Gated photon correlation spectroscopy for acoustical particle velocity measurements in free-field conditions

Triantafillos Koukoulas, Ben Piper and Pete Theobald

Citation: The Journal of the Acoustical Society of America **133**, EL156 (2013); doi: 10.1121/1.4789006
View online: https://doi.org/10.1121/1.4789006
View Table of Contents: https://asa.scitation.org/toc/jas/133/3
Published by the Acoustical Society of America

Gated photon correlation spectroscopy for acoustical particle velocity measurements in free-field conditions

Triantafillos Koukoulas,[a] Ben Piper, and Pete Theobald
Acoustics Group, National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, United Kingdom
triantafillos.koukoulas@npl.co.uk, ben.piper@npl.co.uk, pete.theobald@npl.co.uk

Abstract: The measurement of acoustic pressure at a point in space using optical methods has been the subject of extensive research in airborne acoustics over the last four decades. The main driver is to reliably establish the acoustic pascal, thus allowing the calibration of microphones with standard and non-standard dimensions to be realized in an absolute and direct manner. However, the research work so far has mostly been limited to standing wave tubes. This Letter reports on the development of an optical system capable of measuring acoustic particle velocities in free-field conditions; agreement within less than 0.6 dB was obtained with standard microphone measurements during these initial experiments.

PACS numbers: 43.58.Dj, 43.20.Ye, 43.58.Fm [DC]
Date Received: October 8, 2012 **Date Accepted:** January 7, 2013

1. Introduction

The acoustic pressure at a particular point in space is measured with microphones that produce an electrical output that is proportional to the acoustic pressure in the sound field. Microphones are calibrated using either the coupler reciprocity[1] or free-field[2] reciprocity calibration method that yields the sensitivity of the microphone (dB re 1 V/Pa) over a standard frequency range. However, the existing calibration techniques are only applicable to 1″ and 1/2″ laboratory and working microphones. With this in mind, there is no calibration method applicable to other types of microphones such as 1/4″, 1/8″, 1/16″, and microelectromechanical sytems (MEMS). Neither method realizes the acoustic pascal, and therefore they may seem to be indirect methods when it comes to the realization of the unit of acoustic pressure.

The accurate non-perturbing measurement of acoustic particle velocity, and hence acoustic pressure, using optical methods has been of interest in the field of airborne metrology since the mid 1970s following the work of Taylor.[3] Taylor demonstrated that acoustic pressure could be accurately measured in a standing wave tube (SWT) at a velocity antinode using the Doppler effect of laser light. During the last four decades, a range of optical techniques have been proposed as suitable methods to quantify the acoustic pressure inside SWTs. These have included laser Doppler anemometry and laser Doppler velocimetry (LDA and LDV, respectively), particle image velocimetry (PIV), and photon correlation spectroscopy (PCS).

LDA[4,5] and LDV[6,7] use two laser beams, one which is frequency shifted, that cross to produce moving interference fringes. The demodulation of the resulting FM signal can yield the acoustic particle velocity. PIV[8,9] illuminates a two-dimensional plane and by using a high speed camera, the motion of airborne particles are captured in sequence so that their velocity can be deduced. PCS[10,11] uses two laser beams, both

[a]Author to whom correspondence should be addressed.

un-shifted, that again cross to produce static fringes. By auto-correlating scattered photon sequences, the particle velocity can be measured.

The research work reported in the literature has concentrated on different aspects of the problem at hand (signal processing techniques, seeding, etc.), but all the approaches so far have mostly focused on conditions inside SWTs and open air,[12] but not fully anechoic environments. Measurements in a fully anechoic chamber, necessary for the free-field calibration of a microphone, introduce a number of particular challenges which have to be overcome. In this case, the optical probing would take place at a specific point in space; however, due to the free-field propagation of sound, different velocity components would be present in the optical measurement area. The air flow inside the chamber would impose additional random velocity components that can effectively be averaged with the sound, thus making it difficult to decouple them. Another issue is to clearly design and implement a system that can be installed outside the chamber so that it would not disturb the sound field; in this case, challenges relate to the inverse square law imposed on the received optical signal, in addition to accurately focusing and crossing laser beams over large distances. In order to increase the photon scatter, small amounts of seeding particles (tracers) are used. However, their introduction may cause additional temperature gradients in the natural air flow within the chamber; their size and mass also affect the time during which they remain airborne and are able to facilitate the optical measurements.

If all these obstacles could be minimized, then the absolute realization of the acoustic pascal at a point in free-field space could take place. Then, any microphone of standard and nonstandard dimensions could be placed at the same point, therefore allowing for its free-field calibration to be made in a direct sense. The work reported in this Letter outlines the development of an optical system based on gated PCS, with the potential to achieve this purpose.

2. Optical delivery and collection system

Figure 1 (not to scale) shows the experimental arrangement of the system. The fully anechoic acoustic chamber itself has a volume of approximately 9 m^3, with absorbent wedges placed along all of its walls, floor, and ceiling. The entire optical system was placed outside the acoustic chamber.

The light source was a frequency-doubled Nd:YAG (neodymium-doped yttrium aluminum garnet) diode laser with a wavelength of 532 nm and optical power of 300 mW. The beam splitter divides the main beam into two beams of equal intensity and polarization. Using adjustable mirrors, the beams were directed via small openings

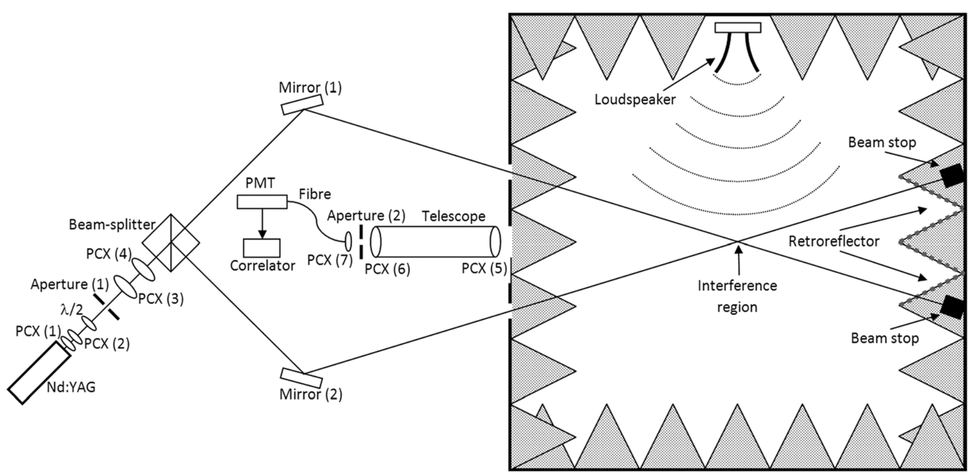

Fig. 1. The experimental optical system and acoustic chamber configuration.

on the wall of the acoustic chamber so that they crossed to produce an ellipsoid volume full of interference fringes at the center of the chamber. Two small telescopic arrangements (PCXs 1-2 and PCXs 3-4) were used so that the focal waist of the intersecting beams inside the chamber was 2 mm. The half angle of the beams intersection was 9.8°, the dimensions of the ellipsoid volume were 2 mm × 11 mm × 2 mm, the fringe spacing was 1.6 μm, and the number of fringes was 1300. The loudspeaker (TOA SC-630 horn speaker; Canford Audio PLC, Washington, UK) inside the acoustical chamber was placed near one of its walls such that the sound field propagation axis and the bisector of the two laser beams were perpendicular to each other. As sound propagates, particles present in the room cross the fringes, therefore producing scattered photons.

The collection part of the system was based on back-scattered radiation. A refracting telescope was aimed at the laser cross-over region (via an additional small opening in the chamber wall) effectively magnifying the image on the eye-piece. An achromatic lens was then used to focus the produced image onto a single mode optical fiber matched to the wavelength of the source. The other end of the fiber was fitted with a small collimator unit that was then optically linked to a photo-multiplier tube (PMT) capable of producing individual photon sequences. In order to increase the intensity of the optical signal, the wedges in the area between the terminated beams inside the chamber were lined up with retro-reflective tape.

3. Estimation of acoustic particle velocities and signal processing

In order to measure the particle velocity due to sound, it is necessary to calculate the auto-correlation function (ACF) of the received photon sequences resulting from the PMT using a suitable hardware correlator board. The theoretical form of the ACF is given by[13]

$$R(\tau) = \left(kE[K_p]g_0 \int_{-\infty}^{+\infty} W(\beta y)(1+\cos Dy)\,dy \right)^2 + \frac{k^2 E[K_p^2]g_0}{2} \int_{-\infty}^{+\infty} \rho_n(y;\tau) R_w(\beta y)(1+\cos Dy)\,dy, \tag{1}$$

where k is a constant that relates to the optical power of the system and the sensitivity of the photo-detector, $E[\,]$ is the expectation operator, K_p characterizes the particle scattering cross section, g_0 is the average number of particles per unit length within the optical measurement volume, $W(\beta y)$ and $R_w(\beta y)$ represent the spatial weighting function representing the Gaussian envelope of the interference fringes and its auto-correlation function, respectively, $\rho_n(y;\tau)$ is the probability density function that relates to the acoustic particle velocity amplitude and frequency, and D relates to the half angle of the intersecting laser beams and the wavelength of the light source. A detailed mathematical analysis[14] of this equation, concludes that the ACF is approximated by a Bessel function and the acoustic velocity is inversely proportional to the time it takes to reach its first minimum ($t_{\min}$)

$$a_m = \frac{3.832\lambda}{4\pi(\sin\theta)t_{\min}}, \tag{2}$$

where λ is the wavelength of the light source and θ is the half angle between the intersecting laser beams.

4. Comparison between optical and microphone measurements

By experimentally acquiring gated ACFs corresponding to different parts of the acoustic cycle, it is possible, via Eq. (2), to obtain a profile of the particle velocities throughout the cycle. This profile will, naturally, follow the sinusoidal nature of the acoustic excitation. In a hypothetical case where there is no mean flow, the peaks of the profile, just like its troughs, would always be of the same amplitude, resulting in the same particle velocity. However, in the presence of mean flow, the peaks and troughs will not be of equal amplitude and it is necessary to decouple the flow from the acoustic velocity. This is done by calculating the difference between the peaks and correcting the peaks so that they are of equal magnitude.

In terms of seeding, the diameter of the chosen particles has to be smaller than the fringe spacing and their mass sufficiently small so that they will remain airborne during measurements. The most suitable candidate in this case would be particles from incense smoke,[15] especially with regard to the diameter (fractions of a μm). In fact, for small volumes offered by SWTs, smoke from incense sticks has been used in the literature. However, for a large volume inside the free-field chamber, this approach is not quite feasible as the particles tend to dissipate rather quickly. Instead, short duration bursts resulting in aerosol particles from a commercial fog generator were introduced. Afterward, the room was closed and at least one hour elapsed before measurements were taken. This allowed the introduced tracers to spread uniformly within the chamber, which in turn produced quite a uniform number of particles per unit area as well as reduced temperature gradients. Also, the elapsed time allowed only the smaller particles to remain airborne, thus providing the opportunity to use particles with sizes less than the fringe spacing of the measurement volume.

Regarding the experiments, Fig. 2 shows gated free-field ACFs resulting from the positive and negative parts of a 1 kHz pure tone. By calculating the time it takes each ACF to reach its first minimum, the mean flow was decoupled, thus enabling the estimation of the acoustic particle velocity and, hence, pressure. Measurements were performed over the frequency range 1 to 4 kHz in increments of 500 Hz and in each case the sound pressure level (SPL) was calculated in dB (re 20 μPa) for the optical method.

Following this, a 1/2″ microphone previously calibrated using pressure reciprocity was placed at exactly the same point where the optical measurements took place and exposed to the same tones using the horn loudspeaker. The required free-field corrections[16] were applied to the sensitivity data from the microphone calibration. Table 1 shows a comparison between the optical method and the microphone measurements. The bin size was the time interval over which the hardware board captures photon sequences which are auto-correlated. The duty cycle of the gating pulses was set to

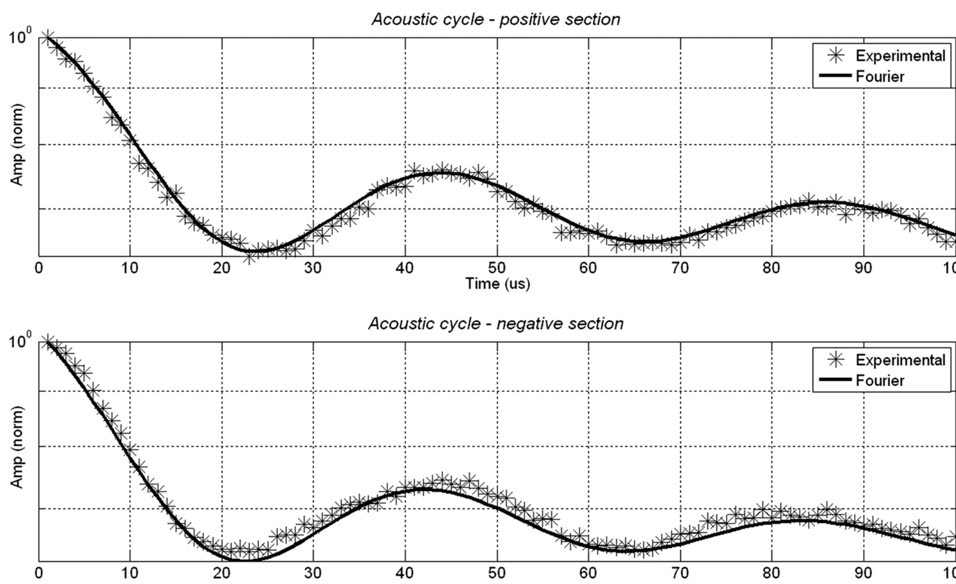

Fig. 2. Experimental gated ACFs from the positive and negative sections of a 1 kHz pure tone.

Table I. Measured particle velocities using the optical method and comparison with microphone.

Frequency (kHz)	Bin size (μs)	Particle velocity (mm s^{-1})	Pressure root-mean-square (Pa)	Optical SPL (dB)	Microphone SPL (dB)	Difference (dB)
1.0	1.0	39.04	11.39	115.11	115.56	−0.45
1.5	1.0	27.97	8.16	112.22	112.69	−0.47
2.0	1.0	35.98	10.50	114.40	114.22	+0.18
2.5	0.5	38.36	11.19	114.96	115.15	−0.19
3.0	0.5	14.83	4.33	106.71	106.96	−0.26
3.5	0.5	27.53	8.03	112.08	111.57	+0.51
4.0	0.5	26.30	7.68	111.68	112.28	−0.59

90° of the acoustic cycle. The agreement between the two methods is fairly reasonable and the disagreement seems to be of random nature.

There are a number of factors that contribute to the discrepancy. The duty cycle of the gating pulses can influence the accuracy of decoupling the acoustic velocity from the mean flow. In theory, the shorter the gate is, the less the mean flow contributes to the acoustic velocity measurement. However, shorter gate durations also mean less photons that can be auto-correlated. This can result in a noisy ACF thus decreasing the accuracy of velocity measurements, or it may make it very difficult to obtain an ACF. Another source of error could also be due to the seeding. Though the amounts of seeding particles used in the chamber were minimal, the fact that the tracers are in the form of vapor particles might slightly increase the humidity of the air thus causing a slight deviation (possibly 1st or 2nd decimal place) to the value of the speed of sound. An additional source of error might include a possible slight misalignment of the microphone's diaphragm to the optical measurement point.

5. Discussion

In previous standing wave tube experiments,[11] the level of received photons was, on average (depending on the level and kind of tracers), in the vicinity of 5×10^6 counts per second (5 Mcps). Also, the collecting optics were positioned quite close to the standing wave tube in order to reduce optical losses due to the inverse square law. For a pure tone of 1 kHz, the duration of the gating pulse with 90° duty cycle would be 250 μs, thus 1250 photon events were present within each gate. In the free-field measurements reported here, the average photon levels were, on average, 30 000 counts per second (30 kcps). Using the above gating example, there were approximately seven photon events within each gate. For acoustic frequencies of 4 kHz, there were approximately only two photons present per gate.

This clearly highlights the sensitivity of the spectroscopic system as it relies on an extremely small number of photons to yield the acoustic velocity and works well over the large distances required. At present, it could well be the case that the upper frequency limit of 4 kHz is not only due to the distortion of the sound source, but also because at least two photons are required per gate. Clearly, more seeding would produce more scattered photons, but this would increase the density of the measurement medium relative to air. Increasing the sensitivity of the collection system (larger magnification on the Keplerian telescope in order to capture more photon events), increasing the number of interference fringes (increasing the probability of scattering), or even using more optical power could result in more received photon levels without the introduction of additional seeding.

The next step of this research will experiment with different physical characteristics of the ellipsoid interference region in order to achieve the best resolution on the optical measurement system. Following, the system will be installed at National Physical Laboratory's large fully anechoic chamber with a lower frequency limit of 125 Hz;

in this case, full optical calibrations with standard and non-standard microphones (including MEMS) will be attempted and compared with the existing calibration methods. It is anticipated that spectroscopy can provide a reliable basis for a new optical free-field calibration standard applicable to all microphones.

Acknowledgments

This work was funded by the National Measurement Office of the UK Department of Business Innovation and Skills. Reproduced by permission of the Controller of HMSO and Queen's printer for Scotland.

References and links

[1]IEC 61094-2:2009, Measurement microphones—Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique.
[2]IEC 61094-3:1995 Measurement microphones—Part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique.
[3]K. J. Taylor, "Absolute measurement of acoustic particle velocity," J. Acoust. Soc. Am. **59**(3), 691–694 (1976).
[4]T. MacGillivray, D. Campbell, C. Greated, and R. Barham, "The development of a microphone calibration technique using laser Doppler anemometry," Acta Acust. **88**, 135–141 (2002).
[5]M. W. Thompson and A. A. Atchley, "Simultaneous measurement of acoustic and streaming velocities in a standing wave using laser Doppler anemometry," J. Acoust. Soc. Am. **117**(4), 1828–1838 (2005).
[6]B. Gazengel, S. Poggi, and J. C. Valiere, "Evaluation of the performance of two acquisition and signal processing systems for measuring acoustic particle velocities in air by means if laser Doppler velocimetry," Meas. Sci. Technol. **14**, 2047–2064 (2003).
[7]A. Degroot, R. MacDonald, O. Richoux, B. Gazengel, and M. Campbell, "Suitability of laser Doppler velocimetry for the calibration of pressure microphones," Appl. Acoust. **69**, 1308–1317 (2008).
[8]M. Campbell, J. A. Cosgrove, C. A. Greated, S. Jack, and D. Rockliff, "Review of LDA and PIV applied to the measurement of sound and acoustic streaming," Opt. Laser Technol. **32**, 629–639 (2000).
[9]B. Gazengel, and S. Poggi, "Measurement of acoustic particle velocities in enclosed sound field: Assessment of two laser Doppler velocimetry measuring systems," Appl. Acoust, **66**, 15–44 (2005).
[10]T. MacGillivray, D. Campbell, C. Greated, and R. Barham, "The development of a microphone calibration technique using photon correlation spectroscopy," Acta Acust. **89**, 369–376 (2003).
[11]T. Koukoulas, P. Theobald, T. Schlicke, and R. Barham, "Towards a future primary method for microphone calibration: Optical measurement of acoustic velocity in low seeding conditions," Opt. Lasers Eng. **46**, 791–796 (2008).
[12]B. Gazengel, O. Richoux, and P. Rouquier, "Characterisation of a loudspeaker free field radiation by laser Doppler velocimetry," Acta Acust. **93**, 447–456 (2007).
[13]T. S. Durrani, and C. A. Greated, *Laser Systems in Flow Measurement* (Plenum, New York, 1977).
[14]J. P. Sharpe, and C. A. Greated, "A stochastic model for photon correlation measurements in sound fields," J. Phys. D **22**, 1429–1433 (1989).
[15]Y. S. Cheng, W. E. Bechtold, C. C. Yu, and I. F. Hung, "Incense smoke: Characterisation and dynamics in indoor environments," Aerosol Sci. Technol. **23**, 271–281 (1995).
[16]IEC 61094-7:2006, Measurement microphones—Part 7: Values for the difference between free-field and pressure sensitivity levels of laboratory standard microphones.