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Feasibility discussion on airborne ultrasound microphone calibration using photon correlation in free-field conditions

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ABSTRACT

Currently the primary standards for free-field sound pressure are realized by the reciprocity method. For airborne ultrasound, 1/4'' microphones may be used as the transmitter and receiver to perform the reciprocity calibration. With the microphone acting as the transmitter, the signal-to-noise ratio is very low; in addition, the reciprocity calibration process is an indirect method, without measuring the sound pressure itself. The measurement of sound pressure using optical techniques is the trend for new primary standards of sound pressure. In this case, when particles pass through the fringes formed by two coherent beams, scattered photons are captured and analyzed, yielding the acoustic particle velocity. Following, the sound pressure can be calculated at each required frequency and the device sensitivity may be obtained. In this paper, the feasibility of calibrating airborne ultrasonic microphones by the photon correlation method is discussed. Compared to the audible frequency range where this particular optical technique has been experimentally established, there are quite a few issues to be solved. The factors to be addressed include the required airborne sound source with adequate sound pressure level, interference volume with sufficiently small spacing as well as the particle ability to faithfully follow the sound at such high frequencies.

Keywords: airborne ultrasound, sound pressure, photon correlation

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1. INTRODUCTION

The requirements of airborne ultrasonic pressure measurement increase with applications such as ultrasonic leak detectors amongst others. The calibration of airborne microphones is the premise of the precise measurement of airborne ultrasound. Currently the primary standards for free-field sound pressure are realized by the reciprocity method[1]. WS3F microphones may be used as the transmitter and receiver to perform the reciprocity calibration above 20 kHz[2-4]. But the signal-to-noise ratio is very low when the microphone is acting as the transmitter. In addtion, the reciprocity calibration process is an indirect method, without measuring the sound pressure itself during the entire calibration.
The measurement of sound pressure using optical techniques is the trend for new primary standards of sound pressure[5-8]. In this case, when particles pass through the interference fringes formed by two coherent beams, scattered photons are captured and analyzed, yielding the acoustic particle velocity. Following, the sound pressure can be calculated at each required frequency and the device sensitivity may be obtained. Koukoulas[9] et al. obtained accurate comparison results in free-field up to 20 kHz with the photon correlation method. The National Institute of Metrology(NIM) in China also developed such a free-field measurement system in the audio frequency range[10].
In this paper, the feasibility of calibrating airborne ultrasonic microphones using the photon correlation method is discussed.

2. SOUND PRESSURE MEASUREMENT BY PHOTON CORRELATION

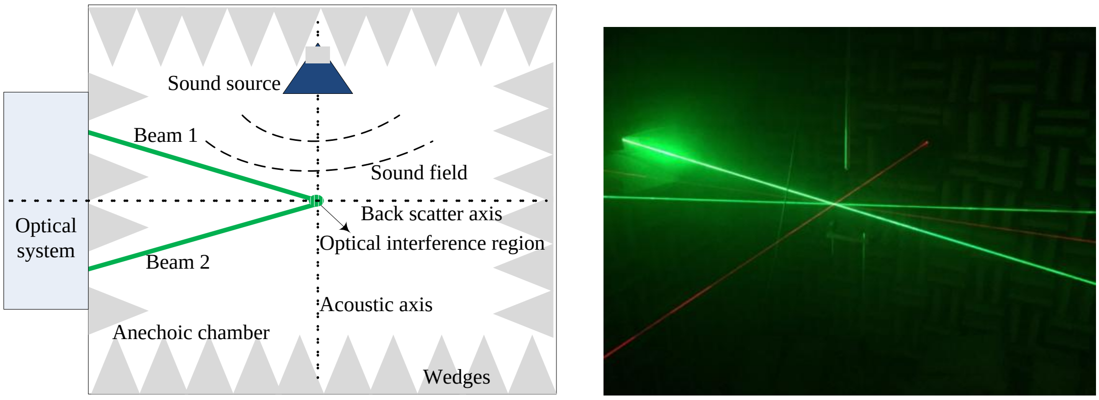

Figure.1 Schematic diagram of the measurement system (left) and optical beams inside the chamber (right)

Figure.1 shows the diagram of the measurement system for free-field measurements. When two coherent laser beams cross, an ellipsoidal probe volume is generated, which consists of dark and bright fringes. The interference fringes act as a static optical 3-dimensional (3-D) ruler with resolution defined by the fringe spacing itself. In the presence of a propagating sound field, air particles cross the fringes in an oscillatory manner, which result in scattered photons which are captured using optics for further analysis. The auto-correlation function (ACF) of photon series from such a process has been formulated and analytically derived [11] in the past. The mathematical analysis deduces that the free-field acoustic pressure p is given by the following:

$$p = \rho \cdot c \cdot \frac{3.832 \cdot f \cdot \lambda}{4 \cdot sin\theta \cdot \sin\left(\pi \cdot f \cdot t_{min}\right)} \quad (1)$$

where ρ is the density of air, c is the speed of sound, f is the acoustic frequency, λ is the wavelength of the laser source, θ is the half-angle of the intersecting laser beams and t_{min} is the time it takes for the ACF to reach its first minimum.

The optical beams inside the chamber at NIM for audio frequency measurements is shown in Figure.1. The two green beams form the probe volume, viz. the measurement area. The red beams were used for alignment purposes for the acoustic axis and the back-scatter axis of the optical system placed outside the chamber.

Until this point, related reported work was performed in the audio frequency range. Compared to the audible frequency range, there are quite a few issues to be solved to calibrate airborne microphone with photon correlation method in the ultrasonic airborne range of interest. The factors to be addressed include the required airborne sound source with adequate sound pressure level, interference volume with sufficiently small spacing as well as the required particles with the ability to faithfully follow the sound at such high frequencies.

3. IMPROVEMENT REQUIREMENTS FOR AIRBORNE ULTRASOUND CALIBRATIONS

3.1 Sound source

The scattering photons result from the movement of the particles and their crossing along the fringes. The higher the sound pressure level (SPL) is, the greater the particle vibration velocity is. In one typical acoustic cycle, many particles cross the fringes resulting in a higher signal-to-noise ratio. Therefore adequate sound pressure level is expected, especially in high frequency. The horn loudspeaker type LTH142 is shown in Figure 1 and its maximum SPL at 20 kHz is approximately 120 dB. Setting the density of air as 1.2 kg/m^3 and the sound speed as 340 m/s, Table.1 shows the acoustic displacement at different frequecies and different SPLs. In the audio frequency range, even for lower SPLs, the acoustic displacement is larger than the displacement at airborne frequencies. For example, the acoustic displacement will only be 0.25 μm at 50kHz, 124 dB.

Table.1 the acoustic displacement at different frequecies and different SPL

SPL/dB	Sound pressure/Pa	Frequency/kHz	Acoustic displacement/μm
114	10.02	1	3.91
114	10.02	2	1.96
114	10.02	5	0.78
114	10.02	10	0.39
114	10.02	20	0.20
124	31.70	20	0.62
124	31.70	30	0.41
124	31.70	50	0.25
124	31.70	80	0.15
124	31.70	100	0.12
134	316.98	80	0.49
144	1002.37	80	1.55

For the system shown in Figure 1 for the audio frequency range, the the fringes spacing is approximately 800 nm, which is nearly equal to the acoustic displacement at 5 kHz, 10 Pa. If the sound pressure remains at 10 Pa for frequencies above 20 kHz, the acoustic displacements of particles will be less than the spacing. Processing methods such as gating method on the photon correlation will be required for precise measurements, which will allow the measurement of the maximum particle velocity component[7]. Even so, if the acoustic displacement is far less than the fringes spacing, the signal of the scatterring photons will be very weak.

The SPL radiated by a high frequency sound source at the measurement point is expected to no less than 124 dB. The commercial loudspeakers cannot fulfill such the requirements. PZT transducers are one way of achieving high SPLs at specific frequencies. A series of resonant PZT transducers were developed at NIM, as shown in Figure.2. The test results showed the transducers could reach to 124 dB or even higher. However, at high frequencies, such as 63 kHz and 80kHz, the heat effect of the PZT material will slightly reduce the sound radiation capacity of the transducer in continuous working condition, so a monitor microphone is needed during the measurement.

Figure.2 Resonant PZT transducer and the SPL measurement in anechoic room

3.2 Optical system

To measure the sound pressure at 124 dB from 20 kHz to 100 kHz, the acoustic displacement ranges from 0.62 to 0.12μm. The fringe spacing is expected to be reduced to 300 nm or even lower. Inside the probe volume, the spacing is defined by the wavelength and the crossing angle of the two beams，

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

where Λ is the spacing of the fringes, λ is the wavelength, and θ is the half crossing angle. In Figure 1, the wavelength is 532nm and the half angle is 19.4°. A laser source with lower wavelength, such as blue beam with 400 nm could be chosen. An alternative way is to increase the half angle. The distance of crossing points at the wall of the chamber where the beams pass through should be further or the focus position of the two beams needs to be closer.

3.3 Tracing particles

The scatterring photons arise from the movement of the tracing particles. It is obvious that the particle size, scattering effiency and motion capability of tracer particles needs to be considered. Sharpe[11] reported 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. For typical seeding materials and acoustic intensities the particle diameter needs to lie between 500 and 800 nm if the acoustic velocity is to be measured over the full audio frequency range with an uncertainty of less than 1%.

For the airborne ultrasonic frequecy range, if the fringe spacing is decided to be around 300 nm due to the SPL limitation of the the sound source, the particle diameter should be less than 300nm. According to the proportion with the seeding for audio frequency, the particle diameter is roughly expected to be 100 to 300 nm. Here the scattering effiency and following features of tracer particles also need to be evaluated. The accelerated motion of particles in sound field causes pressure gradients in the adjacent region. When the frequecy is less than the value of $1/(2\pi\tau_p)$, the viscous force dominates the situation [13]. If the other forces are not taken into account, the particle's vibration velocity could written as,

$$u_p = \frac{u_f}{\sqrt{1+2\pi f \tau_p}} \;, \tau_p = \frac{d_p^2 \rho_p}{18\eta_f} \tag{3}$$

where τ_p is the relaxation time, d_p is the diameter of the particle and ρ_p is the density , η_f is the coefficient of fluid viscosity. Here we set the diameter of particle as 0.3μm, the desity of the particle is as the same as air 1.2 kg/m^3, the coefficient of air viscosity 1.983×10^{-5} Pa s. According to Equation (3) the particle velocity is 95.6 % of the fluid velocity at 50 kHz. If the diameter of particle is 0.5μm, the result will change to 88.9%. As a result, the characteristics of tracer particles would deteriorate as the freqeucy increases. If a fog generator is used to provide the tracers for airborne ulstround measurements, a liquid with specific parameters is required.

4. CONCLUSIONS

The feasibility of calibrating airborne ultrasonic microphones by the photon correlation method is discussed in this paper. Compared to the audible frequency range where this particular optical technique has been experimentally established, the required airborne sound source with adequate sound pressure level is needed, for example 124 dB at least. The interference volume should have sufficiently small spacing, 300 nm or even less. The particle ability to faithfully follow the sound at such high frequencies is also needed, the diameter of the tracer is evaluated as 100 nm to 300 nm.

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