

Development of a LDV system for measuring acoustic particle velocities in enclosed or free fields

by

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ABSTRACT

Although Laser Doppler Velocimetry (LDV) has been used for acoustic particle velocity measurements for many years, its performance in acoustics have not been thoroughly assessed. And yet, this verification appears necessary as the characteristics of acoustic velocities differ significantly from those of fluid flows for which LDV is commonly used. A first step toward a LDV set-up dedicated to airborne acoustics without flow was presented in previous work (Herzog *et al* 1996 ; Valière *et al* 2000). The present study deals first with the validation of LDV measurements in enclosed field using both a commercial equipment (BSA 57N20 by DANTEC), originally built for applications in fluid mechanics, and a system for acquisition and signal processing more specifically dedicated to acoustics. The investigated acoustic frequencies lie between 200 Hz and 4000 Hz while the rms velocities range from 0.1 mm/s to 10 mm/s, which means rapid variations and low amplitudes compared with those usually met in fluid mechanics. Then the present paper focuses on the validation of LDV-measured acoustic velocities in free field : this research is of prime interest as there are many potential applications in acoustics. First results are encouraging but these first experiments need to be followed up by a more complete study and improved experimental conditions are under development for this purpose.

1. INTRODUCTION

Although Laser Doppler Velocimetry (LDV) has been used for acoustic particle velocity measurements since many years (Taylor 1976), its performance in acoustics have not been thoroughly assessed. And yet, this verification appears necessary as the characteristics of acoustic velocities differ significantly from those of fluid flows for which LDV is commonly used.

This paper first briefly reviews the basic theoretical framework of LDV in acoustics. Then it deals with the validation of LDV measurements in an enclosed field using both a commercial equipment (BSA 57N20 from DANTEC), originally built for applications to fluid mechanics (Tropea *et al* 1988 ; Lading 1987), and a system for acquisition and signal processing more specifically dedicated to acoustics. The investigated acoustic frequencies lie between 200 Hz and 4000 Hz while the rms velocities range from 0.1 mm/s to 10 mm/s, which means rapid variations and low amplitudes compared to those usually met in fluid mechanics. Finally the present paper focuses on the validation of the use of LDV for measuring acoustic particle velocities in the free field : this research is of prime interest as there are many potential applications in acoustics.

2. FUNDAMENTALS OF LDV IN ACOUSTICS

2.1. Optical set-up

The optical set-up used is shown in figure 1. The principle of such an LDV system is based on the determining the Doppler shift of light scattered from seeding particles (tracers) suspended in the fluid (air). In the differential Doppler mode (Lading 1971 ; Drain 1980), two laser beams of equal intensity are focused and crossed at the point under investigation, forming an ellipsoidal probe volume consisting of equidistant dark and bright fringes. Any particle moving through this volume backscatters light which is collected at a photomultiplier (PM) ; because of a double Doppler effect, this light is frequency shifted. The particle velocity is derived from an estimate of this frequency shift. The sign of the velocity is determined by means of a Bragg cell, driven at a frequency f_b , introduced into the path of one of the incident beams.



Fig.1. Optical set-up of the LDV system

2.2. Doppler signal model

The PM output electric signal, so-called Doppler signal, can be modelled as a sine-wave modulation weighted by a Gaussian shape depending on the tracer location $x_p(t)$ in the probe volume (Sharpe 1987) :

$$s_D(t) = K e^{-1/b_p(t)^2} \left\{ M + \cos \left[2\mathbf{p} \left(f_b + \frac{x_p(t)}{i} \right) \right] \right\} \quad (1)$$

with

$$\mathbf{b} = \frac{\cos(\mathbf{q}/2)}{r_L}, \quad (2)$$

r_L being the radius of the focused laser beams and \mathbf{q} the angle between them. The factor K is related to the laser beam power, the PM sensitivity, the electronic amplification, the observation direction and the scattering efficiency of the tracer. The exponential term represents the envelope of the fringes due to the Gaussian cross section of the laser beams. M is an offset introduced if the beams are not of equal strength, f_b the Bragg frequency and i the fringe separation.

In the field of airborne acoustics without flow (and negligible convection), the particle velocity inside the probe volume can be written

$$v(t) = V_{ac} \cos(2\mathbf{p}f_{ac}t + \mathbf{j}_{ac}), \quad (3)$$

where V_{ac} and φ_{ac} are the amplitude and phase, respectively, to be determined, and f_{ac} is the frequency of the excitation signal. Then the tracer location becomes :

$$x_p(t) = \frac{V_{ac}}{2\mathbf{p}f_{ac}} \sin(2\mathbf{p}f_{ac}t + \mathbf{j}_{ac}). \quad (4)$$

If we include the frequency shift of the Doppler signal (the purpose of the frequency shift being to move it into a range more easily handled by the processing unit), the frequency-shifted Doppler signal can be expressed as follows :

$$s_D(t) = A(t) \{ M + \cos[2\mathbf{p}f_c t + \mathbf{a} \sin(2\mathbf{p}f_{ac}t + \mathbf{j}_{ac})] \}. \quad (5)$$

The amplitude $A(t)$ cannot be easily modelled unless the tracer location in the probe volume is exactly known. However, preliminary tests (Valeau 1999) have shown that this amplitude remains almost constant over some periods of the acoustic signal. The sinusoidal frequency modulation is centred on the carrier frequency f_c . The modulation index \mathbf{a} , defined by

$$\mathbf{a} = \frac{V_{ac}}{if_{ac}} \quad (6)$$

is proportional to the amplitude \mathbf{x}_{ac} of the particle displacement ($\mathbf{x}_{ac} = \frac{\mathbf{a}i}{2\mathbf{p}}$).

2.3. Signal analysis

The first step of the signal analysis consists of demodulating the frequency-shifted Doppler signal in order to extract the velocity information. Applying synchronous detection to this extracted velocity signal allows an estimation of its amplitude and phase. Figure 2 illustrates the processing principle.

A complete description of the two acquisition and signal processing systems used for the present study can be found in previous work (Poggi *et al* 2000). The Burst Spectrum Analyser (BSA) is a commercial system originally dedicated to flow velocity estimations using real time signal processing techniques. The other system, currently developed in our laboratory, is more specifically dedicated to acoustics. Both involve a short term Fourier analysis. Preliminary experiments were conducted to establish the appropriate sets of signal processing parameters used in the present study (Poggi *et al* 2000).



Fig.2. General signal processing used for the estimation of the acoustic particle velocity by LDV

3. EXPERIMENTAL VALIDATION IN AN ENCLOSED FIELD

3.1. Validation principle

The performance and limitations of the two acquisition and signal processing systems are assessed from comparisons between LDV-measured velocities and acoustical estimations of the velocity based on pressure measurements combined with a sound propagation model (which provided the *reference velocities*). Velocities are measured inside a plane waveguide excited at one end ($x=0$) by a loudspeaker and closed at the other ($x=L$) by a rigid termination. The acoustic field inside the tube is assumed to be described by plane waves up to 3-4 kHz (the theoretical eigenfrequency associated to the first transverse mode is 4914 Hz). Thus, according to a simple one-dimensional propagation model (see for instance Kinsler *et al* 1982), the acoustic particle velocity $v(x)$ estimated at the position x along the guide axis can be expressed as follows :

$$v(x) = \frac{jp(L) \sin(k(L-x))}{rc} \quad (7)$$

where rc is the characteristic impedance of the propagation medium, k the wave number and $p(L)$ the acoustic pressure measured at the end of the tube.

3.2. Experimental set-up

The acoustical set-up dedicated to the validation consists of a cross-sectional square duct made of aluminium except for the measuring section which is made of Plexiglas (figure 3). In order to obtain a large dynamic range for the acoustic quantities, the tube is closed by a rigid termination.

Furthermore, selecting suitable seeding is of major importance. The requirements for seeding are the following : seeding should not soil the windows, seeding particles (tracers) should follow the acoustic movement and should perturb the acoustic field and the properties of the fluid under investigation as little as possible. The seeding SAFEX Fog Fluid Super, injected inside the guide by means of electromechanical valves, provides 1 μm mean diameter tracers and satisfies the two first requirements over the frequency and sound level ranges studied. Errors on temperature and fluid density are estimated in order to take into account the influence of the seeding on the fluid properties ; minimisation of these errors is achieved by controlling the experimental conditions (Poggi 2000).



Fig. 3. Photograph of the enclosed field experiment

3.3. Results

The amplitude and phase differences between the LDV-measured velocities and the reference velocities are shown in figure 4 and figure 5. The results indicate that the two systems give satisfactory results for rms velocities higher than 1 mm/s and acoustic frequencies lower than about 2 kHz. Actually, in both cases, the short term Fourier analysis (involved in both signal processing techniques) leads to a limitation which corresponds approximately to when the modulation index of the Doppler signal equals unity. For smaller indices, more sophisticated Doppler signal analysis tools, for example as developed in our laboratory (Valeau *et al* 1999), should be used.

Finally, the acquisition and signal processing system under development in our laboratory is to be preferred to the BSA for acoustical applications since it requires a very slight seeding : a single Doppler burst may be sufficient to extract the velocity information when its duration is much greater than the acoustic period. The analysis of a single burst is particularly relevant to acoustics since a high seeding concentration (such as required by the BSA) may significantly affect the acoustic field under investigation (Poggi 2000).

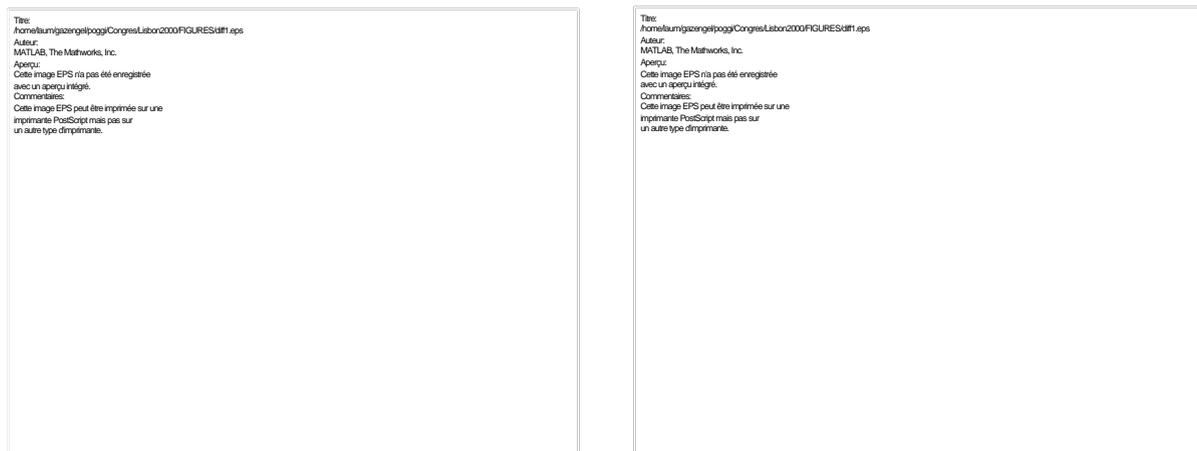


Fig. 4. Amplitude (left) and phase (right) differences between acoustic velocities measured by the BSA and reference velocities.

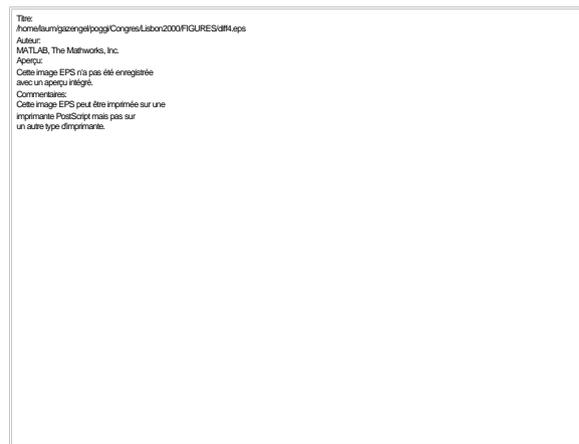
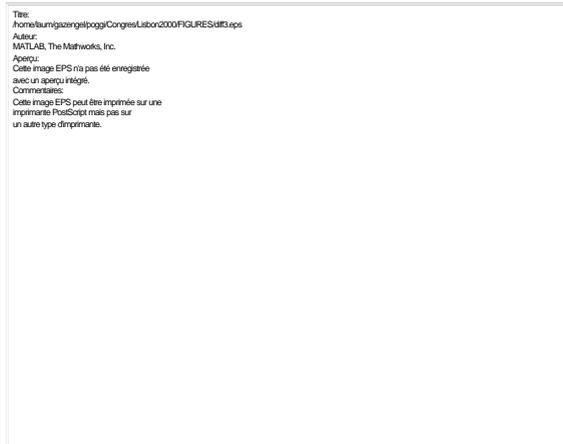


Fig. 5. Amplitude (left) and phase (right) differences between acoustic velocities measured by the acquisition and signal processing developed at LAUM and reference velocities.

4. EXPERIMENTAL VALIDATION IN FREE FIELD

Although acoustic velocity measurements in free field could lead to many new developments in acoustics, this research topic has been seldom studied. To our knowledge, only one preliminary work was performed on this subject (Greated 1986). The following subsections deal with experiments conducted in free field in order to assess the feasibility of such measurements.

4.1. Validation principle

The measured velocities are those radiated on-axis by an electrodynamic loudspeaker mounted in a closed box (see figure 6). LDV measurements are realised using the custom system ; they are compared with velocities (used as *reference velocities*) estimated by means of pressure measurements combined with finite difference estimators (Rouquier *et al* 2000).

4.2. Experimental apparatus and procedure

The experimental apparatus is shown in figure 6. The loudspeaker is driven by a sinusoidal signal whose phase is used as a phase reference. Pressure measurements are made using a single microphone (KE4 Sennheiser) which is mounted at the end of a tube fixed onto the system (Schneeberger) for positioning the optics, and hence the acoustic pressure is measured very close to the probe volume. Acoustic velocities are then derived from successive pressure measurements.

A major concern for free field measurements is the seeding process : the method used consists of introducing a large quantity of tracer and then waiting until this spreads into the whole experimental room and conditions stabilise (i.e. having only small convection movements). Experimental results indicate that it is possible to make the acquisition of a single burst after about half an hour (figure 7).

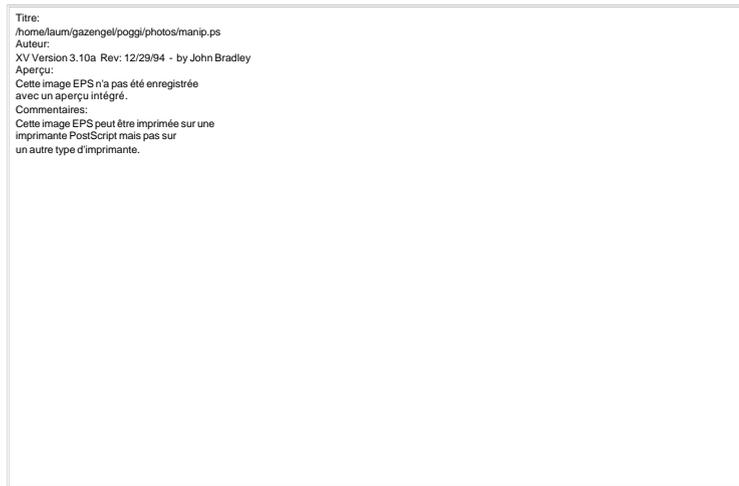


Fig. 6. Photograph of the free field experiment



Fig.7. Experimental Doppler burst. Acoustic frequency : 1000 Hz. Velocity amplitude : 20 mm/s. Acquisition duration : 0.512 s.

4.3. Results

First results are shown in figure 8. On each graph, distances are referenced to the first measurement position (35 mm in front of the loudspeaker dome) taken arbitrarily as the origin. Results show a quite good agreement at 1kHz between the LDV-measured velocities and the estimated velocities used as a reference since differences are less than 15% for the third order finite difference estimator. Actually the main source of error is in the estimation of the reference velocities : using a single microphone makes the velocity estimation very sensitive to the experimental conditions. Using a microphone array would eliminate this problem. Thus, our results are encouraging but development is required to validate the use of LDV for free field measurements over a wide frequency range and a wide dynamic range.

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Fig. 8. Left : profiles of velocities measured by LDV and estimated by the finite difference method for different orders. Right : Amplitude differences between the measured and estimated velocities. Acoustic frequency : 1000 Hz.

5. CONCLUSION

Validation experiments performed in an enclosed field have established the level and frequency ranges for which LDV is suited, using two different acquisition and signal processing systems (both involving Fourier analysis) : the Burst Spectrum Analyser from DANTEC and the system developed in our laboratory. Furthermore, preliminary experiments performed in the free field lead to encouraging results ; these experiments should be followed up by a more complete study and improved experimental conditions are under development for this purpose.

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