NEXT GENERATION OF PRIMARY ACOUSTICAL STANDARDS BASED ON OPTICAL METHODS

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1 INTRODUCTION

Optical methods for acoustic measurement have the potential for high accuracy, high spatial resolution and enable the direct measurement of an acoustic field parameter such as acoustic particle displacement, or acoustic particle velocity without perturbing the field being measured. Potentially, optical methods are well suitable for use as a primary standard for the calibration of microphones. This paper describes a method for the absolute measurement of acoustic particle velocity which uses a Laser Doppler Anemometer[1,2,3] (LDA) optical arrangement coupled with a photon-correlation[4,5] processing technique. This LDA system has been developed as part of a project aimed at developing primary acoustic standards based on optical methods.

2 RATIONALE

For sound in air, measurement standards are realised through the free-field calibration of laboratory standard microphones. Current practice is to use the reciprocity calibration method to yield the sensitivities of the microphones under test. The free-field sensitivity determined is therefore related to the particular sound pressure developed during the calibration, which is governed by practicalities of the calibration procedure rather than the application to which the microphone is put. The microphone when used as a sound source is capable of producing relatively low free-field sound pressure level of 0 dB - 20 dB (20 μPa - 200 μPa) at the receiver microphone position. However, in common practice, microphones tend to be used at much higher levels, from approximately 40 dB up to 140 dB. Special applications might extend this range at both ends by some 30 dB. In most cases the microphones are simply assumed to function linearly and the sensitivity derived in the calibration is extrapolated to these higher levels. The efficiency of the microphone to act as a transmitter of sound also reduces with frequency and places a lower limit on free-field calibration methods of 1 kHz - 2 kHz. Below this limit the free-field response is assumed to be equivalent to the pressure response (measured in a small closed cavity), but this assumption is difficult to validate in practice. Practical measurements will often be concerned with frequencies down to 30 Hz or below.

Free-field standards are established up to 20 kHz. The primary standard uncertainty for microphone calibration is between 1.5% and 3.5% at the 95% confidence level. This current capability is approximately twice the uncertainty of the most demanding industrial user. In future, there will be increasing interest in the calibration of smaller microphones and microphone arrays, devices that are often not well suited to being calibrated using reciprocity techniques. Looking at the options for improving the reciprocity technique, the rewards from its further development are getting ever smaller. The method is made difficult in a free field due to the very low acoustic level that can be produced by a transmitting microphone. Signal-to-noise problems and cross-talk from the electrical signal driving the transmitting microphone place fundamental limits on what can be achieved, hence making it difficult to calibrate smaller and novel devices. Consequently, increasing the accuracy of microphone calibration requires a new initiative.

Optical techniques provide an absolute measurement capability, which are generally traceable to the wavelength of light. Furthermore, optical methods provide very high spatial resolution, are not generally limited in bandwidth and do not perturb the acoustic field being measured. Many of the limitations of current calibration methods could potentially be overcome by employing optical methods to provide a direct calibration of the microphone.

The work described in this paper forms part of a project aimed at developing primary acoustical standards based on optical techniques. For sound in air, the ultimate aim is to develop a measurement system capable of measuring in a free-field chamber with a spatial resolution of 0.3 mm over a frequency range of 30 Hz to 50 kHz where the local sound pressure level is typically 40 dB to 100 dB, with a measurement uncertainty of around 0.3% at lower frequencies increasing to 0.5% at 10 kHz and above.

3 LASER DOPPLER ANEMOMETRY

Laser Doppler Anemometry is a non-intrusive, optical technique for measuring fluid flow. The frequency of a photon scattered by a particle is shifted by an amount directly proportional to the particle's velocity. The technique of LDA is based on the fact that by measuring this frequency shift, the velocity can be determined. If it assumed that the particle faithfully follows the flow, then the measured velocity is equal to the flow velocity. For typical flow velocities, the frequency shift is very small in comparison with the frequency itself and therefore difficult to measure accurately. In practice, therefore, this shift is not measured directly. Instead, an optical fringe pattern is established over a volume of space by the interference of two laser beams. As particles traverse the interference fringes, the emitted light is modulated at the optical frequency. By analyzing the optical signal, the flow velocity can be established.

There are a number of possible optical configurations[1] for an LDA measurement system. This paper considers only the dual-beam mode where the measuring volume consists of interference fringes formed by intersecting laser beams. This configuration interferes a split laser beam at the focal point of a converging lens. A photomultiplier tube (PMT) is positioned such that the fringe volume, which is in the acoustic field, is imaged at the entrance to the detector. The output of the PMT, the LDA signal, is then correlated with itself using either hardware or software. From the autocorrelation function (ACF), the velocity component in the direction perpendicular to the fringes can be determined. This LDA configuration is shown in Figure 1, where Figure 2 shows a close-up of the interference fringes[6].

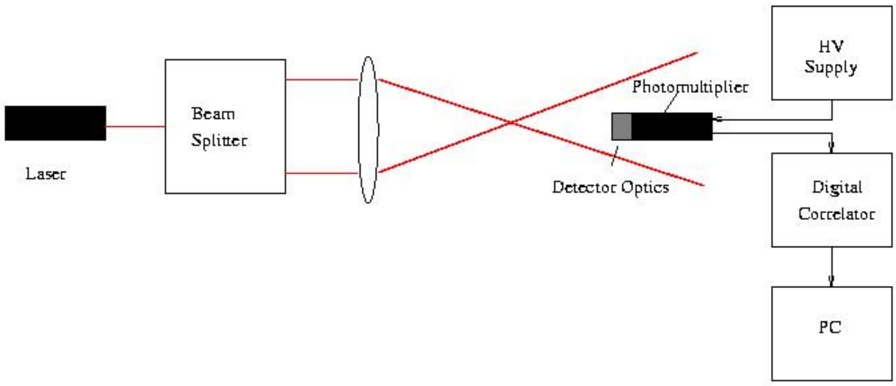

Figure 1. Optical configuration of LDA system.

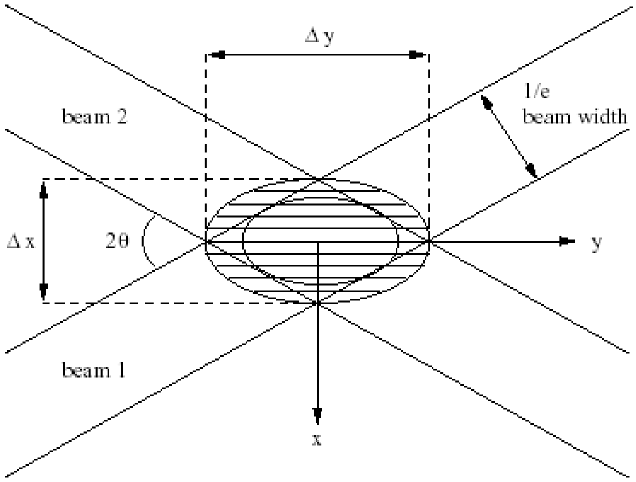

Figure 2. Measurement cross-section of interfering optical beams.

The laser beam has a wavelength λ and is assumed to have a Guassian profile of $\frac{1}{e^2}$ with a diameter d. The half-angle of the beam intersection is θ. The measurement volume has dimensions $\Delta x = \frac{d}{\cos\theta}$, $\Delta y = \frac{d}{\sin\theta}$ and $\Delta z = d$; these values are typically fractions of a millimetre, so LDA can be described as a point measurement technique. Each of the two beams is assumed to be of equal intensity, and the spacing between consecutive fringes is $\frac{\lambda}{2\sin\theta}$.

Small particles suspended in the fluid scatter some of this light. The number of photons scattered depends on a variety of factors, such as the number and size of the particles, the intensity of the laser beam and their position within the interference pattern, and this number changes as the particles follow the fluid motion. A photomultiplier records some of this scattered light; if its intensity is sufficiently small, corresponding to an average of less than 40 million photons per second, individual photons can be counted.

The particle velocity can be obtained from the photomultiplier in a number of ways. If the optical signal is continuous, it can be Fourier Transformed to obtain the Spectral Density Function from which the velocity can be extracted from the frequency spectra by analyzing the location and heights of the peaks and sidebands. Alternatively, the signal can be de-modulated in the time-domain to yield the instantaneous frequency and hence velocity. For a discrete optical signal which can be considered to be a series of individual photon events, the signal can be auto-correlated to determine the velocity. The choice of analysis method therefore depends on the smoothness of the optical signal, which depends on the sample rate and the number of photons detected.

In a free-field environment, the seeding (natural particles) density is relatively low and the distribution is variable. For the work presented in this paper, the auto-correlation analysis method was therefore chosen as the most appropriate method of decoding the particle velocity. The sensitivity of this technique is such that natural impurities in the fluid are frequently sufficient to produce an adequate signal. The photon count and thus the signal to noise can be improved by the addition of seeding particles which faithfully follow the mean and acoustic flow. The photon count could also be increased by the use of a more power laser and thus negate the need for seeding particles.

4 ACOUSTIC VELOCITY MEASUREMENT

The scattering particles are assumed to follow the flow faithfully, and have an instantaneous velocity, u, of the form[7]

$$u(t) = u_m + u_a \sin(\omega_a t) \tag{1}$$

where u_m is the mean flow velocity or DC term, u_a is the acoustic velocity amplitude or AC term and ω_a is the acoustic angular frequency. The fluid motion is therefore considered to be a superposition of a mean flow and an acoustic oscillation.

Normally, the auto-correlated photomultiplier signal detected in the presence of a sound field would result in an ACF that is time-averaged over the entire acoustic cycle. In practice, a gating technique is used where short bursts of the photomultiplier signal are auto-correlated at regular intervals. This restricts the range of velocities contributing to the ACF. If the duty cycle of the gating signal is small, the acoustic velocity is approximately uniform during the period of time when the gating signal is high. The ACF of the photomultiplier signal when the fluid velocity is uniform is simply a damped cosine for which an example is shown in Figure 3.

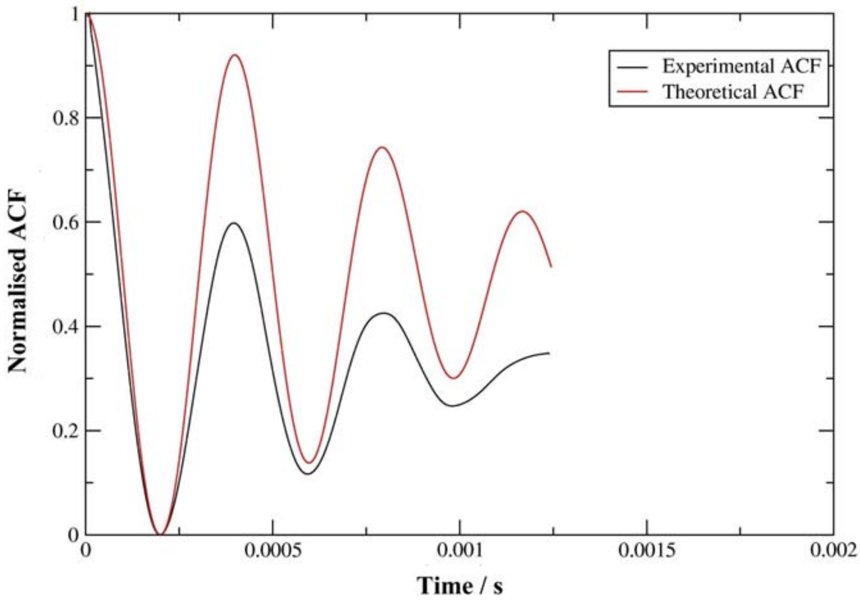

Figure 3. Auto-correlation function produced for a 200 Hz standing wave.

The measured ACF in Figure 3 appears more damped than that predicted theoretically. This was possibly due to the optical beams not being optimally balanced during the measurement.

The time to the first minimum is inversely related to the instantaneous velocity given in equation (1). In the absence of an acoustic field, the mean flow velocity u_m, is given by:

$$u_m = \frac{\pi}{D\tau_{\min}}. \tag{2}$$

For the case where a there is no mean flow, the acoustic velocity u_a, is given by:

$$u_a = \frac{3.832}{D\tau_{\min}} \tag{3}$$

where $\tau_{\min}$ is the time to the first minimum in the ACF for both equation (2) and (3). In each case, D is the optical component related to the fringe spacing and given by,

$$D = \frac{4\pi \sin\theta}{\lambda}. \tag{4}$$

where θ is the half angle of the intersecting optical beams and λ is the optical wavelength. It is equation (4) that provides the traceability to the wavelength of light.

If a number of ACF's are produced at different phase offsets then the time to the first minimum can be plotted as a function of phase offset. This type of plot is shown in Figure 4, where a series of 360 ACF's were obtained at step phase offsets for a 200 Hz acoustic signal in a 1 m long glass standing wave tube. Such a plot provides a means of calculating the mean and acoustic velocities separately.

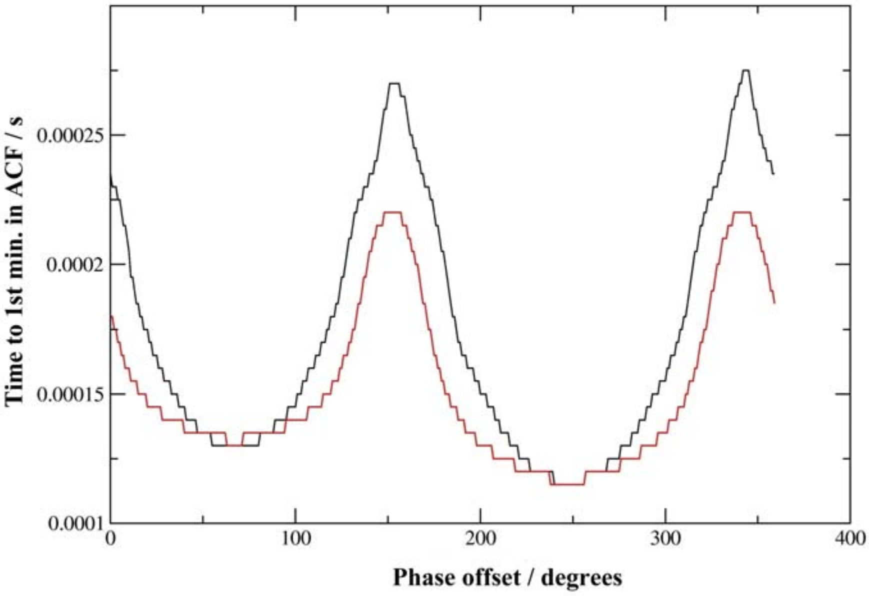

Figure 4. $\tau_{\min}$ as a function of phase offset for a 200 Hz acoustic signal – experimental data in black, theoretical data in red.

The plot shown in Figure 4 is periodic with two distinct peaks and troughs. Since the instantaneous velocity is inversely related to the time to the first minimum of each ACF (see equations (2) and (3)), the peaks in the graph correspond to sections of the acoustic cycle where the instantaneous velocity was lowest and the troughs correspond to the gated ACF's for which the instantaneous velocities were greatest. If there were no mean flow present, the troughs would be positioned at the same value of $\tau_{\min}$. The different values of $\tau_{\min}$ for each trough presented in Figure 4 indicate the presence of a mean flow component. For this example, the mean flow velocity u_m was found to be 1.34 ms^{-1} and the peak acoustic velocity u_a was found to be 0.05 ms^{-1}. The fact that the higher trough occurs first indicates that the mean flow and the maximum acoustic velocity are in different directions.

The agreement between the experimental ACF data (black) and the theoretical $\tau_{\min}$ data (red) obtained was worse at the lower velocities (peaks) than at the higher velocities. One possibility for this was that the sound field may not have been exactly sinusoidal. There were in fact some small harmonics present due to non-linearity in the speaker. This was not of concern as only the maximum velocities are of interest and the acoustic source could easily be replaced with a linear unit.

Although some initial measurements have been performed in a pseudo free-field, the results yielded insufficient signal-to-noise using the current optical arrangement. Future work is planned to test an enhanced optical system capable of a higher photon count. The use of extra seeding in the free-field is both undesirable and impractical due to induced flow during seeding injection. Further studies are also underway to refine the curve-fitting algorithm to enable measurement of non-sinusoidal sound fields. Initial measurements have considered acoustic fields of up to 1 kHz. Future work would intend to extend this to above 20 kHz.

Optical techniques such as LDA also offer a potential solution to other sound measurement areas that are not suited to measurement with a standard microphone. One example of this is the measurement of fan noise using a microphone where the flow in the vicinity of the microphone introduces an additional and undesirable source of noise. The ability of LDA to separate the AC and DC components would enable an accurate acoustic measurement independent of the adverse effects of flow.

5 SUMMARY

An initial measurement system has been demonstrated that is capable of acoustic particle velocity measurement with a high spatial resolution of less than 1 mm. The system employs the Laser Doppler Anemometry optical configuration coupled with a photon correlation processing method for determining the instantaneous velocity. Auto-correlation signal processing techniques have been demonstrated that allow the separation of the mean flow velocity and the acoustic particle velocity without the need for any secondary measurement system. The example presented in this paper demonstrates the measurement of a 0.05 ms^{-1} acoustical velocity at 200 Hz in the presence of a 1.34 ms^{-1} mean flow in a standing wave tube. The ability to measure the acoustic velocity without perturbing the field and the inherent traceability of such an optical technique, make it a particularly good candidate as a future primary standard. Optical methods also offer potential for improvement in other areas of acoustic measurement where a non-perturbing technique is essential.

6 ACKNOWLEDGEMENTS

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