Optica Applicata, Vol. XXV, No. 4, 1995

Digital processing of Doppler signals using fast Fourier transform*

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The paper presents the implementation of two methods of Doppler signal validation for analysis, namely the amplitude trigger and the spectral trigger. Both methods were verified on simulated data as well as real Doppler signal samples taken from the experiment.

1. Introduction

Doppler signals (DSs) of a low signal-to-noise ratio (SNR) are of frequent occurrence in many fields of optical velocimetry. Several methods of processing such signals, including the photon correlation technique [1], Fourier analysis [2], Kalman filtration [3], *etc.*, were developed. In the last few years, spectrum analysis by means of the fast Fourier transform (FFT) has become one of the widespread methods of the DS processing [4]. The FFT spectrum analysis can be implemented in software or hardware and can provide some information about moving scattering objects. Average velocity and its distribution, concentration and size of particles, are the main parameters that can be derived from the FFT spectrum of the DS. The FFT method was applied to both continuous and pulse signals for a wide range of Doppler frequencies from kHz to GHz.

In processing Doppler signals in optical velocimetry, there is a very wide range of frequencies to be dealt with, from single Hz to several GHz. The frequency of a signal depends on the velocity of an object and the Doppler constant, which is shown in Table 1. Apart from the wide range of signal frequencies there is another problem to be overcome. In real conditions there are signals of very different character, from ideal harmonic ones, through series of Doppler bursts, to quasi-stationary random processes (see Fig. 1).

Signal processing options in laser Doppler anemometry can be generally classified into time domain and frequency domain methods [5]. In the time domain method, zero crossings in the signal are detected and the signal parameters, such as frequency and phase, are obtained by averaging over a sufficient number of zero crossings. This method is applied, for example, in counter processors which, however,

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* The paper was presented during the international conference *Optical Velocimetry '95*, organized by SPIE/PL, Warsaw, Poland, May 29–June 2, 1995.

require good signal quality of SNRs larger than about 10 dB for reliable processing. In the frequency domain method, signal processing is based on spectral analysis using the FFT. This method is very robust even for low SNRs.

Table 1. Doppler frequencies for varied velocity of an object and for typical values of the Doppler constant Λ_D. V_D – velocity of an object, f_D – Doppler frequency

	f_D		
V_D	$\Lambda_D = 0.5$ μm	$\Lambda_D = 15$ μm	$\Lambda_D = 50$ μm
1 mm/s	2 kHz	66.7 Hz	20 Hz
1 m/s	2 MHz	66.7 kHz	20 kHz
1 km/s	2 GHz	66.7 MHz	20 MHz

Three main steps in the DS processing, irrespective of the frequency range, SNR level and applied method, should be performed [5]:

- identification and detection of the DS,
- signal validation,
- estimation of parameters of the DS (frequency, phase, SNR, *etc.*).

A signal identification and detection which is well matched to the parameter estimation method used should ideally ensure that only Doppler signals which will also be validated will be passed on to the processor. Thus, an ideal signal detection would estimate the need for signal validation. In the non-ideal case, signals which are rejected by the Doppler burst validation only reduce the processing speed, since the parameter estimation has been unnecessary. Hence, a reliable real-time signal identification has the potential to speed up the signal processing tremendously.

The criteria of signal validation may be separated into two broad categories, *i.e.*, amplitude and spectral ones. The DS detection for laser Doppler anemometry measurement is, in many cases, performed in the time domain based on the comparison of either the pedestal or the band-pass filtered signal with a fixed amplitude threshold level (*e.g.*, counters). We call it an amplitude trigger. The principle of such a method is shown in Fig. 2. This method can cause severe biases in the mean quantities when the trigger level is not selected properly and, for instance, signals from small particles fall below this threshold level. An appropriate setting of the trigger level is virtually impossible when the flow conditions, *e.g.*, particle density, change during the measurement of a profile. For strong variations in the particle concentration it is inevitable that the trigger level must be readjusted. A wrong setting of the threshold results in statistical errors. On the other hand, too low a trigger level would result in increasing effort for data validation and processing. Even when the trigger level is set appropriately, it is necessary to correct the counting bias in favour of larger particles, since the probability of detecting larger particles is higher, entailed by the fact that signals from small particles may disappear in the noise level or are rejected due to a poor SNR.

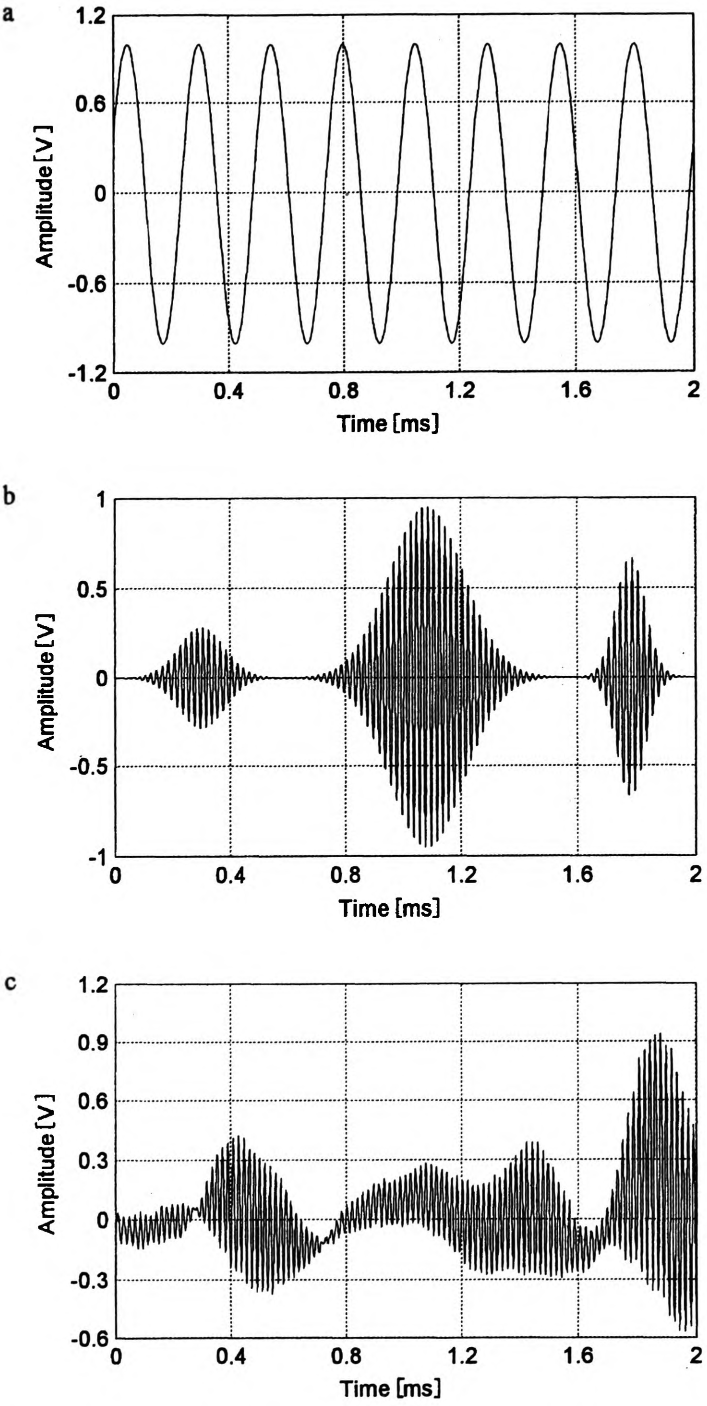

Fig. 1. Examples of real Doppler singals: a — an ideal harmonic signal, b — a series of Doppler bursts, c — a quasi-stationary random process

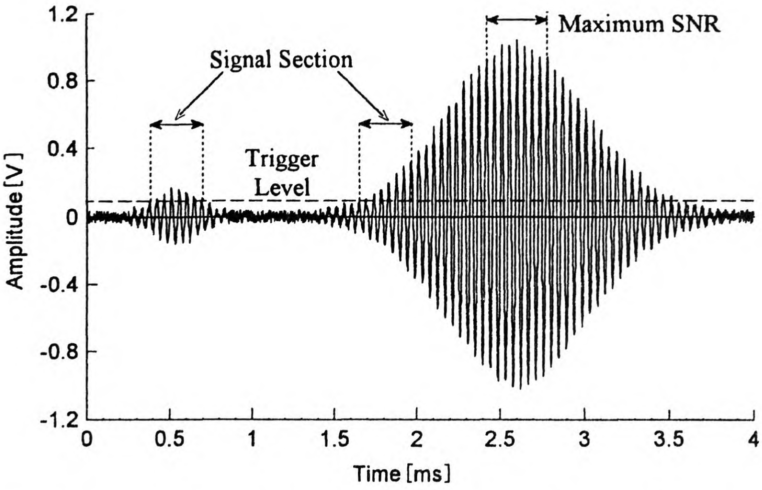

Fig. 2. Principle of amplitude trigger for detection of a Doppler signal

Another disadvantage of a fixed amplitude trigger level is that the DS parameters are generally evaluated from the initial portion of the DS (especially for signals of large amplitude) where the SNR is low, which inevitably results in higher parameter estimation errors when using, for example, the FFT method.

A DS detection in the spectral domain using the FFT can be very reliable even at low SNR levels. We have implemented two methods of signal validation for analysis: the amplitude trigger and the spectral trigger. In the first method, after validation of the signal with the amplitude trigger (*i.e.*, when the amplitude of the signal exceeds a fixed value), the temporary spectrum with the Gaussian window centred on the peak amplitude point is computed using the FFT. The spectrum averaging procedure is applied to improve the SNR. In the second method, the validation trigger is based on analysis of the SNR obtained from the spectrum computed from a short record (64 or 128 points). In this case, the SNR may be specified as the ratio of the peak power of the signal spectrum to the mean noise power. If the SNR thus defined exceeds a fixed value, the signal is subject to further processing. We call it a spectral trigger. The DS parameters are evaluated from samples that represent the maximum SNR level. The accuracy of SNR estimation is strongly dependent on the FFT record length. The results of the accuracy for SNR estimation using the FFT indicate that a record length of 64 points is satisfactory for accurate and efficient detection of DSs [5]. A 64-sample FFT is, however, not fast enough to be used for real-time DS detection unless sophisticated and expensive electronics are used. After validation the spectrum of a 1024-sample record is computed using the FFT and the averaging procedure is next performed.

2. Conditions of the experiment

We built a laboratory model of the differential laser Doppler anemometer (LDA) [6]

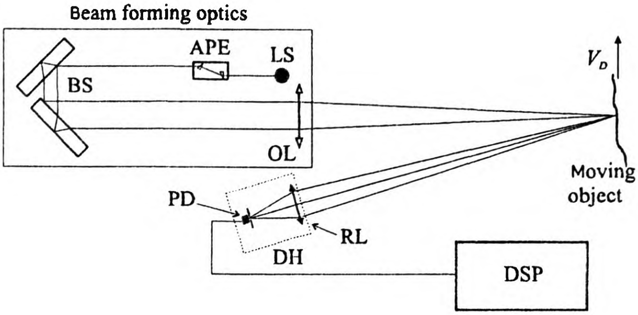

Fig. 3. Experimental set for Doppler signal measurement: LS — light source, APE — anamorphic prismatic expander, BS — beam splitter, OL — output lens, DH — detection head, RL — receiving lens, PD — photodetector, DSP — digital signal processor, V_D — object velocity

to verify both methods on real signals. The experimental setup is shown in Fig. 3. The change of the SNR was performed by changing the scattering properties of a moving object or by changing the geometrical parameters of the LDA. A rotating metal disk was used as the moving object. The horizontal component of the velocity vector was measured. This component is perpendicular to the fringe structure in the measurement volume of the LDA. A helium-neon laser was employed as a light source. Two values of the fringe period in the measurement volume of the LDA can be set: 33 or 55 μm, according to the focal length of the applied output lens: 600 mm and 1000 mm, respectively. The number of fringes can vary in a range from 25 to 65.

An avalanche photodiode BPYP52 and a preamplifier of a 15–500 kHz bandwidth were used to detect the DS. The sensitivity of the photodiode is 30 A/W. We inserted a diaphragm with a pinhole in the image plane of the receiving lens. The measured velocity range is from 0.5 to 25 m/s. We were using a PC 486 machine equipped with the 12-bit CompuScope 1012 oscilloscope card with a memory buffer of 512 kB as a digital signal processor.

For several samples of DSs of different SNR level both methods of processing, *i.e.*, an amplitude trigger and a spectral trigger, were applied and compared. The SNR trigger method is more reliable especially in case of signals of a low SNR level. Both methods enable the frequency estimation of uncertainty better than 0.5%.

3. Results of the experiment

3.1. Comparison between two criteria of signal validation

In order to improve the results of the measurements a Gaussian window was applied to the signal. In addition, a special averaging procedure was worked out and employed. In this procedure records of temporary spectra are added and averaged over a fixed number of records. This scheme allows quite small signal samples (*e.g.*, 1024 points) to be processed instead of very long ones. Since the time t_c of calculating the FFT is proportional to the product of the number of calculated points N and the

2-based logarithm of this number

$$t_c \propto N \cdot \lg_2 N \tag{1}$$

it is obvious that for very long samples calculation of the FFT would take very long time and therefore signal processing would be extremely slow.

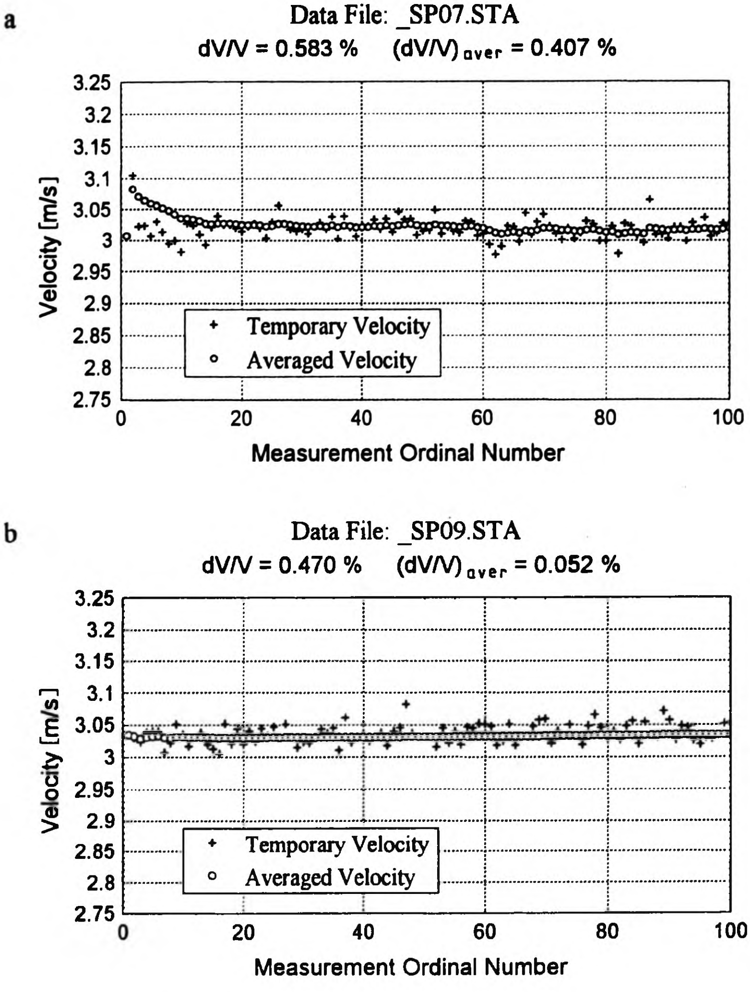

Fig. 4. Exemplary results of velocity measurement with spectral trigger

The exemplary results of measurement with the use of spectral trigger are presented in Fig. 4. A single graph represents a series of measurements. It shows the values of velocity obtained in subsequent measurements. A quotient dV/V is the ratio of the standard deviation of velocity to the mean velocity. It describes the dispersion or, in other words, uncertainty of velocity. The dispersion of results in Fig. 4a for both temporary and averaged velocity is about 0.5%. Quite large uncertainty for averaged velocity is mainly due to the change of mean velocity during the time of measurement. The dispersion of temporary velocity in Fig. 4b is about 0.5% as in the previous case, but after applying the averaging procedure this parameter is one order of magnitude lower.

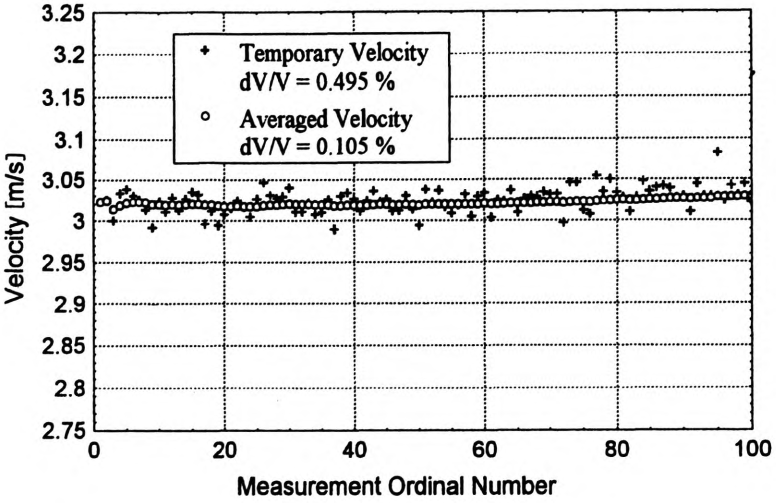

Fig. 5. Dispersion of velocity for the amplitude trigger

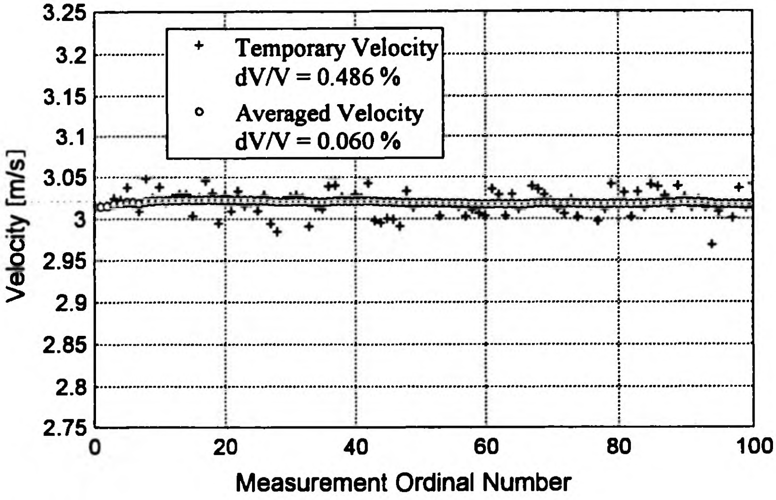

Fig. 6. Dispersion of velocity for the spectral trigger

The comparison between the two criteria of signal validation is shown in Figs. 5 and 6. The uncertainty of results for temporary velocity is of order 0.5% in both cases. For averaged velocity the dispersion of results of order 0.1% was obtained and in the case of the spectral trigger even less than 0.1%.

3.2. Validation criterion

The influence of the spectral triggr level on dispersion of velocity was investigated. Results of this research are compared in Tab. 2. According to expectations, the higher the trigger level, the lower the dispersion of velocity values. It is clearly demonstrated that at the same time the percentage of accepted data decreases. The accepted data are the signal samples that meet the validation criterion, *i.e.*, that exceed the spectral trigger level.

Table 2. Influence of the trigger level on the results of measurement with the spectral trigger. V — velocity of an object, s_V — standard deviation of velocity, s_V/V — dispersion of results for temporary velocity, $(s_V/V)_{\mathrm{aver}}$ — dispersion of results for averaged velocity

Trigger level [dB]	V [m/s]	s_V/V [%]	$(s_V/V)_{\mathrm{aver}}$ [%]	Accepted data [%]
−5.0	3.0205	0.541	0.175	100.0
0.0	3.0245	0.554	0.095	99.01
10.0	3.0255	0.407	0.073	48.08

3.3. Influence of the number of averaged records on the results of measurement

The results of research on the influence of the number of records, over which the temporary spectrum is averaged, on the dispersion of velocity values, are compared in Tab. 3. These investigations were carried out for the spectral trigger. The comparison demonstrates that with the increasing number of averaged records of the temporary spectrum the uncertainty of velocity decreases.

Table 3. Influence of the number of averaged records on the results of measurement with the spectral trigger (for explanation, see Tab. 2)

	Trigger level = 0.0 dB		
Number of records	V [m/s]	s_V/V [%]	$(s_V/V)_{\mathrm{aver}}$ [%]
5	3.0233	0.583	0.407
20	3.0245	0.554	0.095
50	3.0317	0.470	0.052

4. Conclusions

The developed methods of processing Doppler signals by means of the fast Fourier transform allow us to achieve the dispersion of velocity of order 0.1% or even lower, down to 0.05%. Although they are not the real time methods (the analysis of a 1-kB sample takes about 70 ms on our computer), they can be applied to the estimation of slowly varying velocities in practical anemometers used in industrial environment.

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Received October 10, 1995