A NOVEL APPROACH TO THE ESTIMATION OF ACOUSTIC DOPPLER SIGNALS

D. M. McNamara, A. Goli, and A. K. Ziarani

Department of Electrical and Computer Engineering
Clarkson University, NY,13699 USA

ABSTRACT

This paper presents a novel approach for frequency estimation of acoustic Doppler signals for use in speed and distance estimation of acoustic sources. The basis of the proposed approach is a nonlinear adaptive algorithm capable of tracking the amplitude, phase and frequency of nonstationary sinusoids. The approach provides a real time estimation of instantaneous frequency with very high time-frequency resolution and has a high level of noise immunity. This offers advantages over traditional Fourier-based methods as well as current Wigner-Ville based approaches seen in the literature. Examples using simulated and real signals will be shown to demonstrate the capabilities and strengths of this approach; comparisons to existing techniques are presented.

Index Terms— Adaptive signal processing, Doppler measurements, Frequency estimation, Time-frequency analysis, Velocity measurement

1. INTRODUCTION

Doppler signals are a class of signals that occur naturally or by man-made radar and sonar systems. These signals have a frequency that is changing proportionally to the speed and distance of a moving object. The description of the perceived change in frequency of a moving acoustic source is the Doppler effect phenomenon. The Doppler effect has been well-studied since its conception by Christian Doppler in 1849. It is the basis of most modern radar and sonar systems. Due to their time varying nature, Doppler signals are highly nonstationary which make them challenging to properly interpret with traditional well-known linear signal processing methods.

Systems using Doppler effect fall into two forms: active and passive; passive acoustic Doppler signals will be the focus of this paper. Passive acoustic techniques provide a simple, portable and easy to implement estimation method that is very appealing for certain applications. An example of an acoustic Doppler signal is a stationary observer perceiving a frequency change as the aircraft flies overhead. This leads to the concept of instantaneous frequency (IF) [1] which describes the frequency of a signal at every instant of time. An observer frequency model was first introduced by Ferguson [2]; it can be used to extract aircraft flight parameters from recorded acoustic data. Ferguson and others have successfully used this model in processing acoustic Doppler signals [2]-[5].

Traditionally, radar and sonar systems that employ frequency estimation have relied heavily on Fourier-based signal processing techniques to estimate frequency. The same holds true for acoustic Doppler signals. Where popular techniques such as the short-time Fourier transform (STFT) and Wigner-Ville distribution transforms [3] have been applied. However, Fourier-based techniques have well-known shortcomings such as leakage effect and the tradeoff between time and frequency resolution which make for a poor IF estimator [1].

To overcome these shortcomings, more recent signal processing techniques have been applied for accurate IF estimation such as matching pursuit wavelet method [6] and the chirplet transform [7]. Wigner-Ville distributions (WVD) [4] have also been applied; however, they have the drawback of leaving artificial artifacts and performance degradation with noisy signals. The main shortcoming of these more recent approaches is that they work well for a class of nonstationary signals that vary linearly with time [8]. However, Doppler signals do not fall into these class of signals, because these signals are highly nonlinear and do not vary linearly with time. Due to the nonlinearity within Doppler signals, IF estimation of these signals become inaccurate and information reported by these algorithms can become inaccurate. To overcome these known weakness, a new approach was created called Dopplerlet transform [8]. This method provides a great improvement over the algorithms mentioned before and can be used to represent Doppler signals. The Doppler transform works by using an interactive matching approach based on dilated and translated Doppler functions.

However, the authors of this paper believe that they have an approach that can provide finer time-frequency resolution while having a simple structure requiring lower computational load. The sinusoid tracking algorithm (STA), first introduced in [11], is the basis of the new approach. Its stability and mathematical formation shown in [10]. The

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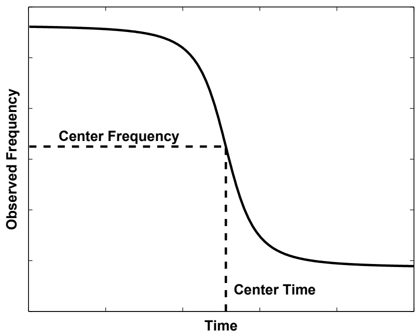

Fig. 1. Instantaneous frequency of an acoustic Doppler signal.

concept of using the algorithm as a time-frequency method was shown in [9]; from this, the algorithm was further developed into an IF estimation tool. This algorithm is capable of providing a real-time estimation of instantaneous amplitude, phase and frequency. A feasibility study using simulated and real experimental data is conducted and presented in this paper. A review of the Doppler effect seen in the acoustic observer model will be presented in the next section. Following that, the proposed approach and underlying algorithm will be presented in section III. Then results from simulated experiments will be presented and will be compared to currently used techniques in section IV; observations and conclusions will be discussed in the last section.

2. ACOUSTIC DOPPLER EFFECT OBSERVER MODEL

A review of the acoustic Doppler effect phenomenon is presented in this section. The Doppler effect is well known and studied as the perceived change in frequency of sound as an object moves relative to the observer. The observed frequency then begins to move in a manner shown in Fig. 1 where the observed frequency shifts to a lower observed frequency as the object moves past the observer.

The Doppler shift shown in Fig. 1 is derived from

$$f = \frac{u}{u + \frac{v^2(t-t_c)}{\sqrt{l^2+v^2(t-t_c)^2}}} f_c \tag{1}$$

where f is the instantaneous frequency. The frequency of the emitting source, f_c, is the same as the center frequency at the center time of t_c of the observed Doppler signal. The speed at which the sound travels through the medium is u, and the object itself travels at speed v. It is assumed that the observer will be stationary in which l will be the perpendicular length to the object. From (1), it follows that when $t < t_c$ the frequency is greater than the source or center frequency when $t > t_c$ the frequency is less than the source frequency.

3. PROPOSED APPROACH

The proposed approach consists of using a sinusoidal tracking algorithm, to track the instantaneous frequency changes that occur in the recorded acoustic data. As mentioned before, the algorithm is capable of tracking with very high resolution, changes in amplitude, phase and frequency all in real time. After the instantaneous frequency is estimated, it is used in a parameter estimation algorithm developed in [2]. A brief review of the sinusoid modeling used in this approach and the governing equations for the sinusoid tracking algorithm implemented in this approach will follow.

3.1. Sinusoidal Model

A Doppler signal without reverberations can be thought of as a monocomponent nonstationary signal. Monocomponent signals, may in general be expressed as:

$$u(t) = A(t)\sin(\phi(t)) + n(t) \tag{2}$$

in which the variables $A(t)$ and $\phi(t)$ are the potentially time-varying amplitude and phase. The variable $n(t)$ denotes the superimposed disturbance/noise. The total phase $\phi(t)$ term can be expanded into

$$\phi(t) = \int_t \omega(\tau)d\tau + \delta(t) \tag{3}$$

in which $\omega(\tau)$ is the instantaneous frequency of this signal in rad/s, $\delta(t)$ is the constant phase which is assumed to potentially time varying. With this model in mind, the next section will introduce the sinusoid tracking algorithm that will be used in this approach.

3.2. The proposed algorithm

The governing differential equations of the STA are reviewed here from [10]-[11]. From the last section let $y(t)$ be the monocomponet we wish to estimate as $\hat{y}(t)$:

$$\hat{y}(t) = \hat{A}(t)\sin(\int_t \hat{\omega}(\tau)d\tau + \hat{\delta}(t)), \tag{4}$$

and the error signal $e(t)$ as:

$$e(t) = u(t) - \hat{y}(t). \tag{5}$$

The dynamics of the proposed algorithm, which takes $u(t)$ as its input signal and extracts the $\hat{y}(t)$ is as follows:

$$\frac{d\hat{A}(t)}{dt} = \mu_1 e(t)\sin\hat{\phi}(t), \tag{6}$$

$$\frac{d\hat{\omega}(t)}{dt} = \mu_2 e(t)\hat{A}(t)\cos\hat{\phi}(t), \tag{7}$$

$$\frac{d\hat{\phi}(t)}{dt} = \hat{\omega}(t) + \mu_3 e(t)\hat{A}(t)\cos\hat{\phi}(t). \tag{8}$$

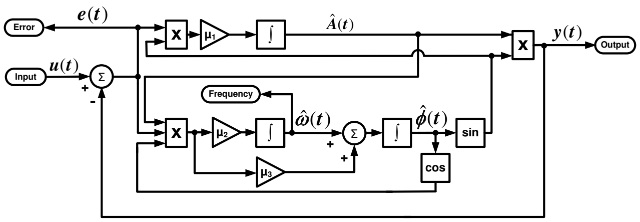

Fig. 2. Block diagram of the Sinusoid tracking algorithm.

The instantaneous frequency estimated by the algorithm is $\hat{\omega}$. The above equations (5)-(7) show the continuous system equations but the system can also be implemented in discrete time form and is shown in the following equations, using a first order approximation for derivatives are used with T_s being the sampling period:

$$y[n] = A[n]\sin(\phi[n]) \quad (9)$$
$$e[n] = u[n] - y[n] \quad (10)$$
$$A[n+1] = A[n] + T_s\mu_1 e[n]\sin(\phi[n]) \quad (11)$$
$$\omega[n+1] = \omega[n] + T_s\mu_2 A[n]e[n]\cos(\phi[n]) \quad (12)$$
$$\phi[n+1] = \phi[n] + T_s\omega[n] + T_s\mu_3 A[n]e[n]\cos(\phi[n]) \quad (13)$$

The μ's control the speed and accuracy, for the application of Doppler measurements we chose high μ_2 values to assure that the instantaneous frequency is very accurate with the rapid frequency change. In addition to using high μ values and given the nature of Doppler signals, μ_3 have been given a time-varying value in which both of them are multiplied by $\frac{N}{n}$ in which N is the length of data and n is the sample number. With this configuration, it is assumed that the length of data is not too large and has a length that is necessary for Doppler estimation. This changes (13) to:

$$\phi[n+1] = \phi[n] + T_s\omega[n] + \frac{N}{n}T_s\mu_3 A[n]e[n]\cos(\phi[n]). \quad (14)$$

With this slight change to the system equations, the algorithm is capable of quickly locking onto the component of interest and track rapid frequency changes. Once the instantaneous frequency is estimated by the algorithm, the results are sent into a parameter estimation algorithm developed in [2]. This approach uses the estimated frequency to estimate values for speed and distance based on minimizing a cost function derived from (1) using a Gauss-Newton method.

4. PERFORMANCE OF THE PROPOSED ALGORITHM ON SIMULATED DATA

This section will demonstrate the capabilities of the proposed approach to be used with acoustic Doppler signals. A simulated signal is created to demonstrate the capabilities of the algorithm and to match the experimental data presented in section IV. Comparison will be made to algorithms based on the STFT or WignerVille transforms as presented in [3].

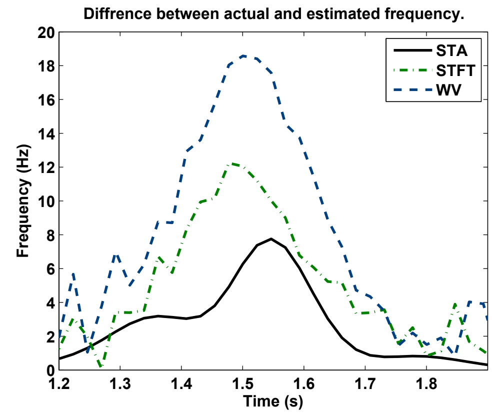

Fig. 3. Difference between actual and estimated frequency.

4.1. Simulation

A simulation was created to match the parameters that are in the experimental data seen in the next section. A Doppler signal was created with a center frequency of f_c=2997Hz, a distance of l=4.1m, speed of v=24.8 m/s and a center time of t_c=1.5s. The u is known a priori and it is u=340.45m/s, Gaussian noise was added to give it an SNR of 0dB, with the sampling rate of 22050Hz. The μ's were chosen to be μ_1=10, μ_2=50000, and μ_3=25. Fig. 3 and table below illustrate the performance of the algorithm in terms of instantaneous frequency estimation.

Parameters	ℓ(m)	ν(m/s)	$f_c(Hz)$
Estimated with STFT	4.1450	24.8927	2997.1
Estimated with WV	5.3542	27.0298	2997.2
Estimated with STA	4.1956	24.9233	2975.1
Actual	4.1	24.8	2997

The following results illustrate the capability of the STA in tracking instantaneous frequency, without much parameter setting; i.e. these μ parameters can work for a range of Doppler signals. The STFT and Wigner-Ville window size and time resolution were carefully chosen to give these algorithms the best results which are observed not to be as good as that of the STA technique.

4.2. Experimental Data Results

This section shows the performance on experimental data reported in [8]. The experiment consisted of a tone being played out of a loudspeaker mounted on a car traveling toward a microphone at a near constant speed and distance. The parameters in this experiment were the same as those of the simulated data set. Fig. 4 shows the estimated instantaneous frequency of the experimental data for all techniques. The estimated parameters reported by the STA were very close to the actual

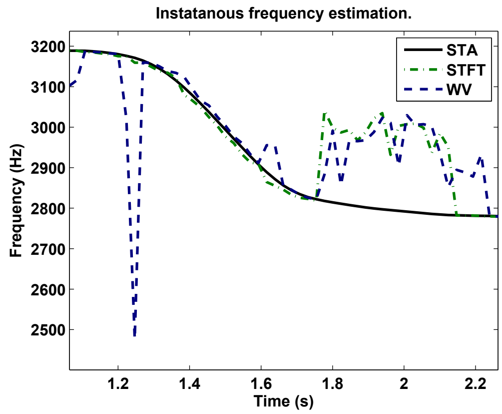

Fig. 4. Instantaneous frequency estimation of experimental data.

parameters presented in [8] while the other algorithms did not preform well. Fig. 4 shows the real performance advantage of the proposed technique over existing algorithms, which offer little or no noise immunity in IF estimation.

Parameters	$\ell(\mathrm{m})$	$\nu(\mathrm{m/s})$	$f_c(Hz)$
Estimated with STFT	5.8783	26.8497	2991
Estimated with WV	2.6030	17.8973	2945
Estimated with Dopplet	4.2	25.1	2996
Estimated with STA	4.01	24.9602	2997
Measured	4.1	24.8	2997

5. CONCLUSION

The authors believe that the approach presented in this paper has shown itself to be a very powerful tool for analyzing acoustic Doppler signals. The proposed technique offers a very high resolution estimate of instantaneous frequency which could then be used to estimate parameters such as velocity and distance. It offers superior performance over the window-based techniques such as the STFT and Wigner-Ville. The presented technique also offers a good alternative to the Dopplerlet with its matching pursuit approach which can be complex to setup and can be computationally intense. The STA offers a simple and computationally efficient algorithm that makes it very suitable for implementation in the field in a wide array of devices.

6. ACKNOWLEDGEMENT

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