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Technical note

Impact of tracer particle size on optical measurement of sound fields

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ABSTRACT

This note deals with the effects of tracer particle size in laser Doppler measurement of the acoustic velocity in audio-frequency range sound fields in air. We use a computer model to study the role of particle size and find that both large and small particles can lead to systematic errors in the measured velocity, the former due to slippage and the latter due to diffusion. We show that for typical seeding materials and acoustic intensities the particle diameter needs to lie between 0.5 and 0.8 μm if the acoustic velocity is to be measured over the full frequency range with an uncertainty of less than 1%. We then report measured size distributions for two common seeding materials and demonstrate experimentally the need to weight the particle distribution by the optical scattering efficiency. We show that it is possible through light scattering to monitor the particle size distribution simultaneously with the acoustic measurement.

1. Introduction

Optical methods that can be used for acoustic velocity field measurements [1] have been studied for nearly 40 years; for acoustical metrology applications, photon correlation spectroscopy has been investigated as a potential new primary standard. The technique relies on seeding the air with small particles which move with the acoustic vibration. Light projected into the sound field is scattered from these particles and the optical signal analysed to deduce the velocity and thence the pressure. The existing primary standard is based on the reciprocity principle [2] which yields the device sensitivity in V/Pa. Coupler reciprocity offers typical uncertainties between 0.03 dB and 0.1 dB in the range from 500 Hz to 20 kHz [3,4] while mathematical corrections [5] applied to convert the sensitivities to free-field equivalents contribute additional uncertainties between 0.02 dB and 0.33 dB. Alternatively, free-field reciprocity can be attempted directly [6] with typical uncertainties in the region 0.07–0.15 dB [7]. In comparison, photon correlation spectroscopy offers typical uncertainties of about 0.5 dB at present [8,9].

Compared to reciprocity the optical approach does however offer unique advantages. Apart from realizing the acoustic pascal with direct traceability to natural constants, it is applicable to all microphones of all geometries and it can be used for free field calibration. It should be noted that reciprocity-based calibrations are only applicable to a very limited number of condenser microphones in terms of dimensions and types. However, even excluding the deleterious effects of advection of the air [10], using laser Doppler velocimetry for airborne acoustics is challenging. On the one hand, the particle motions are very small (amplitudes of a few microns for even quite loud sound fields) while on the other the accelerations are very large (hundreds of m/s^2 at higher frequencies). Because air has a low viscosity these large accelerations mean that the tracking particles should not be too big otherwise they will not faithfully follow the acoustic vibrations. However, this low viscosity also means that the diffusion coefficient is high so if the particles are too small they will move around under thermal agitation and this can mask the scattered light signal due to the acoustic vibrations. In previously reported work a variety of materials have been used as scattering particles. These include smoke from tobacco [11] and sandalwood [8] as well as atomized liquids from commercial fog generators [9]. The particles in these situations are often very poorly characterized in terms of their size distribution, as well as their refractive index and density.

In this note we focus on the role of particle size. We first use a computer model that allows for quantitative investigations and can clearly delineate the range of particles that should be used to attain a prescribed accuracy of measurement. We report experimentally determined particle size distributions of two common seeding particles and show their effect on acoustic measurement. We finally show how it is feasible to monitor the particle size optically and simultaneously with the acoustic measurements.

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2. Modelling the effect of particle size on optical measurement

The effects of size on the fidelity of particles tracking the flow of fluids has been extensively studied [12,13]. The principal concern has been with the slippage of particles when they become too large or dense and thus unable to follow the flow fluctuations. In the case of very small particles it has been recognized that the diffusion can lead to motion of the tracking particles that is unrelated to the flow under investigation [14].

We consider here a computer model based on the numerical solution of the Langevin equation which gives the particle position as a function of time [15,16]. Once the position is known then the intensity of the scattered light can be computed. In one dimension the Langevin equation in this case is given by

$$m\frac{dv}{dt} = -\gamma v + \gamma v_f + \sqrt{2kT\gamma}W(t) \tag{1}$$

where m is the particle mass, v is the particle velocity, k is Boltzmann's constant, T is the absolute temperature and W(t) is a Wiener process. γ is the drag coefficient and given by $\gamma = 6\pi\mu r$ with μ the dynamic viscosity ($\sim 18 \times 10^{-6}$ Pa s for air) and r is the particle radius. v_f is the fluid velocity where

$$v_f(t) = v_m \sin(\omega t)$$

with ω the acoustic angular frequency and $v_m = a_m\omega$ the velocity amplitude where a_m is the amplitude of the acoustic vibration. Eq. (1) is written ignoring the effect of the displaced fluid and the Basset history term. These simplifications are appropriate given the great difference in density between most seeding particle materials and the surrounding air [13].

Eq. (1) can be written in a finite difference scheme

$$m\frac{x_i - 2x_{i-1} + x_{i-2}}{(\Delta t)^2} = -\gamma\frac{x_i - x_{i-1}}{\Delta t} + \gamma v_m \sin(\omega t_{i-2}) + \sqrt{2kT\gamma}\frac{w_i}{\sqrt{\Delta t}}$$

where Δt is the time increment and the random numbers, w_i, are drawn from a zero mean, unit variance Gaussian distribution. This difference equation can then be solved iteratively [16] to get the particle position.

When the particle position is known it can be used to calculate the intensity of the scattered light. In the discussion that follows here we consider using a Doppler system where two laser beams are crossed in the flow to form a fringe pattern and only one particle at a time moving through the fringe pattern. If the particle position as a function of time is given by $x(t)$ the intensity of the scattered light is

$$I(t) = \frac{1}{2}(1 + \cos(Kx(t)))$$

where K is the fringe pattern wavenumber

$$K = \frac{4\pi\sin(\theta)}{\lambda}$$

and θ and λ are the half-angle between the intersecting beams and wavelength of the light, respectively.

Once the optical signal due to the particles moving through the air has been generated this can be processed to see if one can recover the original particle velocity. There are a number of processing methods available to do this (summarized in Ref. [17]) and here we choose to focus on the autocorrelation method of signal analysis, which is compatible with the lower seeding densities generally used with acoustic flows [9,11,18,19]. It can be shown that the oscillatory part of the autocorrelation function of the light intensity for a sinusoidal motion of the scattering particle takes the form

$$R(\tau) \propto J_0\left(\frac{2Kv_m}{\omega}\sin(\omega\tau/2)\right) \tag{2}$$

where J_0 is a Bessel function of the first kind and τ is the autocorrelation lag time. In practice the sine term can often be replaced with its argument and the velocity amplitude obtained by locating the first minimum of the Bessel function.

We ran the computer simulation to examine the effect of different diameter particles for a range of acoustic frequencies up to 20 kHz. For each setting of the velocity amplitude we generated the corresponding optical intensity autocorrelation function and from that estimated the velocity amplitude *via* Eq. (2). Fig. 1 plots the ratio of the velocity amplitudes deduced from the autocorrelation function to the true amplitudes as a function of the particle size.

We see that at high frequencies larger particles lead to an under-estimate of the true acoustic velocity. This is expected, as the inertia of the larger particles leads to slippage between the particle and the air. However, we also found that very small particles led to an *over-estimate* of the acoustic velocity. The cause of this over-estimate is apparent when one examines the output correlation function where it is seen that the diffusion of the smaller particles causes a damping of the correlation function and moves the first minimum of the Bessel function in Eq. (2) toward shorter correlation times and this manifests itself as a higher velocity. The key point to emerge from the simulation is that the particle diameters must be fairly tightly constrained if the sound velocity amplitude is to be accurately measured across the whole acoustic range. From Fig. 1 we see that this range, at 110 dB SPL, is a particle diameter of about 0.5–0.8 µm.

3. Measurement of particle size and effect of particle size on scattered light

To experimentally examine the effects of particle size in acoustic measurement we used the National Physical Laboratory facilities described previously [9]. Briefly, these are comprised of an anechoic chamber with small holes in the side permitting focussed light beams from a $\lambda = 532$ nm DPSS laser to enter and intersect with a half angle of 18.5°. Back-scattered light exits through another hole and is collected using a 25 cm focal length, 2 cm diameter lens onto a Perkin Elmer (now Excilitas) APD photon counting module through a 35 µm diameter pinhole. With the power in each laser beam about 300 mW and with the seeding as described below, some 10^4–10^6 photo-counts per second are generated. Photo-counts were processed using a Brookhaven TurboCorr correlator. Sound fields were generated within the chamber using a horn loudspeaker, allowing fields of up to 120 dB at the optical measurement position.

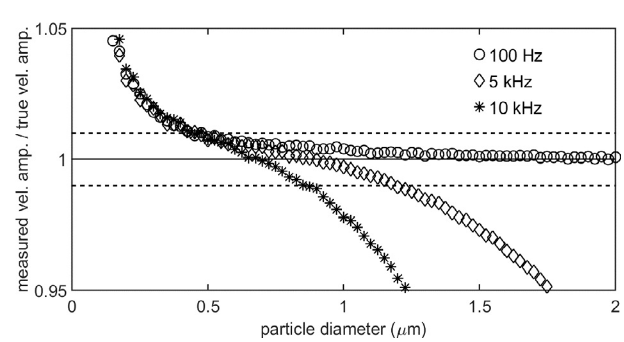

Fig. 1. Results of the computer simulation showing the ratio of the measured to the known velocity amplitudes as the particle diameter is varied. The simulation uses a fringe spacing of 0.5 µm, at a temperature of 300 K. The simulation is reported for three different frequencies with velocity amplitudes of 22 mm/s. These amplitudes correspond to a sound pressure level of 110 dB (re 20 µPa). The dashed lines show the range for which the measured velocity amplitudes are within 1% of the true velocity, corresponding to an uncertainty in the sound pressure level of 0.1 dB.