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ADVANCES IN THE FREE-FIELD MEASUREMENT OF ACOUSTIC PARTICLE VELOCITY USING GATED PHOTON CORRELATION SPECTROSCOPY

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1 INTRODUCTION

Gated photon correlation spectroscopy (PCS) offers a viable alternative to the current free field primary standard for microphone calibration which is based on the reciprocity method[1]. For a calibration in a pressure field, reciprocity can be performed to a high level of certainty. However, the uncertainty in free field reciprocity calibrations is strongly dominated by the free field correction applied and suffers from low signal to noise ratios above 10 kHz. Reciprocity based calibrations are also limited to a small number of microphone types that feature a standard geometry.

Gated PCS is an optical method that measures particle velocity directly, and therefore is an absolute measure of acoustic pressure, at a single point. In this case, two coherent laser beams intersect and produce an interference fringe pattern; as particles cross through fringes, photons are scattered with a periodicity directly related to the particle velocity. Analysis of the first minima in the auto-correlation function (ACF) of the measured time series of these scattered photons allows for the calculation of the acoustic particle velocity using Equation 1[2], where f is the acoustic frequency λ is the optical wavelength, θ is the half angle between the intersecting laser beams and t_{min} is the time to the first minima in the ACF:

$$u_m = \frac{3.832\, f\, \lambda}{4 sin(\theta)\, \sin(\pi f t_{min})} \qquad (1)$$

The free-field acoustic pressure is directly proportional to the measured particle velocity through knowledge of the speed of sound and density of air. This measurement can be used as a direct reference to calibrate a microphone of any type and shape including MEMS microphones.

Previous research has mainly focused on applying PCS[3-5] and other optical techniques, such as Laser Doppler Anemometry (LDA)[6-8], Laser Doppler Velocimetry (LDV)[9,10] and Particle Image Velocimetry (PIV)[11,12], in standing wave tubes. The most recent research has explored how gated PCS can be applied in a free field chamber[13,14], placing the optical system outside and passing the beams through the chamber walls. Results have been shown that give a good agreement with a laboratory standard microphone for frequencies in the range 1 - 4 kHz at sound pressure levels (SPLs) between 106 dB and 116 dB.

One of the main challenges in using gated PCS for measuring particle velocities in a free-field chamber, is the existence of non-acoustic air flow, which has a mean velocity with turbulent fluctuations for a given measurement period. These velocities will be averaged with the acoustic velocity and therefore a signal processing approach is required which will allow for the mean flow to be decoupled. One approach to overcome this is to make separate measurements at the positive and negative peaks of the acoustic particle velocity and find the average therefore cancelling out the contribution of the air flow on each.

This paper describes the latest development of this work with details of hardware improvements that allow for measurements to be made over a wider range of frequencies and a comparison of two approaches to gating the velocity peaks.

2 OVERVIEW OF THE GATED PCS SYSTEM AND IMPOROVMENTS TO THE MEASUREMENT SYSTEM

Figure 1 shows the set-up of the measurement system. The optical delivery and collection systems are placed outside the chamber and the beams are based through holes in the chamber wall. Inside the chamber single frequency sine waves are produced by a horn coupled compression driver.

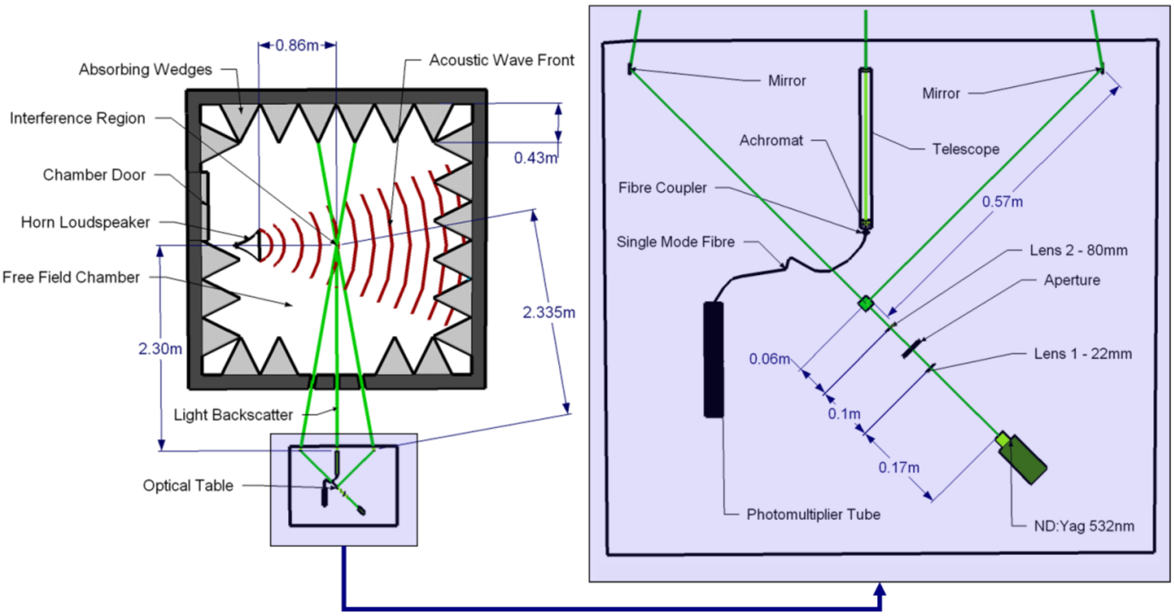

Figure 1 – Set-up of gated PCS system for measuring acoustic particle velocities inside a free field chamber.

2.1 Optical Delivery System

The aim of the optical delivery system is to create a stable interference region at the centre of the chamber where the beams intersect at their focal waists. This is achieved by expanding the laser beam and then focussing it in the far field. The main optical source is a frequency-doubled Nd:YAG laser, with a wavelength of 532 nm and 300 mW optical power. The primary beam is split into two beams of equal intensity by a cubic beam splitter. A pair of mirrors is then used to direct the two beams into the chamber. Previous measurements[14] using this system have featured an ellipsoid region with dimensions of 2 mm * 11 mm * 2 mm and with a fringe spacing of 1.6 µm.

A pair of plano-convex lenses, with focal lengths 22 mm and 80 mm, is placed 100mm apart in the laser path. This allows the focusing of the crossing laser beams in the chamber, producing an ellipsoid with approximate dimensions of 1 mm * 5.5 mm * 1 mm and a fringe spacing of 1.48 µm. In the previous measurements[14] the measurement plane was also subject to a small degree of tilt such that one laser beam was rising slightly as it passed into the chamber and the other was falling, but nevertheless crossing accurately via suitably adjusting the mirrors. This was due to instability in the mounting of the laser source and slight misalignment of the beam splitter. To overcome these issues the laser source has been mounted on a specially engineered heavy duty fixed platform and the beam splitter has been mounted on an adjustable tilting platform, allowing for any misalignment to be corrected. These improvements have also improved the stability of the set-up reducing the need for time consuming realignments.

2.2 Optical Collection System

The optical collection system consists of a custom made refracting telescope, an achromatic lens, a single mode fibre which is matched to the wavelength of the laser source, and a photomultiplier tube. The telescope effectively magnifies the image of the interference region inside the chamber through a small opening in the chamber wall. An achromatic lens is placed directly after the telescope to focus the image collected by the telescope into the opening of the single mode fibre. The single mode fibre is then coupled to the photomultiplier tube via a collimator arrangement. The telescope used for the measurements in this paper was mounted on a tilting platform aligned along the measurement axis such that the vertical angle could be matched to the return angle of the backscatter, maximising the number of photons captured from the interference region.

2.3 Improvements to the Acoustic Delivery System

The acoustic delivery system consists of a power amplifier and a compression driver coupled to a horn to maximise the efficiency of the driver. Such a system allows for the production of an undistorted high amplitude signal. Previously a Canford Audio TOA SC-630 horn speaker was used driven by a Sony TA-F 500 ES. This was capable of producing the required signal between 900 Hz and 4 kHz although featuring some distortion at the SPLs required for measurements at 4 kHz. This set-up was replaced with a Samson 200 servo amplifier and a Faital Pro HF144 coupled to a Faital Pro LTH142 horn. Figure 2 shows the measured frequency response of the loudspeaker and horn at 1 m for a 1 W input signal assuming a nominal load of 8 Ω. The loudspeaker has a power handling rating of 80 W and therefore it is capable of delivering SPLs in excess of 120 dB (re: 20 μPa) across the frequency range of interest.

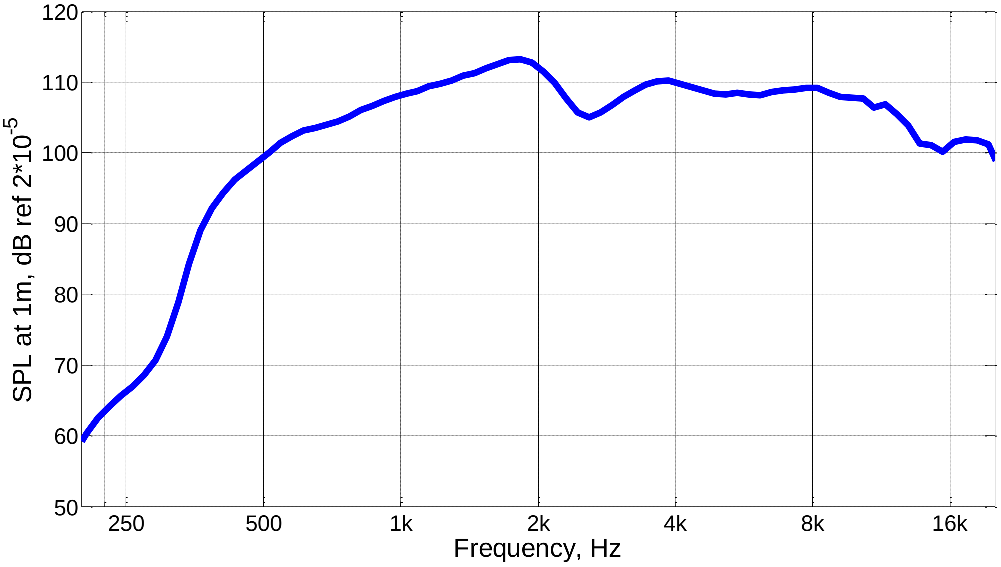

Figure 2 – Measured Frequency Response of Faital Pro HF144 coupled to Faital Pro LTH142 Horn at 1 m for a 1 W input signal assuming nominal load of 8 Ω

2.4 Methods of Gating the ACFs

Gating is used to allow the auto-correlation measurement to take place for the peak acoustic particle velocity of the sine wave being measured, whilst rejecting the lower velocity components that occur between the positive and negative peaks. Measuring both the positive and negative peaks allows the velocity component generated by the mean air flow in the chamber to be isolated and removed. This is a valid approach if the mean flow velocity in the axis of the acoustic wave is less than half the peak acoustic particle velocity. The gating is applied to the auto correlation measurements by using a pulse as a trigger. The frequency of the pulse is set to twice the frequency of the acoustic wave to be measured with a 50% duty cycle. This gives a gate length of ¼ of the acoustic wavelength. A delay is used to control which part of the acoustic wave is being gated allowing for the total phase response of the system to be accounted for.

Two gating approaches are used in this paper. **Method A** consists of measuring two separate ACFs, one for the positive velocity peak and one for the negative velocity peak. The results are then analysed and the average of the two is found. This assumes that the mean air flow is steady over a measurement period of a few minutes. Analysis of the difference between the two ACFs gives an estimate of the mean flow present during the measurement which can be useful for ensuring the quality of the measurements. **Method B** consists of measuring alternate positive and negative velocity peaks in the same measurement. This is achieved by setting the number of cycles in the pulse trigger to 2 meaning that both peaks are measured in every second cycle of the acoustic wave. This approach has the advantage of averaging out the mean flow on individual cycles of the acoustic signal but the result is a single measurement so analysis of the first minima alone does not give an indication of the magnitude of the mean flow velocity.

3 OPTICAL MEASUREMENT RESULTS AND COMPARISON TO MICROPHONE MEASUREMENTS

The measurements shown in this section use the set-up and methods described in the previous section. In order to collect enough photons to measure a meaningful ACF a small amount of seeding particles must be introduced into the chamber of dimensions similar to the fringe spacing of the interference region. For these measurements a commercial fog generator was used. A burst from a fog generator was put into the chamber and then the chamber doors were closed. The fog was left for at least an hour to settle so that the larger particles gradually fall due to gravity, thus allowing only the smaller particles to remain airborne and the air flow and temperature gradients introduced to the room by the seeding are reduced to a minimum. This resulted in measurement counts of 20-40 thousand photon counts per second (kpcs) for the duration of the measurements. It is possible to measure ACFs using counts as low as 10 kpcs using the same set-up but the ACFs feature higher levels of noise and therefore the quality of the measurements degrade and the velocity estimations are more variable.

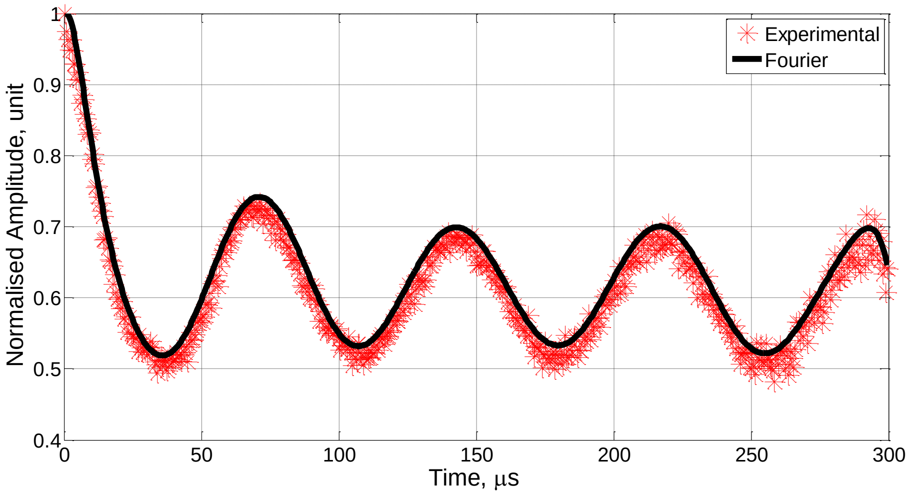

Figure 3 - Experimental gated ACF from positive peak of a 750 Hz pure tone

Figure 3 shows an ACF measured for a 750 Hz sine wave gated on the positive peak. An 8th order Fourier fit is applied to the data to give a computational estimate of the time of the first minima. This is considered an acceptable approach since a single velocity component will result in the ACF being a Bessel function. As the gate length is several times larger than the time to the first minima the ACF shows several peaks and troughs. At higher frequencies the gate length is shorter since it is set as ¼ of a wavelength and therefore the number of peaks and troughs is reduced. The result of this is that higher SPLs are required to measure meaningful ACFs at higher frequencies with the required SPL at 10 kHz for the first minima to occur clearly within the ACF being approximately 117dB (re: 20 μPa), depending on the exact details of the measurement set-up.

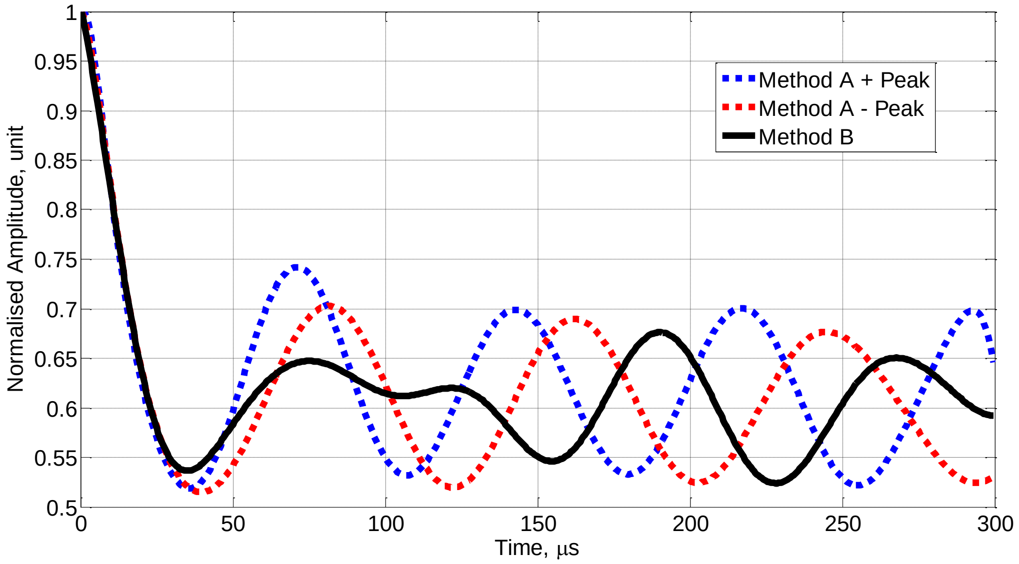

Figure 4 – Comparison of ACFs measured using gating method A and B

Figure 4 shows the Fourier functions fitted using gating methods A and B. By examining the two ACFs which make up method A, it is clear that the first minima corresponding to the negative peak occurs at a larger time shift than the first minima corresponding to the positive peak. This is due to the influence of the mean flow. The velocities are found by applying Equation 1 to these time shifts and the average velocity of the two gives the acoustic particle velocity. The ACF measured using method B shows a similar first minima to the positive peak of method A. The structure after the first minima however is different and deviates from the average between the two curves of method A. Understanding of what causes this deviation may offer an alternative approach for assessing the quality of the measurement to that of method A, where the magnitude of the mean flow contribution is considered.

ACFs, using both gating methods, were measured for a number of frequencies between 500 Hz and 8 kHz. For each frequency at least 3 valid ACFs were measured for each method, with the gates positioned approximately at the velocity peaks of the acoustic waves. The bin size of each ACF was set to give at least 250 points in each measurement. Measurements were made in a number of sessions over several days. In between each session a Bruel and Kjaer 4180 ½” microphone, which had been calibrated using the pressure reciprocity method, was positioned at the interference region pointing in the direction of the loudspeaker. The peak to peak output voltage of the microphone was measured using an oscilloscope. These voltages where then converted into SPL using the sensitivity data generated by the reciprocity calibration and the pressure to free field correction given by IEC 61094-7[15].

Table 1 shows a comparison of the SPLs measured using the two gating methods and the microphone. The differences appear to be similar for both methods and mostly lower SPLs than those measured by the microphone. The differences are higher at the frequency extremes. It is likely that the free field chamber is not truly anechoic at 500 Hz and therefore the large differences shown here may be due to reflections of the acoustic wave. At high frequencies the SPLs required are high and the ACFs have a shorter length meaning fewer photons are captured so the influence of measurement noise is higher. The uncertainty in the microphone measurement is also higher at high frequency since the free field correction is larger and inaccuracies in the microphone placement will be more significant. It is unclear at this stage whether method A or B is better since any systematic difference is lost within the measurement uncertainties.

Frequency kHz	Bin size μs	Optical SPL Method A dB	Optical SPL Method B dB	Microphone SPL dB	Difference Method A dB	Difference Method B dB
0.5	0.5	105.18	105.05	105.48	-0.30	-0.42
0.75	0.5	110.76	110.94	110.68	0.08	0.26
1	0.5	111.72	111.78	112.04	-0.31	-0.26
1.5	0.5	112.60	112.95	112.84	-0.24	0.11
2	0.25	111.34	111.22	111.57	-0.22	-0.35
2.5	0.25	112.91	112.89	112.93	-0.01	-0.04
3	0.25	115.75	115.98	115.60	0.15	0.39
3.5	0.25	118.67	119.00	119.06	-0.39	-0.06
4	0.25	119.12	119.05	118.94	0.19	0.11
5	0.1	119.45	119.78	119.93	-0.49	-0.15
6	0.1	119.37	119.69	119.46	-0.09	0.23
7	0.1	119.76	120.08	120.21	-0.44	-0.12
8	0.1	119.85	119.97	120.15	-0.30	-0.18

Table 1- Measured SPLs using the optical method for separately gated peaks (Method A) and simultaneously gated peaks (Method B) and comparison with microphone.

These results demonstrate that the improvements made to the measurement system have allowed the frequency range to be extended down to 500 Hz and up to 8 kHz. This is a significant improvement on the 1 – 4 kHz range that was previously possible.

One further issue which effects the measurements is the need to centre the measurement gate exactly on the acoustic velocity peak. The horn, compression driver and amplifier all introduce a phase shift and there is a delay due to time of flight and any latency in the signal processing. To find the total lag at an individual frequency, measurements need to be made at a number of gate positions within the acoustic cycle. Figure 5 shows examples of this for 2 kHz and 5 kHz where a significant difference in peak position is shown between the two frequencies.

The next stages of this research include analysing the sources of uncertainty, measuring the true phase response of the system, examining alternative signal processing methods which allow for measurements to be made at lower SPLs, characterising and quantifying the effect of the seeding particles and implementing the system in a larger free-field chamber allowing for measurements at lower frequencies.

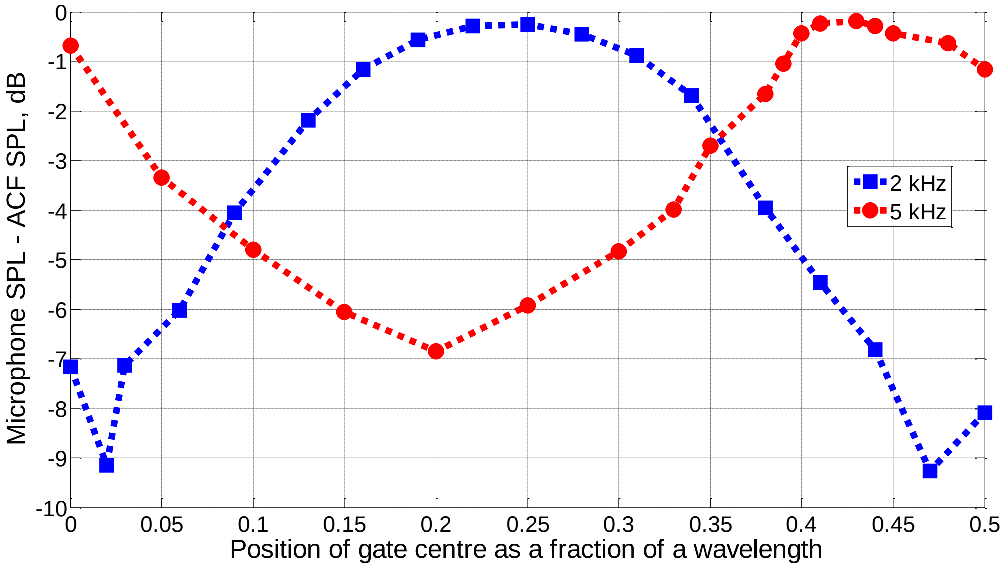

Figure 5 – Difference between SPL measured with a Microphone and SPL measured using gated PCS for gates centre at a number of positions within the acoustic cycle at 2 kHz (blue) and 5 kHz (red).

4 CONCLUSIONS

This paper has described a system for measuring free field acoustic particle velocity using a gated photon correlation spectroscopy method. This work is motivated by the need to directly measure the unit of acoustic pressure and may lead to the realisation of a new primary standard for free field microphone calibration.

Details of the measurement system are given with the latest improvements highlighted including improvements to the optical delivery system producing a smaller interference region, the collection telescope allowing for more efficient collection of the backscatter and an upgrade of the acoustic delivery system.

Measured data is shown for two gating methods and compared to measurements made with laboratory standard microphone. The measurements show good agreement of less than 0.6 dB for all measurements. Experimental identification of the acoustical particle velocity is shown for 2 frequencies demonstrating that knowledge of the phase response of the system is crucial to improving the accuracy of the measurements.

Further work to improve the accuracy and repeatability of the system has been identified which should allow the system to be developed into a new standard for the free-field calibration of microphones.

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