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Towards a future primary method for microphone calibration: Optical measurement of acoustic velocity in low seeding conditions

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ABSTRACT

Laser Doppler anemometry (LDA) is conventionally used for flow velocity measurements of particles in liquids and gases. The application of LDA to acoustic fields provides the potential for non-intrusive and direct measurement of acoustic velocity. This paper describes a dual-beam LDA system developed for the measurement of acoustic particle velocity in minimal photon scatter/seeding environments using a photon-correlation method and low optical power. The system has been used to measure the acoustic pressure in a standing-wave-tube with a 0.2 dB agreement with that of a standard $\frac{1}{2}$-in microphone at low frequencies. The optical method offers the potential for the direct calibration of microphones against acoustic pressure, rather than an indirect method such as reciprocity that is the current internationally accepted method.

1. Introduction

The reciprocity method is currently the internationally accepted method for the primary calibration of laboratory standard microphones to establish both the pressure [1] and the free-field [2] sensitivities. For pressure calibration, the uncertainty for the lower frequency limit of 63 Hz is 0.03 dB re 1 V per Pa and gradually increases up to 0.18 dB re 1 V per Pa at the upper frequency limit of 20 kHz at the confidence level of 95%. This technique provides the sensitivity of microphones at discrete frequency points.

The advantage of reciprocity, which is the reason it has been so widely used, is that the pressure sensitivity of a microphone can be established from electrical measurements without any knowledge of the acoustic pressure. As a primary method for microphone calibration, this is also a disadvantage as the method is considered to be indirect. A direct method that allows the sensitivity of the microphone to be established to a known acoustic pressure would be more favourable as a primary method. Reciprocity also requires the transducer to produce an adequate signal when driven as a transmitter. Current measurement microphones are capable of achieving this, but new, miniature devices based on MEMS technology produce small pressure levels and it becomes impractical to use the technique for their calibration in a reciprocity arrangement. Other sources of error arise from electrical cross-talk, poor SNR at low pressure levels and increasing uncertainty with frequency. In all, there are fundamental limitations to how much the method can be improved to operate in a wide range of pressure levels and frequencies, for a variety of microphones with non-standard dimensions.

To meet the demands of future microphone technology a new calibration approach is necessary that will potentially become the new primary standard [3]. Velocimetry based on optical methods, in particular laser Doppler anemometry (LDA), does offer a very attractive alternative to reciprocity. The technique uses coherent light to extract the velocity of particles moving due to an acoustic field, with the velocity being directly proportional to the acoustic pressure. LDA is non-intrusive so there is no perturbing effect due to the presence of a measurement device. The method also offers high spatial resolution and traceability to the wavelength of the light source.

LDA has traditionally been used for flow measurement in gases and liquids and has also been applied to the measurement of acoustic velocity in air and water [4]. In water, extraction of the velocity can be compromised by the acousto-optic effect on the intersecting laser beams [5]. However, in air, the pressures are such that the acousto-optic interaction is negligible [5], and successful measurements of acoustic velocity have been obtained in a seeded air environment. Taylor [6,7] as well as Valiere et al. [8] produced results for the velocity evaluation based on frequency modulation spectrum, while Loizeau et al. [9] as well as Cullen et al. [10] exploited the amplitude modulation of the Doppler signal. Other work in the literature [11–14] has focused

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on the use of the photon correlation technique in which individual photon events (number of photons counted by a suitable photomultiplier tube (PMT) at discrete intervals) from a seeded air environment are captured and analysed in order to calculate the velocity.

The classical dual beam LDA intersects two laser beams to form an interference volume. Natural or seeding particles oscillating due to the effect of an acoustic field cross this region and it is then possible to individually count photon events from the scattered volume. Due to the small number of photons scattered, it is necessary to use a PMT, the output of which is auto-correlated to obtain the time-dependent auto-correlation function (ACF). This method is known as photon correlation. The analysis of this function yields the velocity of particles moving due to the acoustic field.

MacGillivray et al. reported that it is possible to achieve agreement between LDA and reciprocity down to 0.1 dB using frequency domain analysis [15] and 0.2 dB using photon correlation spectroscopy [16] with the addition of seeding. Artificial seeding is used for LDA applications to increase the photon scattering potential of the air. Natural particles in the air will produce very little photon scattering and so seeding can be added in the form of smoke, water or oil particles. Although these increase the number of scattered photons and thus the potential to detect an acoustic field, they do change the properties of the air being measured.

An alternative optical method for the measurement of acoustic velocity is particle image velocimetry (PIV). In this method, artificial seeded airborne particles are illuminated using a laser source and by analysing subsequent "frames", the displacement of particles yields the motion of the fluid. It has been reported [17] that PIV can be applied for such measurements but, however, it requires even larger amounts of seeding and higher optical power compared to LDA. Most importantly, PIV measures the velocity over an area of the flow, whereas LDA provides exact point measurement.

For microphone calibration, large amounts of seeding change the properties of the medium and therefore the properties of the sound field to be measured. In addition, the particle velocity at a particular point is required, not the area. This paper considers the LDA photon-correlation method, which is better suited to minimal photon count applications than LDA-based frequency domain analysis or PIV. Results are presented, demonstrating the use of the photon-correlation method for the measurement of acoustic pressure in a standing wave tube (SWT) using negligible seeding.

It should be noted at this point that typical examples published previously require typical seeding durations of 4 [15] and 2 s [16] to achieve a very good agreement between LDA and reciprocity. Similarly [16], the typical volume of the SWT was $0.632 \times 10^{-3}\,\mathrm{m}^3$, the required laser power was 20 mW, the fringe spacing of the actual interference volume was just over 3 μm, and the lower frequency limit of measurements was 600 Hz. A different application for calibrating a micromachined particle velocity microphone reduced the lower frequency limit down to 250 Hz [18].

2. Dual beam acousto-optical arrangement

An Nd:YAG laser source was used with a wavelength of 532 nm and an output power up to approximately 70 mW. Using suitable neutral density filters, it was possible to reduce the power of the primary beam as required. The main reason for using this particular laser was essentially the opportunity of operating at power levels much higher than those offered by He:Ne laser sources in order to examine the dependence between laser power, seeding and clarity of the obtained ACFs.

A convex–concave double lens configuration reduced the beam waist, $D_{e^{-2}}$, down to around 0.5 mm. A suitable beam-splitter and a subsequent polariser produced two secondary beams of equal intensity and identical linear polarisation. Using a 75-mm plano-convex lens, the focal waist of the beams was reduced lower than 0.2 mm and the two beams were converged to intersect, creating a small interference region. This region is essentially an ellipsoid with dimensions:

$$\Delta x = \frac{d_{e^{-2}}}{\cos\theta} \tag{1}$$

$$\Delta y = \frac{d_{e^{-2}}}{\sin\theta} \tag{2}$$

$$\Delta z = d_{e^{-2}} \tag{3}$$

where $d_{e^{-2}}$ is the focal waist of the intersecting beams and θ is the half-angle of the intersecting beams.

The fringe spacing (Λ) and the number of fringes (N_f) in this region are given by

$$\Lambda = \frac{\lambda}{2\sin\theta} \tag{4}$$

$$N_\mathrm{f} = \frac{2d_{e^{-2}}}{\lambda}\tan\vartheta \tag{5}$$

The interference volume is shown in Fig. 1. For the configuration considered in this paper, $\theta = 7.59^\circ$, $d_{e^{-2}} = 0.11$ mm, $\Delta x = 0.11$ mm, $\Delta y = 0.83$ mm, $\Delta z = 0.11$ mm, $\Lambda = 2.01$ μm, $N_\mathrm{f} = 55$. In addition, very careful alignment of all lenses is required to reduce the effects of astigmatism [19] and the half-angle should not be too sharp to avoid distortions in the fringes [20].

A BrookHaven Instruments PMT employing a custom telescopic arrangement that allows manual focusing on the area of interest was placed at a short distance from the interference region to detect the photon events from the forward scattered volume. The PMT output signal was then processed by a BrookHaven BI-9000AT PC-based correlator board, which produced the required ACFs. A small aperture was also placed in front of the PMT to block the direct exit beams.

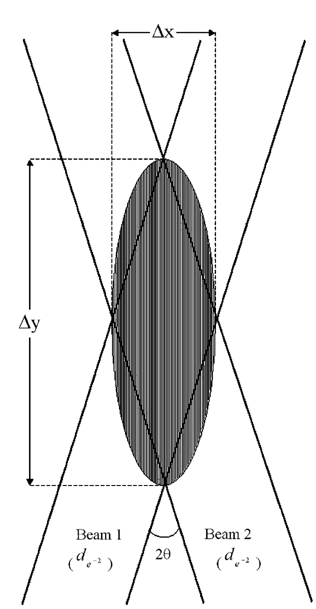

Fig. 1. Fringe pattern created by the intersection of two beams.