Characterization of a loudspeaker free field radiation by Laser Doppler Velocimetry

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Abstract

The performances of a Laser Doppler Velocimetry (LDV) system adapted for measuring the acoustic particle velocities is assessed for measuring acoustic velocities in free field. In this condition, the flow velocity due to natural convection is taken into account. The assessment is performed by comparing the acoustic velocities measured by means of LDV to reference acoustic velocities estimated by means of a sound intensity probe. The LDV systems delivers a signal made of many bursts which are modulated in amplitude and frequency. The signal processing used for estimating the acoustic velocity is divided in three steps (detection of burst, frequency demodulation and acoustic velocity amplitude and phase estimation). The minimum measurable acoustic displacement depends on the frequency demodulation technique (Short Time Fourier Transform in this work) and the minimum measurable acoustic frequency depends on the convection velocity. Taking into account these constraints, the assessment is performed for 500, 1000 and 2000 Hz and for acoustic velocities greater than $2\,mm/s$. Results show that this system can measure acoustic velocities at 500, 1000 Hz and 2000 Hz in free field. For 2000 Hz, the velocity amplitude estimated by LDV differs slightly from this measured by the sound intensity probe. The acoustic radiation of a loudspeaker is characterised for 500 Hz using the LDV and the sound intensity probe. Results obtained in the near field of the loudspeaker show that the velocity amplitude calculated by means of a radiation model and the measured velocity amplitudes differ with a bias of 10%. In the far field, the experimental conditions do not respect the hypothesis used in the radiation model. For this reason, the measured and calculated velocity amplitude differ with a systematic bias.

Keywords : Acoustic velocity measurement, Laser Doppler Velocimetry, loudspeaker radiation.

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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 velocity sensors are not commonly used.

Velocity measurement techniques can be divided into two families. On the one hand, indirect methods give an estimation of the particle velocity using at least two pressure measurements and a model of sound propagation. On the other hand, direct methods give an estimation of the acoustic velocity using three major approaches, the hot wire anemometer, the Particle Image Velocimetry (PIV) and the Laser Doppler Velocimetry (LDV).

The hot wire anemometer working principle has been described in [1, 2] and its application to acoustic velocity measurement is given in [3]. Works using this probe for measuring impedance or intensity measurements have been presented in [4, 5]. The Particle Image Velocimetry (PIV) technique has been used for measuring high acoustic velocity amplitude (typically more than 2 m/s)[6]. This technique has been applied for measuring acoustic velocity profiles in tube [7] and acoustic velocity profiles in boundary layers [8, 9].

LDV is an optical technique developed by Yeh and Cummings [10] based on interferometry. This technique has been applied since 1976 for measuring acoustic impedance [11], for calibrating microphones [12] or hot wire anemometer [13], for measuring the acoustic streaming [14] or for characterizing self-excited combustion excitation [15]. For acoustic excitation, the signal delivered by a LDV system is frequency modulated and specific signal processing techniques are needed in order to estimate the acoustic velocity. Detailed principles of the signal processing techniques are given in [6, 16, 17, 18, 19].

The performances of the LDV sensor (accuracy, resolution, range of operation) have been assessed experimentally in enclosed field for different signal processing techniques such as the Short Time Fourier Transform (STFT) [20] or the Wigner-Ville transform [16]. These studies show that the LDV system can be used for measuring acoustic velocity in enclosed field, in the frequency range [100-4000Hz] and for velocity amplitude greater than 0.1 mm/s.

Free field measurements have been performed by different authors [21, 22, 23] using LDV. Mazumder [21] uses LDV for localising a loudspeaker in a anechoïc chamber using the cross-correlation of two LDV signals, Greated [22] compares the acoustic level measured by a microphone and by LDV and the study of a dipole acoustic radiation has been reported by Souchon *et* *al.* [23]. However, the performances of LDV have not been assessed for measuring the acoustic velocity in free field conditions. In these conditions, the convection flow due to the experimental room must be taken into account.

The aim of this work is to assess the performances of LDV in free field using the STFT as the signal processing method. The method used in this work consists in comparing the velocities measured on the axis of a loudspeaker by means of LDV and obtained by a reference method. The reference methods estimates the acoustic velocity by a two microphone technique. The LDV is then applied for characterizing the acoustic radiation of a loudspeaker and to evaluate the validity of a radiating model. Section 2 presents the basics of LDV for acoustics and section 3 develops a simple loudspeaker radiation model. In the fourth section, the experimental setup is exposed and the validity of LDV for measuring acoustic velocities in free field is discussed in section 5. Finally the validity of the physical model is evaluated by comparing measured and calculated acoustic velocities.

2 Laser Doppler Velocimetry (LDV) for acoustics

2.1 General principle

The Laser Doppler Velocimetry (LDV) is an optical technique using a coherent laser light (as a light source). In the differential Doppler mode [24], two coherent beams cross and form the probe volume in which a fringe pattern is created. The velocity information for a moving scattering particle (used as tracer, see figure 1) is contained in the scattered field due to the Doppler effect.When a tracer q moves through the volume, the scattered light intensity, called a burst, is modulated in amplitude and frequency. The frequency of modulation f_q is called Doppler frequency and is related to the velocity v_q of a tracer q along the $x-$axis (see figure 1) and to the fringe-spacing i (expressed as a function of the angle θ between the incoming laser beams and their optical wavelength λ_L) by

$$f_q = \frac{v_q}{i} = \frac{2v_q}{\lambda_L}\sin(\frac{\theta}{2}). \tag{1}$$

The scattered light is collected by means of a collecting lens. The optical signal is converted into an electrical signal, called Doppler signal, with a photomultiplier (PM).

[Figure 1 about here.]

In the case of acoustic harmonic excitation at frequency f_{ac}, the particle velocity for a single particle q can be written

$$v_q(t) = V_{f,q} + V_{ac}\cos\left(2\pi f_{ac} t + \varphi_{ac}\right), \tag{2}$$

where $V_{f,q}$ is the flow velocity of the particle q due to natural convection in the fluid, V_{ac} and φ_{ac} are the respectively amplitude and phase of the acoustic particle velocity to be measured. $V_{f,q}$ is considered to be constant during the transit time of a single particle q in the probe volume but can be different from a particle to another. For common acoustic measurement in free field, the velocity amplitudes. V_{ac} and $V_{f,q}$ are low compared with flow velocities encountered in fluid mechanics problems. Typically for 94 dB in free field, $V_{ac} = 2.5$ mm/s and $V_{f,q} \simeq 10-30$ mm/s. For this reason it is necessary to increase the probe sentivity by choosing a low interfringe value, which leads to choose high values of angle θ (typically 28^o for this application).

2.2 Doppler signal processing for free field conditions

In free field conditions, the acoustic velocity parameters (V_{ac} and φ_{ac}) remain constant during the measurement duration. However the flow velocity $V_{f,q}$ can change from a particle to another (turbulent flow at low velocity).

For a single particle q, the expression of the Doppler signal is

$$s_q(t) = A_q(t)\cos\Phi_q(t), \tag{3}$$

where $A_q(t)$ is the Gaussian envelope of Doppler signal due to the Gaussian cross section of the laser beams and depending on the position (x,y,z) of the particle in probe volume frame [24]. The phase of the Doppler signal is

$$\Phi_q(t) = 2\pi f_c t + \frac{2\pi}{i}V_{f,q}(t-t_q) + \frac{V_{ac}}{if_{ac}}\sin\left(2\pi f_{ac}(t-t_q)+\varphi_{ac}\right) \tag{4}$$

where t_q is the time at which the particle crosses the center of the probe volume assuming there is no acoustic excitation. f_c is a carrier frequency which enables to discriminate the particle propagation direction [20]. The term $\frac{V_{ac}}{if_{ac}}$ is the modulation index.

Knowing that the acoustic displacement is sinusoïdal, equation 4 shows that the Doppler signal is frequency modulated at frequency f_{ac} with a varying amplitude $A_q(t)$.

The aim of the signal processing is to estimate the flow velocity $V_{f,q}$ of each particle q, the amplitude V_{ac} and the phase φ_{ac} of the acoustic particle velocity.

Assuming that N particles cross the probe volume at different random time t_q and without temporal overlapping of bursts q and $q+1$, the complete Doppler signal can be written

$$s_D(t) = \sum_{q=1}^{N}\{s_q(t)\} + n_D(t) = A_D(t)cos[\Phi_D(t)] + n_D(t). \tag{5}$$

where

$$\begin{cases} A_D(t) = A_q(t), & t \in [t_{bq}, t_{eq}], \\ \Phi_D(t) = \Phi_q(t), & t \in [t_{bq}, t_{eq}]. \end{cases} \quad (6)$$

t_{bq} and t_{eq} are respectiveley the beginning and ending time of the burst q which has been detected [25] for being analyzed. $n_D(t)$ is zero mean white Gaussian additive noise due to the PM.

[Figure 2 about here.]

Signal processing principle is presented in figure 2. First part consists in the detection of each burst. This detection is realized by comparing the envelope amplitude $A_q(t)$ with a threshold determined by the user. The beginning and ending time t_{bq} and t_{eq} are calculated such that the transit time $T_q = t_{eq} - t_{bq}$ equals a whole number of acoustic periods. Second part is a frequency demodulation. It is performed by using a Short Time Frequency Transform (STFT) of the Doppler signal $s_D(t)$ and enables to give an estimation of the instantaneous frequency of the Doppler signal [16, 26, 17, 18]. The last operation is a Fourier series [26] analysis applied to the estimated instantaneous frequency for each detected burst. The acoustic frequency f_{ac} being known, this technique allows to estimate N values of the flow velocities $V_{f,q}$ and a average value of the amplitude V_{ac} and phase φ_{ac}.

The performances of these signal processing techniques are described by Gazengel *et al.* [26] for measurement performed without flow. Main results show that the STFT can be used for modulation index (see eq. 4) greater than 1 corresponding to $V_{ac} \simeq 1 = mm/s$ (86 dB in free field) at 1000 Hz for our experimental system. In this case, the STFT and the Fourier Series analysis overestimate the acoustic velocity amplitude compared with a reference. For $V_{ac} = 5$ mm/s, the bias is estimated to be 1% at 500 Hz, 3% at 1000 Hz and 10% at 2000 Hz. Rouquier et al [27, 28] show that the STFT and the Fourier Series enable to estimate the acoustic velocity if the transit time $T_{f,q}$ equals at least a single acoustic period T_{ac}. Knowing that

$$T_{f,q} \simeq \frac{d_x}{V_{f,q}}, \tag{7}$$

where d_x is the lenght of the probe volume along the x axis (see figure 1), this condition can be written

$$f_{ac} > \frac{V_{f,q}}{d_x}. \tag{8}$$

In our configuration ($d_x \simeq 0.1$ mm and the mean flow velocity $\bar{V}_{f,q} \simeq 15$ mm/s), the lowest measurable acoustic frequency is estimated to be 150 Hz. This minimum frequency can lowered by using a greater probe volume or by increasing the apparent transit time $T_{f,q}$ using other signal processing techniques [29].

3 Loudspeaker radiation model

In this section, the radiation of a loudspeaker is studied by means of an analytical model assuming that the loudspeaker vibrates as a equivalent piston placed at a abscissa x_p in the reference frame (x_0, y_0) of the loudspeaker as defined in figure 3. In this way, x_p is the reference point of the loudspeaker.

[Figure 3 about here.]

Considering that the loudspeaker is mounted in an infinite baffle and that it radiates in a half space, the velocity along the piston axis is [30, 31]

$$v(x) = V_p e^{-jkx}(1 - \frac{x}{\sqrt{x^2 + R_p^2}} e^{-jk\sqrt{x^2+R_p^2}-x}), \tag{9}$$

where V_p is the piston velocity, x is the abscissa of the observation point in the (x,y) frame, R_p is the radius of the piston, $k = \frac{2\pi f_{ac}}{c}$ is the wave number and c is the sound speed.

The experimental determination of the velocity V_p, of the piston radius R_p and of the acoustic center abscissa x_p enables to predict the acoustic velocity amplitude and phase profiles along the loudspeaker axis using equation 9. These three parameters (R_p, V_p, x_p) values are estimated as described in appendix A by comparing the measured and calculated pressure field along the loudspeaker axis. This comparison shows that the physical model is not valid for $x > 20\,cm$ because of the experimental conditions (see appendix A).

4 Experimental set-up

4.1 Acoustical set-up

The acoustical set-up consists of a loudspeaker (model Audax HP130M0) mounted in a baffle (dimensions 2 m x 1.5 m). The back load of the loudspeaker is a closed cavity (volume $\simeq 1.5\,10^{-3}\,m^3$). The acoustic pressure inside this cavity is measured by means of a $1/4$ inch microphone (ref $BK4136$). This back cavity is built such that there is as few leakage as possible. At the front, the loudspeaker radiates in free field. The whole system (loudspeaker and baffle) is put on a table. In order to avoid reflection on the table, absorbing materials are put on the table surface. The intensity probe is made of two $1/4$ inch microphones spaced by $1\,cm$ and calibrated using the GRAS 51AB calibrator. The probe is mounted on a traverse system (three axis Schneeberger system) used for scanning with a resolution of $2.5\mu m$. The intensity probe axis is placed on the loudspeaker axis (see figure 4).

4.2 Estimation of the reference velocity

This section presents the technique used for estimating the reference velocity. An intensity probe enables to estimate the reference velocity by measuring the acoustic pressure at two points located at the front of the loudspeaker. The intensity probe is made of two microphones mounted face to face separated by a distance Δx (see reference [32] for more details about this technique). Using the Euler equation and assuming that the acoustic wavelength is great compared with the probe spacing Δx, the acoustic velocity component v_x along the probe axis (x axis) is estimated at the middle of the probe by [33]

$$\rho \frac{\partial v_x}{\partial t} \simeq -\frac{p(x_2) - p(x_1)}{\Delta x}, \tag{10}$$

where ρ is the air density, p is the acoustic pressure and $\Delta x = x_2 - x_1$. Equation 10 can be written for harmonic excitation at angular frequency ω_{ac} as

$$j\omega_{ac}\rho v_x \simeq -\frac{p(x_2) - p(x_1)}{\Delta x}. \tag{11}$$

Taking into account the microphone response, equation 11 leads to the estimation of the acoustic velocity (along the x axis) amplitude

$$V_{ac} \simeq \left|\frac{U_1}{M_1}\right| \frac{1 - \frac{H_{12}}{M_{12}}}{\omega_{ac}\rho\Delta x}. \tag{12}$$

where U_1 is the voltage delivered by microphone 1, $H_{12} = \frac{U_2}{U_1}$, M_1 is the sensitivity of microphone 1 and $M_{12} = \frac{M_2}{M_1}$. In the same way, the phase of the acoustic velocity along the x axis is estimated by

$$\varphi_{ac} \simeq \varphi_{U_1} - \varphi_{M_1} + arg(1 - \frac{H_{12}}{M_{12}}) - \frac{\pi}{2}. \tag{13}$$

4.3 LDV system

The LDV apparatus used in this study is a dual beam system operating in the differential Doppler mode. In order to avoid as many external perturbations as possible, all noisy equipments and heat sources are placed outside of the experimental room. The laser source is installed in another room and laser beams are brought with the help of fiber optics. In order to get enough light intensity despite the back scattering configuration, a $1\,W$ argon laser is chosen. Yet only a small part of this power is used for the measurements since the laser output is set to $100\,mW$, leading to a $20\,mW$ power at the location of the probe volume (i.e. at the focal distance of the emitting optics which is equal to $1000\,mm$). The laser source is set to operate in a single mode, producing a $514.5\,nm$ wavelength in air.

The velocity sign is discriminated using of a Bragg cell, introduced on the path of one of the incident beams, operating here in the -1 mode and drived at $f_B = 40\,MHz$. The probe volume lenght along the x axis is $d_x \simeq 0.1$ mm. It is located just above the intensity probe center (see figure 4).

The seeding (mean diameter of particles of $1.04\mu m$) is created by means of the Safex fog generator (Dantec). The particles are composed of water and alcohol and are assumed to be spherical. Using this assumption, the Mie scattering theory [34] enables to estimate the angle $\theta/2$ between the incident beam and the receiving optics such that the received optical intensity is maximum in the back scattering configuration. The angle θ is set to 28^o , which leads to an interfringe $i = 1.063\,\mu m$ corresponding to almost 100 fringes. The seeding is introduced into the experimental room about 20 minutes before beginning the experiment. This waiting time depends on the temperature gradient in the room. In the case of high temperature gradient, sheets of fog may remain above the measuring region and many seeding operations are necessary to lead to an homogeneous fog distributed over the whole room. This procedure must be respected in order to get a low seeding density for minimizing the fluid density estimation errors.

The receiving optics is a 100 mm diameter with a 1 m focal length in order to avoid acoustic diffraction on the optical system. The optical signal is converted into electrical signal by means of a photomultiplier using a 1200 V high voltage due to the back scattering optical configuration.

[Figure 4 about here.]

The Burst Spectrum Analyser (BSA 57N20 of DANTEC) enables to high pass filter the electrical signal and to amplify the signal (gain of 30 dB). The BSA delivers the frequency shifted Doppler signal (see equation 4) and the Doppler signal envelope. The envelope is converted into a trigger by means of a analog comparator which enables to detect the bursts. The acquisition system is a Concurrent Computer system using two synchronized acquisition boards which sampling frequencies are respectively $100\,kHz$ and $1.5\,MHz$. The acoustic pressure signals and the doppler envelope feed the first board (sampling frequency of $100kHz$) and the Doppler signal feeds the second board. The signal processing principles are presented in section 2.2. The obtained data rate is very low (1 to 2 Hz) with a mean Signal to Noise Ratio (SNR) of 12 dB, each detected burst being processed for estimating the velocity parameters $V_{f,q}$, V_{ac} and φ_{ac}.

4.4 Phase reference

The excitation signal of the loudspeaker is used as a phase reference for the two microphone signals (intensity probe) and for the Doppler signal. The reference phase value is estimated using a Fourier Series applied to the excitation signal.

5 Results

This section presents the perfomances of the LDV system for measuring acoustic velocities in free field. Using this experimental technique, the validity of the radiation model presented in section 3 is discussed.

5.1 LDV assessment for acoustic velocity measurement

The performances of the LDV sensor are assessed by comparing the LDV measured velocities with the reference velocities estimated by means of the two microphones method (see section 4.2).

In a first step, the convection velocity was measured at 2 days (6 measurements per day each hour) in the far field and in the near field of the loudspeaker for acoustic frequencies $f_{ac} = 500Hz$, $1000\,Hz$, $2000\,Hz$. A statistical analysis shows that the convection velocity mean value is estimated to be $12.38\,mm.s^{-1}$ (far field condition) and to $8.08\,mm.s^{-1}$ (near field condition) with a standard deviation respectively equal to $9.92\,mm.s^{-1}$ and to $6.19\,mm.s^{-1}$. According to these results (maximum convection velocity of $50\,mm.s^{-1}$) and to the condition given by equation 8, the minimum measurable acoustic frequency is estimated to be 500 Hz.

5.1.1 Acoustic velocity amplitude

The amplitude of the acoustic velocity estimated by LDV and by the reference technique (two microphone probe) are compared for $f_{ac} = 500,\ 1000,\ 2000$ Hz. Using a constant input voltage for the loudspeaker, the acoustic velocity amplitude is changed by locating the probe volume at different distances from the loudspeaker (see figure 4). The measurement is performed in the near field ($x \in [8.5\,cm, 16.5\,cm]$) and in the far field ($x \in [37.5\,cm, 97.5\,cm]$) of the loudspeaker. Figures 5, 6 and 7 show the acoustic velocity amplitude measured by LDV as a function of the reference velocity amplitude for $f_{ac} = 500\,Hz$, $1000\,Hz$ and $2000\,Hz$ respectively. Each velocity amplitude is obtained by averaging 50 estimated values for the LDV and the reference technique. Assuming that the statistical distribution of the acoustic velocity measured by LDV is Gaussian, the bars represent the double of the standard deviation $\sigma_{V_{ac}}$ (confidence interval at 95 %) of the 50 measurements. The relative uncertainty in the acoustic velocity amplitude is given by

$$\frac{u_{V_{ac}}}{V_{ac}} = \frac{1}{N}\frac{2\sigma_{V_{ac}}}{V_{ac}}, \tag{14}$$

where N is the number of measurement (50). The uncertainties are estimated to be $\pm 2\%$ at 500 Hz, $\pm 3\%$ at 1000 Hz and $\pm 2\%$ at 2000 Hz.

The bars representing the uncertainty in the reference velocity are lower than $0.1\,mm.s^{-1}$ which explains that they are not shown on the figures.

[Figure 5 about here.]

[Figure 6 about here.]

[Figure 7 about here.]

For $f_{ac} = 500$ Hz, the acoustic velcity amplitude measured by LDV and estimated by means of the sound intensity probe agree. For $f_{ac} = 1000$ Hz, the velocity amplitude measured with LDV is near from the reference velocity. However, the variance in the LDV measured velocity is greater than for $f_{ac} = 500$ Hz. For $f_{ac} = 2000$ Hz, the acoustic velocity amplitude measured by means of LDV is overestimated compared with the velocity deduced from the intensity probe. The bias observed between the two curves can be explained by the bias due to the signal processing (see section 2.2). Indeed, the signal processing leads to overestimate the acoustic velocity amplitude, the bias observed between the two curves (reference velocity and measured velocity) being the same order of magnitude than the bias observed in [26] due to the signal processing. Morever, this difference may be explained by the fact that the two measurements (LDV and reference) are not performed at the same point, the LDV probe being placed at a few millimeters from the sound intensity probe.

5.1.2 Acoustic velocity phase measurement assessment

The phase difference between the acoustic velocity estimated by LDV and by the reference technique (two microphone probe) are studied for $f_{ac} = 500, 1000, 2000$ Hz and in the near and far field of the loudspeaker. The position of the probe on the loudspeaker axis are the same as those used in the section 5.1.1. The phase characteristics (mean, variance) are estimated by acquiring 120 Doppler signal, each signal duration being 1 second.

Results are the following. We obtain at $f_{ac} = 500Hz$ a mean phase difference of 10.31^o and a standard deviation of 8.8^o, at $f_{ac} = 1000Hz$ a mean phase difference of 17.7^o and a standard deviation of 9.47^o, at $f_{ac} = 2000Hz$ a mean phase difference of 1.57^o and a standard deviation of 11.84^o. These results show that it is possible to estimate a mean phase with a standard deviation less than 20 degrees.

5.1.3 Discussion

The measurement of the acoustic velocity amplitude and phase with LDV can be performed in free field using the Short Time Fourier Transform (STFT) for frequencies ranging from 500 Hz to 2000 Hz for acoustic velocity amplitudes greater than 2 mm/s at 500 Hz, 3 mm/s at 1000 Hz, 4 mm/s at $2000Hz$ corresponding to 92, 95.5 and 98 dB SPL in free field. The low frequency limitation (500 Hz) is due to the flow velocity amplitude (smaller than $50\,mm/s$) and to the signal processing technique which requires that a single acoustic period is analysed during a burst duration (see eq. 7). The amplitude limitation is due to the signal processing method, which is adapted for high acoustic levels [26] corresponding to acoustic velocity amplitude greater than $i.f_{ac}$ (see equation 4).

5.2 Loudspeaker radiation model limits

This section presents the evaluation of the loudspeaker radiation model by comparing the on-axis velocity measured by LDV and by the sound intensity probe with the on-axis velocity calculated by means of the model described in appendix A. The parameters used for the model are estimated experimentally using the techniques described in appendix B and the acoustic velocity is calculated using equation 15. The experiment is conducted for $f_{ac} = 500\,Hz$ in order to be able to use the model presented in section 3 which assumes that the acoustic wavelenght is much greater than the dimensions of the back cavity. The comparison of theoretical and experimental pressure profile (see figure 11), shows that the model is valid up to $x = 10$ cm. After this limit, the experimental boundary conditions do not satisfy the hypothesis of the model.

5.2.1 Far field radiation

The far field velocity pattern is presented in figure 8. Each point represents the mean value of 50 estimations of acoustic velocity and the confidence interval at $95\,\%$ ($2\sigma_{V_{ac}}$) made by the LDV probe, the sound intensity probe and the physical model.

As shown in the previous section, the acoustic velocity amplitude measured by means of LDV and estimated by the sound intensity probe agree, the acoustic frequeny being low enough for enabling precise estimations by means of LDV. The acoustic velocity amplitude estimated by means of the propagation model has the same profile as this of the measured velocity. However, a bias can be observed between the measured and the calculated velocity (about $3\,mm/s$). This bias is due to the error made in the physical parameters estimation which is based on a model assuming a free field propagation whereas the far field propagation does not respect the Sommerfeld condition because of the experimental conditions (finite dimension of the table supporting the loudspeaker mounted in the baffle). This bias can be also observed on figure 11 giving the theoretical and experimental pressure profile.

[Figure 8 about here.]

5.2.2 Near field radiation

[Figure 9 about here.]

The near field velocity pattern is presented in figure 9. Each point represents the mean value of 50 estimations of acoustic velocity and the confidence interval at $95\,\%$ ($2\sigma_{V_{ac}}$) made by the LDV probe, the sound intensity probe and the physical model. The acoustic velocity amplitude estimated by means of the propagation model is near from this measured by means of LDV, the bias being about 1 mm/s. This bias is very low and confirms that the estimation of radiation model parameters (C_a and b_0) is based on the analysis of pressure measured in the near field of the loudspeaker as shown in appendix B. Figure 9 shows two different regions.

- For $x < 10$ cm, the acoustic level is high ($110\, dBSPL$) and the frequency is low ($500\, Hz$), which enables to use LDV with confidence. The velocity measured by means of LDV agrees with the theoretical velocity, the maximum bias being less than 0.5 mm/s (less than 0.4 dB). This bias is also shown by figure 11 for the pressure profile. The velocity estimated by means of the probe intensity differs from the theoretical one and from the LDV measurement. The evanescent nature of the acoustic field in this region (near field) may introduce many estimation errors of the velocity using the two microphone method due to amplitude and phase mismatch [35, 33]. A more complete explanation of this phenomenon would need a complementary study of the intensity probe located near a sound source.

- For $x > 10\, cm$, the acoustic velocity amplitude measured by means of LDV and estimated by the sound intensity probe agree, the bias being lower than 0.5 dB. The bias observed between the experimental and theoretical velocities is $1 mm/s$ ($\simeq 1$ dB) as shown in figure 11).

6 Conclusion

In this paper, the performances of a measuring LDV system are assessed for measuring acoustic particle velocities in free field. In this context, the acoustic velocity is estimated by taking into acccount the flow velocity due to natural convection. Once the frequency and amplitude range are determined, this system is used for characterizing the acoustic radiation of a loudspeaker.

In these experiments, the LDV bench is used in the back scattering configuration. The velocity measured by means of LDV is estimated using three steps. At first, bursts are detected with a threshold technique. This enables to estimate the beginning an ending time of each burst and to derive the signal to noise ratio of the doppler signal for each burst. In a second step, the instantaneous frequency of the doppler signal is estimated using a Short Time Frequency Transform (STFT). Finally a post-processing is applied on the instantaneous frequency at different times corresponding to the existence of bursts. This enables to estimate the velocity parameters (acoustic amplitude and phase, flow velocity). The uncertainty in the acoustic velocity amplitude and phase estimation is calculated using the standard deviation of 50 estimations of these parameters. The reference velocity is estimated using a sound intensity probe put in the vicinity of the probe volume. The uncertainty in the reference velocity are minimized using a relative calibration of the probe.

Taking into account the constraints associated with the signal processing techniques, the LDV bench is assessed in the [500 Hz - 2000 Hz] range. Results show that the LDV bench associated with the signal processing techniques described above enables to estimate the acoustic velocity amplitude for 500, 1000 Hz and 2000 Hz for amplitude greater than 2 mm/s. Difference observed between LDV measured velocity and reference velocity are the same order of magnitude than these observed by numerical simulations for measurement performed without flow [26]. Concerning the acoustic velocity phase, the measurement of many bursts enables to estimate the phase with a standard deviation less than 20 degrees.

The acoustic radiation of a loudspeaker is studied at 500 Hz using the LDV bench. The acoustic velocity is calculated using a physical model and is measured by means of the LDV probe and by means of a sound intensity probe. The parameters used in the physical model are estimated by comparing the measured and calculated acoustic pressure on the axis of the loudspeaker in the near field and far field. In the far field, results show that the LDV probe and sound intensity probe agree whereas the radiation model does not predict well the acoustic velocity. This difference (about $3\,mm/s$) is explained by the fact that the experimental conditions do not respect the hypothesis used in the model. In the near field, the velocitiy amplitudes measured by LDV, estimated by the sound intensity probe and calculated using the propagation model differ from about $1\,mm/s$. The difference observed between the three velocity amplitudes (LDV, sound intensity probe, model) in the far field are mainly explained by the bad estimation (due to the experimental configuration) of the physical parameters used in the radiation model. The difference observed in the near field are explained by the fact that the acoustic field is mainly reactive in the near field of the loudspeaker. In this case, the amplitude and phase mismatch of the two microphone can affect the acoustic velocity estimation [33].

These results show that it is possible to measure the acoustic velocity of a radiating structure in free field and encourage to characterize the near field acoustic radiation of a vibrating structure, for which the flow velocity should be low due to viscous effect on the structure. The accuracy of the LDV system should be increased by using a front scattering optical arrangement or by using a more powerful laser beam in order to get a higher signal to noise ratio. The use of other frequency demodulation technique should enable to decrease the minimum measurable acoustic displacement, *i.e.*, to decrease the minimum measurable acoustic velocity amplitude or to increase the maximum measurable acoustic frequency. The use of other detection process should enable to increase the useful duration of burst (apparent length of the probe volume) and then to decrease the minimum measurable frequency [36].

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A On-axis acoustic velocity

Considering that the loudspeaker is mounted in an infinite baffle and that it radiates in a half space, the radiated field at position $\vec{r}$ (in (x,y) frame) is calculated using the Rayleigh integral

$$p(\vec{r}) = \frac{jk\rho c}{2\pi} V_p \int_{S_p} \frac{e^{-jk|\vec{r}-\vec{r_0}|}}{|\vec{r}-\vec{r_0}|} dS_0, \tag{15}$$

where S_p is the surface of the piston, V_p is the piston velocity, $k = \omega_{ac}/c = 2\pi f_{ac}/c$ is the wavenumber, ρ is the air density and c is the sound speed. $\vec{r_0}$ is the position of an elementary source of the piston in the piston reference frame and dS_0 is the surface of the elementary source. For a circular piston of radius R_p, the pressure along the piston axis is

$$p(x) = \rho c V_p e^{-jkx}(1 - e^{-jk\sqrt{x^2+R_p^2}-x}). \tag{16}$$

Using the Euler equation, the velocity along the piston axis is

$$v(x) = V_p e^{-jkx}(1 - \frac{x}{\sqrt{x^2+R_p^2}} e^{-jk\sqrt{x^2+R_p^2}-x}). \tag{17}$$

The far field approximation (given by $R_p << x$) leads to the expression of the far field acoustic velocity

$$v_{ff}(x) = \frac{1+jkx}{2\pi}\frac{Q_p}{x^2}e^{-jkx}, \tag{18}$$

where $Q_p = \pi R_p^2 V_p$ is the acoustic volume velocity of the loudspeaker. Equation 18 gives the expression of the acoustic velocity due to a monopole of volume velocity Q_p. The comparison of the equations 9 and 18 enables to define the near field of the loudspeaker. Figure 11 shows the two velocty profiles for $f_{ac} = 500Hz$ and $R_p = 5cm$ (see section B). The near field of the loudspeaker is arbitrarily defined when the two velocity amplitudes differ from 1%. This leads in this particular case to a near field limit $d_{ff} = 37cm$ in this case.

[Figure 10 about here.]

B Radiation model parameters estimation

The equivalent piston radius R_p is estimated by measuring the diameter of the suspension as proposed by Le Roux [37].

In order to estimate the velocity of the piston V_p used in the propagation model, the volume velocity generated by the loudspeaker is measured. This is done by using a closed cavity at the back of the loudspeaker. Assuming that there is no leakage, the volume velocity generated by the loudspeaker Q_p is deduced from the pressure measured inside the cavity p_c, for a harmonic excitation at angular frequency ω_{ac}, by

$$Q_p = j\omega_{ac} C_a p_c, \tag{19}$$

where C_a is the acoustic compliance of the back cavity. The estimation of the membrane surface S_p using the measured radius R_p enables to deduce the membrane mean velocity.

The value of the acoustic compliance C_a of the back cavity is estimated by measuring the acoustic pressure amplitude profile along the loudpseaker axis given by

$$\left|\frac{p(x)}{p_c}\right|^2 = 2\left(\frac{\omega_{ac}\rho c C_a}{S_p}\right)^2 \left[1 - \cos\left[k(\sqrt{(x-x_p)^2 + R_p^2} - (x - x_p))\right]\right] \tag{20}$$

Using the measured acoustic pressure on the loudpseaker axis, a least square method enables to estimate the two parameters C_a and x_p [28]. The experimental and calculated pressure pattern are presented in figure 11. This shows that the values of parameters C_a and x_p enable to predict well the very near field pressure ($x < 10cm$).

[Figure 11 about here.]

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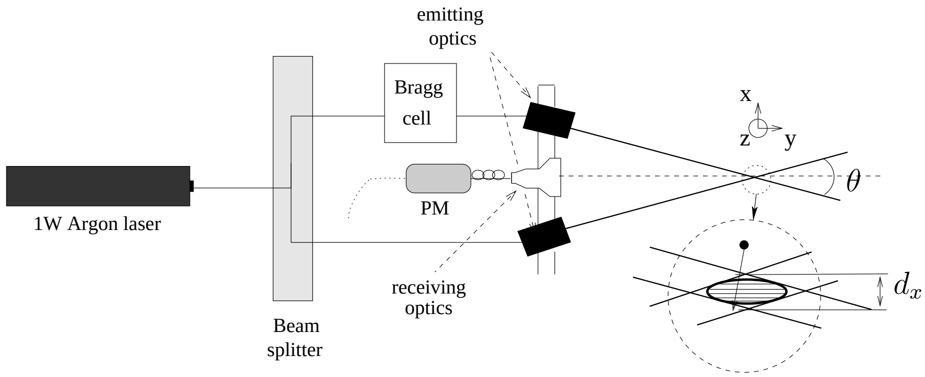

Figure 1: Optical set-up of the LDV system. The probe volume is ellipsoidal and contains fringes. Particles are represented by black circles. Arrows represent the particle velocities.

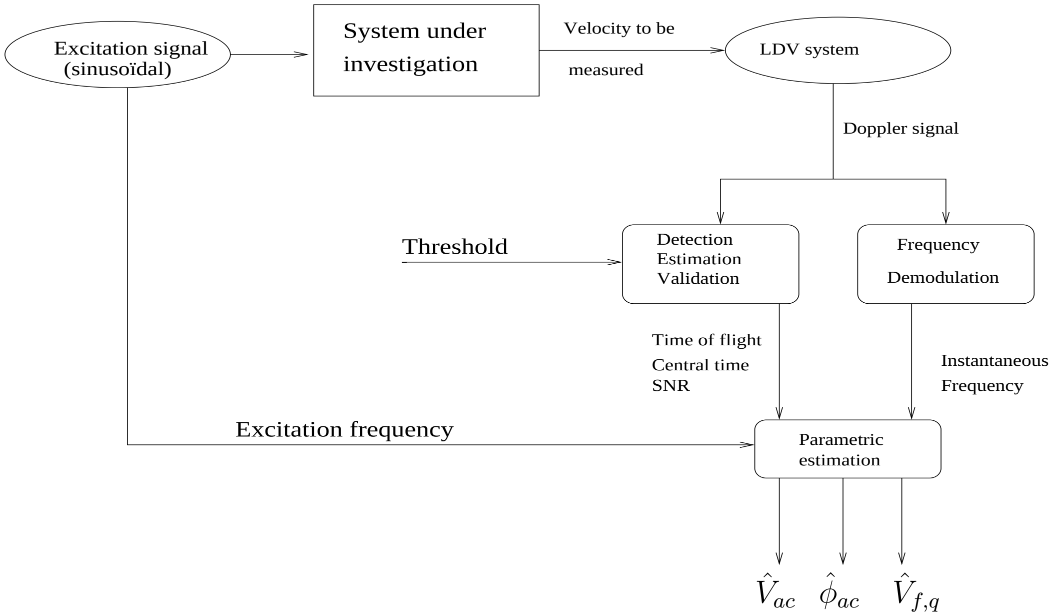

Figure 2: General principle of the signal processing for acoustic velocity estimation.

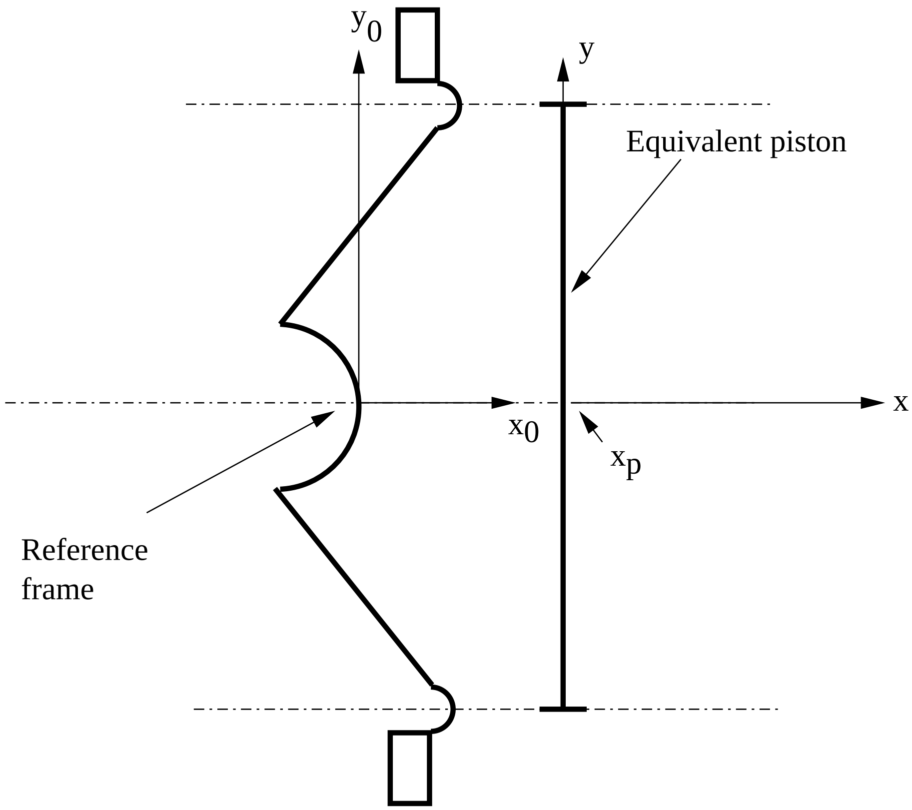

Figure 3: Schematic view of the loudspeaker. x_p is the abscissa of the equivalent piston in the loudspeaker reference frame (x_0, y_0).

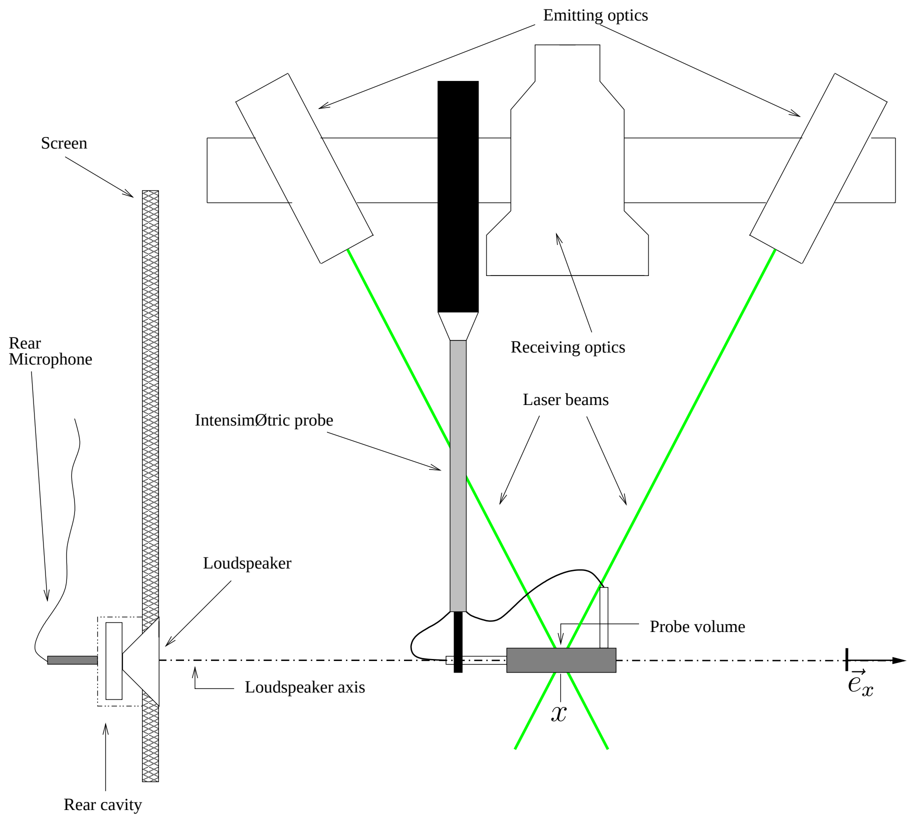

Figure 4: Schematic view of the experimental system

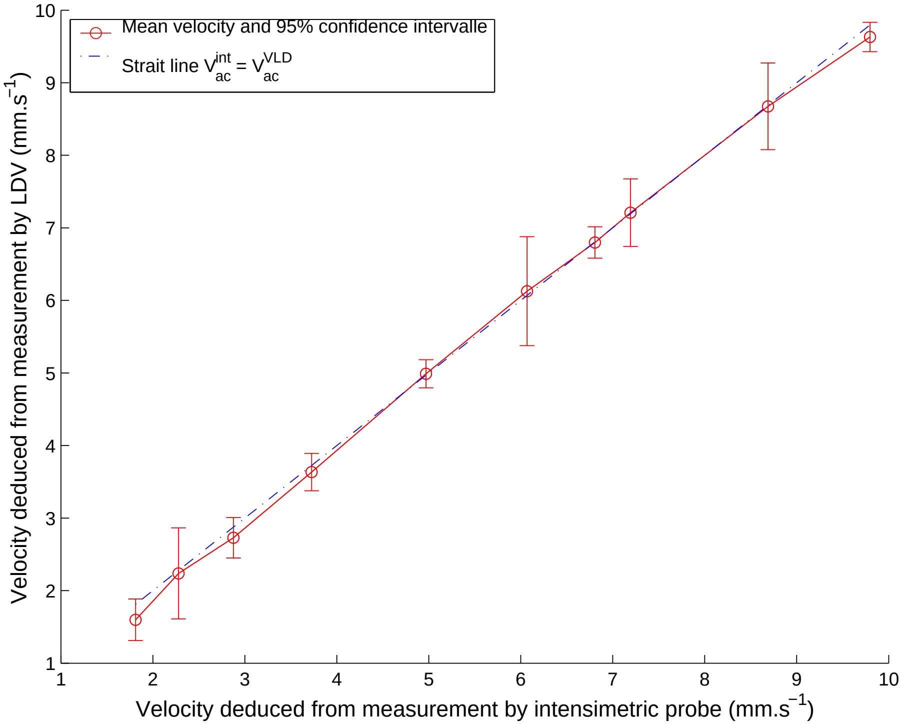

Figure 5: Amplitude of the acoustic velocity measured by LDV *vs* amplitude of the reference velocity measured in near and far field for $f_{ac} = 500$ Hz. Bars represent the 95 % confidence interval ($2\sigma_{V_{ac}}$).

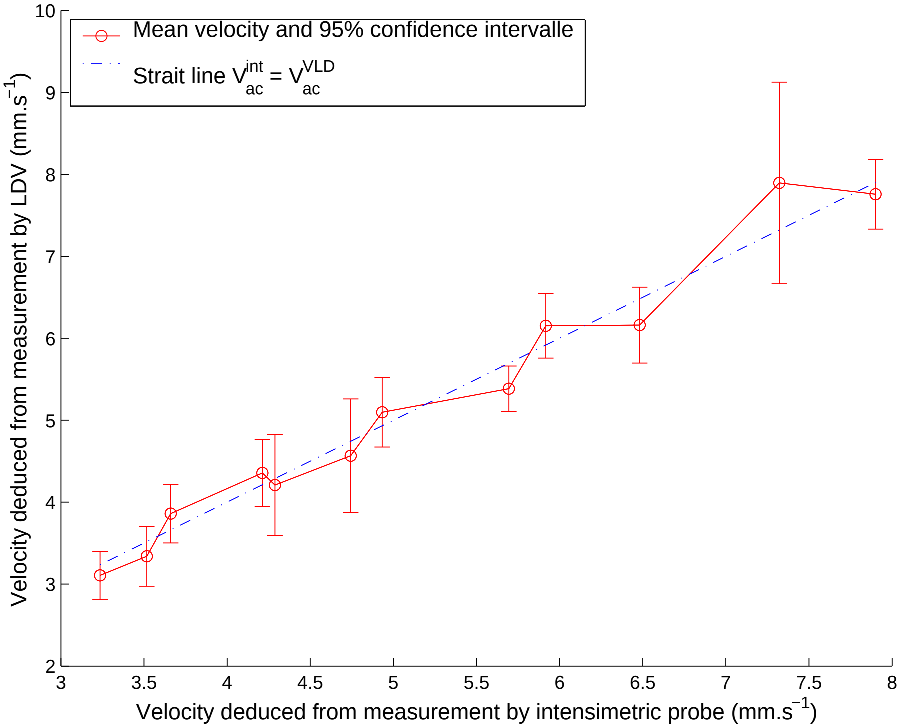

Figure 6: Amplitude of the acoustic velocity measured by LDV *vs* amplitude of the reference velocity measured in near and far field for $f_{ac} = 1000$ Hz. Bars represent the 95 % confidence interval ($2\sigma_{V_{ac}}$).

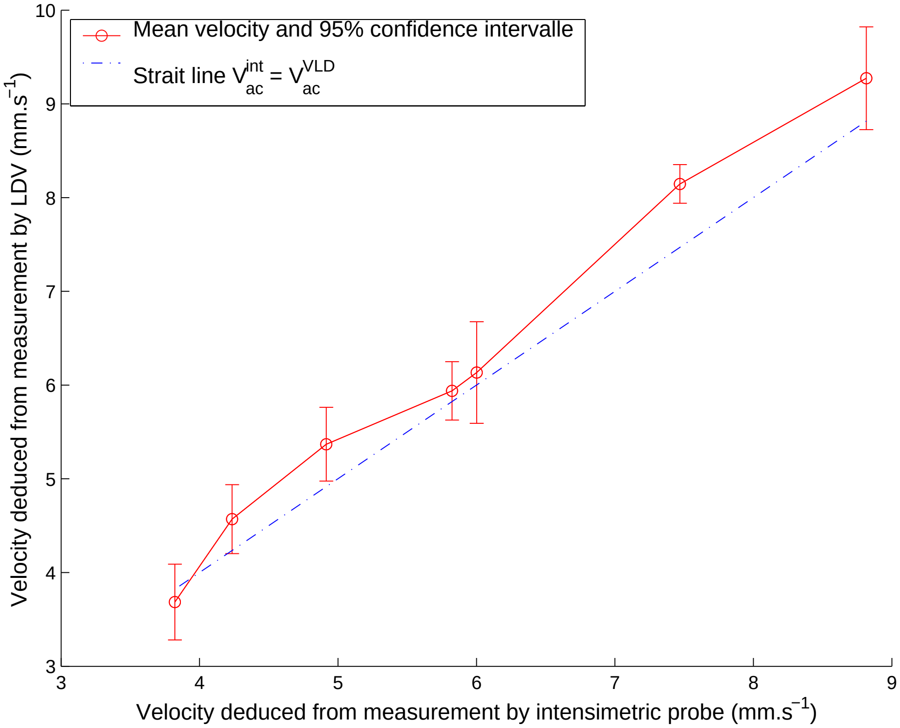

Figure 7: Amplitude of the acoustic velocity measured by LDV *vs* amplitude of the reference velocity measured in near and far field for $f_{ac} = 2000$ Hz. Bars represent the 95 % confidence interval ($2\sigma_{V_{ac}}$).

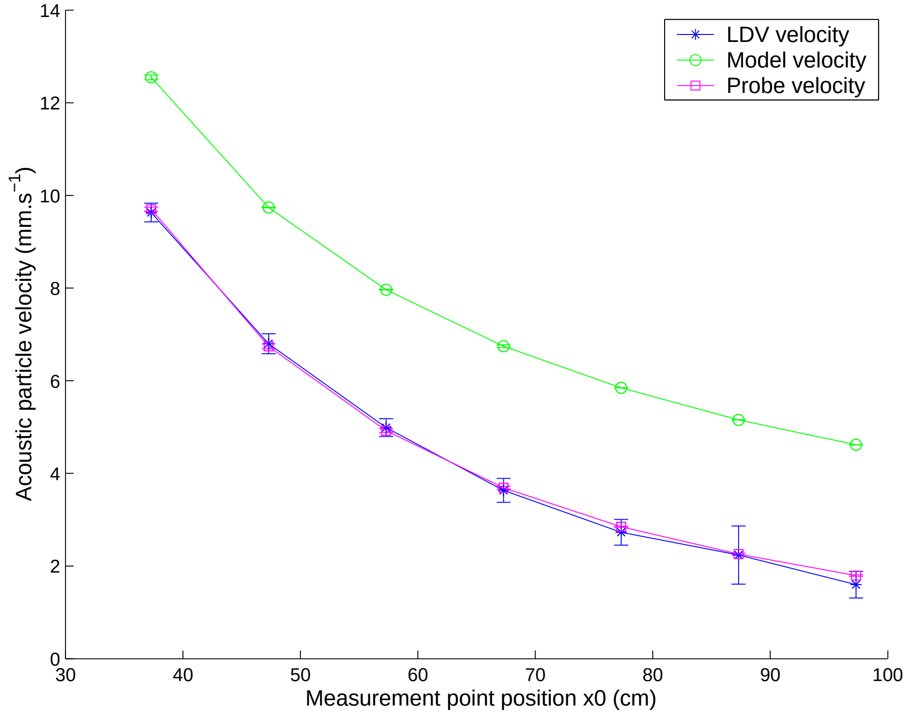

Figure 8: Far field acoustic velocity amplitude as a function of distance x from the loudspeaker for $f_{ac} = 500$ Hz. LDV measurement (star), probe measurement (square), model (circle).

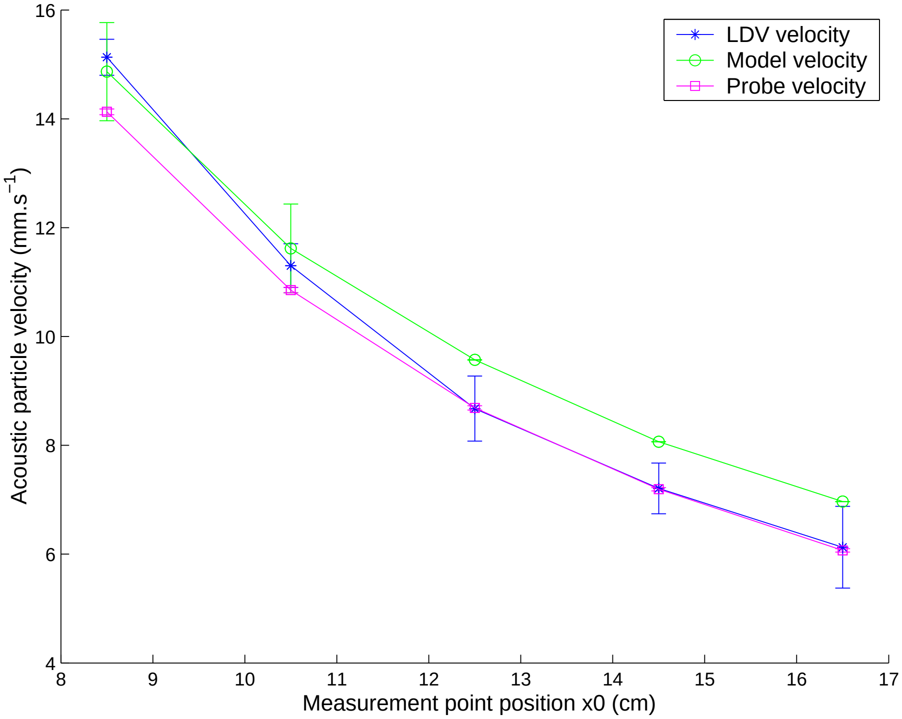

Figure 9: Near field acoustic velocity amplitude as a function of distance x from the loudspeaker for $f_{ac} = 500$ Hz. LDV measurement (*), probe measurement (), model (o).

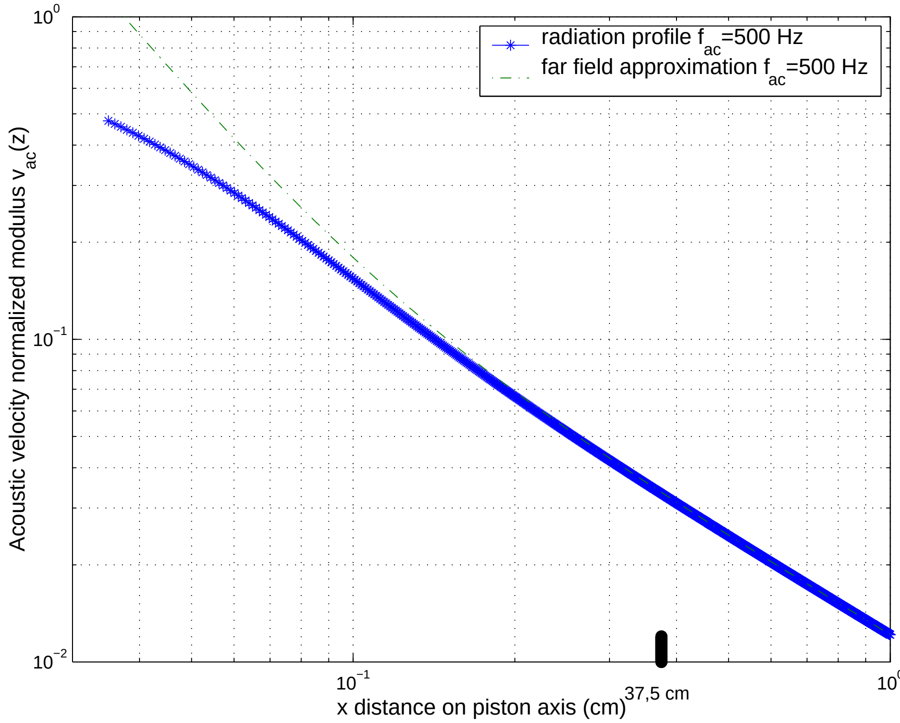

Figure 10: Acoustic velocity amplitudes calculated in the axis of a radiating piston by means of the Rayleigh integral (*) and the monopole model (-.). Acoustic frequency $f_{ac} = 500Hz$, piston radius $R_p = 5cm$.

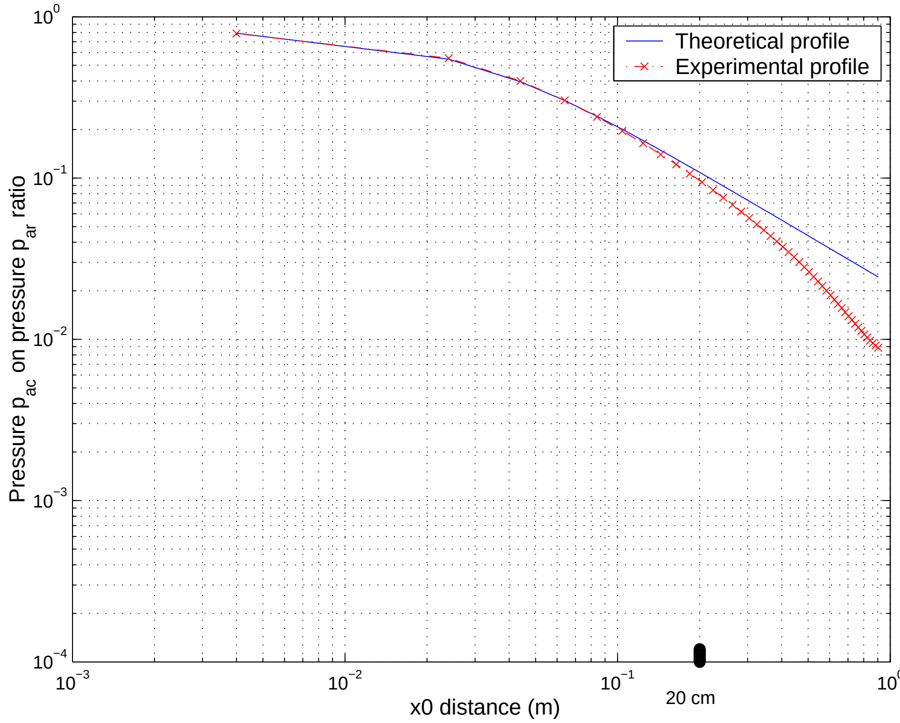

Figure 11: Acoustic pressure amplitudes in the axis of a radiating piston. Acoustic frequency $f_{ac} = 500Hz$, piston radius $R_p = 5cm$. x : experimental. - : calculated.