acoustic tonal frequencies of rotating machinery that have
been the primary source of acoustic energy for detection and classification by passive sonar.
However, there are still exploitable acoustic signatures in the form of short duration acoustic
events, called transients, that can be used to detect and to classify underwater acoustic
signatures. Traditional sonar signal processing techniques based on Page test and FFT are not
well suited for processing many transient signals of concern due to their short duration and
their non-stationary nature. In the present thesis, a fast method for analyzing underwater
transients buried in noise is presented to handle both the problems. The challenge here has
been to develop a method applicable to different types of transients with unknown
waveforms and arrival times. The TFM adopted here for transient analysis is Wave packet
transform, a variant of Wavelet transform, which has well known time localization
capabilities. By using Wave packet transform, the entire frequency band can be analyzed. As
for the implementation, instead of the conventional Filter bank implementation scheme, a less
computationally intensive method, namely Lifting scheme is adopted here. Because of this
fast implementation, almost 60% reduction in processing time has been achieved. So, both
detection as well as analysis can be done by Wave packet transform without hardware
complexity. From the ROC curves, comparing the performance with the conventional Page
test, the present method combining Wave packet transform and Lifting scheme provides a 6
dB improvement in detection. Hence this method is ideal for real-time applications like
sonar.
10.1.4 Accurate Echo Characterization in Active Sonar using Wigner Ville Distribution (WVD)

Effective classification of contacts in active sonar is becoming a mandatory requirement in the new generation sonars. In this thesis, the potential of WVD for characterization echoes, which in turn facilitates classification, has been explored. Among all time-frequency representations, WVD is the best for characterization of signals in terms of achievable time and frequency resolutions. However, it is the least used, mainly because of the problem of cross-terms. With multi-component signals and noisy signals, the WVD representation is heavily distorted by cross-terms, thereby affecting the signal analysis required for echo characterization. Many techniques have been developed to reduce these cross terms namely pseudo WVD and members of Cohen class. They all achieve the cross-term reduction at the cost of time or frequency resolution or both, and also have high computational complexity. In this thesis, a novel and fast 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 analysis 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 approach performs equally well with non-linear chirps and CW pulses. As a base algorithm for active target classification, the developed WVD-FrFT combination algorithm, has been proved to achieve excellent echo characterization.

10.1.5 Fast Generation of Wide-band Ambiguity Function and Improved Matched Filtering in Active Sonar using Fourier Mellin Transform

As a waveform evaluation tool and core operator in matched filtering in active sonars, the importance of Ambiguity function is not small. Due to implementation problems, the narrow-band ambiguity function is widely used in many active sonar systems. Also, for narrow-band signals and low speed targets, the phenomenon of Doppler can be approximated by a translation in time and frequency. But, when the signal under analysis is not narrow band, this particular form of ambiguity function is no longer adequate. Thus there is a
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requirement to consider the WB AF. But such broad-band functionals cannot be computed by standard techniques. In this thesis, the Fast Mellin transform algorithm by Ovarlez has been adopted for the implementing WB AF. Simulations of Matched filtering using this new implementation when compared with the conventional scheme using narrow-band assumption clearly demonstrate a 2 dB improvement in matched filtering. Also, the ambiguity diagrams of typical waveforms like LFM and HFM using both the equations have been plotted. The ambiguity diagrams generated using the WB AF implementation are giving a more convincing and realistic picture, when compared to the Narrow-band ambiguity diagrams.

Table 10.1 – Summary of Results

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Type Of Sonar</th>
<th>Function</th>
<th>Time-Frequency Method</th>
<th>Performance Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Active Sonar</td>
<td>Detection</td>
<td>FrFT</td>
<td>3 dB</td>
</tr>
<tr>
<td>2</td>
<td>Intercept Sonar</td>
<td>Parameter Estimation</td>
<td>FrFT</td>
<td>11 dB</td>
</tr>
<tr>
<td>3</td>
<td>Passive Sonar</td>
<td>Transient Detection</td>
<td>Wavepacket(lifting scheme)</td>
<td>6 dB</td>
</tr>
<tr>
<td>4</td>
<td>Active Sonar</td>
<td>Echo Characterisation</td>
<td>WVD and FrFT</td>
<td>7 dB</td>
</tr>
<tr>
<td>5</td>
<td>Active Sonar</td>
<td>Fast Computation of WB AF</td>
<td>WB AF(using FMT)</td>
<td>2 dB</td>
</tr>
</tbody>
</table>

10.2 Scope For Further Investigations

The thesis reports the results of the research work carried out on the application of time-frequency methods for improving the performance of the sonar systems. But this does not foreclose further work that can be carried out. The present thesis has picked some of the pebbles from the vast shore lines of Signal Processing techniques for improving the sonar performance and many more are likely to be present. Some of the possible areas for further studies are suggested below.

FrFT equations for non-linear chirps are not available in literature. So, in the simulations of this thesis, the equation for linear chirps has been adopted for non-linear chirps as well. However, to cater for the spread of FrFT peaks of non-linear chirps, more bins have been retained during the IFrFT operation in the chirp extraction procedure. Chris Capus et al[87] recommends subdividing non-linear chirps into sections and then using the equation of
linear chirps. But, a more precise expression for non-linear chirp processing can yield better results. This is an open problem which requires further investigation.

The echo characterization method proposed in the present thesis can be used as the base algorithm for further target classification using standard classification algorithms. The active classification is one area which is very much essential in the new generation sonars, where a lot more remains to be done.

In addition to the TFMs that have been explored, there are numerous others that have been developed over the last fifty years. Cohen [15] has introduced a general form for representing all bilinear TFRs which facilitates us with the design of the desired TFRs. Three prominent members of Cohen class are Choi-William Distribution, Cone-shaped Distribution and Signal dependent TFM. The potential of these distributions in sonars is worth exploring.

Signal waveform design is a very important step in active sonar system design. The signal waveform not only decides the signal processing method, but also affects the performance of detection, estimation, interference resistance and target tracking. Theoretical analysis is therefore the solution. That is, to synthesize the waveform from the ambiguity characteristics. These new classes of waveforms can provide superior reverberation processing and other desirable properties compared to the conventional CW and FM waveforms, thereby enhancing the performance of active sonars in reverberation-limited conditions.