A New Velocity Estimation Method using Spectral Identification of Noise

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In all measurement techniques one seeks accuracy and precision. In ultrasonic Doppler velocimetry, those qualities strongly depend on signal-to-noise ratio of the Doppler signal and on the performance of the velocity estimator. The most widely used estimation method in ultrasonic Doppler velocimetry is the Pulse Pair method. Its success is due to the computation efficiency of the algorithm combined to an unbiased estimator. Unfortunately, in a wide range of experimental fluid flows, the pulse pair estimation is less efficient, especially in clear water or concentrated mud where the signal-to-noise ratio can be very low, or in highly turbulent flows where the Doppler signal has a broad spectrum. Our approach is based on the treatment of the Doppler Spectral Information. It uses a simple parametric identification inspired by theoretical models and experimental observations. It acts through noise subtraction and subsequent cutting. Thus, we have developed a fast velocity estimation algorithm superior to the Pulse Pair in terms of accuracy. Robustness of the method was evaluated by adding different levels of white Gaussian noise to an experimental Doppler signal. Results demonstrate an increase of noise immunity up to one decade compared to the Pulse Pair method.

Keywords: frequency estimation, Doppler signal, spectral analysis, variance

1 INTRODUCTION

There are several methods for flow velocity evaluation. One of the commonly used is the pulsed ultrasound technique: the estimation of the flow velocity at different depths along a profile can be obtained by Doppler evaluation from the backscattered acoustic signals [1]. In this approach, every sample volume is defined by the ultrasound beam geometry and the range gate of the pulse [2]. The ultrasonic signal is the result of reflection on moving scatterers in the insonified volume. This pulsed ultrasound technique generates, after coherent quadrature demodulation, a vector of samples for each depth volume in the profile. This signal is a complex Gaussian process, with addition of complex white Gaussian noise in first approximation.

Velocity in the depth volume is obtained by extraction of the Doppler information, estimated by the first spectral moment of the signal. The difficulty is mainly due to the random fluctuation of the Doppler frequency associated with each particle in the considered sample volume, even if there is no noise. The most used technique to estimate the moment of this complex signal is so called the Pulse Pair technique, which computes the autocovariance in order to extract the spectral mean frequency [3]. This estimator is in addition the maximum likelihood solution under Gaussian asumption.

Nevertheless, acoustic signal might present multiplicative noise, and data acquisition systems might introduce perturbation that deteriorates the performance of the Pulse Pair technique, and implies that the estimation variance can be larger then the Cramer-Rao lower bound. In this context, a new estimation method [4], based on the identification of the spectrum of the Doppler signal can be of great interest. The aim of this paper is to compare the new spectral method with the Pulse Pair in the case of white Gaussian noise conditions.

This paper is organized as follow. First, a model for moving scatterers in the insonified volume is presented, taking into account beam width and velocity distribution of the particles. Second, a novel method of first moment estimation is presented based on the identification of signal and noise in the spectrum. Finally, simulation results are discussed, presenting the noise range where this method is of interest.

2 DESCRIPTION OF THE METHOD

2.1 Doppler signal model

This study uses a basic time model corresponding to a Gaussian Doppler spectrum. The assumption of such a Gaussian spectrum is widely used [5-6] and is experimentally observed [7-8]. We consider a set of particles uniformly distributed in the fluid. Each particle appears in the Doppler signal as a wavelet when crossing the ultrasonic beam [7]. The complete signal is the sum (equ. 1) of those wavelets randomly delayed (τ_i). Each single wavelet is the product of a complex exponential function with a Gaussian shape (with a standard deviation σ and amplitude a).

$$s_D(t) = \sum_{i=1}^{N} a \cdot \exp - \frac{(t-\tau_i)^2}{2\sigma^2} \cdot \exp j(2\pi f_D t + \varphi_i) \tag{1}$$

The Doppler frequency f_D of this demodulated signal is proportional to the particles velocity and the corresponding phase φ_i is a random uniform variable.

2.2 Algorithms description

The Pulse Pair method was first introduced by [3]. It is the most widely used for the Doppler velocity estimation. This method supposes a white Gaussian noise and is based on a correlation calculation:

$$f_D = \frac{f_e}{2\pi} \arctan \frac{\operatorname{Im}(R(1/f_e))}{\operatorname{Re}(R(1/f_e))} \tag{2}$$

where f_e is the sampling frequency equal to the Pulse Repetition Frequency (PRF) and R is the autocovariance function of the complex Doppler signal.

The newly proposed velocity estimation method is based on the identification of the spectrum by a Gaussian model:

$$M(f) = A_S \cdot \exp - \frac{(f - f_D)^2}{2\sigma_D{}^2} + A_N \tag{3}$$

This approach is similar to that proposed in [4] which use the Levenberg-Marquard non-linear regression. The evolution of the algorithm is optimized in term of calculation efficiency and is forty time faster than the previous one but stay ten times slower than the Pulse Pair. The algorithm act as follow (see fig. 1):

- In the first step the Doppler spectrum is calculated from the square of the Fast Fourier Transform (FFT) magnitude.
- This spectrum is smoothed by a third order FIR (Finite Impulsion Response) filter until one can extract a single peak when cutting the spectrum at the first third of its magnitude.
- The forth step consist in the estimation of the mean f_D and the standard deviation σ_D of a Gaussian function cutting the spectrum at the same points.
- The linearization of the data is then done by the use of a new variable f':

$$f' = \exp - \frac{(f - f_D)^2}{2\sigma_D{}^2} \tag{4}$$

- This allows to estimate the parameters A_S and especially A_N by least square.
- The noise is then suppressed by a simple subtraction of the A_N value from the spectrum and all the values out of the $[f_D - 3\sigma_D ; f_D + 3\sigma_D]$ interval are set to zero. This operation gives an estimate of the spectral density of the Doppler signal $D_S(f)$.
- The last step is to estimate the mean frequency of the Doppler Signal by the calculation of the spectral first moment:

$$f_D = \frac{\sum f \cdot D_S(f)}{\sum D_S(f)} \tag{5}$$

The estimation can be enhanced by cumulating the magnitude-squared FFT of a few observed Doppler signals [9] before the smoothing step.

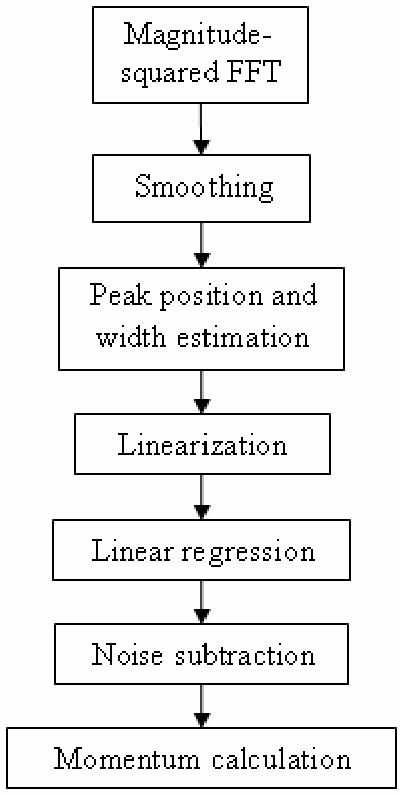

Figure 1: Steps of the spectral estimation method

3 PERFORMANCE

3.1 Simulation and estimation procedure

Several simulations for performance evaluation were conducted. We focused our attention on the comparison of the two methods by calculating the bias and the variance of each estimator for different SNRs. We varied the Doppler frequency to be estimated and the spectral width. The latter is related to the wavelet duration.

The simulated signal duration consisted of 5x64 samples. Depending on the used method, we calculated the mean value of the autocorrelation or the magnitude squared spectrum averaged over the 9 blocs of 64 samples. Indeed, in order to improve the performance of the estimation process, we use an overlapping of 32 samples between two adjacent blocs.

Normalization is done by dividing the bias and standard deviation on the frequency estimation by the length of the frequency range (corresponding to the PRF). In the different figures, the Doppler frequency is normalized by the PRF:

$$f = \frac{f_D}{f_e} \tag{6}$$

The normalized width w is driven by the duration of the Doppler wavelet directly linked to the beam width. This spectral width is chosen equal to:

$$w = \frac{6 \cdot \sigma_D}{f_e} \tag{7}$$

with $\sigma_D = \left(2\sqrt{2}\pi\sigma\right)^{-1}$ the standard deviation of the Gaussian function modeling the Doppler spectrum of the signal described by equation (1).

3.2 Model validation

The first step of this work is the validation of the signal model in comparison with the experimental data. This validation consists in the observation of the estimator behavior when the signal-to-noise ratio decreases. In this procedure, a portion of an experimental Doppler signal with a low noise level is selected. This signal has a normalized central frequency of 0.88 and a normalized spectral width (at 6 sigma) of 0.18. Then a signal is simulated with the same properties of mean frequency and spectral width, according to the model described by equation (1). Finally, noise is progressively added to those vectors of samples.

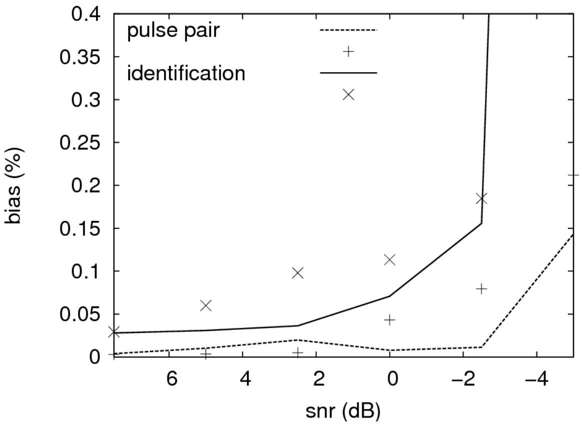

Figure 2: Comparison of the bias for the two methods with experimental data (points) and simulated data (lines).

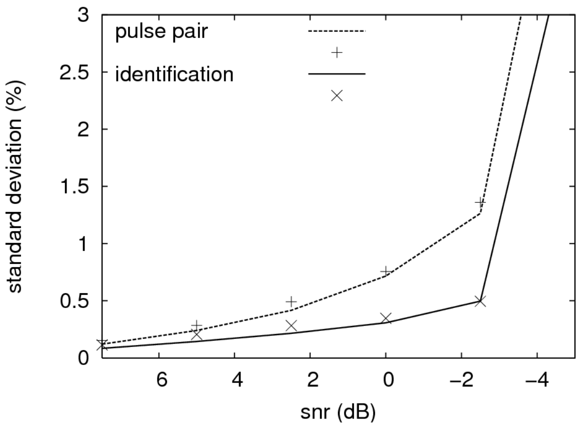

Figure 3: Comparison of the standard deviation for the two methods with experimental data (points) and simulated data (lines)

Figures (2) and (3) present the variation of the bias and the standard deviation while adding noise. In both cases the difference between the experimental signal and the simulated one is less than 0.1%. This validates the use of the model for the comparison of the two estimators. Nevertheless, the simulation results are a bit more optimistic than the simulated data.

3.3 Simulation results

The normalized bias and standard deviation of the two estimates are shown in figures (4) and (5) for different values of frequencies and for a normalized spectral width of 0.16.

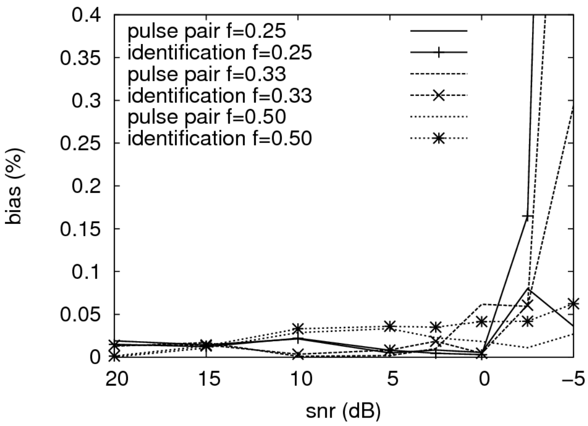

Figure 4: Comparison of the bias at different normalized frequencies.

The bias is less than 0.05 percent for any signal to noise ratio greater than 0 db. The results for the two methods are quite similar but for low signal to noise ratio, the pulse pair is globally more efficient.

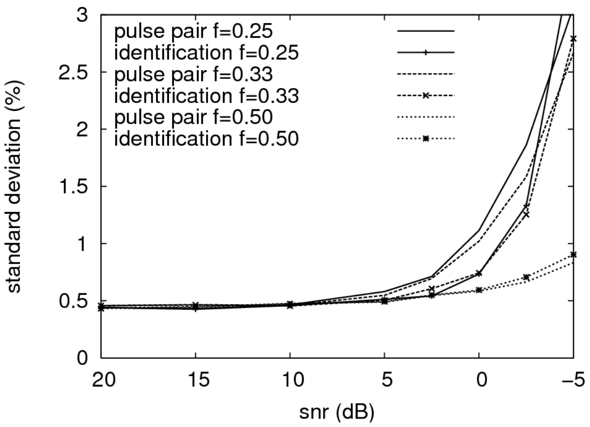

Figure 5: Comparison of the standard deviation at different frequencies.

As shown in figure (5), the main difference between the two methods is in term of standard deviation. It can be up to 40% greater for the Pulse Pair than for the identification method. This difference greatly depends on the central Doppler frequency f_D and mostly grows up with the frequency reduction.

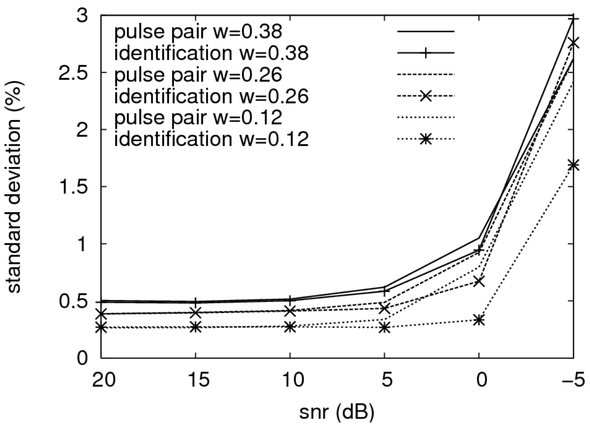

Figure 6: standard deviation comparison for different spectral widths.

Figure (6) present the results of the two methods for different width of the Doppler spectrum.

Those results show a significant improvement of the standard deviation when using the identification method, especially for narrow spectra. The identification method can be up to two times more precise.

4 SUMMARY

A novel estimation algorithm, based on spectral identification, has been evaluated. Compared to the traditional Pulse Pair, this method has globally the same bias, but is better in term of standard deviation. This method delivers better standard deviation for a signal to noise ratio in the range going from 10 to 0 dB.

Moreover, this novel method is more robust for experimental signals, especially when the data contain additional perturbations. Simulations with those kinds of perturbations (asymmetry between in-phase and quadrature signals, non Gaussian or/and coloured noise) have still to be done.

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