Linear frequency modulated reverberation suppression using time series models

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ABSTRACT

When active radar and sonar systems are used for target detection and tracking, boosting target detection, and tracking efficiency is the most important challenge in real-time reverberation. To eliminate reverberation when transmitting linear frequency modulated (LFM) signals, this study employs time series techniques such as autoregressive (AR), moving average (MA), and autoregressive moving average (ARMA). The primary purpose of this research is to whiten LFM reverberation by transforming it to a fractional domain using the fractional Fourier transform (FrFT). The LFM reverberation is a highly coloured noise whose frequency fluctuates according to the stationary hitting frequency. As a reference signal, the proposed methods make use of the adjacent signal block. The effectiveness of FrFT-based AR, MA, and ARMA pre-whitening for LFM reverberation reduction was assessed, and the results were presented.

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1. INTRODUCTION

In the last few decades, there have been many improved techniques for producing and studying signal processing in the applications of Radar and Sonar systems. So that we can determine their characteristics even though they are statistically time variable or non-stationary. When detecting targets in an underwater scenario, reverberation has a significant impact on the efficiency of target detection. There are broad applications of spectral analysis in different sources. For example, the spectral content of the received signals in active sonar systems provides information on the location of the targets in the field of view [1].

Because the linear frequency modulated (LFM) reverberation is heavily coloured, the LFM signal will be in time and frequency domains tightly related to the non-stationary and emitted signals. Because of this limitation, matched filtering is ineffective. The whitened current block's reverberation by modelling the preceding block's reverberation with pre-whitening time series models such as autoregressive (AR), moving average (MA), and autoregressive moving average (ARMA). However, the method is based on the assumption that the signal is locally stationary, and, in fact, the signal output may be poor due to variations in the frequency of the LFM signal. There are three methods of spectrum estimation, i) model-based (parametric), ii) classical (nonparametric), and iii) subspace methods. Burg, Covariance, Yulle-Walker, and Modified Covariance methods are examples of parametric methods, Spectrogram, Periodogram, Welch, Coherence, and Cross-Spectrum methods are examples of nonparametric and Examples of subspace are multiple signal classification (MUSIC), Pseudo Spectrum and Eigenvector methods. AR, MA, and ARMA models have been used in active sonar and radar systems for modeling processes such as reverb suppression similar to all-pole filtering, FIR filtering, and pole-zero filtering. Schuster developed classical estimation methods for the spectrum of power signals in 1898, model-based methods were developed in 1927 by Yule, further developed and used by Walker in 1931, Bartlett in 1948, Parzen in 1957, Tukey and Blackman in 1958, and other researchers [2]-[4]. Qian and Luan [5] pioneered the calculation of fractional Fourier transforms in quantum mechanics in the 1980's. Fractional fourier transform (FrFT) is a more generalised Fourier transform technique. We know that for Fourier transform=π/2, but not for FrFT. The FrFT approach is a time-frequency distribution that provides us with an external degree of independence, providing us with additional benefits above the standard Fourier transformation [6]-[11]. In many applications, all-pole or autoregressive signals are the most common. By placing the A–polynomial zeros close to the unit circle, the AR equation can model narrow-pit spectra. Because narrowband spectra are so common in practice, this is an important feature. Furthermore, parameter estimation in the AR signal model is a well-known topic; the linear equation technique solution defines estimates, and the stability of the generated AR polynomial can be ensured.

Filtering white noise with a FIR or all-zero filter yields the MA signal. The MA equation, due to its all-zero form, cannot simulate a spectrum with sharp peaks unless the MA order is sufficiently high. For specific spectra with sharp zeros and large peaks, the MA model gives a good approximation. Because such spectra are more common in applications than narrowband spectra, utilizing the MA signal model for spectral estimation has minimal engineering appeal. The non-linearity of the MA parameter assessment problem is another explanation for the lack of interest.

The objectives of this paper are to i) whiten the LFM reverberation by converting it to a fractional domain using the fractional fourier transform ii) evaluate the result using Matlab. The literature review is included in section 2. The creation of the LFM signal is presented in section 3. In section 4, presents the FrFT applications for LFM reverberation suppression. In section 5, presents the ARMA model. Section 6 presents the conclusion as well as the future scope.

2. LITERATURE SURVEY

Wu *et al.* [12] developed reverberation suppression methods for seafloor trial data. Thus, the developed algorithm is feasible for tracking applications, but it does not efficiently suppress the color noise. Different LFM reverberation suppression schemes are discussed in [13]. Thus, the developed algorithms are feasible for target detection and tracking applications, but it does not efficiently suppress the color noise. Fractional Fourier transform-based space-time prewhitener for LFM reverberation method discussed in [14]. Thus, the developed method is suitable for target detection and other applications, but it does not efficiently suppress the noise. The theory, implementation, and error analysis of fractional Fourier transformations are explained in [15]. They are mostly interested in fractional Fourier transform applications in engineering and other disciplines. However, modern DSP techniques are not being applied to improve performance. Fractional Fourier transform based separation of HFM and NLFM signals introduced in [16]. Thus, the developed method is suitable for target detection and other applications, but it does not efficiently suppress the color noise. Based on the literature review, FrFT based LFM reverberation suppression models are attempted in this paper, and their analysis was carried out.

3. LINEAR FREQUENCY MODULATED SIGNAL

If a signal is changing with respect to time, then it is called a non-stationary signal or a stationary signal. The frequency of a signal can be increased or decreased over time using up chirp and down chirp, respectively. It is used commonly in sonar, radar systems, and spread spectrum communications due to its characteristics. To increase the bandwidth of waveform while maintaining pulse duration such that $\tau \gg \frac{1}{\beta}$ we can use linear frequency modulation technique. $\beta\tau \gg 1$ is time bandwidth product. The most commonly and extensively used signal in practical radar and sonar systems is linear frequency modulation (LFM) waveform. R.H. Dickie was invented LFM signal in the year 1945. A linear frequency modulated signal is in (1) [17]:

$$l_{fm}(t) = e^{j2\pi\left(\left(f_c - \frac{B_w}{2}\right)t + \frac{B_w}{(2T)}t^2\right)} \equiv e^{j2\pi\left(f_0 t + \frac{mt^2}{2}\right)} \quad \text{for } 0 \le t \le 1 \tag{1}$$

where bandwidth is B_w, duration is T, central frequency is f_c, starting frequency is f_0, frequency modulating coefficient is (2).

$$m = \frac{B_w}{T} \tag{2}$$

4. FRACTIONAL FOURIER TRANSFORM

We choose FrFT instead of traditional FT because it is a time-frequency distribution that provides us with an extra degree of freedom that benefits us in other areas. This work converts a time-domain LFM signal to a fractional domain signal. FrFT is better than standard Fourier transform when processing the linearly frequency modulated signal. By considering the numerical kernel value with the numerical $\propto$ parameter value, when the magnitude of the response of FrFT reaches its limit, and when the axis of rotation corresponds to the signal's frequency. This method of treatment is called fractional transformation optimization [18]. The Fourier transformation is denoted,

$$Y_\alpha(f) = \int_{-\infty}^{\infty} B_\alpha(f,t)\, y(t)dt,$$
$$y(t) = \int_{-\infty}^{\infty} Y_\alpha(f) B_{-\alpha}(f,t)df \qquad (3)$$

where $B_\alpha(f,t)$ transform kernel, t time, and f frequency.

$$B_\alpha(f,t) = \exp(-i2\pi ft) \qquad (4)$$

FrFT is considered by modifying the Fourier kernel in the form.

$$B_{\propto(m,n)} = R_\propto \exp\left[i\pi\left(m^2\cot(\propto) - 2mn\csc(\propto) + n^2\cot(\propto)\right)\right]$$

$$\text{where } R_\propto = \exp[-\frac{i\pi sgn(\sin(\propto))}{4} + \frac{i\propto}{2}] * |\sin(\propto)|^{-\frac{1}{2}} \qquad (5)$$

m and n define the fractional domain axes. Rather than defining the fraction of the transform as angle, $\propto$, in the interval $[-\pi, \pi]$ radians, a new variable distinct as the order of the transform, adopt, in the interval $[-2, 2]$ and is distinct as $\propto = \frac{a_{opt}*\pi}{2}$. The fractional Fourier transformation has many applications such as noise removal, signal processing and signal restoration. This method can be used in various applications with lower expenditure. It plays a vital role in the prewhitening methods of LFM reverberation signal [19]-[20].

5. AUTOREGRESSIVE MOVING AVERAGE

The ARMA model was introduced by Peter Whittle in his thesis in 1951. The autoregressive moving average model is a statistical model of persistence (or self-correlation) in a time series. Noise reduction, speech and audio signal augmentation, hydrology, dendrochronology, econometrics, and other fields regularly use ARMA. The overlapping of many LFM reflection signals causes reverberation [21]-[24]. The autoregression and moving average (ARMA) models are used in time series analysis to characterise stationary time series. These models illustrate time series formed by passing white noise through a recursive and nonrecursive linear filter in succession. Autoregression is a time series model that predicts the value at the next time step by using prior time step data as input to a regression equation. In a variety of time series scenarios, simple notions can lead to solid forecasts [25], [26]. Selecting a suitable ARMA model for a given time series is a typical statistical difficulty that arises in many applications [27], [28]. The reverberated signal is separated into blocks and rotated along an axis with a fractional order parameter. In every single block, FrFT is utilised for linear variable frequency components on a single frequency, as shown in Figure 1, and the frequency modules for the next two blocks will be the same for FrFT. This occurs even though a distinct LFM reflection can be sliced into adjacent time blocks.

The proposed ARMA pre-whitening approach based on FrFT is summarized as follows:

Step 1: Determine the optimized value 'a' according to the LFM signal being transmitted.
Step 2: Split the obtained track data into blocks using a sliding window.
Step 3: Apply FrFT to each block of current data with an optimized value of a= 1.046
Step 4: Now, we can whiten the pre-whitening to create a clearer signal.
Step 5: We recover the whiten signal from the fractional to the time domain by applying inverse FrFT with a= -1.046

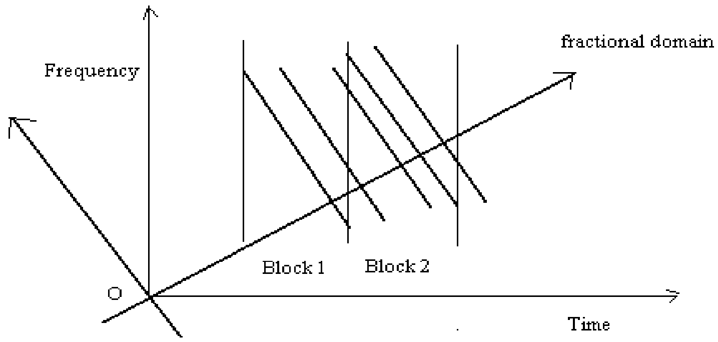

Figure 1. FrFT with LFM reverberation

6. RESULTS AND DISCUSSION

In a real-time scenario using an experimental hardware setup, the proposed FrFT based AR, MA, and ARMA prewhitening techniques were used to suppress LFM reverberation. An experiment was conducted using two personal computers and sound cards. The experimental setup consists of a transmitter and the receiver sections separated by a minimum distance. Regular speakers were used as transmitters in the experimental configuration, and microphones were used as receiver antennas to receive LFM signals. The data received from the trial was analyzed on personal computers using MATLAB software. The transmitted signal was LFM with a bandwidth of 2.5 kHz, a pulse length of 0.1 sec, and reverberation data of 3 sec. The time-domain plot of received trial data for an input LFM signal (without prewhitening) is shown in Figure 2. Figure 2 was plotted between time and amplitude. The mesh plot of received trial data for an input LFM signal (without prewhitening) is shown in Figure 3.

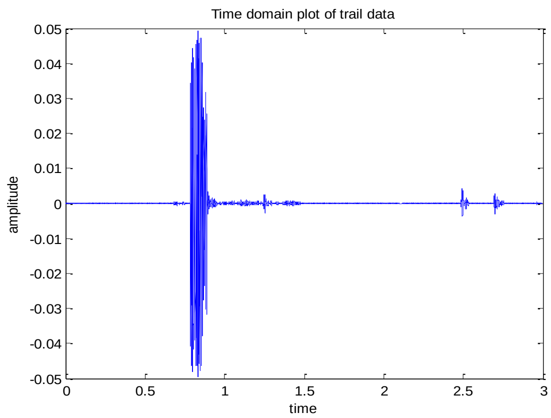

Figure 2. Time domain plot of received trail data

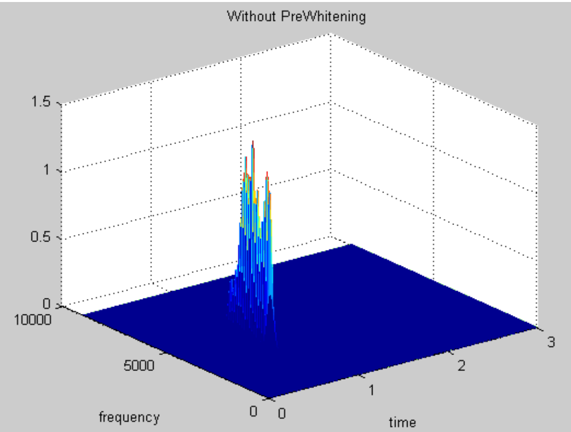

Figure 3. Mesh plot of received trial data without applying the prewhitening method

FrFT based MA prewhitening method with a filter order of 4 is applied on the trail data. This method is used to suppress the LFM reverberation. The mesh plot of after applying the FrFT based MA prewhitening method on the trail data is shown in Figure 4.

FrFT based AR prewhitening with a filter order 16 is applied on the trail data. This method is used to suppress the LFM reverberation better than FrFT based MA prewhitening method. The mesh plot after applying the FrFT based AR prewhitening on the trail data is shown in Figure 5. The proposed FrFT based ARMA prewhitening method was applied to the received trail data. The time-domain plot is shown in Figure 6.

The mesh plot of FrFT based ARMA prewhitening method is shown in Figure 7. From the simulation results of all prewhitening methods, it is observed that the proposed FrFT based ARMA prewhitening method suppresses the LFM reverberation much better than FrFT based AR prewhitening and MA prewhitening methods. The proposed method is used to detect the targets efficiently and extract the signal characteristics efficiently.

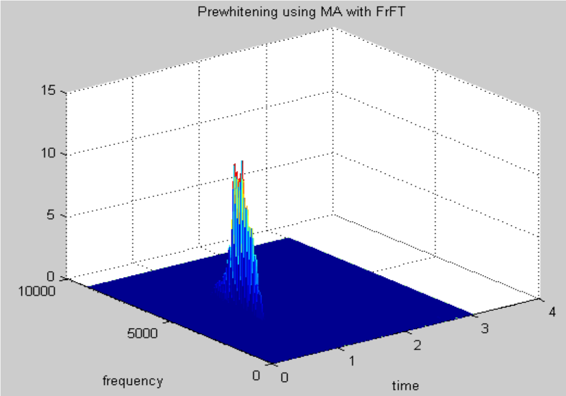

Figure 4. Mesh plot of after applying FrFT based MA prewhitening

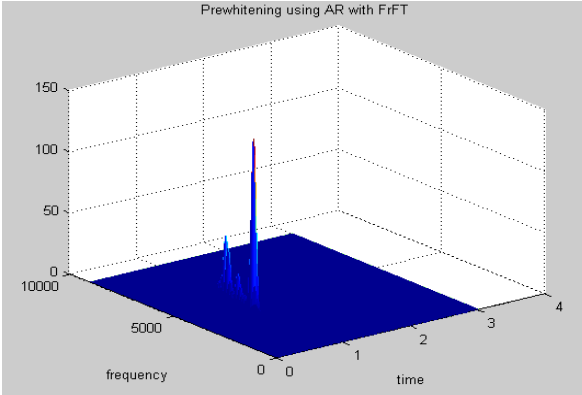

Figure 5. Mesh plot of after applying FrFT based AR prewhiteing

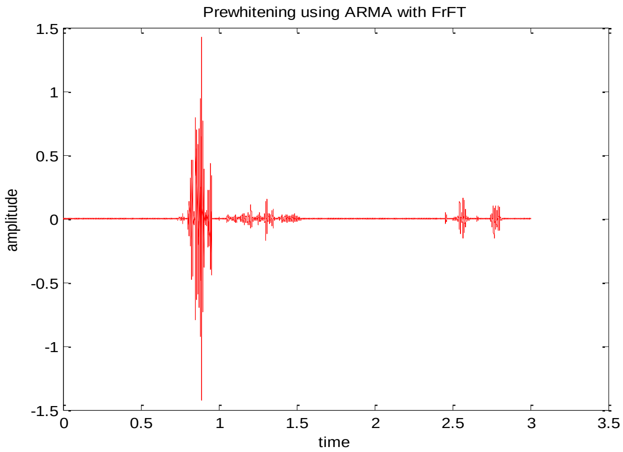

Figure 6. Time domain plot after applying proposed FrFT based ARMA prewhitening method

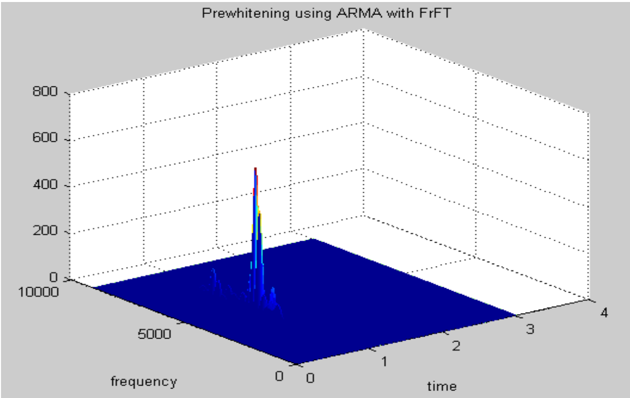

Figure 7. Mesh plot of after applying proposed FrFT based ARMA prewhitening

7. CONCLUSIONS AND FUTURE SCOPE

The purpose of this work is to compare the analysis of LFM reverberation suppression utilising FrFT-based AR and MA pre-whitening models to the proposed FrFT-based ARMA pre-whitening model. Experiments using actual LFM reverberation data confirmed that the proposed FrFT-based ARMA pre-whitening method provided superior whitening for LFM reverberation reduction when compared to FrFT-based AR and MA pre-whitening approaches. The proposed approach will be evaluated on movable platforms in the future.

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