EXPERIMENTAL ASSESSMENT ON THE EFFECT OF BACK CAVITY OF SOUND SOURCES ON ANTI-NODES AND STANDING WAVE PATTERNS INSIDE ACOUSTIC TUBES

Jian Kang, Triantafillos Koukoulas, and Longbiao He

National Institute of Metrology, Mechanics and Acoustics Division, P.R.China
email: helb@nim.ac.cn

Standing wave tubes are widely used in acoustical measurements for sound-in-air applications. With the sound source mounted at one end of the tube and the other end been rigidly terminated, the gradient of sound pressure inside the tube changes along its length axis similar to the standing wave pattern, making it necessary to accurately identify the position of the velocity or pressure antinodes achieved due to the standing wave pattern. This requirement is very crucial when comparisons are required to be performed between different optical and acoustical methodologies for sound assessment. Measuring the physical length of such tubes and calculating parameters such as harmonic numbers, frequencies and length coordinates of velocity and pressure anti-nodes may indeed seem as quite a trivial task. However, the back cavity of the sound source will alter the actual length of the tube itself, therefore changing the air-column characteristics, making a comparison between optical methods quite inaccurate. This paper describes the experimental assessment based optical velocity and microphone measurements to identify as accurately as possible the position of the required antinodes achieved within standing wave tubes. Acoustical velocities are obtained through the optical photon correlation method without any disturbance of the sound field inside the tube.

Key Words: sound source, standing wave tubes, optical & acoustical measurements

1. Introduction

In standing wave tubes, sound wave is generated at one side and reflected at the other side, so that a sound pattern (a spatially ‘frozen’ pattern to be exact) is generated within the acoustical tube. The locations where the amplitude is minimum are called nodes and the locations where the amplitude is maximum are called antinodes. The number of node/antinode pairs depend on the harmonic number and the frequency at which the air column has been excited within the tube. There is a 90° phase difference between particle velocity and sound pressure, which means that velocity antinodes are essentially pressure nodes and vice versa.

The photon correlation method utilizes photon events generated by interacting particles in sound fields moving through intersecting laser beams which create an ellipsoid volume with light and dark interference fringes. Subsequently, photon sequences are auto-correlated to obtain the auto correlation function (ACF) whose time to the first minimum is inversely proportional to the velocity of the oscillating particles [1-3]. By measuring the particle velocity at a point in the sound field, the corresponding sound pressure may be obtained. The above measurement and signal processing may be performed using the auto-correlation method [4-6] or spectrum analysis [7-10]. Both optical and microphone methods are used in this paper to find the location of the antinodes within standing wave tubes as well as investigating the formation of the expected standing wave patterns.
2. Details of the experimental optical system

Fig. 1 shows the experimental arrangement of the optical system. The standing wave tube which is made of plexiglass has an inner diameter and length of 50mm and 755mm respectively. A loudspeaker is mounted at one end of the tube while a microphone mounted on the other end. In terms of the laser system, it consists of two parts named the delivery and collecting systems.

![Diagrammatic sketch of the experimental arrangement](image)

The laser source was a frequency-doubled Nd:YAG (Laser Quantum Torus) with a wavelength of 532nm. Laser light emitted by the source is split into two identical beams by a non-polarizing beam splitter and intersected at a specific point by two adjustable mirrors. The mirrors are mounted symmetrically between the beam splitter and the tube to ensure that the two beam paths from the beam splitter to the beams crossing point exhibit equal path length. The half angle of the laser intersection was 19.43° and the fringe spacing was 800nm. Due to the propagating sound within the standing wave tube, particles from within the ellipsoid volume oscillate through the fringes and therefore scatter photons.

On the other side and, of course, outside the standing wave tube (along the optical forward scattering axis), the photon collecting part of the system is placed where scattered photons from the interference region within the tube are collected by a plano-convex lens whose focal length was 50mm. A subsequent 30μm pinhole is placed at the focal point of the lens and a suitable single photon counter (Excelitas SPCM-AQRH-13) is placed immediately behind the pinhole. The counter produces electrical pulse sequences, where each pulse corresponds to a single photon event captured.

3. Acoustical measurements in standing wave tube

When the standing wave tube is rigidly terminated on both ends and when odd harmonic numbers are generated within the tube, a pressure antinode will exist at the end of the tube while a velocity antinode will exist at the centre of the tube. Therefore, in order to perform a valid comparison, a pressure microphone should be placed at the end of the tube. However, the back cavity of the sound source (loudspeaker) can have a significant effect on the properties of the generated standing wave patterns within the tube and therefore the location of the node/antinode pairs.

The harmonic frequencies can be obtained through the equation:

\[ f = \frac{nc}{2L} \]  

where \( n \) is harmonic number, \( c \) is speed of sound and \( L \) is the length of the tube.
Using the B&K PULSE measurement system, a calibrated B&K 4190 condenser microphone and a moving coil loudspeaker, frequency sweep were carried out within the standing wave tube in order to investigate this in detail. Figure 2 and 3 are the frequency sweep of the loudspeaker with large and small back cavity.

![Figure 2: Frequency sweep result of a loudspeaker with large back cavity](image1.png)

![Figure 3: Frequency sweep result of a loudspeaker with small back cavity](image2.png)

As the length of the tube was measured to be 755mm, Table 1 shows the comparison between theoretical and measured frequencies at different harmonics, where \( n \) is the harmonic order, \( f \) is harmonic frequency and \( L \) is the length of the tube. The theoretical lengths of the tube are calculated first and the theoretical frequencies of each harmonics were obtained through Eq.1. The measured frequencies correspond to peak values of the frequency sweep and the measured lengths are also obtained through Eq.1.

Compared to the loudspeaker which has large back cavity, the difference of \( f \), \( L \) and \( n \) are much smaller when the loudspeaker with small back cavity were used. With such large back cavities, the position of nodes/antinodes pairs as well as the form of the standing wave pattern itself can be significantly distorted inside such acoustical tubes.

<table>
<thead>
<tr>
<th>( n(\cdot) )</th>
<th>theory</th>
<th>measured</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f(\text{Hz}) )</td>
<td>( L(\text{mm}) )</td>
<td>( f(\text{Hz}) )</td>
<td>( L(\text{mm}) )</td>
</tr>
<tr>
<td>1</td>
<td>228</td>
<td>756.5</td>
<td>226</td>
</tr>
<tr>
<td>3</td>
<td>683</td>
<td>756.5</td>
<td>680</td>
</tr>
<tr>
<td>5</td>
<td>1139</td>
<td>756.5</td>
<td>1139</td>
</tr>
<tr>
<td>7</td>
<td>1595</td>
<td>756.5</td>
<td>1603</td>
</tr>
<tr>
<td>9</td>
<td>2050</td>
<td>756.5</td>
<td>2055</td>
</tr>
</tbody>
</table>

(a): Loudspeaker with small back cavity
4. Optical measurements and pressure comparison

Photon events detected by the single photon counter are converted into electrical voltage pulses and forwarded to a suitable external hardware correlator board (Brookhaven Instruments TurboCorr) which can compute the required auto-correlation function (ACF). It has been mathematically formulated[11] that in such experiments the ACF is approximated by a Bessel function and the acoustic velocity is inversely proportional to the time during which it reaches its first minimum ($\tau_{\text{min}}$):

$$u_m = \frac{3.832 \cdot f \cdot \lambda}{4 \cdot \sin \theta \cdot \sin(\pi \cdot f \cdot \tau_{\text{min}})}$$

where $\lambda$ is the wavelength of the laser source, $f$ is the acoustic frequency and $\theta$ is the half angle of the intersection between the two laser beams. Fig 4 is the typical curve of the auto-correlation result at 1.139kHz and 113.7dB.

![Figure 4: Typical ACF curve at 1.139kHz and 113.7dB](image)

Having measured the acoustical particle velocities, the sound pressure in the standing wave tube is given by:

$$p = \frac{\rho c u_m}{\sin[2\pi f (1-x/c)]}$$

where $\rho$ is density of air, $f$ is the frequency of the sound field and $c$ is speed of sound which is given by:

$$c = 331 + 0.6 \cdot T$$

where $T$ is the temperature in degrees Celsius.
When odd harmonics are excited in the tube, there is a velocity antinode at the center of the tube and a pressure antinode at the end of the tube, provided that the back length of the sound source hasn’t introduced shifts on the standing wave pattern. Optical measurements were subsequently performed with 11 measurement step points been distributed symmetrically along the centre of the tube with the interval being 2 mm. Sound pressure levels were measured at each point and the maximum was regarded as the sound pressure level (SPL) at the velocity antinode. Table 2 shows the comparison between optical and microphone measurement results.

Table 2: Optical and microphone comparison with small back cavity

<table>
<thead>
<tr>
<th>n(-)</th>
<th>f(Hz)</th>
<th>P_optical(dB)</th>
<th>P_mic(dB)</th>
<th>P_diff(dB)</th>
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<tbody>
<tr>
<td>3</td>
<td>680</td>
<td>112.46</td>
<td>113.20</td>
<td>-0.74</td>
</tr>
<tr>
<td>5</td>
<td>1139</td>
<td>113.01</td>
<td>113.80</td>
<td>-0.79</td>
</tr>
<tr>
<td>7</td>
<td>1603</td>
<td>114.13</td>
<td>114.60</td>
<td>-0.47</td>
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<tr>
<td>9</td>
<td>2055</td>
<td>113.27</td>
<td>113.90</td>
<td>-0.63</td>
</tr>
</tbody>
</table>

where \( n \) is the harmonic order, \( f \) is harmonic frequency, \( p \) is sound pressure level measured by the optical method, microphone and their respective difference.

5. Conclusion

Through acoustically measured frequency sweeps, it was shown that the back cavity of the sound source will shift the nodes/antinodes and therefore the wave pattern inside standing wave tubes. Optical measurements were used to verify this effect and the corresponding SPLs measured by the photon correlation method were compared with the microphone measurements showing comparison agreement to better than 0.79dB. This approach can be used in characterising sound sources and the effect of their associated back cavities when they will be used in applications where waveguides or acoustical tubes are required to produce well defined patterns and resulting node/antinode pairs.

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REFERENCES


