USV procedure for flowing fluids and suspensions

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To measure fluid velocity in flow and also powders under sedimentation a non-invasive method is developed in this paper: the Ultrasonic Speckle Velocimetry (USV). Sedimentation of polymethyl metacrylate and silica particles in water, with known diameter distribution, is carried out to improve the method where the USV procedure, the signal processing and data analysis is particularly described. The optimization conditions are linked to space resolution, temporal resolution, dynamic and results show that USV is a useful technique to measure velocities between 10^{-5} and 1 m/s, using appropriate ultrasonic transducers. The choice of speckle window allows a 0.1ns temporal resolution obtained after signal processing. In the context of our sedimentation experiments, we showed that velocities measured by USV are in close agreement with those predicted by theory.

Keywords: Ultrasonic Speckle Velocimetry, Sedimentation flow, Signal processing, Data analysis

1 INTRODUCTION

Fluids research need more and more data about velocity fields for many applications. Ultrasonic techniques are well known to characterize opaque fluids compared to optical techniques such as Particle Image Velocimetry (PIV) [1, 2] and make this method a non-invasive quantitative techniques highly suited to study complex fluids. There are two main ultrasonic methods: Doppler echo ultrasound techniques - widely used in hydrodynamics, in particular, in clinical applications [3, 4], but hindered by complex electronic systems - and ultrasonic speckle techniques. The latter method is based on the ultrasonic speckle scattered by ultrasound contrast agents dispersed in flowing fluids. Ultrasonic Speckle Velocimetry (USV) is a recently developed technique [5] and does not require new transducer development. Moreover, USV has been recently successfully applied [6, 7] to measure the complex fluid velocity in all direction and to characterize flowing instabilities such as shear banding of opaque fluids. In spite of its interesting applications, USV is not widely used for flow velocities measurement due difficulties related to the signal processing description needed to improve the poor signal-to-noise ratio of the ultrasonic backscattered response [8]. However, recent recording system with efficient signal processing allows considering USV as a high-performance method compared to Doppler methods. Through the study of particle sedimentation in Newtonian fluid, this paper reports experimental procedures to optimize USV measurements. Signal processing conditions and data analysis are carried out and discussed in terms of accuracy, dynamics and resolution.

2 METHODS

2.1 USV Principles

An ultrasonic pulse backscattered by seeded particles in flowing fluids create a speckle signal [5, 7]. Its intensity results from the coherence of the all acoustic waves backscattered by the seeded particles - with a volume fraction of contrast agents comprised between 10^{-11} and $10^{-12}m^{-3}$ [5] - with a very high frame rate. Hence, the fluid vector velocity v can be determined by the cross-correlation (Eq. 1) of two successive speckles separated by a pulse repetition time t_{PRF} (Fig. 1 a).

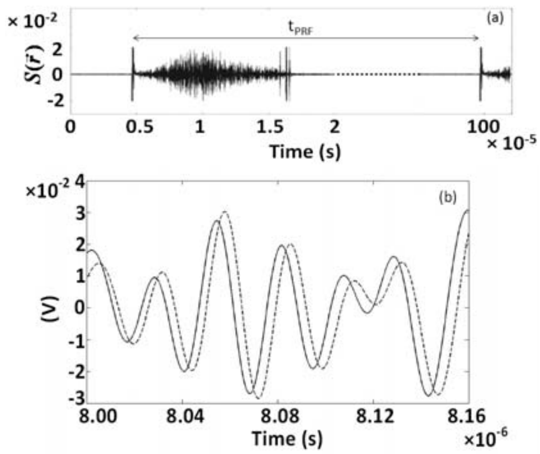

Figure 1: a) Speckle signal recorded between two successive acoustical pulses. t_{PRF} is the time between the two pulses; b) Zoom of two speckle signals at t (solid line) and $t + t_{PRF}$ (dashed line).

$$C(\vec{r}) = \sum_{r-\Delta r}^{r+\Delta r} S(\vec{r},0)S(\vec{r},t_{PRF}) \quad (1)$$

t_{PRF} is a tunable parameter controlled by the pulser-receiver unit. Fig. 1.a presents the backscattered signal S between two successive pulse echoes while Fig. 1.b shows the coherence between two successive speckle signals. C is calculated for a speckle window $\Delta r=n\lambda$, where λ the acoustic wavelength and n is a whole number typically comprised between 2 and 20. The displacement of the scatterers at r is given by the time value δt that maximizes C. Finally, by assuming that the seeded particles behave as Lagrangian tracers, Eq. 2 give the fluid velocity along the ultrasonic beam axis.

$$v(\vec{r}) = \frac{1}{2} c \frac{\delta t}{t_{PRF}} \quad (2)$$

2.2 Particle Velocimetry Sedimentation

A sedimentation of particles in a Newtonian fluid is developed and built in a rectangular Plexiglas cell (2.4×3.6×5cm). The USV is then operated by placed the acoustic transducer in the base and the acoustic axis characteristic of the wave vector direction coincides with the sedimentation axis (Fig. 2).

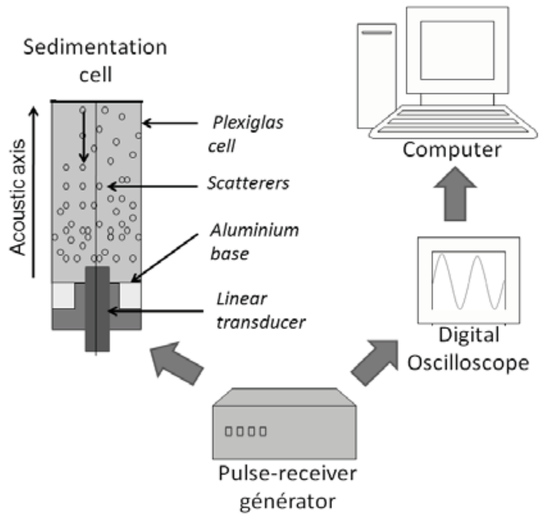

Figure 2: Schema of the sedimentation device.

Two commercial ultrasonic linear transducers (Olympus V312-SM), with 2.25MHz and 25MHz frequencies are controlled by a pulser-receiver generator Olympus Panametrics connecting to a digital oscilloscope Lecroy, Wave Runner MXi6400. Different speckle signals are recorded with the oscilloscope and triggered at a pulse repetition frequency, $PRF = (t_{PRF})^{-1}$, tunable from 0 to 20kHz.

Here, we studied the sedimentation of three different particle populations:

• Polymethyl méthacrylate (PMMA) particles (Dantec Dynamics). These particles contain rhodamine and are used for PIV experiment. Their mean diameter is around 10 µm and the impedance ratio between water and PMMA is about 0.5.

• Polydisperse silica particles (Arena) with a wide diameter distribution centred on 67.5 µm. The impedance ratio is about 0.1.

• Monodisperse silica particles with a narrow diameter distribution centred on 56.5 µm obtained by sifting of the polydisperse silica particles.

3 EXPERIMENTAL PROCEDURE

3.1 The device

The diameter distribution of the ultrasound scatterers allows choosing the ultrasonic transducer frequency [9]. 2.25MHz and 25MHz transducers are thus used to study the sedimentation of the silica and PMMA particles where the wavelengths are 670µm and 60µm, respectively.

The main parameters of the pulse generator are the bandwidth BW with the attenuation A and the gain G which limit the transducer frequency range, the damping current C controlling the shape of the ultrasonic pulse, and finally, the transducer energy E. For the following results, the setting is: A=-1dB, G= 54dB, C=50Ω and E=32µJ for both transducers. The bandwidths were comprised between 1 and 10MHz and comprised between 10 and 50MHz for the 2.25MHz and 25MHz transducers. Previous experiments or theory are necessary to evaluate the velocity particles in order to adjust the PRF. In our case, the particles velocity is estimated considering Stockian flows described by Eq. 3.

$$v(d) = \frac{\rho g d^2}{18\eta}\left(1 - \frac{\rho_w}{\rho}\right) \quad (3)$$

ρ and ρ_w are the volume weight of the particles and water and η is the water viscosity. Consequently, the PRF was fixed at 200Hz for the PMMA particles and 1kHz for the silica particles.

The signal recording is carried out with the oscilloscope using sampling frequencies of 500MHz and 50MHz for the PMMA and silica particles.

3.2 Signal Processing

In order to measure with high accuracy the velocity toward the sedimentation time, 10 successively S are recorded 200 times for each experimental condition. Between two acoustical pulses, the whole S is divided into N windows (Eq. 4) where each one has a 50% of overlapping with the previous windows, which allow measuring the velocity at N positions in the sedimentation cell.

$$N = \sum_i N_i \approx \frac{2L}{n\lambda} - 1 \quad (4)$$

Here L is the cell height. Typically, N=190 for PMMA with n=4. The cross-correlation function is then computed automatically for each speckle window couples $\{N_i(kt_{PRF}), N_i((k+1)t_{PRF})\}$, where k comprised between 1 and 9.

Fig. 3 present two 3D-representations of S in function of t_{PRF} and of the flowing time. Fig. 3.a shows a high level of coherence where C gives a well-defined maximum while Fig. 3b presents a low level of coherence and here the C are characterized by secondary maxima with amplitude close to the main peak.

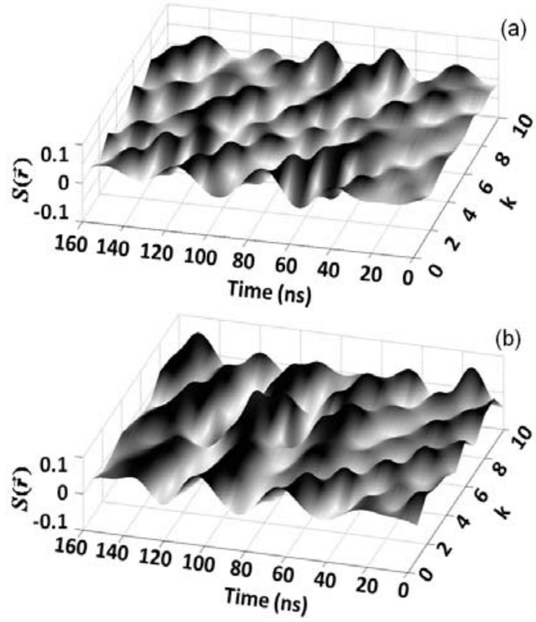

Figure 3: 3D-representations of speckle signal S vs time and the number of acoustic pulses. a) Example of a coherent speckle; b) Example of a noisy speckle.

This latter case is predominant and requires specific procedures to be analyzed: for each i speckle windows, we calculated the averaged cross-correlation functions C_i, determined the maximum C_{imax} and plotted the maxima in according to i.

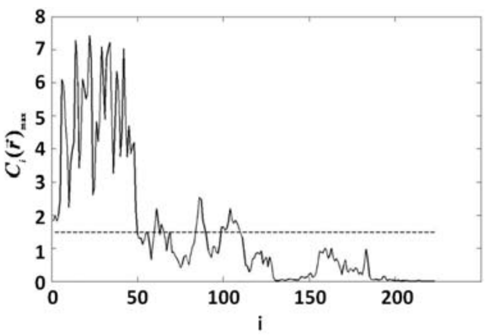

Figure 3: Maximum of the mean cross-correlation C_{imax} function vs the number of speckle windows i. Dashed line represents the criteria of 20 % of the maximum of C_{imax}

A criteria was defined to leave out all the cross-correlations given a C_{imax} value lower than 20% of the curve of the maxima and with all the cross-correlations having a secondary-primary peak amplitude ratio higher than 50%. From all C_i verifying the criteria, the velocities were finally calculated.

Space resolution is governed the speckle windows $\Delta r = n\lambda$. For PMMA, n=[4; 16] yield to [240; 960] µm and for silica particles n=[4; 8] yield to [2.6; 5.2] mm.

The measured minimum velocity is obtained from the minimum of δt while the maximum measured is given by Eq. 5 from the width of the speckle traces.

$$v_{max} = \frac{n\lambda}{2t_{PRF}} \qquad (5)$$

Then, USV technique presents a very important dynamics, authorizing velocity measurements along the acoustic axis between [1.5 10^{-5}; 4.8] m/s for PMMA and [1.5 10^{-5}; 5.3] m/s for silica particles.

Three steps of procedure for signal processing are established. Firstly, the offset signal has to be removed. Secondly, numerical filter is applied between 10 and 50 MHz with -60 dB of attenuation to suppress the non-speckle signal. Subsequently, to obtain a temporal resolution of 0.1 ns with the 50 and 500 MHz sampling frequencies, the speckle data is re-sampled with a zero filling signal processing [10].

4 RESULT AND DISCUSS

Experimental velocities distributions of the three particle families are compared with those calculated from theory in Fig. 4, where mean velocities and standard deviations are assembled in Tab. 1.

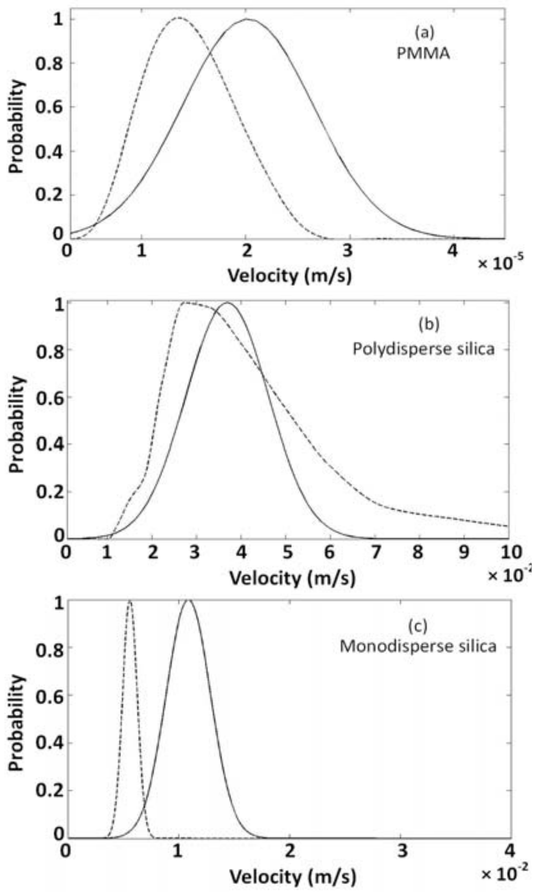

Figure 4: Velocities distribution of PMMA , polydisperse silica and monodisperse silica particles for a length of speckle window corresponding to n=4. Dashed lines represent the theoretical Stockian velocities and the solid lines represent the experimental values.

Table 1: Values of mean velocities and of standard deviations for PMMA, polydisperse silica and monodisperse silica particles for different length of speckle windows.

Particles	Mean velocity (m/s)		Standard deviation (m/s)	
n	4	8	4	8
Polydisperse silica ($x10^{-2}$)	3.69	3.50	0.92	1.08
Monodisperse silica ($x10^{-2}$)	1.12	1.21	0.29	0.40
PMMA ($x10^{-5}$)	2.0	1.8	0.6	0.9

These results allow checking that USV has a significant dynamics and is able to measure the velocity over 6 decades. From the size distributions, it is possible to plot the theoretical velocity distribution in the Stockian regime (Fig. 4). Comparing both theoretical and experimental distributions, USV experiments clearly give mean velocities shifted towards the higher values. This shift is emphasized for the polydisperse silica particles and can be explained by considering that the multiple ultrasound scattering efficiency is obtained for the larger diameter particles when the theoretical velocity calculus gives the same weight for all the particles. The USV results in Fig. 4 also show the effect of the size distribution of silica particles. The mean velocity (1.12 and 3.69cm/s for monodisperse and polydisperse silica particles) depends on the mean particle diameter (56.5 and 67.5µm, respectively) while the velocity standard deviation increases with the particle size distribution.

The USV space resolution is studied by changing the speckle window length Δr (for n= 4, 8 and 16) for the three particle families and authors have show that the mean velocity is less affected by a change of Δr. On the other hand, the velocity distribution width changes with the speckle window length and the standard deviation seems to increase with *n*. This effect is due to a widening of the characterized area in the sedimentation cell.

Finally, Fig. 5 shows the variation of the velocity along the sedimentation axis for the polydisperse silica particles.

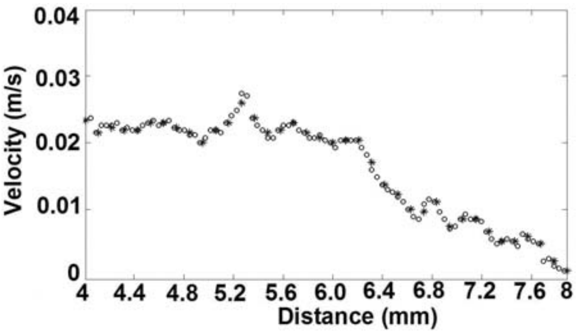

Figure 5: Velocity profile along the acoustical axis for polydisperse silica particles.

One can observe that the velocity decreases with the distance, which can be explained by the particle diameter effects on the sedimentation velocity.

5 CONCLUSION

USV is shown as a useful method to study the velocity profile in full flow on the basis of particle sedimentation experiments. Here three numerical stages have been developed before data processing. Moreover, a cross correlation criteria was defined to optimize data processing. We studied the effects of speckle window length on the measured velocities and found that the results are more accurate with the smallest window length.

The sedimentation velocities are measured for three different particle families - PMMA, monodisperse and polydisperse silicate particles, which are characterized by different density, acoustical impedance and size distribution - using 2.25 and 25MHz transducers were used. In our signal processing conditions, the temporal resolution could reach 0.1 ns for both the transducers. We measured velocities comprised between 20µm/s and 3cm/s, showing the wide dynamic potentiality of USV and the coherence with theoretical velocities.

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