Optics & Laser Technology 42 (2010) 1038–1043

Contents lists available at ScienceDirect

Optics & Laser Technology

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

Signal processing of laser Doppler self-velocimeter

Jian Zhou *, Xingwu Long

College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha 410073, China

ARTICLE INFO

Article history:
Received 27 November 2009
Received in revised form
4 January 2010
Accepted 18 January 2010
Available online 6 February 2010

Keywords:
Laser Doppler
Signal processing
Cramer–Rao low bound

ABSTRACT

A frequency spectrum refinement and correction algorithm has been put forward to improve the accuracy of measurements, and the Cramer–Rao lower bound (CRLB) of Gaussian group Doppler signal was given based on the introduction of acceleration. Results of simulations and experiments showed that the Goertzel refinement algorithm could improve the resolution of the spectrum of the Doppler signal; the ratio correction algorithm made the results closer to the real value. The CRLBs of the estimated parameters were related to the sampling data, the signal to noise ratio (SNR) and the broadness of Gaussian group, and it can be decreased by increasing the length of the sampling data or improving the SNR; the gap between the variances of the measuring results and the CRLBs narrowed when the SNR of the signal was improved, and was almost eliminated when the SNR was higher than 6 dB.

1. Introduction

Laser Doppler velocimeter (LDV) has become a very useful tool for the measurement of its own velocity in the vehicle inertial navigation system [1,2]. Precision of measurements, fast response time and low invasiveness are among the advantages leading to the success of LDV, in which the Doppler shifted and backscattered light from a target is coherently mixed with the source light to produce a beat-frequency intensity modulation. Fast Fourier transform (FFT) is used to obtain the velocity by calculating the beat-frequency of the signal spectrum. The Cramer–Rao low bound (CRLB) is often used to evaluate the accuracy degree of the measurement for signal processing.

Firstly, if we regard the frequency of the spectral peak as Doppler frequency, the accuracy would not be high [3]; secondly, ignoring the acceleration, the CRLB of simple-frequency sinusoidal signal was used as an approximate value in previous literature [4]. So, in this paper, a frequency spectrum refinement and correction algorithm was put forward to improve the accuracy of measurements, and the CRLB of Gaussian group Doppler signal was given based on the introduction of acceleration.

2. Signal processing

The primary result of LDV is a current pulse from the photodetector. This current contains the frequency information relating to the velocity of the measured point and many kinds of noise, such as photodetection shot noise, light scattered from outside the measuring volume, and so on. To better estimate the Doppler frequency of noisy signals, frequency domain processing techniques are used. With the fast development of digital signal processing, the fast Fourier transform (FFT) is usually used in processing Doppler signals. The power spectrum S of a discretized Doppler signal x is given by

$$S_k = |\sum_{n=0}^{N-1} x_n \exp(-j2\pi kn/N)|^2 \qquad (1)$$

where N is the number of discrete samples and $k=-N,-N+1,\ldots,N-1$. The Doppler frequency is given by the peak of the spectrum.

On the other hand as a matter of fact, if we put the frequency of spectral peak as the Doppler frequency, the accuracy would not be high because the frequency resolution of FFT is given by

$$\Delta f = f_s/N \qquad (2)$$

where f_s is the sampling frequency.

It seems that we can improve the frequency resolution by decreasing the sampling frequency f_s or increasing the number of the sampling data N. However, f_s cannot be decreased because of the wide range of the measured velocity, and N cannot be increased because of the huge extent of computation. Hence a frequency spectrum refinement and correction algorithm was used to improve the frequency resolution. To assist in understanding, a block diagram of the signal processing is shown in Fig. 1.

* Corresponding author. Tel.: +86 13739091383; fax: +86 073184576314.
E-mail address: wttzhoujian@163.com (J. Zhou).

0030-3992/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.optlastec.2010.01.027

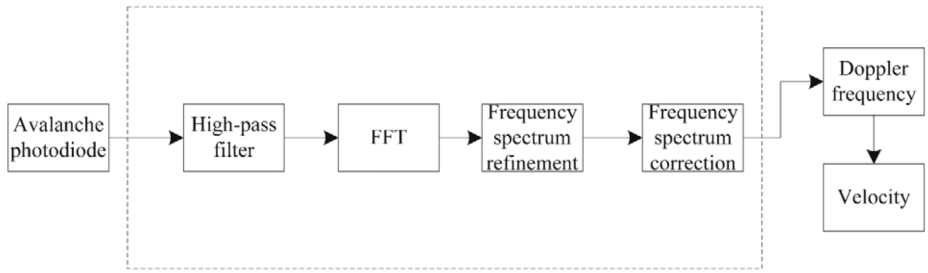

Fig. 1. Signal processing block diagram.

2.1. Frequency spectrum refinement using Goertzel algorithm [5–7]

There are many frequency spectrum refinement algorithms, including Goertzel refinement, phase compensation refinement and complex modulation refinement. The Goertzel refinement is the most suitable method in LDV, because it has the least extent of computation and the highest speed [8].

If $x(r)$ is a N point sequence its Fourier transform is given by

$$X(k)=\sum_{r=0}^{N-1} x(r)e^{-j(2\pi/N)rk} \tag{3}$$

where r=0,1, … ,$N-1$ and k=0,1, … ,$N-1$. Defining $W_N=e^{-j(2\pi/N)}$, and Eq. (3) reduces to

$$X(k)=\sum_{r=0}^{N-1} x(r)W_N^{rk} \tag{4}$$

The periodicity of twiddle factor is used in Goertzel algorithm to reduce the extent of computation. The equation is given by

$$W_N^{-kN}=e^{(-j(2\pi/N))(-kN)}=1 \tag{5}$$

where W_N^{-kN} is the twiddle factor. Using Eqs. (5), (4) reduces to

$$X(k)=\sum_{r=0}^{N-1} x(r)W_N^{kr}W_N^{-kN}=\sum_{r=0}^{N-1} x(r)W_N^{-k(N-r)} \tag{6}$$

Defining $y_k(n)$ as follows:

$$y_k(n)=\sum_{m=-\infty}^{\infty} x(n)W_N^{-k(n-m)}u(n-m) \tag{7}$$

where $-\infty<n<\infty$ and $-\infty<m<\infty$; $u(n)$ is a step function whose definition is given by

$$u(n)=\begin{cases}1 & (n\geq 0)\\ 0 & (n<0)\end{cases} \tag{8}$$

We know that when $n<0$ and $n\geq N$, $x(n)$=0. Using Eqs. (7) and (8), Eq. (6) reduces to

$$X(k)=y_k(n)|_{n=N} \tag{9}$$

In other words, $y_k(n)$ is the response of $x(n)$ with the pulse response $W_N^{-kn}u(n)$. Specifically, $X(k)$ is the output when n=N. In order to further reduce the extent of computation, the transfer function $H_k(z)$ is simplified as follows:

$$H_k(z)=\frac{1}{1-W_N^{-k}z^{-1}}=\frac{1-W_N^{k}z^{-1}}{(1-W_N^{-k}z^{-1})(1-W_N^{k}z^{-1})}=\frac{1-W_N^{k}z^{-1}}{1-2\cos(2\pi k/N)z^{-1}+z^{-2}} \tag{10}$$

The calculation flowchart is shown in Fig. 2.

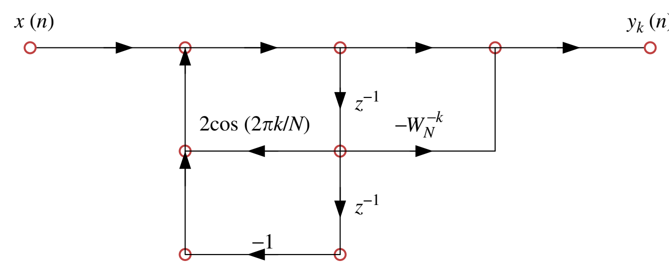

Fig. 2. Calculation flowchart of Goertzel algorithm.

2.2. Frequency spectrum correction using ratio algorithm [9]

There are many frequency spectrum correction algorithms, including energy centrobaric correction, ratio correction and phase difference correction. But the ratio correction is the most suitable method in LDV, because it has a simple formula, the least extent of computation and the highest accuracy [9–11].

The basic principle of ratio correction is setting up a equation using two spectral lines near the spectral peak to determine the corrected frequency. Define the Hanning window as follows [12]:

$$w(n)=0.5[1-\cos(2\pi n/(N-1))] \tag{11}$$

This considered as a high resolving window or raised cosine window. The frequency spectrum function of the Hanning window is given by

$$g(f)=\mathrm{FT}\{w(n)\}=\frac{\sin(\pi f)}{\pi f}\frac{1}{2(1-f^2)} \tag{12}$$

where FT stands for the Fourier transform and f is the corrected frequency. The main equation is given by

$$g(f)/g(f+1)=y_k/y_{k+1} \tag{13}$$

where y_k is the discrete frequency spectrum of f, y_{k+1} the discrete frequency spectrum of f+1 and k the digital frequency of f. From Eqs. (12) and (13), we know that

$$f=(y_k-2y_{k+1})/(y_{k+1}-y_k) \tag{14}$$

3. CRLBs of the Doppler circular frequency and its first order rate of change

When LDV is used to measure the velocity of solid target, especially aircrafts, missiles and tanks, they not only have high speed but also large acceleration. Because of the existence of acceleration, the velocity changes when the particles pass through the volume of LDV, which broadens the spectrum at the Doppler