DOPPLER ACOUSTIC VELOCIMETRY OF FLUID FLOW FROM BOREHOLE FRACTURES

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Abstract

This work is concerned with the evaluation of the velocity of a fluid flow emerging from borehole fractures. Two kind of Pulsed-Doppler techniques are employed to estimate flows velocity. First one is based on frequency shift estimation, and second one on time-domain velocity estimators. Numerical and experimental results are presented.

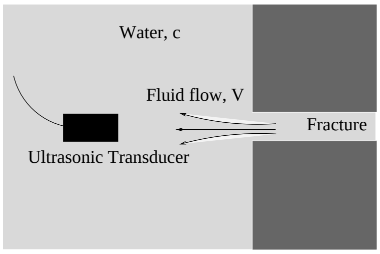

Figure 1: Problem configuration

1 Introduction

This investigation deals with the evaluation of fluid flows emerging from borehole fractures. The objective is to develop an acoustical Doppler velocimetry system for the quantitative description of the fluid movements in subsurface fractured rocks [1]. To delve more deeply into this issue, different Doppler methods were investigated. The first classic one consists in finding an estimation of the frequency shift generated by moving particles that are present in the fluid. Various frequency estimators were implemented (FFT, pulse-pair method, ...), providing an accurate estimate of the fluid velocity, provided that the measurement is made during at least a few period of the research Doppler frequency. In order to release from this limitation, time-domain velocity estimators were investigated. Thus, in the case of very slow flows the use of a time-domain method is proposed. This method is based on determination of the time shift between successive backscattered signals. It enables a direct measurement of the particles velocity (e.g. without Doppler frequency estimation). The performances of these techniques were first evaluated using numerically-simulated data. Then, an important experimental study has been carried out in a laboratory tank simulating a fractured borehole.

2 Theoretical aspects and numerical study

2.1 General principle

The studied problem is reprensented on figure 1. A fluid (water) flow emerges from a borehole fracture (modelised by a hole in the borehole wall). The aim of this study consists in evaluation of mean velocity of the flow via an ultrasonic pulsed Doppler system.

The pulses are sent at the pulse repetition frequency PRF (see figure 2). The fluid velocity is measured through the shift in position of the ultrasound scatterers during the interpulse interval. To determine this position shift (thereby the velocity), one can either measure the phase shift between received signals, or cross-correlate the received signals in order to estimate the position of the cross-correlation peak. The later technique, termed Time-domain Cross Correlation, was first introduced by Philips Corp. in their Color Velocity Imaging (CVI) devices [3].

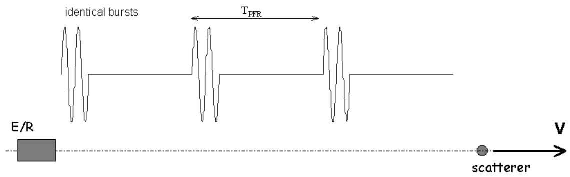

Figure 2: Principle of Pulsed Wave Doppler

2.2 Configuration for numerical simulations

Configuration chosen for numerical simulations is closed from the experimental one presented in part 3.

The ultrasonic pressure distribution in the half space in front of a transducer is evaluated via the impulse response of spherically focused radiators [4], [5]. Calculations are achieved for transducers used in subsequent experiments (Panametrics focused transducers), whose characteristics are : working frequency: $f_o = 2.25MHz$, focal length : 1 inch, beamwidth (-3dB) at focal length (for $f_o = 2.25MHz$) : 1.15mm.

The emitted plused is chosen to be a sinusoidal signal of principal frequency $f_o = 2.25MHz$ whith a gaussian envelop function (see figure 3).

The propagation medium (water) is an homogeneous, isotropic, and non-attenuating fluid. The shape of the flow is chosen to be a cylinder of radius $R = 3.5mm$. The velocity profile is described by the Poiseuille relationship, that is to say that the velocity of a parti-

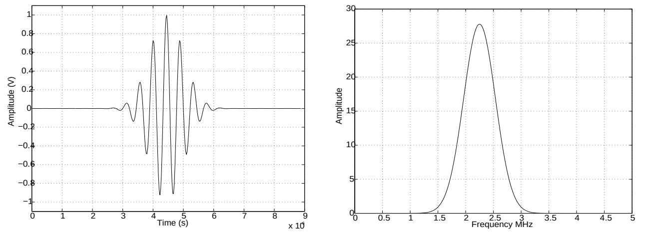

Figure 3: Example of the synthetic emitted pulses and the corresponding spectrum

cle regarding to its distance r to the flow axis follows $v(r) = V[1 - (\frac{r}{R})^2]$, where V is the maximum velocity in the middle of the flow.

Particles in the flow are assumed to be perfect reflectors, and the diffraction by these particle is neglected. The backscattered signal is reconstructed only from the information about the instantaneous position of each target.

Simulated RF lines result from the sum of the signatures of the Np particles inside the cylindrical volume of radius R and length equal to 1.5 times the focal length of the sensors. The center of the sampling volume coincides with the focal point (see figure 4). Thus, it has been chosen to neglect the contribution to the global acoustic signature of the particles lying in the near field of the transducer.

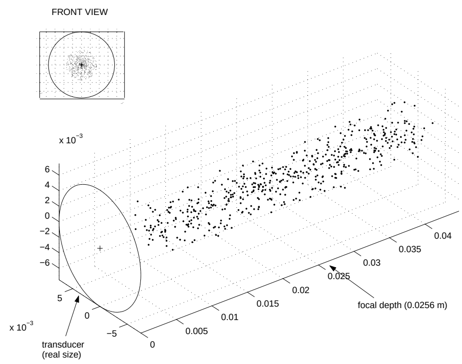

Figure 4: Particles repartition in the simulated sampling volume (Np=500 particles)

2.3 *Velocity measurement using Pulsed Wave Doppler (PWD) frequency*

After one "shot" (emission of a pulse) at time t we calculate the so-called "RF signal" which is backscattered by particles. RF signal is sampled at frequency Fs. At time $t + T_{PRF}$, taking into account the displacement of each individual particle distinctively, a new RF line is produced. From pulse to pulse, a time$\times$time figure can be constructed (see an exemple in figure 5).

Let us consider the simplest case of one single moving target. If one particular point is chosen in the

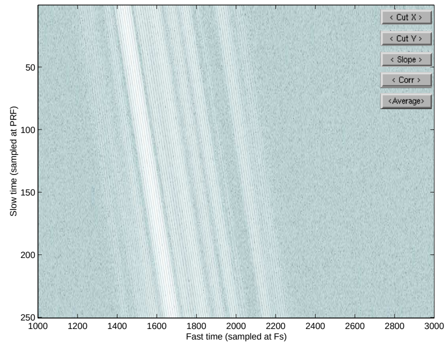

Figure 5: Time$\times$time representation of simulated RF lines. (250 shots, SNR=20dB, V=5cm/s)

abscissa, that is to say that one particular depth in the propagating medium is chosen, then the evolution within the slow timebase (sampling period PRF) of the corresponding backscattered signal exhibits a dilated replica of the emitted signal[6] (see figure 6). The time-dilatation (frequency-compression) factor is :

$$\frac{2V}{c} = \frac{t}{T} \equiv \frac{f_D}{f_o} \tag{1}$$

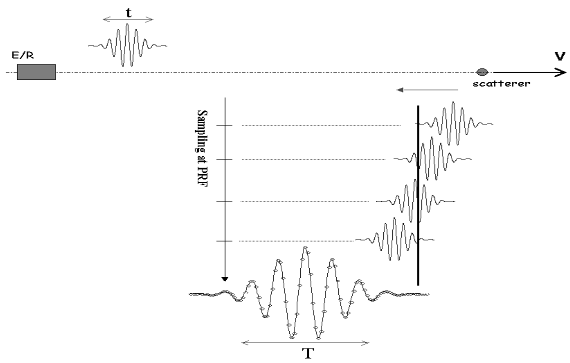

Figure 6: Reconstruction of a Doppler signal through sampling in slow-time timebase

In fact, many scatterers are present in the flow, and it is impossible to measure any period of dilated pulses. Nevertheless, sampling and holding the superimposition of all particles contributions at PRF still produces the so-called "Doppler signal". The mean frequency f_D of this Doppler signal, leads to fluid velocity via equation 1. An example of synthetic "Doppler signal" is given in figure 7. It was computed for 10 000 particles present in the sampling volume with a maximum flow velocity of $V = 5cm \cdot s^{-1}$.

In this particular case, the estimation of the mean Doppler frequency does not present any difficulties because few period of Doppler signal can be observed. Various frequency estimators (FFT, Pulsed-Pair Method

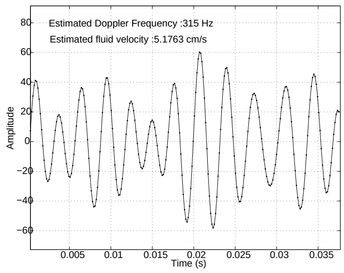

Figure 7: Simulated Doppler signal (10000 particles)

[2] have been implemented. They agree on a value of velocity of $5.17cm/s$, and provide a good estimate of the velocity chosen in numericals simulations ($5.0cm/s$). Nevertheless, Doppler frequency estimation can become more difficult for very slow flows. In this case, observing Doppler signal during few periods can collide with experimental limitations in real borehole logging conditions. Thus, in the case of very slow flows, we propose to use a time-domain method, which enables direct measurement of the particles velocity (e.g without Doppler frequency estimation).

2.4 Velocity estimation using time shifts

This method is based on the estimation of the time shift between successive backscattered RF lines. The time shift is not induced by Doppler effect but by the interpulse global displacement of the fluid [7].

The time shift between two successive pulses is determined by the position of the maximum of the cross correlation function of the RF signals. In experimental conditions, the cross correlation function will be calculated over a window, which contains only a sample of the backscattered signal. This allows to determine the local velocity at the corresponding depth.

In the ideal case of noiseless signals, only two shots are needed to accurately determine the flow velocity. But for real signals, small discrepancies in the time shift can lead to erroneous estimation of the velocity due to large multiplication factor $\frac{c}{V}$. One solution consists in calculating the correlation between the first RF line, considered as the reference, and the following lines. The slope of the curve of the correlation maxima produces converge to the searched value (see figure 2.4).

3 Experimental study

3.1 Experimental set-up

The experimental set-up is reprensented on figure 9. It comprises a cylindrical tank of diameter 40.5 cm and height 60 cm. An external pump allows the injection of water through a hole of diameter 4 mm. Particles of kaolinite were added to water (concentration $5 \cdot 10^{-3} g \cdot cm^{-3}$).

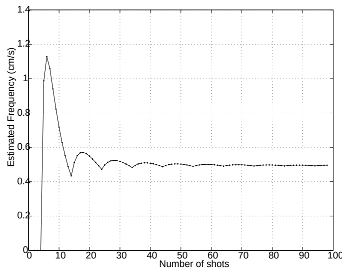

Figure 8: Evolution of velocity estimate with number of shots (noiseless signal).

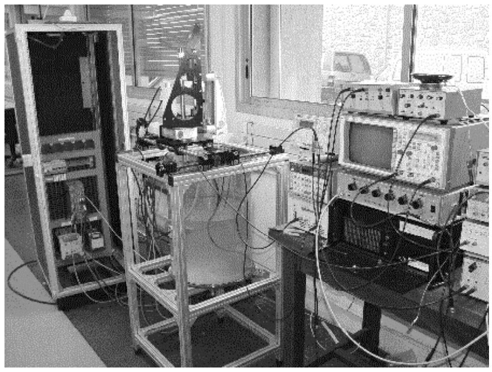

Figure 9: Experimental set-up

The emission signal is Gaussian burst (see Fig.3) of frequency $f_o = 2.25MHz$, emitted with repetition frequency (PRF) of $10MHz$.

3.2 Experimental results

The figure 10 represents details of the time$\times$time images for 3 various flow rates. Two echos can be observed : the first one reflected by moving particules and the second one (fixed) reflected by the wall of the tank. Estimated velocities for both methods are collected on table 1.

Table 1: Estimated velocities for various flows via both methods

	FFT of Doppler signal	Cross-correlation Method
(a) : 3l/h	6.25 cm/s	6 cm/s
(b) : 6 l/h	10.1 cm/s	11 cm/s
(c) : 12l/h	15.45cm/s	15.5 cm/s

4 Conclusion

In this paper we have studied two doppler methods for estimation of fluid flows velocities through a borehole fracture. Results presented in table 1 show a good agreement between frequency and temporal methods. All exprimental results have been obtained for a simple

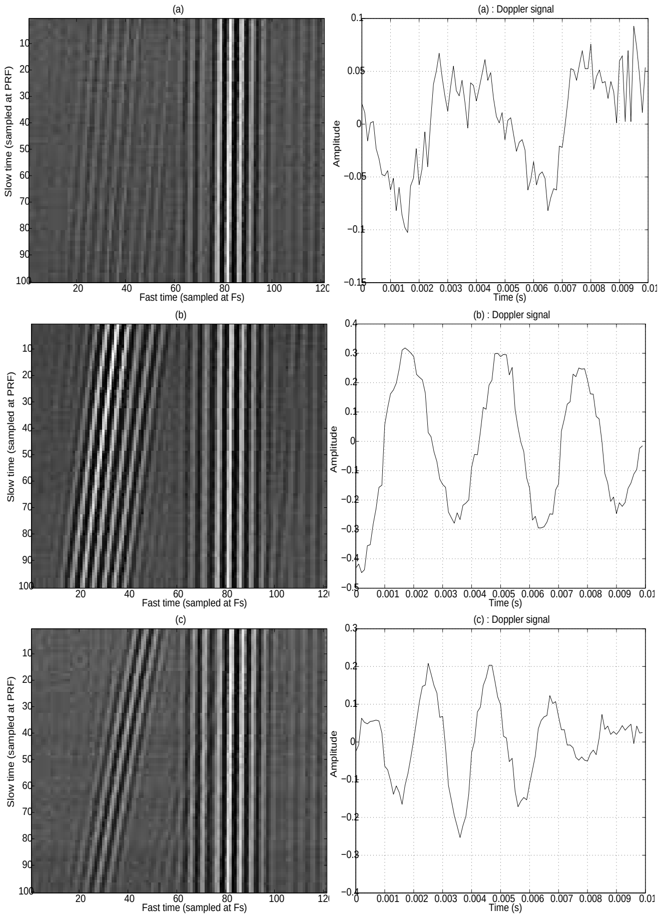

Figure 10: Time×time representations and Doppler signals in the case of 3 l/h (a), 6 l/h (b) and 12 l/h (c) flow rates.

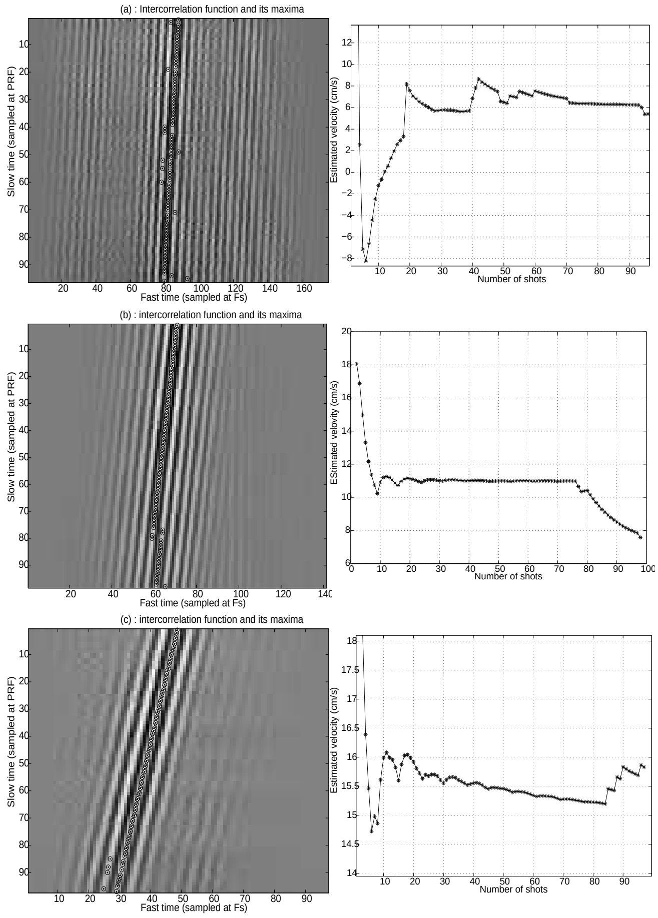

Figure 11: Velocity estimator via interrcorelation method for (a):3 l/h, (b):6 l/h and (c):12 l/h flows rates

fracture (circular hole) that not corresponds to realistic borehole fractures. Future experimental work will focus on estimating fluid flows from a more realistic fracture such as a flat plane intersecting the borehole wall.

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