Integrated Multi-Signal Adaptive Microphone

2008 Final Project Report

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Summary

The goal of the project is to develop the technology for signal processing to extract and separate acoustic sources and to integrate this technology with optical microphones that have low noise and high bandwidth. The Gradient flow (GF) algorithm is used for source separation, and arrays of optical microphones with force feedback capability are used as array elements. Both gradient and omnidirectional optical microphones are employed in this study [1, 2].

In the past year of the project, integration and characterization of low noise micromachined optical microphones with high sensitivity and directivity to enable effective implementation of GF microphone arrays was shown. In addition, force feedback capability of the optical detection method was demonstrated and this method was evaluated in terms of sensitivity and noise. In this last period of the project, the pressure gradient measurement capability of these optical gradient microphones and their application in sound intensity measurements is investigated. In the first part of this report, the development of the impedance tube method to verify the pressure gradient (consequently particle velocity) measurement is summarized. Then, the comparison results of the optical gradient microphone with a commercial Larson Davis calibration microphone are presented. The results show that the higher order omni-directional modes of the microphone membrane need to be controlled better to achieve more accurate pressure gradient measurements.

Grant Period	Accomplishments
03.2008-12.2008	• Developing a test setup and procedure for pressure gradient based particle velocity measurements using an impedance tube. • Verification of particle velocity measurement with optical gradient microphones.

Table 1. ***Project milestones over grant period***

1. Introduction

The diffraction based optical detection method described earlier (Hall *et al.*, 2005; Cui *et al.*, 2006; Degertekin *et al.*, 2006) makes the small sized, low noise microphones used in this study feasible. In the previous periods of this project, low noise and small sized omnidirectional and gradient optical microphones were implemented with opto-electronics integration, characterized and the force feedback capabilities of these microphones were investigated. It is already shown that using electronic feedback for damping the microphones gives low thermal noise microphones with the desirable frequency response, bandwidth and the dynamic range. It is also shown that with electronic force feedback, the device characteristics can be tuned in a favorable manner without adding significant noise [3, 4].

Efforts of this period of the project are focused on investigating the pressure gradient measuring capability of the directional optical microphones. This study is important for gradient flow algorithm implementation and for the feasibility of using these microphones in sound intensity probes. Although the efforts started in 1930s measuring sound intensity has always been an active research area because measuring sound intensity is not as trivial as measuring sound pressure. Usually two pressure microphones are used to obtain velocity by integrating the difference of microphone outputs [5]. In this period of the project the novel gradient microphone was tested as a small sized, high bandwidth sound intensity probes overcoming the limitations of current intensity probe and pressure gradient measurement technology. The current technology with the intensity probes is not adequate enough in terms of sensitivity, noise, bandwidth and size requirements. The feasibility of addressing some of these problems using optical microphones to measure the gradient of the pressure and to use this gradient in particle velocity calculation was investigated.

2. Sound Intensity Measurement Method

The sound intensity in a specified direction is the rate at which the sound energy is transmitted through a unit area that is perpendicular to that direction. Therefore sound intensity is a vector quantity and very useful in sound power measurements, and identification of different sources and sound fields.

There are mainly two different methods, namely pp and pu-method, to measure the sound intensity. The pp-method uses a pp-probe that is composed of two pressure microphones. The particle velocity in the direction of the axis of the probe can be calculated from the finite difference approximation using the Euler's equation of motion. Then the sound intensity can be calculated from the time averaged product of the sound pressure and the corresponding particle velocity from the equation;

$$I = \langle p.u \rangle_t = \left\langle \frac{p_1(t)+p_2(t)}{2} . \int_{-\infty}^{t} \frac{p_1(\tau)-p_2(\tau)}{\rho.\Delta r} .d\tau \right\rangle_t$$

where $< >_t$ indicates the averaging over time t , p_1 and p_2 are the pressure output of two microphones, ρ is the density of air and Δr is the separation distance between two microphones.

The pu-method uses a pressure microphone and a transducer that measures the corresponding particle velocity or the pressure gradient. The sound intensity can be calculated directly from the measured pressure and velocity using the equation;

$$I = \langle p.u \rangle_t = \frac{1}{2} . \mathrm{Re}\{p.u^*\}$$

where * represents the complex conjugate of the velocity.

Both pu and pp methods have advantages and disadvantages. The most important challenges in the pp-method come from the finite difference approximation and phase mismatch between the two pressure microphones. The accuracy of the finite difference approximation directly depends on the separation distance between the microphones. In order to get accurate results in different frequency range, different separation distances should be used which is impractical. The microphones that are used with the pp-method should be nearly perfect phase matched especially in the low frequency range. The other important challenges with the pp-method are the size and the sound field in which the measurement is done. Because of the required spacer dimensions, the sizes of the pp-intensity probes are large that makes the sound intensity measurements of small objects or limited spaces impossible. In addition to this, 3D sound intensity probes consist of 6 microphones which make the size of the probes impractical. The last disadvantage of the pp intensity probes is that they have difficulties in sound fields that have high pressure-intensity index which is caused by reflections, diffuse sound fields or additional noise sources. The optical gradient microphone becomes a good alternative for pp measurements since it can potentially provide high sensitivity in a large frequency range.

3. Measurement Setup for Pressure Gradient

In order to investigate the differential optical microphone for measurement of the gradient of the pressure a well controlled environment is needed. Pressure is simple to measure with using a single microphone, however gradient of the pressure which is used for calculating the particle velocity is more difficult and requires more precision. Impedance tube is used to create a medium such that the pressure and velocity is known at every point in that medium. Impedance tube is a hollow cylinder, with rigid plunger at one end and a sound source at the other. The picture and a simple schematic view of this impedance tube can be seen from figure 1. Microphone ports are mounted at two locations along the wall of the tube. At the top picture of figure 1, the impedance tube is shown as open ended. Rigid plunger can be used to close that end in order to create a reflection surface.

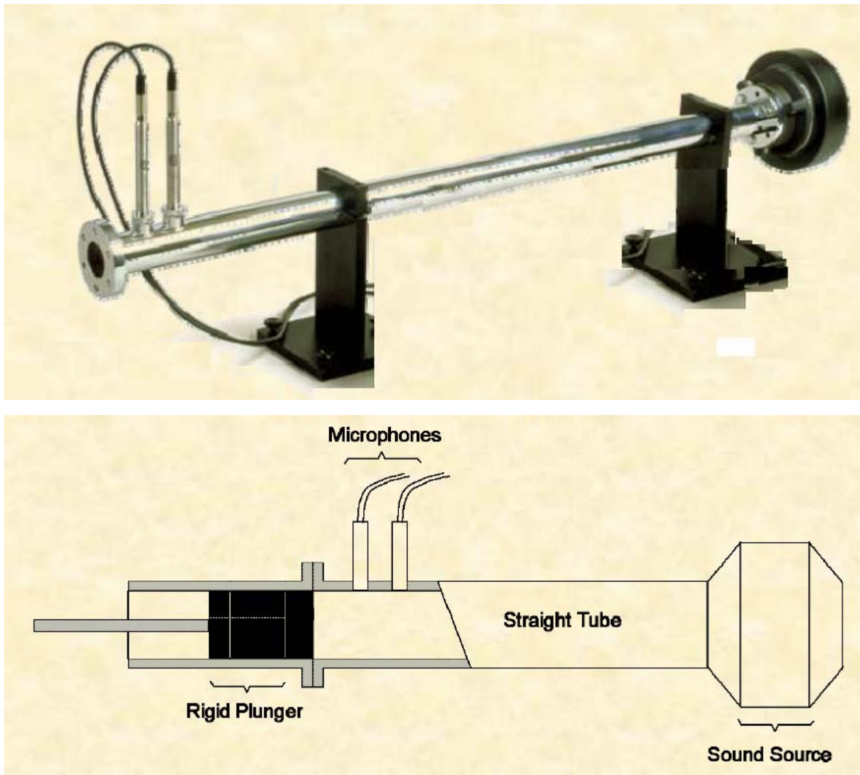

Figure 1. The picture and the schematic view of the impedance tube

Frequency range	50 Hz – 5700 Hz
Maximum SPL in tube	~ 150 dB
Ambient noise in tube	< 30 dBA
Microphones	accepts standard ½ inch
Tube inside diameter	34.9 mm
Tube outside diameter	41.3 mm
Overall length	1.20 m (with sample holder)
Total mass	10.5 kg
Distance from face to center of downstream port	50.62mm
Distance between two ports	29.31mm

Table 2. Specifications and dimensions of the impedance tube

Specifications and dimensions of the impedance tube are listed in Table 2. The most important characteristic of the impedance tube is the frequency range. The working frequency range is:

$$f_l < f < f_u$$

where, f is the operating frequency in hertz, fl is the lower working frequency of the tube, and fu is the upper working frequency of the tube. The lower frequency limit depends on the spacing of the microphones and the accuracy of the analysis system. It is recommended that the microphone spacing exceed one percent of the wavelength corresponding to the lower frequency of interest. The upper frequency limit, fu, and the corresponding wavelength, lu, depend on the diameter of the tube and upon the speed of sound. In order to maintain plane wave propagation, the upper frequency limit is defined as follows:

$$fu < K\, c\, /d$$

where, fu is the upper frequency limit in hertz, c is the speed of sound in the tube in m/s, d is the diameter of the tube in m and K = 0.586. Using the diameter of the tube, the upper frequency of the impedance tube is found to be 5.7 kHz.

The experimental setup includes the impedance tube that is described above, 2 Larson Davis ½ in. (LD2560) random incidence microphones, power supplies for these microphones, SIGLAB hardware and a laptop for data acquisition and processing. Figure 2 shows the picture of the setup and equipments.

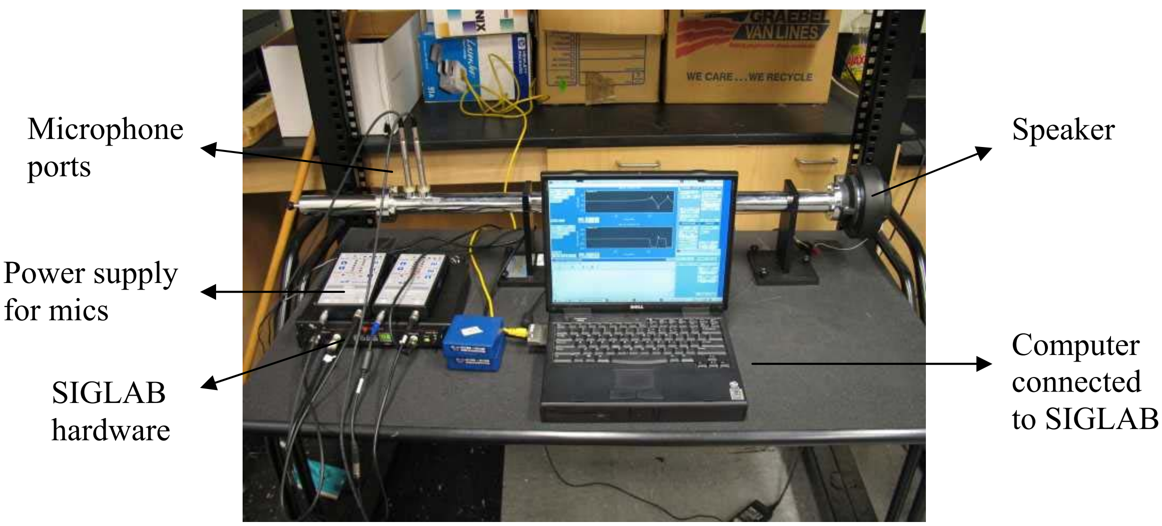

Figure 2. Picture of the impedance tube experimental setup

In order to fully characterize the impedance tube, two microphone-method is used. The speaker is driven by virtual function generator (by SIGLAB) that applies a random signal with V_{rms}= 1.0 Volt, bandwidth = 5.0 KHz, and sampling frequency=12.8 KHz. The microphone outputs are recorded with a length of 1024 samples (dF=12.5Hz) and averaged 200 times. All the experiments are performed for two different configurations, namely;

1) Without rigid plunger attached (open end)
2) With rigid plunger attached (close end)

Then all the data is collected for those two different configurations by swapping the microphones. So the microphone which is in the upstream port (close to the speaker) will be in the downstream port (away from the speaker) and vice versa.

4. Calibration Results of the Impedance Tube

a) Signal to Noise Ratio (SNR) Analysis:

SNR is a good indication of whether the data is accurate enough or not. First experiment is done to find the SNR values for the different configurations mentioned above. SNR vs. frequency data is plotted in figure 3. In the open end case, we can get SNR > 20 dB down to 90 Hz and with the close end case, we can go down to 20 Hz with SNR > 20 dB. As a result of this, the data is good enough at the frequencies which are higher than 90 Hz. These SNR values can be increased by increasing the output level of speaker; however the distortion of the microphones should be taken into consideration. The difference in SNR values between open end and close end case comes from the background noise in the room. The background noise in the tube is higher for open end case which decreases the SNR. However with the measured background noise, SNR is good enough for characterization in the impedance tube above 100Hz.

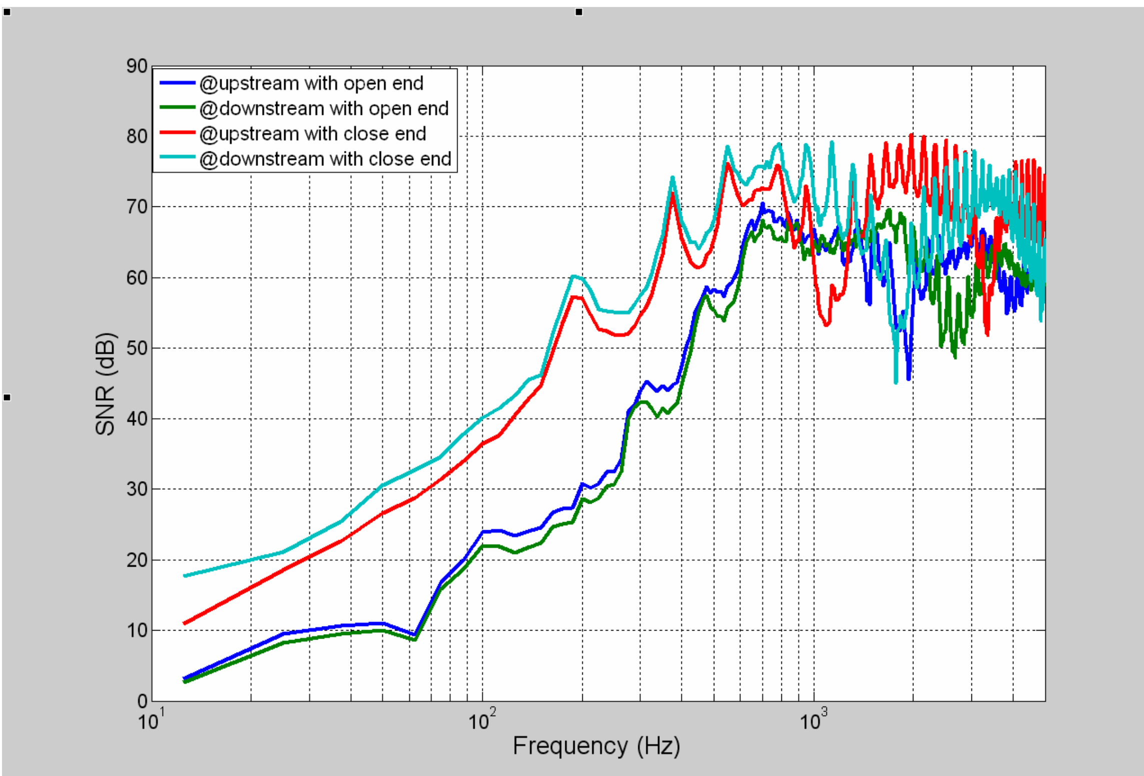

Figure 3. Signal to Noise Ratios at two different microphone port (upstream, downstream) with two different configurations (open end, close end)

b) Pressure and Velocity Characterization of the Impedance Tube:

Using two Larson Davis microphones at 2 different microphone ports, the pressure at those points are easily measured. In order to find the particle velocity of these two points, the reflection coefficient should be calculated according to the different end condition configurations. Transfer function method is used to find the reflection coefficient in the tube. Te transfer function is a complex ratio of the acoustic pressure responses and any mismatch in the amplitude or phase responses of the two microphone systems will affect the accuracy of the transfer function measurement. Therefore a calibration function should be obtained in order to compensate for the amplitude and phase mismatch between two microphones.

The first step in the process is to measure the transfer function between the two microphones, H_{12}. Then the microphones are swapped so that the upstream microphone becomes a downstream microphone. In this configuration, the transfer function between the two microphones, H_{21}, is measured again. The calibration factor can be found as:

$$H_{cal} = (H_{12} \times H_{21})^{1/2} = |H_{cal}| \cdot e^{j.\phi_{cal}}$$

The magnitude and the phase of the calibration function are plotted in Figure 4. The magnitude is the correction for the amplitude mismatch and the phase is the correction for the phase mismatch between two microphones. After obtaining the calibration factor, the transfer function that is calculated directly from the complex ratio of the Fourier transform of the acoustic pressure at the microphone at downstream to the Fourier transform of the acoustic pressure at the microphone at the upstream can be corrected.

$$H = \frac{\overline{H}}{H_{cal}}$$

where, $\overline{H}$ is the measured transfer function,

H_{cal} is the calibration function and

H is the corrected transfer function.

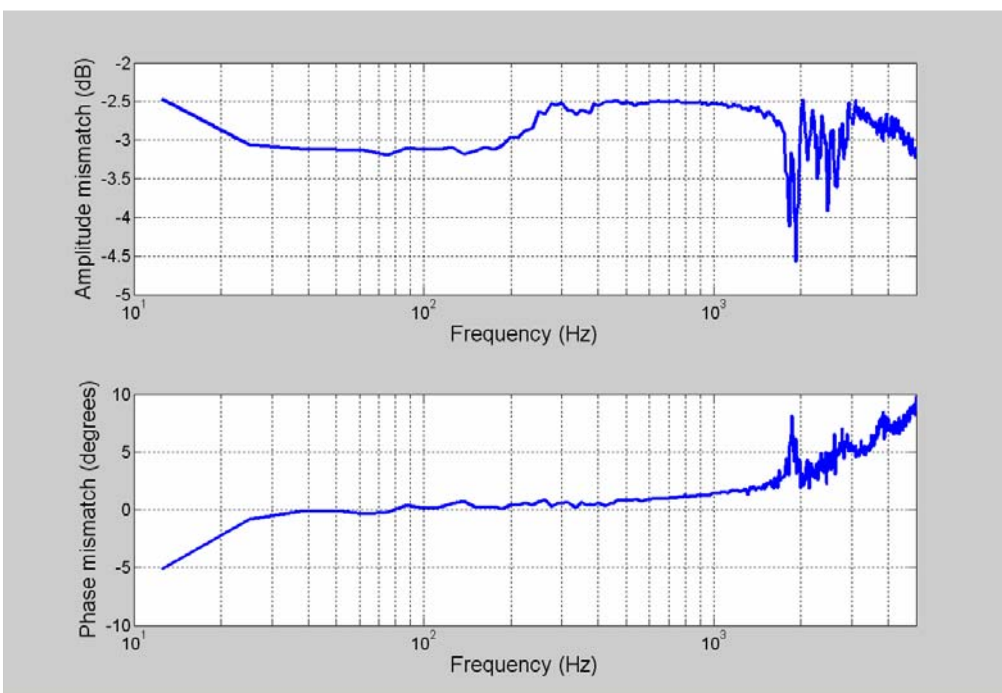

Figure 4. Amplitude (upper) and phase (lower) mismatch between two LD microphones

After obtaining the corrected transfer functions between the microphones, the reflection coefficient can be found as follows.

$$P_{upstream} = P^{+} \cdot (e^{j.k.(l+s)} + R.e^{-j.k.(l+s)}) \quad , \quad P_{downstream} = P^{+} \cdot (e^{j.k.l} + R.e^{-j.k.l})$$

$$H = \frac{P_{downstream}}{P_{upstream}} = \frac{P^{+} \cdot (e^{j.k.(l+s)} + R.e^{-j.k.(l+s)})}{P^{+} \cdot (e^{j.k.l} + R.e^{-j.k.l})}$$

where, R is the complex reflection coefficient, l is the distance between the tube termination and center of downstream microphone, s is the spacing distance between upstream and downstream ports and k is the wavelength. R can be extracted from this equation as follows;

$$R = |R| \cdot e^{j\phi_R} = \frac{H - e^{-j.k.s}}{e^{j.k.s} - H} \cdot e^{j.2k.(l+s)}$$

where, R is the magnitude and ϕ_R is the phase of the reflection coefficient. Figure 5 shows the reflection coefficient vs. frequency for open end and close end cases. For the open end case, when the frequency increases reflection coefficient decreases. However for the close end case, because of the reflections, reflection coefficient is close to 1 for all the frequency range as expected.

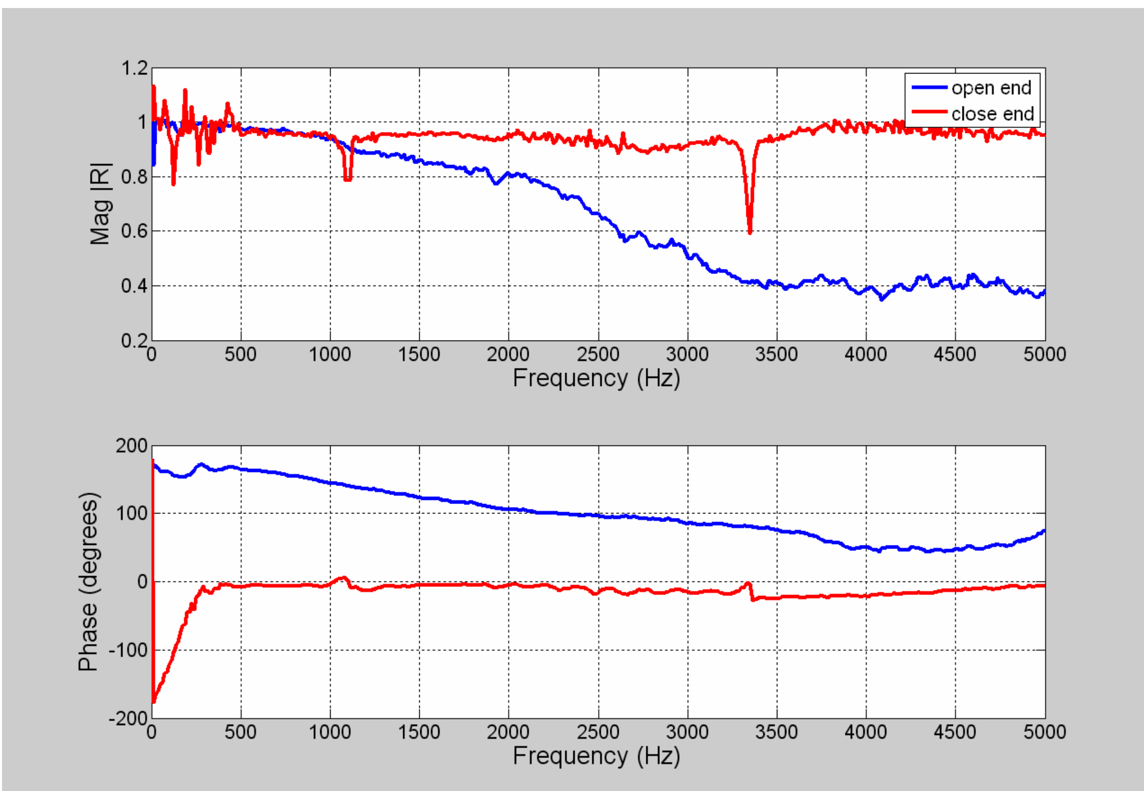

Figure 5. Magnitude (upper) and phase (lower) of the reflection coefficient vs. frequency

Since the pressure at two microphone ports are measured directly and the reflection coefficient is found for different configurations, the particle velocity can be calculated using the equations below.

$$U_{upstream} = \frac{P^+}{Z_0} \cdot (e^{j.k.(l+s)} - R.e^{-j.k.(l+s)}) \quad , \quad U_{downstream} = \frac{P^+}{Z_0} \cdot (e^{j.k.l} - R.e^{-j.k.l})$$

where, Z_0 is the specific acoustic impedance in the tube.

Measurement of the pressure with LD microphone is plotted in Figure 6. The output of the microphone is converted into Pascal using the sensitivity of the microphone. This plot shows the pressure vs. frequency information at the upstream port with open and close end case.

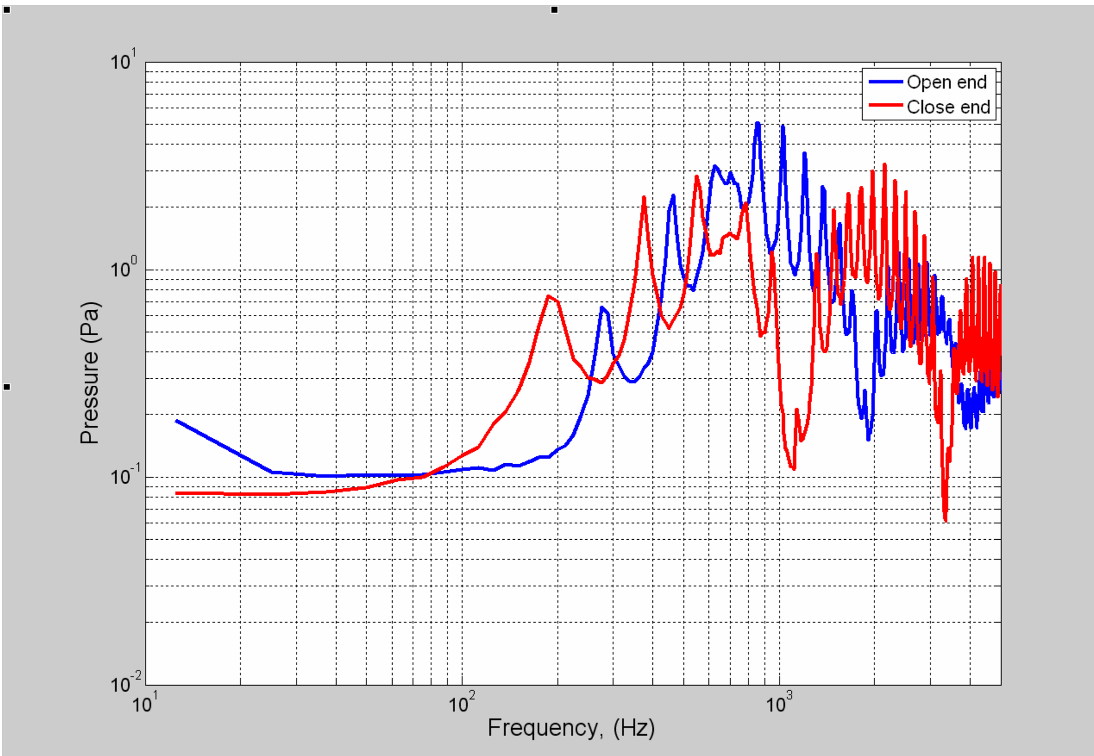

Figure 6. Measured pressure vs. frequency at the upstream port (close to the speaker) of the impedance tube with open end and close end case

At this point, using the appropriate formulas, the particle velocity at any point in the impedance tube can be found. Figure 7 shows the particle velocity vs. frequency plot at the upstream port with open and close end. Figure 6 and 7 shows the pressure and the particle velocity at upstream port.

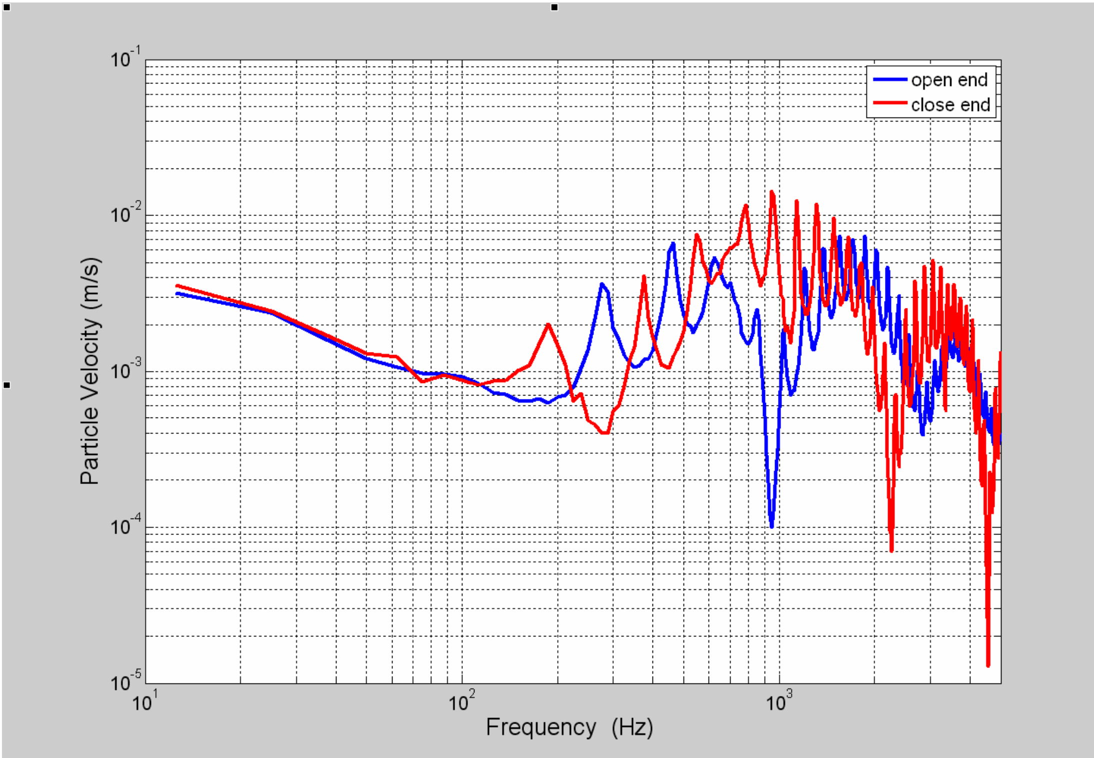

Figure 7. Calculated particle velocity vs. frequency at the upstream port (close to the speaker) of the impedance tube with open end and close end case

5. Comparison of Optical Gradient Microphone with Larson Davis Calibration Microphone

After finding the particle velocity in the impedance tube, the gradient microphone is used at the same position to see if this measured particle velocity can be calculated from the measured pressure gradient of the optical gradient microphone. In order to do that, the comparison of the measured velocity with two different microphones is compared. The results of this comparison can be found in figure 8. Blue curve shows the measured particle velocity with using 2 Larson Davis calibration microphones. The black curve shows the measured velocity with the optical gradient microphone while keeping all the other parameters constant. It can be seen that below 100 Hz, there is a difference in measured velocity between these two methods. However, with using the port spacing of the impedance tube, the calculated velocity using two Larson Davis microphones has also errors because of the mismatch of the microphones. In the useful frequency range, between 100Hz to 3-4 kHz, the measured velocities show that the optical gradient microphone can measure the gradient of the pressure so that the particle velocity can be found using this information. Some of the minima obtained by the optical gradient microphone are not as deep as the LD microphones. Our analysis shows that this is primarily due to the second mode of the optical microphone diaphragm which responds to average pressure and degrades the pressure gradient measurement obtained from the first mode. This issue can be resolved by either moving the resonance frequency of the second mode beyond the audio range or having optical readout from either end of the microphone diaphragm and use the difference signal.

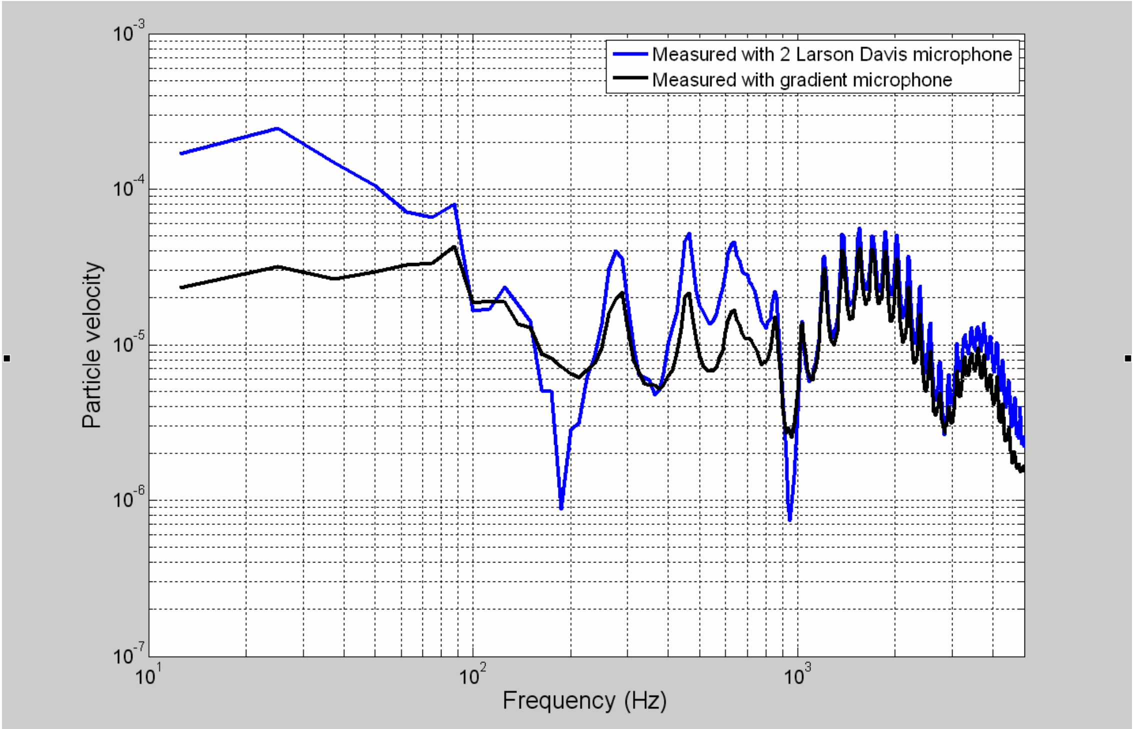

Figure 8. Comparison of measured particle velocities using Larson Davis and optical gradient microphones.

6. Conclusion

The optical microphones studied in this research have numerous advantages over traditional condenser microphones. Low thermal mechanical noise, high sensitivity to size ratio and force feedback capability are some of the key features of these microphones. In this period of this research project, the capability of these optical microphones for pressure gradient measurement and their application to sound intensity probes is investigated. An impedance tube measurement method is developed for this purpose. Signal to Noise ratios of these measurements are shown to be good enough to provide accurate results in particle velocity measurements over 100Hz. The distortion limit of the microphone has also been obtained. The experiments and initial verification indicates that these optical gradient microphones can be good candidate for pressure gradient measurement and consequently can be used as velocity transducers in sound intensity probes. Further improvements in microphone design and readout are under investigation to enhance the gradient response of the optical microphones.

7. REFERENCES

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