ILLUMINATING SOUND: A REVIEW OF HOW SOUND CAN BE MEASURED USING LIGHT

B Piper National Physical Laboratory, Teddington, Middlesex, UK
T Koukoulas National Physical Laboratory, Teddington, Middlesex, UK
I Butterworth National Physical Laboratory, Teddington, Middlesex, UK

1 INTRODUCTION

There are many applications that make use of the interaction between light and sound from acousto-optic tunable filters used in confocal microscopy to the stimulation of acoustic waves in photo-acoustic devices. This paper will focus on the application of light to measure sound in air and in particular two possibilities, non-invasive sensing of the absolute particle velocity at a single point and measurements of the spatial characteristics of sound fields. The latter set of methods are often more qualitative than quantitative in their outcomes, although there are several recent examples of quantitative measurements under specific conditions, and these lend themselves well to exploring the relative qualities of sound such as directivity and scattering patterns. Most of the methods covered here are flow measurement and visualization techniques which have been adapted for oscillating fields. The methods discussed are all modern methods developed in the last 40 years, although there are older methods such as Schlieren imaging which are mentioned to give a reference point. This paper is intended as an overview of modern methods in their current state rather than a comprehensive and complete literature review.

2 ABSOLUTE MEASUREMENTS AT A SINGLE POINT

Measurements of sound that are made with microphones or other direct measurement devices are always subject to the effects of the device on the radiating sound. It is the classic observer effect problem and the reason for 'type of field' corrections ('free field', 'pressure field' and 'diffuse field'). Therefore it is beneficial to measure sound in a non-invasive manner. This can be achieved by exploiting the effects of sound on light. Since Taylor[1] there have been several pieces of research in this area, where a number of different techniques have been explored. The majority of these methods have only been implemented with any degree of success in standing wave tubes although there has been some recent success in applying Photon Correlation Spectroscopy to measurements in an acoustic free field chamber.

2.1 Laser Doppler Anemometry and Laser Doppler Velocimetry

2.1.1 What is it?

Laser Doppler Anemometry (LDA) and Laser Doppler Velocimetry (LDV) are two highly related optical heterodyne methods which measure flow velocity through analysing the Doppler shift of laser light. They make use of two beams that are crossed to form an interference region. One of these beams is modulated which gives a frequency modulated signal which is then demodulated to give the Doppler shift and hence velocity.

2.1.2 How has it been used to measure sound?

Figure 2.1, from Taylor[1], shows a typical setup used for measuring sound using LDA in a standing wave tube. Sound is delivered by a speaker fixed at one end of the tube creating a standing wave pattern where acoustic velocity remains constant at a given point. Two laser beams are then crossed at a measurement point where one is a frequency shifted version of the other. This creates a modulating optical interference pattern. As particles that are driven by the acoustic field cross the interference region they scatter light causing a Doppler shift in the light to occur. This is then detected using a photodiode or other similar light detector. These measurements were subject to extremely poor signal to noise conditions, and were unable to challenge microphone measurements.

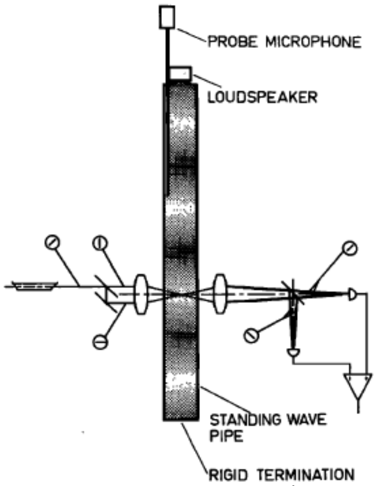

Figure 2.1 - Schematic of LDA set-up, from Taylor[1], for measuring acoustic particle velocity in a standing wave pipe.

The most recent research in applying this method to the measurement of sound can be found in MacGillivray[2], Thompson[3], Gazengel[4], Degroot[5], Campbell[6] and Gazengel[7]. All of these experiments apply the technique in standing wave tubes with a focus on the possibility of using the technique to calibrate the sensitivity of measurement microphones.

2.1.3 What are the key strengths and weaknesses?

LDA and LDV are relatively simple optical systems to implement in air and they can give high quality measurement of the magnitude and direction of an acoustic flow. The main disadvantage of such systems is that they require the introduction of a large amount of seeding particles, which changes the fundamental properties of the fluid, in order to have a high enough sensitivity to detect acoustic velocities. This has meant that successful measurements outside a standing wave tube, such as in a free field, are difficult to achieve and involve significant manipulation of the properties of air present in the field.

2.2 Photon Correlation Spectroscopy

2.2.1 What is it?

Photon correlation spectroscopy (PCS) is a method for measuring particle velocity by capturing a stream of photons scattered from an optical interference region created by two beams of coherent unmodulated laser light. The optical interference region contains lines of light and dark, known as fringes, which is analogous to comb filtering in an acoustic field. As a particle moves through this pattern, photons are scattered with a periodicity directly related to the velocity of the moving particle.

2.2.2 How has it been used to measure sound?

Early working applying PCS to acoustic fields can be found in Barnes[8], Greated[9] and Sharpe[10, 11, 12]. The development of a stochastic model[13] in 1989 details the maths behind the technique showing that the acoustic velocity can be found from the time to the first minima in the autocorrelation function according to Equation 2.1 where a_m is the velocity amplitude, *D* is the Doppler frequency to velocity conversion factor, which is dependent on the angle at which the beams are crossing, and τ is the time shift of the first minima in the autocorrelation function.

$$a_m = 3.832/D\tau \quad \text{(Equation 2.1)}$$

Like LDV, PCS requires seeding particles to be added to the measurement space. It was shown in Koukoulas[14] that PCS requires only minimal seeding to work effectively giving it a distinct advantage over LDA when applying optical methods to the calibration of microphones.

Almost all measurements of this type were conducted in standing wave tubes until recent advances have allowed for it to be applied to measurements in an acoustic free field. Details of the first application to a free field can be found in Koukoulas[15] where the frequency range was very limited due to the sensitivity of the optical set-up and the limitations of the audio system. Advances to both aspects allowed the frequency range to be extended up to 8 kHz in Piper[16]. This has been increased further with the most recent results showing that it is possible to measure up to 20 kHz. Reaching the upper frequencies does require large sound pressure levels and requires an efficient audio system such as a high power compression driver coupled to a horn.

Figure shows a PCS set-up for measurements in a free field. The optical components are placed outside the free-field chamber and the light is passed through the chamber walls to the focal point inside the chamber. The scattered photons are then collected by a Keplerian telescope coupled to an avalanche photo diode by a single mode optical fibre matched to the wavelength of the laser light. The stream of photons is auto correlated in order to find the periodicity and hence the acoustic particle velocity.

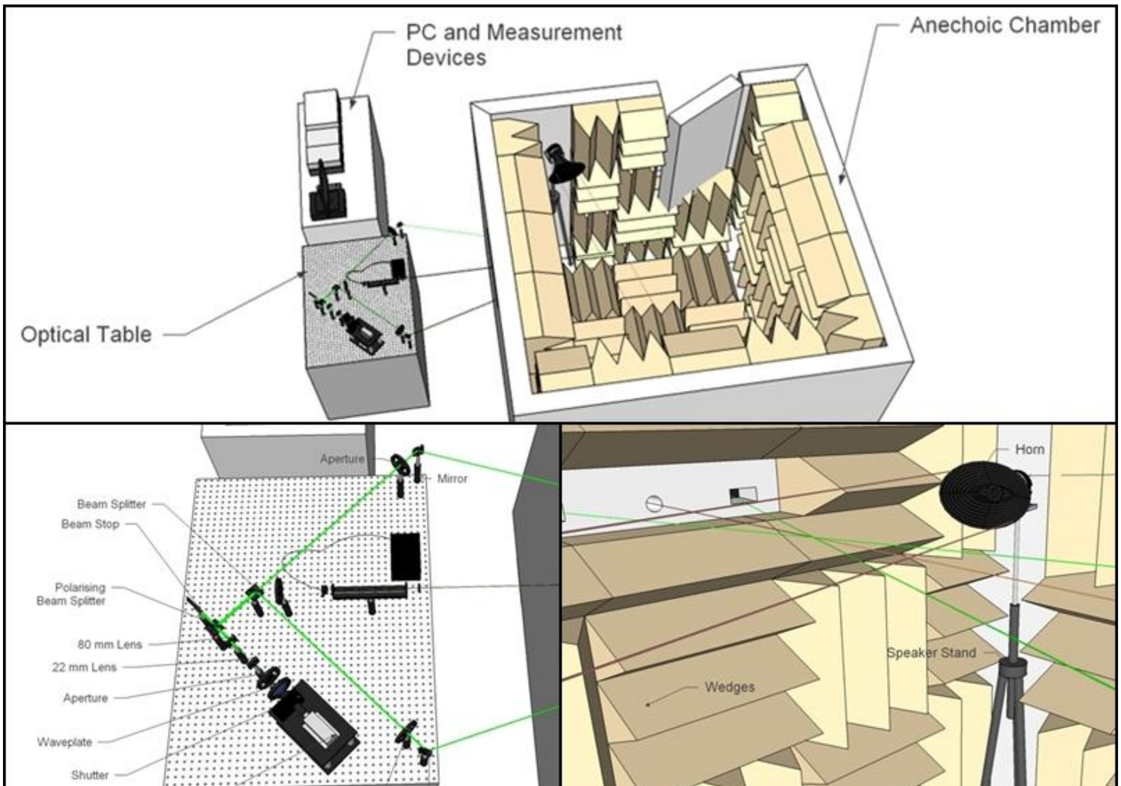

Figure 2.2 - Views of Photon Correlation Spectroscopy set-up for measurements in an acoustic free field - Whole system (top), Optical table (bottom left), Inside free field chamber (bottom right)

2.2.3 What are the key strengths and weaknesses?

The key advantage of PCS is that it requires very little seeding and therefore the properties of the air in which the measurements are taking place are not altered significantly. The speed of sound is changed in the order of +/- 0.001ms^{-1} which has a negligible effect of the measured velocities. High levels of seeding can actually prevent PCS working correctly in a free field as the level of optical absorption becomes too high for the telescope to collect enough scattered light from the interference region. The key weakness of using PCS to measure acoustic particle velocity is that it can only give a measure of the magnitude of a velocity.

3 2D AND 3D SOUNDFIELD VISUALISATION USING REFRACTO-VIBROMETRY

The use of light to map the distribution of sound in 2D fields has been in existence for more than 300 years going back to the first experiments in Schlieren imaging and shadowography[17]. Schlieren imaging is a method of recording flows by comparing the deflection of light caused by a refractive index gradient to undeflected light. Shadowgraphy is very similar to Schlieren however it is a measure of the shadows caused by inhomogeneities in a transparent media rather than the deflection of light caused by refractive index changes. Figure 3.1 shows examples of the types of images that can be generated from these techniques focussing on the shockwaves generated by bullets. Both of these techniques have received a large amount of attention in literature so it is beyond the scope of this paper to give full reviews of either.

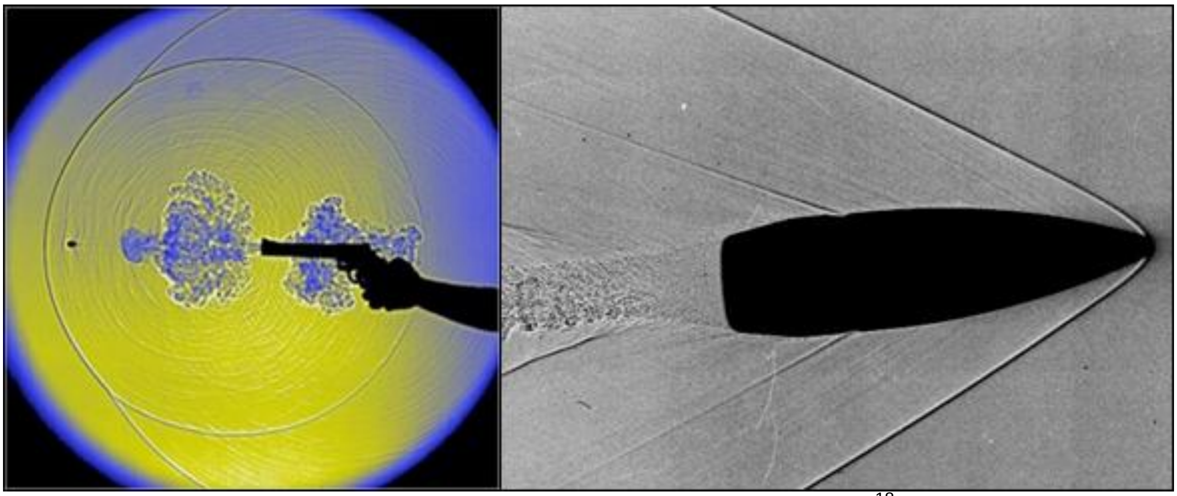

Figure 3.1 - Examples of the images generated by Schlieren Photography[18] (left) and Shadowgraph Photography[19] (right).

Modern techniques that have been enabled by advances in computing and hardware technologies include Particle Image Velocimetry (PIV), TV Holography, Digital Speckle Photography (DSP) and Refracto-vibrometry which is a form of LDV. A number of these methods have been explored as methods for measuring the radiation of sound from instruments[20, 21, 22] with a variety of results shown. This section will focus on Refracto-vibrometry since it appears the most promising of these techniques for a variety of applications and there have been a number of important recent advancements to this approach.

3.1 Refracto-Vibrometry

3.1.1 What is it?

Refracto-vibrometry uses a form LDV to measure refractive index changes in the air. Typically this type of LDV is applied to measuring the vibration of surfaces. These are often used to explore the behaviour of mechanical systems such as car engines and are readily available as a complete commercial measurement system.

This form of LDV is different from the type discussed in Section 2.1. Instead of crossing the two beams at the measurement location the beams are split inside the measurement device, one is delivered to and reflected back from the measurement surface whilst the other is passed through a Bragg cell and then retained within the device as a reference beam. The return beam is then combined with the reference beam and the demodulation of these combined beams yields a measure of the vibration of the measurement surface. In order to measure a 2D surface the vibrometer uses a mechanical system to scan the measurement beam across the surface of interest. This can be extended further by using a set of 3 vibrometers scanning the surface synchronously creating 3D measurement where the direction of the vibration is known and can be treated as a vector. Figure 3.2 shows a schematic of a vibrometer setup[23].

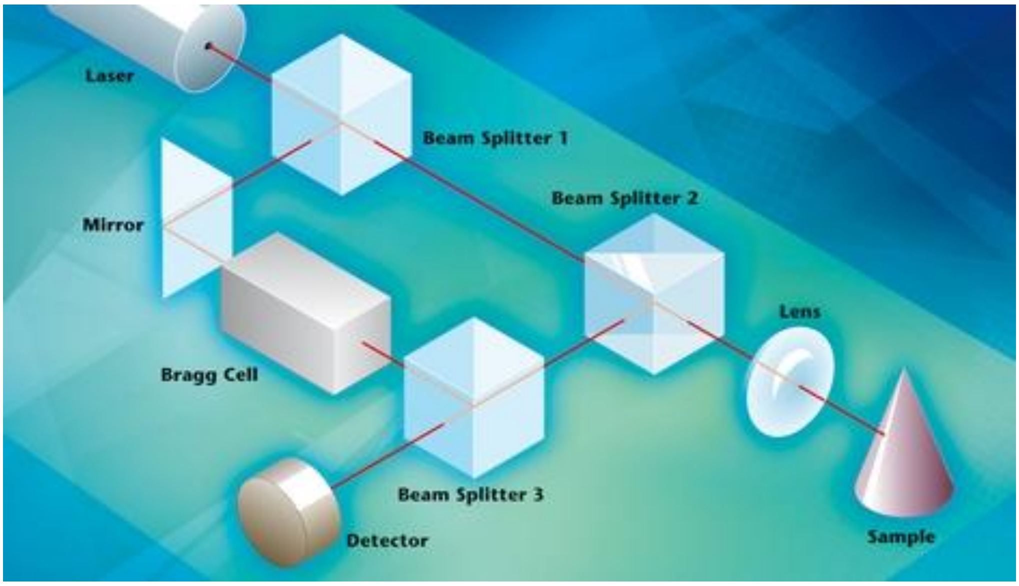

Figure 3.2 - Schematic of Laser Doppler Vibrometer system, courtesy of Polytec Ltd.

3.1.2 How has it been used to measure sound fields?

One of the uncertainties in using this type of LDV to measure a vibrating surface is the effect of pressure variations along the path of the laser light between the vibrometer and the surface. Pressure variations cause changes to the refractive index of air and this can be detected as small Doppler shifts by the vibrometer. As sound is a local variation of pressure this uncertainty can be exploited to measure sound fields. Therefore if the measurement beam is passed through a sound field and reflected by a static reflector the velocity measured by the system is an integral of the velocity found along the path of the laser beam. So long as a suitable reflecting surface is found the beam can then be scanned through the sound field to build an image of the field in one plane. As the light will hit the surface at different angles the surface needs to be retro-reflective. An alternative approach would be to move the sound field relative to the vibrometer and fix the beam and the reflector. This has the advantage of fixing the geometry of the scan and allowing for the vibration of the reflecting surface to be monitored with an accelerometer. In comparison to the scanning approach this set-up needs more equipment making it less quick.

There have been some interesting examples of this methods application to measuring sound fields including examining the effect of cabinet geometry on the radiation of sound from loudspeakers[24]. Another example is shown in Figure 3.3 where the technique has been used to compare the absorption of sound by a wedge shaped piece of foam and a block shaped piece of foam.

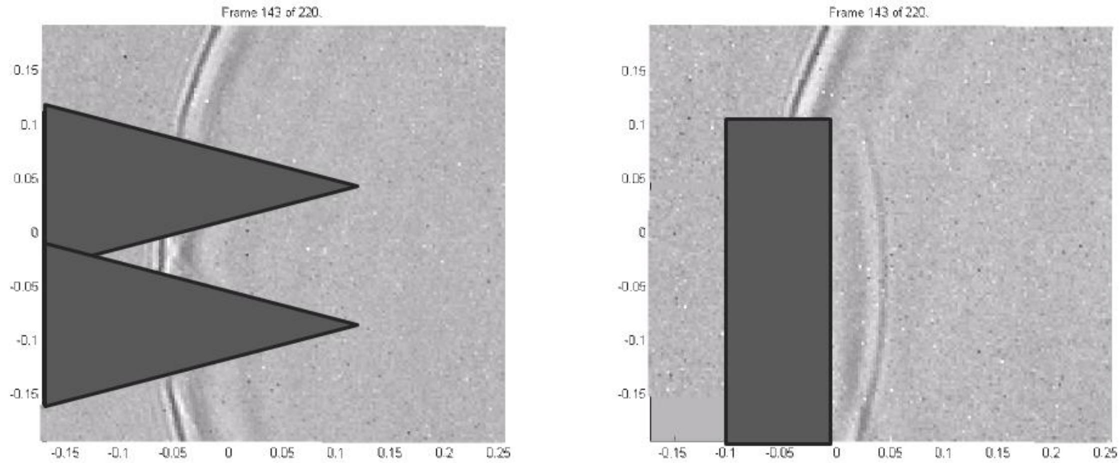

Figure 3.3 - Impulse absorption and reflection by acoustic foam wedges (left) and block (right) recorded using refracto-vibrometry.

These measurements only offer a relative measurement of the sound field and the absolute sound pressure level is not readily measureable without some changes to the method. Work has been done to extract absolute fields using Radon transforms[25] and known source radiation patterns[26]. Both approaches show promise but the set ups are complicated and the types of field measured are currently limited. A further approach is to use computed tomography to reconstruct the 3D sound field and thus extracting the pressures from the line integrals. Figure 3.4 shows an image of the 3D sound field of a loudspeaker generated in this way. To create this measurement the 2D space was measured in front of the loudspeaker for a large number of rotation angles of the loudspeaker. A high power computer was then used to process the large amount data generated by these measurements. Despite this the spatial resolution of the data was still low.

3.1.3 What are the key strengths and weaknesses?

Refracto-vibrometry can generate visualisations of sound fields with a simple set-up and the measurements are relatively quick to make providing a suitable reflective surface is available. They are also free from the disturbances that a microphone array would create. This makes it a useful technique for making like for like comparisons between different sound radiators and scatterers. Vibrometers are commercially available but they are not cheap and therefore access to such equipment is a limitation. Due to the underlying physics it is difficult to obtain objective measurements using refracto-vibrometry although research in this area looking at the use of Radon transforms, computed tomography and sources with known radiation patterns show that the technique has potential.

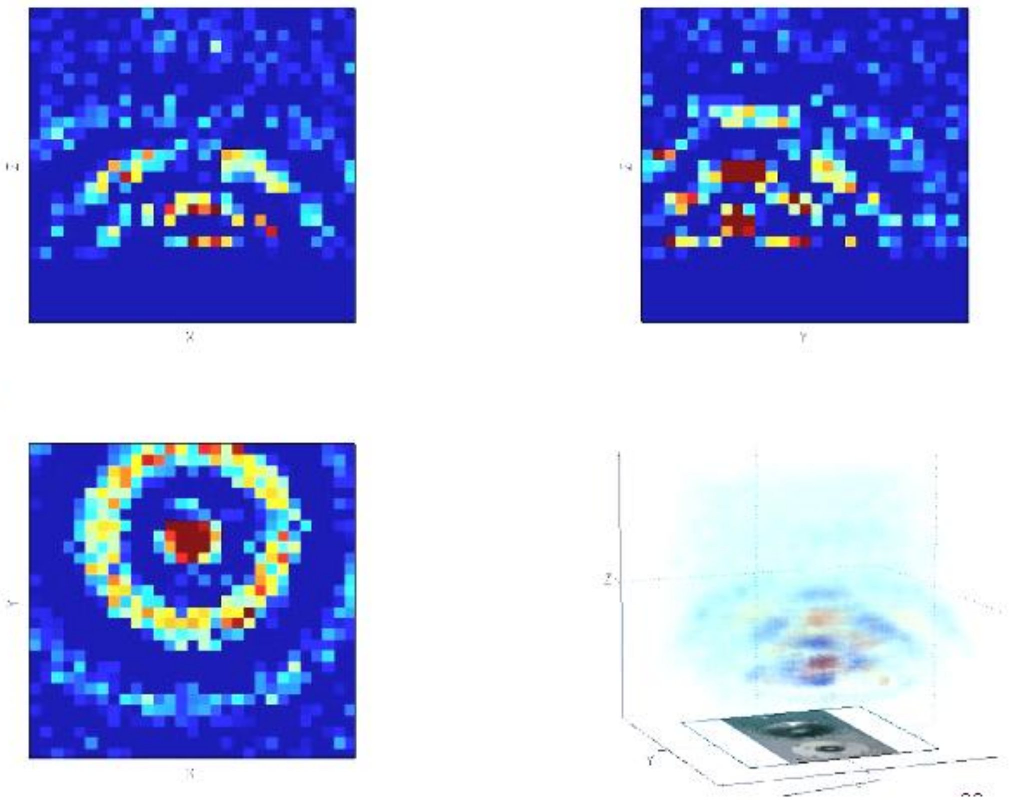

Figure 3.4 - Sections of a Computed Tomographic reconstruction of the sound field radiating from a loudspeaker, XZ plane (top left), YZ plane (top right), XY plane (bottom left), All planes (bottom right).

4 SUMMARY

Using optical methods to measure sound is of interest because it allows measurements of sound without the physical disturbances caused by microphones. Research in this area goes back 300 years to the earliest experiments in Schlieren imaging but it is only the technological advances of the last 60 years, in particular the development of lasers and computer technology, that have allowed a wider range techniques to be developed into viable methods for measuring sound. This paper has discussed a number of techniques with a focus on applying PCS for measuring absolute sound pressure at a single point and the use of LDV in the form of refracto-vibrometry for mapping 2D and 3D sound fields. These methods, whilst not the only ones in current research, show the most promise for the optical realisation of the unit of sound pressure, in the case of PCS, and for the quick and accurate mapping of sound fields, in the case of refracto-vibrometry.

5 REFERENCES

1. K.J. Taylor, Absolute measurement of acoustic particle velocity, J. Acoust. Soc. Am., Vol. 59, No.3, 691-69 (1976).
2. T. MacGillivray, D. Campbell, C. Greated, and R. Barham, The development of a microphone calibration technique using laser Doppler anemometry, Acta Acust. Vol. 88, 135–141 (2002)
3. 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. Vol. 117, No. 4, 1828–1838 (2005).
4. 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. Vol. 14, 2047–2064 (2003).

5. A. Degroot, R. MacDonald, O. Richoux, B. Gazengel, and M. Campbell, Suitability of laser Doppler velocimetry for the calibration of pressure microphones, Appl. Acoust. Vol. 69, 1308–1317 (2008).
6. 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. Vol. 32, 629–639 (2000).
7. B. Gazengel, and S. Poggi, Measurement of acoustic particle velocities in enclosed sound field: Assessment of two laser Doppler Velocimetry measuring systems, Appl. Acoust, Vol. 66, 15–44 (2005).
8. F. H. Barnes, Q. I. Daudpota, C. A. Greated and I. Grant, Application of photon correlation techniques to the measurement of flow with a sinusoidal perturbation, The Physics of Fluids, Vol. 20, No. 2, 211-215, (1977).
9. C. A. Greated, Measurement of acoustic velocity fields, Strain, Vol. 22, No.1, 21-24 (1986).
10. J. P. Sharpe and C. A. Greated, Laser measurement of random and periodic sound fields, Proc. IOA, Vol. 9, No. 3 (1987).
11. J. P. Sharpe and C. A. Greated, The measurement of periodic acoustic fields using photon correlation spectroscopy, J. Phys. D: Appl. Phys. Vol. 20, 418-423 (1987).
12. J. P. Sharpe, C. A. Greated and D. M. Campbell, The measurement of complex acoustic impedance using photon correlation spectroscopy, Acustica, Vol. 66, 286-289 (1988).
13. J. P. Sharpe and C. A. Greated, A stochastic model for photon correlation measurements in sound fields, J. Phys. D: Appl. Phys, Vol. 22, 1429-1433 (1989).
14. 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. Vol. 46, 791–796 (2008).
15. T. Koukoulas, B. Piper and P. Theobald, Gated photon correlation spectroscopy for acoustical particle velocity measurements in free field conditions, J. Acoust. Soc. Am. 133, EL156 (2013)
16. B. Piper, T. Koukoulas, A. Torras-Rosell and P. Theobald, Advances in the free field measurement of acoustic particle velocity using gated photon correlation spectroscopy, Proc. IOA, Vol. 35, 207-214 (2013).
17. J. Rienitz, Schlieren Experiments 300 years ago, Nature, Vol. 254, 293-295
18. transvaal, http://transvaal.tumblr.com/post/49846411198, (2013), Accessed 28/08/2014.
19. bullet2.jpg, http://www.aerospaceweb.org/question/aerodynamics/bullet/bullet2.jpg, (2012), Accessed 28/08/2014.
20. N-E. Molin and L. Zipser, Optical Methods of Today for Visualizing Sound Fields in Musical Acoustics, Acta Acustica United with Acustica, Vol. 90, 618-628 (2004)
21. P. Gren, K. Tatar, J. Granström, N-E Molin and E. V. Jansson, Laser vibrometry measurements of vibration and sound fields of a bowed violin, Meas. Sci. Technol., Vol. , - (2006).
22. M. Campbell, Advances in musical acoustics over last 40 years, Acoustics Bulletin, Vol. 39, Issue 5, 26-28 (2014).
23. Polytec Ltd. http://www.polytec-ltd.co.uk/
24. National Physical Laboratory and Professional Monitor Company Ltd, Laser-based acousto-optic mapping, press release (2013).
25. A. Torras-Rosell, S. Barrera-Figueroa and F. Jacobsen, Sound field reconstruction using acousto-optic tomography, J. Acoust. Soc. Am, 131, 3786-93 (2012).
26. R. Malkin, T. Todd and D. Robert, A simple method for quantitative imaging of 2D acoustic fields using refracto-vibrometry, J. Sound Vib., Vol. 333, 4473-4482 (2014).