Burst detection and particle time of flight estimation with wavelets for acoustic velocity estimation

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Abstract

This paper presents the principle of acoustic velocity measurement in weak flow with Laser Doppler Velocimetry (LDV). It discusses a processing technique which enables to detect and localize in time domain the presence of Doppler bursts in case of acoustic excitation. A Wavelet Transform (WT) realized in the time-scale domain enables to give a noiseles representation of the Doppler signal, called scalogram. A detection scheme applied to this representation uses a comparison between the noise and the burst representation. An estimation scheme is developed using two steps. First step is based on the analysis of the scalogram over the time axis and gives an estimation of the central time. Second step, bases on the analysis of the scalogram over the scale axis gives an estimation of the time of flight of each detected burst. The performances of the detector are characterized with ROC (Receiver Operating Characteristic) curves. Finally, the estimator performances are studied by means of Monte Carlo trials obtained from synthesized LDV signals.

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1 Introduction

The complete experimental determination of an acoustic field needs to measure both the acoustic pressure and the acoustic velocity. This enables to estimate the acoustic intensity or impedance and gives many information about source radiation or acoustic energy exchange. Today, the acoustic pressure can be measured easily by means of microphones. Acoustic velocity can also be measured but acoustic velocity sensors are not commonly used yet. Acoustic velocity differs from usual flow velocity because the amplitude is much lower (some mm/s instead of some m/s) and the temporal variations are much more rapid (some kHz). Usual measurement techniques used today for estimating the acoustic velocity are the hot wire technique, PIV and LDV. Since LDV is non intrusive, linear and enables to estimate low velocity amplitude (some mm/s), it can be used for measuring acoustic velocity.

LDV is currently used for measuring acoustic velocities in two configurations. On the one hand, industrial applications need to measure the acoustic velocity in flow (some m/s) for high acoustic levels (greater than 120 dB). This measurement enables to estimate the local acoustic impedance or acoustic intensity [1] and can be used for example for characterising the acoustic treatment of airplane nacells. On the other hand, LDV is used for characterising acoustic velocities in weak flow (some mm/s) corresponding the common laboratory conditions. In this case, measurements are performed for estimating mean acoustic levels (between 60 and 120 dB) using frequencies ranging from 50 Hz to 4000 Hz. These measurements enable to validate physical models of acoustic velocity fields, to measure acoustic impedance and intensity, or to calibrate sensors. In this context, acoustic impedance measurements have been studied by Davis *et al* [2]. Microphone calibration has been performed with LDV by Taylor [3], MacGillivray *et al* [4] and an acoustic velocity sensor has been studied using LDV by Raangs et al [5]. LDV has also been used for characterizing thermoacoustic resonators [6, 7].

For a forced sinusoïdal acoustic excitation, the signal produced by the LDV system, called Doppler signal, is frequency modulated and the frequency modulation is the acoustic frequency. For measurements performed in high flow, the time of flight of particles is very low and the frequency modulation is not visible over the burst duration. The acoustic velocity is estimated thanks to specific data processing which uses non uniform sampling techniques such as sample and hold [8] and slotting technique [1].

For weak flow measurements, the frequency and amplitude modulation exists over the burst duration. For very low flow velocity (typically 1 mm/s) and high frequency (greater than 2 KHz), many modulation periods appear over the burst duration. In this case, signal and data processing aim at estimating the acoustic velocity amplitude and phase. They also determine the flow velocity amplitude assumed to be constant over the burst duration. Different signal processing techniques have been used. First is the spectral analysis as used by Taylor [9]. Second is the photon correlation method developed and validated by Greated *et al* [10, 11, 12, 13]. Third technique is the time approach which enables to estimate the instantaneous frequency which is proportionnal to the Doppler signal phase and to deduce the acoustic velocity parameters from a parametric approach. This technique has been developed and validated experimentally by Valière *et al* [14, 15, 16, 17, 18]. Finally parametric methods such as maximum likelihood Method and Kalman filtering have been developped and validated by Mellet [19] and Le Duff [20]. As the measurement is performed in weak flow conditions, these techniques are usually applied to a single burst which contain enough information for estimating the acoustic velocity parameters. However it is interesting to estimate the acoustic velocity from many bursts. This enables to establish experimental uncertainties using a statistic approach performed on many burst analysis. Finally it enables to facilitate the measurement procedure by using an automatic processing.

The estimation of acoustic and flow velocity parameters using many bursts produced by many tracers crossing the probe volume at different random times needs to establish if a particle crosses the probe volume (detection / decision problem) on the one hand and to estimate the central time and the time of flight of each particle on the other hand (estimation problem). The aim of this work is to develop and validate a technique for detecting burst and for estimating the central time and the time of flight of each particle.

Different authors have developed techniques for detecting burst and for estimating arrival times and times of flight of particles. Howard and Edwards [21] proposes a likelihood test performed using the autocorrelation of the Doppler signal. This enables to detect burst for a negative signal to noise ratio (-10 dB). Galtier [22] uses a detection-estimation technique for real time measurement which enables to estimate Doppler frequencies and signal amplitude for each detected burst. Qui *et al* [23] use two real-time Doppler burst identification schemes for PDA measurements in two-phase flows. The first method is based on the evaluation of the signal magnitude in the spectral domain and the second method on the continuous estimation of the SNR using an analogue circuit. Both methods allow the detection of Doppler signals with SNR values as low as -10 dB. Van Maanen and Nijenboer [24] use wavelet transform to detect burst and to estimate the time arrival and the Doppler frequency of simulated data. As the use of wavelet technique results in noise suppression by fitting real data to realistic burst model (wavelet), it appears to be very interesting to apply it to detection. The wavelet transform was used by Harteveld *et al* [25] who developed a processor of LDA data which uses the combination of a wavelet technique and algorithms that can process dual bursts. It has also been used by Nobach and Van Maanen [26] for estimating the frequency and the arrival time of signals measured with a LDA.

This paper presents a technique using the wavelet transform for detecting burst in the case of acoustic excitation and for estimating the arrival time and the time of flight of detected burst. First, the model of the Doppler signal is recalled for acoustic excitation at a single frequency. Second, the general principle of the whole signal processing is presented in order to understand the role of detection in this process. Then we present the wavelet detection-estimation method principle and the results obtained with simulated data.

2 Doppler signal model

In case of acoustic sinusoïdal excitation at frequency F_{ac}, the velocity of a tracer q can be written

$$v_q(t) = V_{f,q} + V_{ac}\cos(2\pi F_{ac}t + \phi_{ac}), \tag{1}$$

where V_{ac} is the amplitude of the acoustic velocity, ϕ_{ac} the acoustic velocity phase and $V_{f,q}$ the flow velocity of particle q, supposed as constant in the probe volume. The high-pass filtered electrical signal delivered by the photo-detector, called burst, is

$$s_q(t) = A_q(t)\{\cos[2\pi F_B t + \phi_q(t)]\} + n(t), \tag{2}$$

where

$$\phi_q(t) = \frac{2\pi x_q(t)}{i} + \phi_0 \tag{3}$$

is the phase of the Doppler signal expressed as a function of the particule position $x_q(t)$ in the probe volume frame, of the interfringe i, and of the initial phase due to optics ϕ_0. The magnitude of the Doppler signal related to particle q is $A_q(t) = Ke^{-\{\beta x_q(t)\}^2}$ where β is related to the probe geometry. F_B is the Bragg frequency and n(t) is the additive noise which can be considered as Gaussian for high level signals but which should be modelled with Poisson process for low level signals [27, 28]. The position of the particle $x_q(t)$ in the probe volume frame is given by

$$x_q(t) = V_{f,q}(t - t_{c,q}) + \frac{V_{ac}}{2\pi F_{ac}}\sin(2\pi F_{ac}t + \phi_{ac}), \tag{4}$$

where $t_{c,q}$ is the time at which the particle reaches the center of the probe volume without acoustic excitation, called central time.

Signal processing methods need to define the analytic signal $z_q(t)$ of $s_q(t)$, written as $z_q(t) = A_q(t)e^{j\phi_q(t)}$ where

$$\phi_q(t) = 2\pi\frac{V_{f,q}(t - t_{c,q})}{i} + \alpha\sin(2\pi F_{ac}t + \phi_{ac}), \tag{5}$$

and

$$\alpha = \frac{V_{ac}}{iF_{ac}} \tag{6}$$

is the modulation index proportionnal to the acoustic displacement $X_{ac} = \frac{V_{ac}}{2\pi F_{ac}}$. In practice, $z_q(t)$ is approximated by $z_q(t) = s_{q1}(t) + js_{q2}(t)$ where

$$\begin{aligned} s_{q1}(t) &= A_q(t)\cos\phi_q(t) + n_1(t), & (7)\\ s_{q2}(t) &= A_q(t)\sin\phi_q(t) + n_2(t), & (8) \end{aligned}$$

$n_1(t)$ and $n_2(t)$ being sequences of zero-mean independant Gaussian random variable. $s_{q1}(t)$ and $s_{q2}(t)$ are obtained thanks to a Quadrature Demodulation (QD) technique (figure 1) which shifts down the carrier frequency of the Doppler signal to zero. The doppler signal due to N particles is $z(t) = A(t)e^{j\phi(t)} = \sum_{q=1}^{N} z_q(t)$. An example of an experimental Doppler signal is presented in figure 2 and shows the frequency modulation.

3 Signal processing for acoustics

The aim of signal processing in LDV applied to acoustic velocity measurement is to give an estimation of the acoustic parameters V_{ac}, ϕ_{ac} from $s_{q1}(t)$ and $s_{q2}(t)$, written $\hat{V}_{ac}$, $\hat{\phi}_{ac}$ and to estimate the uncertainty in $\hat{V}_{ac}$ and $\hat{\phi}_{ac}$. The estimation of the flow velocity $\hat{V}_{f,q}$ for each

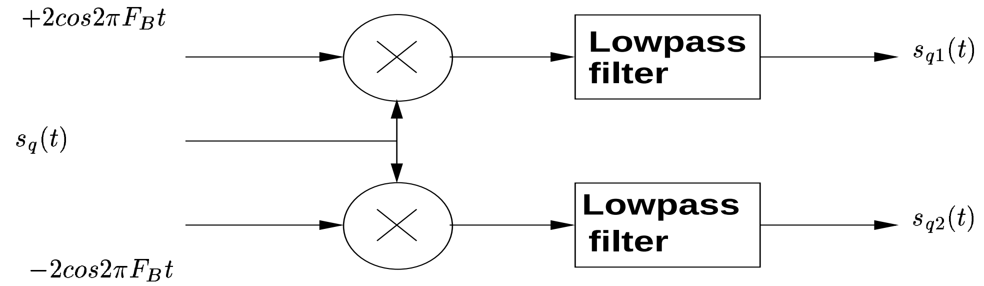


Figure 1: Scheme of quadrature demodulation technique.

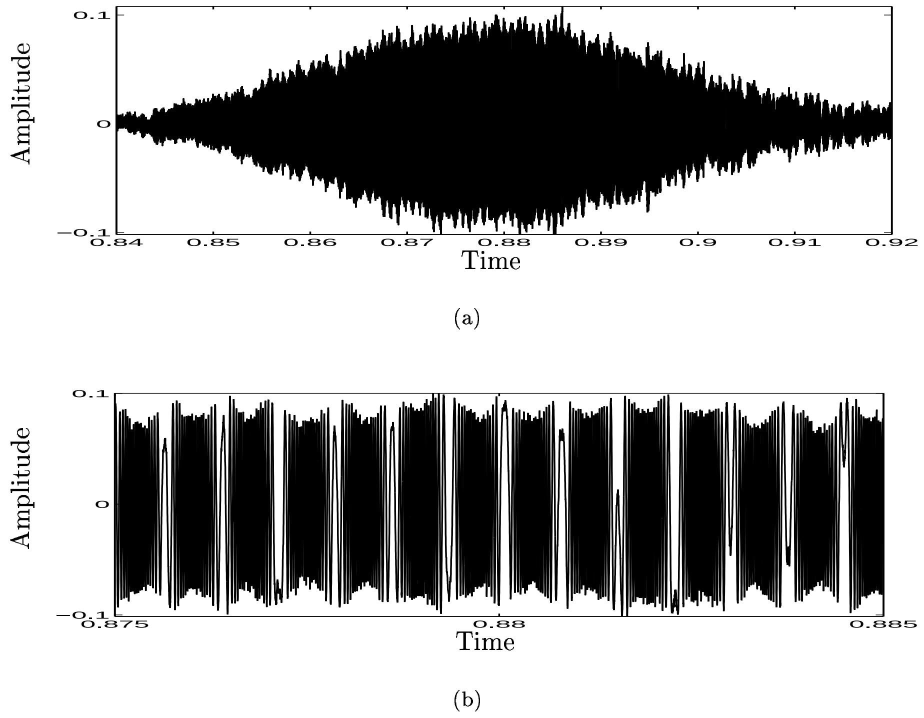


Figure 2: View of an experimental signal $s_{q1}(t)$. (a) View of a single burst. (b) Zoom of the burst.

burst q is not useful for acoustics measurements, the flow velocity being usually considered as a difficulty for estimating the acoustic parameters. The signal processing principle is presented in figure 3. The three parameters $\hat{V}_{ac}$, $\hat{\phi}_{ac}$ and $\hat{V}_{f,q}$ are obtained using the instantaneous frequency defined by $IF(t) = \frac{1}{2\pi}\frac{d\phi}{dt}$. If the different burst do not overlap, the instantaneous frequency can be written

$$IF(t) \simeq \sum_{q=1}^{N} \frac{d\phi_q(t)}{dt} \simeq \sum_{q=1}^{N} \frac{1}{i}[V_{f,q} + V_{ac}\cos(2\pi F_{ac}t + \phi_{ac})] + n_{IF}, \tag{9}$$

where n_{IF} is the noise associated with the demodulation of noises n_1 and n_2. Figure 4 shows a schematic view of the instantaneous frequency for a flow velocity which increases with time.

The estimated instantaneous frequency $\hat{IF}(t)$ is obtained using time frequency transforms such as Short Time Fourier Transform (STFT), Cross Wigner Wille Transform [14], Phase Derivative Based Estimator [29] or Synchronous Time Frequency Detector [15]. Assuming that the acoustic velocity characteristic do not change during the observation duration, the N values of $V_{f,q}$ and the two parameters V_{ac}, ϕ_{ac} are estimated using a parametric estimation method (Fourier Series analysis or least mean square method) applied to $\hat{IF}(t)$ for $t \in [t_{c,q} - T_{f,q}/2, t_{c,q} + T_{f,q}/2]$ (see figure 4), where $T_{f,q}$ is the time of flight of particle q defined by

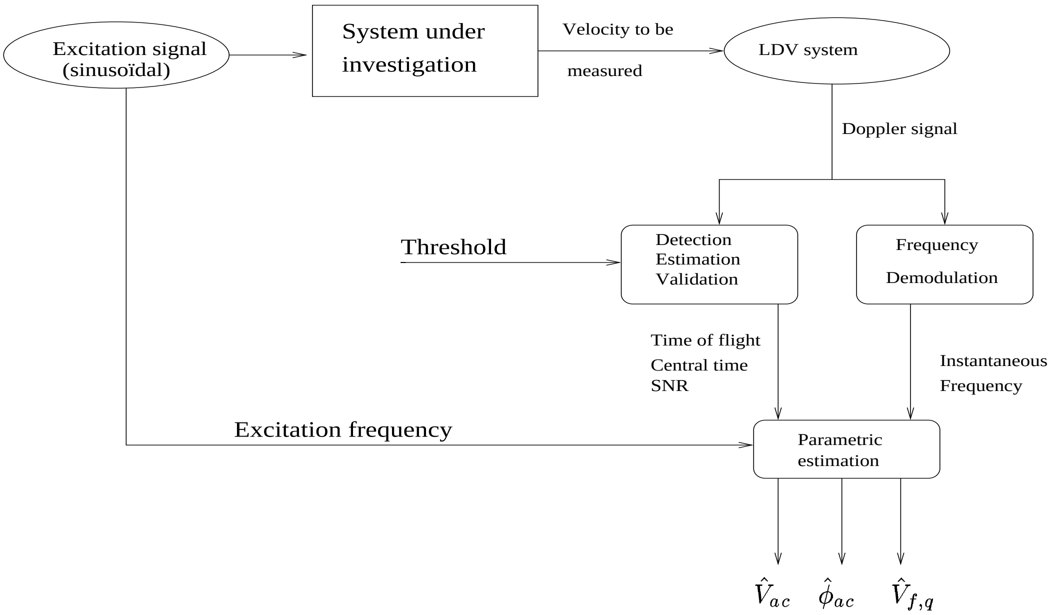


Figure 3: General principle of the signal processing for acoustic velocity estimation.

$$T_{f,q} = 4\sigma_q = \frac{4}{\sqrt{2}\beta V_{f,q}}. \tag{10}$$

For this reason, the estimation of the three parameters V_{ac}, ϕ_{ac} and $V_{f,q}$ can only be performed if each burst is detected and if the central time $t_{c,q}$ and the time of flight $T_{f,q}$ are estimated. Moreover, burst which overlap should not be considered for estimating the acoustic parameters, which could bias the instantaneous frequency estimation.

The minimum variance in the acoustic parameters estimation is given by the Cramer Rao Bounds (CRB) established by Le Duff [30]. This variance depends on the Signal to Noise Ratio (SNR), on the modulation index α and on the flow velocity $V_{f,q}$. Low variance are obtained for high SNR, high modulation index and for low flow velocity amplitude corresponding to high time of flight. The estimation of the theoretical uncertainty in the acoustic velocity parameters given by the CRB needs to know these three parameters. The modulation index is deduced from the known acoustic frequency and from the acoustic velocity amplitude. The flow velocity is deduced from the instantaneous frequency analysis (mean frequency of each burst). Finally the Signal to Noise Ratio (SNR) of each burst has to be determined using the noise power and the burst power calculated by means of central time and time of flight.

4 Wavelet detection-estimation

4.1 Principle

The general principle of the detection-estimation process consists in four steps. First step is the signal transform which leads to a representation in the time-scale domain, called scalogram, that suppresses noise. Second step is the detection process. The analysis of the scalogram uses a threshold and enables to detect the events (burst) contained in the signal. Third step is the estimation process. For each detected burst, the central time $t_{c,q}$ and the time of flight of the burst $T_{f,q}$ are respectively estimated using an analysis over the time axis and over the scale axis. Finally, a validation procedure is used in order to apply the parametric estimation in good conditions (high SNR and low flow velocity). The principle of the detection is presented in figure 5.

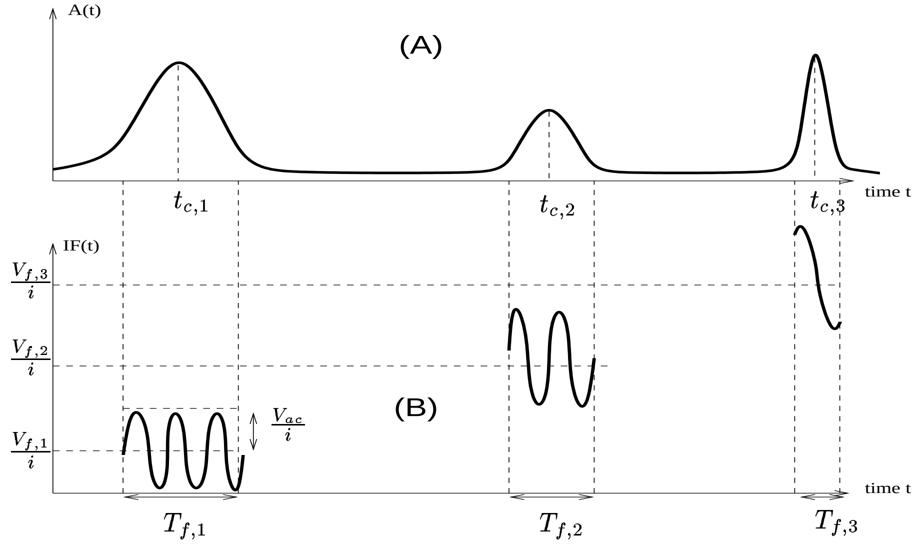


Figure 4: Schematic view of the Doppler signal amplitude (A) and of the instantaneous frequency signal obtained for different flow velocities (B).

4.2 Signal representation

The signal representation is performed using a Continuous Wavelet Transform (CWT) [24, 26] of the doppler signal $z(t)$ defined as

$$W_z(t_0, a) = \langle z, \psi_{t_0,a} \rangle = \int_{-\infty}^{+\infty} z(t) \frac{1}{\sqrt{a}} \psi^*(\frac{t - t_0}{a}) dt, \tag{11}$$

where the kernel is the Morlet wavelet defined by $\psi(t) = (\pi t_0)^{-1/4} e^{-\frac{1}{2}(\frac{t}{t_0})^2} e^{j2\pi f_0 t}$ [31].

According to its time-frequency localisation properties, the wavelet transform performs an analysis with constant relative spectral resolution $\frac{\triangle f}{f_0} = k_1$ It means that for each wavelet timewidth and bandwidth vary inversely. In other word, high frequency components of a signal are analyzed on a smaller duration than for low frequency components. Due to Heisenberg incertainty relationship we have also $\triangle f \triangle t = k_2$, so we obtain: $\triangle t = \frac{k_2}{k_1 f_0}$.
This last relation is very close to equation 10 were $\triangle t$ is equivalent to $T_{f,q}$ and f is equivalent to $\frac{V_{f,q}}{i}$. We can conclude that a wavelet constitute a mathematical model of a burst. For this reason, the CWT can be seen as a scalar product of the kernel and of the signal which allows to obtain an accurate decorrelation with the noise.

4.3 Detection

The burst detection problem is a binary hypothesis problem. It consists in determining if one or multiple bursts are present in an signal $z_{T_w}(t)$ observed in a noisy environment during a observation duration T_W . The observation is performed on time windows which do not overlap. For each window, the time lenght is $T_W = 10\hat{\sigma}_q$ (eq. 10), where the estimation $\hat{\sigma}_q$ of the standard deviation σ_q is at first obtained using a FFT analysis of the complete Doppler signal.

Using the CWT, the detector indicates the presence of signal on the window T_W when

$$\left[|W_z(t_0, a)|^2 \right]_{T_W, max} > \gamma. \left[|W_b|^2 \right]_{max}, \tag{12}$$

where $[|W_z(t_0, a)|^2]_{T_W,max}$ is the maximum of scalogram on T_W, γ is a threshold defined by the user and $[|W_b|^2]_{max}$ is the maximum of the scalogram of a noisy portion of the tested signal.

4.4 Estimation

The estimation procedure of the central time $\hat{t}_{c,q}$ and the time of flight $\hat{T}_{f,q}$ is performed in two steps. The first step consists in getting a more accurate localisation of the detected information

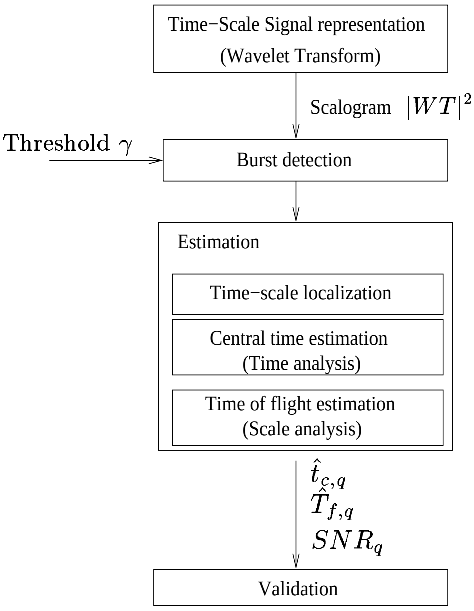


Figure 5: Principle of the detection process in the case of acoustic velocity estimation.

in time-frequency domain (figure 6.b). The second step leads to an estimation of the time parameters ($\hat{t}_{c,q}$, $\hat{T}_{f,q}$) (figure 6.a).

First step gives an estimation of the time width $\hat{T}$ and the scale width $\hat{A}$ which verify

$$|W_z(\hat{T},\hat{A})|^2 > \gamma \left[|W_b|^2\right]_{max}. \tag{13}$$

The second step leads to the central time $\hat{t}_{c,q}$ and the time of flight $\hat{T}_{f,q}$ estimations. $\hat{t}_{c,q}$ is calculated from width $\hat{T}$ by derivating the marginal of the scalogram along the time axis

$$\xi_{deriv,t_0} = \frac{d}{dt_0}\left(\int_a |W_s(t_0,a)da|^2\right). \tag{14}$$

Scalogram maximum are localized thanks to zero crossing of the derivative ξ_{deriv,t_0}, and scalogram maximum leads to bursts envelop maximum. Then, zero crossings give an estimation of burst central times $\hat{t}_{c,q}$. The time width $\hat{T}_{f,q}$ is estimated using the derivative of the marginal along the frequency axis $\zeta_{deriv,f}$ given by

$$\zeta_{deriv,f} = \frac{d}{df}\left(\int_{t_0} |W_s(t_0,\frac{f_0}{f})dt_0|^2\right), \tag{15}$$

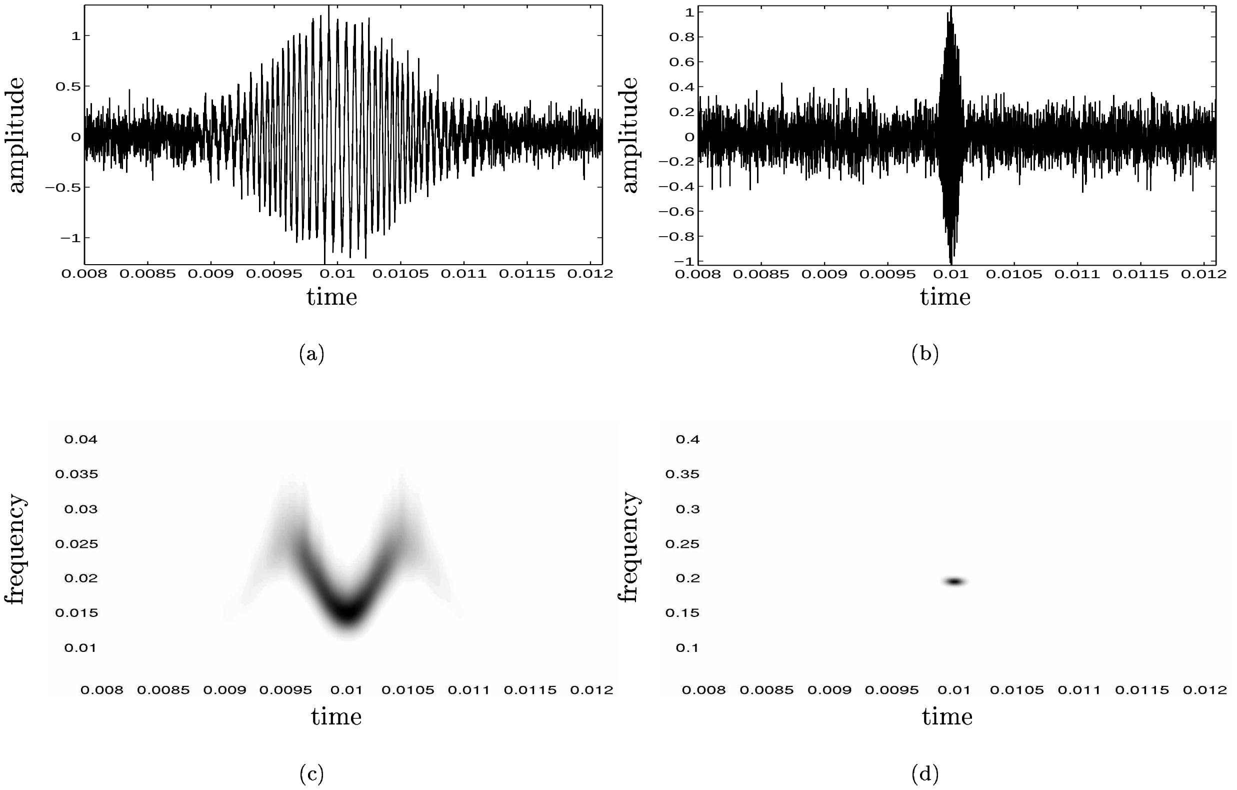
thanks to the analogy $a \equiv f_0/f$. All zero crossings of $\zeta_{deriv,f}$ give an estimation of time of the flow velocity $V_{f,q}$ and of the flight estimation $\hat{T}_{f,q}$ thanks to equation 10.

5 RESULTS

Detector validation and estimations are realized on simulated data for 1000 Monte Carlo simulations (one event for one simulation) at various SNR (Signal to Noise Ratio). Each event contains at least one burst (H_1) or no burst (H_0).

Different parameters of the LDV system have been tested as shown in table 1. Signal parameters are $\beta = 4.6407.10^4\ m^{-1}$, $i = 1.06336.10^{-6}\ m$, $K = 1$, $\phi_0 = \pi$ and $T_e = 10^{-6}\ s$.

Results are obtained with a set of parameters corresponding to low acoustic displacement amplitude and high convection flow which corresponds to difficult conditions for the instantaneous frequency estimator [14]. These conditions are defined by $f_{ac} = 4000\ Hz$, $\alpha = 0.01$



(a) (b) (c) (d)

Figure 6: (a) : Synthetized Doppler burst, (c) : Scalogram of the Doppler burst ($F_{ac} = 1000\ Hz$, $\alpha = 5$ and $V_{f,q} = 20\ mm/s$). (b) : Synthetized Doppler burst, (d) : Scalogram of the Doppler burst ($F_{ac} = 1000\ Hz$, $\alpha = 5$ and $V_{f,q} = 200\ mm/s$)

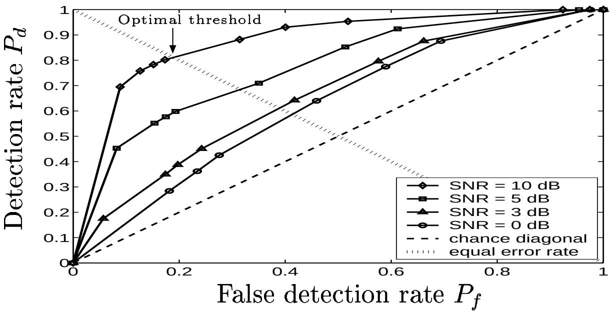
$\alpha = DV_{ac}/f_{ac}$	10^{-2}	1	10
$f_{ac}\ (Hz)$	100, 1000, 4000		
$V_{c,q}\ (mm/s)$	20, 200		

Table 1: Numerical values used for the simulations

(acoustic level of 58 dBSPL in free field) and $V_{f,q} = 200\ mm/s$. ROC curves (figure 7) show the detector behaviour for different SNR (0 dB, 3 dB, 5 dB, 10 dB).

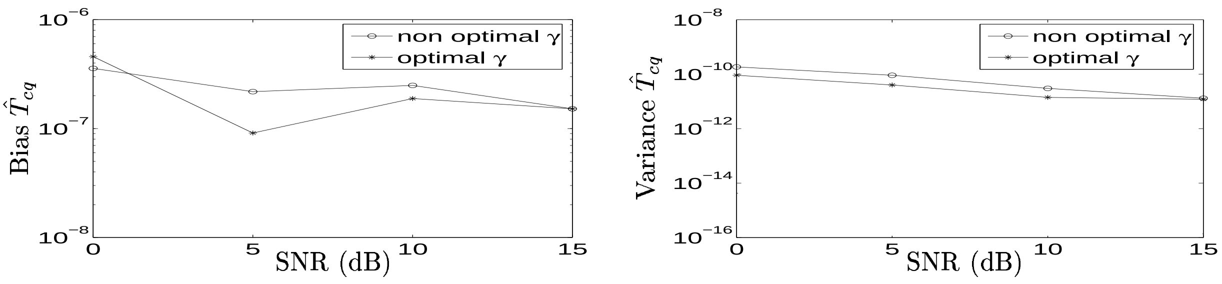
Classically, we can notice an increase of the area located under each ROC curve together with the augmentation of the SNR. Moreover, it is possible to extract an optimal threshold from each curve in a sense were it matches with minimax criteria [32]. On the ROC curve it corresponds to point for which we get equality beetween false alarm rate and non detection rate (also called equal error rate): $P_f = 1 - P_d$. The optimal threshold is then use by the detector for the estimations.

Figure 8 presents the estimator bias and variance on flight time $T_{f,q}$ for two values of the threshold γ. Bias $b_{\hat{T}_{f,q}}$ and variance $\sigma^2_{\hat{T}_{f,q}}$ are smaller with an optimal threshold γ, determined thanks to ROC curves (figure 7). The standard deviation $\sigma_{\hat{T}_{f,q}}$ is at worse 10 μs (SNR of 0 dB) and at best 3 μs (SNR of 15 dB), with $T_{f,q} = 176\ \mu s$ for $V_{f,q} = 200\ mm/s$. The bias $b_{\hat{T}_{f,q}}$ is at worse 0.5 μs (SNR 0 dB) and at best 0.1 μs (SNR 15 dB). Using the same set of parameters, standard deviation $\sigma_{\hat{t}_{c,q}}$ in the central time estimation $\hat{t}_{cq}$ is at worse 0.7 μs (SNR 0 dB) and at best 0.1 μs (SNR 15 dB). The bias $b_{\hat{t}_{c,q}}$ is at worse 0.2 μs (SNR 0 dB) and at best 0.05 μs (SNR 15 dB). Results concerning the detection-estimation step in LDV set-up allows to optimize the



(a)

Figure 7: ROC curves for wavelet detector ($F_{ac} = 4000\ Hz$, $V_{f,q}$=200 mm/s and $\alpha = 0.01$)



(a)

(b)

Figure 8: (a) Time of flight bias . (b) CRB and time of flight variance, for $\alpha = 0.01$ and two values of γ ($F_{ac} = 4000\ Hz$ and $V_{f,q}$=200 mm/s).

estimators linked to the caracterization of bursts (V_{ac}, ϕ_{ac} and $V_{f,q}$).

According to the experimental condition in which acoustics measures are achieved, results obtained by the detection-estimation procedure are satisfactory and will allow to optimize the estimators linked to the characterization of bursts (V_{ac}, ϕ_{ac} and $V_{f,q}$).

6 CONCLUSION

The LDV measurement of acoustic fields obtained with sinusoïdal excitation lead to generate bursts which are modulated in frequency and amplitude at the acoustic frequency. The acoustic velocity amplitude and phase are estimated using three signal processing steps. A frequency demodulation is applied in order to give an estimate of the instantaneous frequency, proportionnal to the derivative of the Doppler signal phase, *i.e.* to the particle velocity. A parametric estimation (Fourier Series or Least Mean Square method) is applied on the estimated instantaneous frequency at the times corresponding to the crossing of particles with the LDV probe volume. In order to apply the parametric estimation in an automatic way, the central time and the time of bursts have to be determined. A detection process based on Wavelet Transform has been developed and evaluated.

The detection process uses a Morlet wavelet transform in order to obtain a noiseless representation (scalogram) of the Doppler signal. This representation is used for detecting the burts using a comparison of the noise level and the burst level in the time-scale domain (scalogram). For each detected burst, an time analysis gives an estimate of the central time and a frequency (scale) analysis gives an estimate of the mean velocity which is linked with the time of flight.

The detector performances are evaluated by means of numerical simulations. ROC curves are used to extract an optimal threshold.

The estimator performances are evaluated by comparing the estimated times (central time and time of flight) with the Cramer Rao Bounds calculated from the Doppler signal model. Results show that the choice of the optimal threshold leads to minimum values of bias and variance.

This detection-estimation process should enable to perform automatic measurement of acoustic velocity by means of LDV. However further work will consist in detecting dual burst which should not be processed in order to avoid to bias the instantaneous frequency estimation. To achieve it, the zero crossing technique applied to the derivative of the marginals along the time and frequency axis will be used. Finally, another way to improve the true detection rate will be to use wavelets having a finest relative bandwitdh characteristics.

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