Signal Processing 99 (2014) 92–102

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Parameter estimation for HFM signals using combined STFT and iteratively reweighted least squares linear fitting

Shuai Yao *, Shiliang Fang, Xiaoyan Wang, Li Wang

Key Laboratory of Underwater Acoustic Signal Processing of Ministry of Education, Southeast University, Nanjing 210096, People's Republic of China

ARTICLE INFO

Article history:
Received 6 June 2013
Received in revised form
19 November 2013
Accepted 26 December 2013
Available online 3 January 2014

Keywords:
Hyperbolic frequency modulated signals
Instantaneous frequency
Zero crossing interval
Short-time Fourier transform
Iteratively reweighted least squares

ABSTRACT

This paper presents a fast and robust method for estimating the starting frequency and period slope of hyperbolic frequency modulated (HFM) signals. The method involves, first, the instantaneous frequency (IF) estimation of HFM signals based on the peak of short-time Fourier transform (STFT) and, second, taking reciprocal of the estimated IF to get the zero crossing interval (ZCI). Parameter estimation of HFM signals is then achieved by using iteratively reweighted least squares (IRLS) linear fitting method to fit the ZCI which is a linear function of time. Both the approximate analysis of the magnitude spectrum and the formula used to determine the window length of STFT are derived for HFM signals. The lower bound of the estimator's variance and bias of the parameters of HFM signals are also derived in order to compare the performance of the proposed method. At last, both the simulation results and processing of sea trial data are presented to justify the validity and feasibility of the proposed method.

1. Introduction

The detection of moving target is an important issue in pulsed radar and sonar system. The most widely adopted method used to solve moving target detection for pulsed radar and active sonar is matched filter, however, this technique is sensitive to the Doppler effect [1]. In addition, the performance of underwater acoustic communication also suffers from significant loss if the Doppler effect could not be effectively handled. Due to the HFM signals' inherent Doppler-invariant property that the linear and sinusoid FM signals do not have [2], the HFM signals have been widely used in pulsed radar and sonar systems for detecting moving target, especially for the detection of small target moving at high speed, such as torpedo [3]. The starting frequency and period slope are two basic characteristic parameters of the HFM signal, once they are estimated, the HFM signals can be reproduced with the knowledge of pulse duration, which is important for confronting pulsed radar, active sonar and underwater acoustic communication systems. Therefore, it is crucial to develop a fast and robust method for estimating these two parameters.

Up to now, there are limited detailed reports about the parameter estimation for HFM signals. In Ref. [4], two different methods have been proposed. The first method is phase unwrapping combined with linear regression. The variances of the first method attain the Cramer–Rao lower bounds (CRLBs) at high signal-to-noise ratios (*SNR*s). However, the parameter estimation accuracy reduces drastically with the decrease of *SNR*. Although the above problem can be eliminated by adopting the second method, the calculation load of this method is very huge as the maximum likelihood estimation (MLE) does not exist in a closed form for the HFM parameter estimation. Therefore, two-dimensional (2-D) grid search is needed, and the parameter estimation accuracy depends on the accuracy of 2-D search. In Refs. [5–7], the HFM parameters

* Corresponding author. Tel.: +86 15105199177.
E-mail address: yaoshuai@126.com (S. Yao).

0165-1684/$ - see front matter
http://dx.doi.org/10.1016/j.sigpro.2013.12.029

are estimated via a nonlinear least-square (NLS) matching approach. The NLS matching approach, similar to the second method proposed in Ref. [4], is proved to be very computationally intensive.

The starting frequency and period slope of the non-stationary HFM signals are included in the expression of the IF curve. Therefore, if the IF of the HFM signal can be obtained, these two parameters can be further estimated accordingly. Methods for estimating IF such as phase difference estimators and smoothing thereof, zero crossing-base, adaptive methods and time–frequency distributions (TFD)-based techniques were reviewed in Ref. [8]. Among those methods, the TFD-based techniques have received considerable attention recently. The TFD-based IF estimation techniques are mainly based on the peak of TFD [9–15]. In Ref. [9], the proposed approach, combining the TFD and modified version of Hough transform (HT), can be used to estimate the parameters of HFM signals. However, limitations arise as the IF of HFM signal is very intricate to transform into a parameters space of HT. In Ref. [10], image processing techniques were used in the TFD to estimate the IF of HFM signals. However, it is very computationally intense because a repeated TF peak filtering preprocessing is needed in this technique. In Ref. [11], the confidence intervals (ICI) rule was used to estimate the IF. To minimize the mean squared error, a large amount of computation is needed to choose an appropriate window width from a set of windows. In Refs. [12–15], the complex-time distribution (CTD) has been proposed. The CTD, capable of estimating highly-varying nonlinear IFs [13], can be defined as the convolution between the Wigner distribution (WVD) of the signal and the Fourier transform (FT) of the complex-lag concentration function in the frequency domain [14,15]. It is easy to know that the computation load for WVD is much larger than the STFT [16], so the CTD needs much more calculation than the STFT.

The main goal of this paper is to develop a fast and robust method for parameter estimation of HFM signals. The proposed method combines the advantages of both STFT and IRLS linear fitting. The STFT, less sensitive to the noise influence than the higher-order techniques, such as WVD [17], can be achieved by fast Fourier transform (FFT). The FFT represents a very efficient and commonly applied approach. The proposed method estimates the IF of HFM signals based on the peak of STFT first. The window length of the STFT is invariable leading to a poor time–frequency resolution [18]. However, as long as the estimated IF of the HFM signals can keep its hyperbolic characteristics, the parameters of the HFM signals can be further estimated. Because of the facts that the IF of the HFM signal is a hyperbolic function of time, it is hard to estimate the parameters of HFM signals directly from the IF. On the other hand, the ZCI, obtained by taking reciprocal of the estimated IF, is a linear function of time, so parameters estimation of HFM signals can be achieved by linear fitting of the ZCI. Owing to the signal distortion caused by the ocean ambient noise and multipath propagation through underwater acoustic channel, there exist outliers in the estimated IF. The IRLS linear fitting method proposed in Ref. [19] is improved to fit the ZCI. The improved IRLS linear fitting method, independent of the absolute value of the estimated ZCI, can overcome the impact of outliers on the parameter estimation accuracy.

The rest of the paper is organized as follows. In Section 2, the proposed parameter estimation method is described and the formula for determining the window length of STFT is also derived. In Section 3, the lower bounds of the estimator's variance and bias are derived for the starting frequency and period slope of the HFM signals. In Section 4, computer simulations, calculation complexity analysis and processing of the real sea trial data are carried out to analyze the performance of the estimator. Finally, conclusions are reported in Section 5.

2. Parameter estimation method

2.1. Signal model and basic characteristics

The complex form of HFM signal is defined by [3]

$$s(t)=A\exp\{j\varphi(t)\}=A\exp\left\{j\left[-\frac{2\pi}{k_0}\ln(-k_0t+1/f_1)\right]\right\},\quad 0<t<\tau \tag{1}$$

where A is the magnitude, $\varphi(t)$ is the instantaneous phase (IP), f_1 is the starting frequency, τ, set to be known in advance, is the pulse duration and k_0 is a constant factor defined as period slope, given by $k_0=(f_2-f_1)/(\tau f_1 f_2)$, where f_2 represents the end frequency.

In a discrete time system, Eq. (1) can be expressed as

$$s(n)=A\exp\left\{j\left[-\frac{2\pi}{k_0}\ln(-k_0nT_s+1/f_1)\right]\right\},\quad n=0,1,2\ldots N-1 \tag{2}$$

where T_s is the sampling interval, its reciprocal f_s is the sampling frequency and $N=$ int(τf_s).

The sampled discrete-time HFM signal embedded in white Gaussian noise is modeled as

$$z(n)=s(n)+w(n),\ n=0,1,2\ldots N-1 \tag{3}$$

where $\{w(n)\}$ is an independent and identically distributed sequence of complex Gaussian random variables with zero mean and variance σ^2. Estimating the parameters of the HFM signals using a nonlinear least-squares (NLS) approach in [5–7] is given by

$$(\hat{f}_1,\hat{k}_0)=\arg\min_{(f_{nls},k_{nls})}\sum_{n=1}^{N}\left|z(n)-A\exp\left\{j\left[-\frac{2\pi}{k_{nls}}\ln(-k_{nls}nT_s+1/f_{nls})\right]\right\}\right|^2 \tag{4}$$

where f_{nls} and k_{nls} are the predictive parameters of the NLS approach for estimating the parameters of HFM signals. Eq. (4) can be simplified into

$$(\hat{f}_1,\hat{k}_0)=\arg\max_{(f_{nls},k_{nls})}\sum_{n=1}^{N}\left|z(n)\exp\left\{j\left[\frac{2\pi}{k_{nls}}\ln(-k_{nls}nT_s+1/f_{nls})\right]\right\}\right| \tag{5}$$

It is worth noting that the quantity to be maximized does not depend on A. However, the objective function in Eq. (5) is nonlinear in f_{nls} and k_{nls}, there exist no analytical solutions. Therefore, numerical techniques have to be used. The solution for such NLS problems may present the following two difficulties:

(1) Exhaustive search may be very time consuming.