Calibration Test Report for the Phone-Or 3D Optical Energy Density Probe

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Abstract

This report contains the calibration tests undertaken on the Phone-Or 3D optical Energy Density probe. A number of tests were performed for testing the calibration for the omni-directional pressure and 3-axis pressure gradient measurements. The calibration results were found to be generally consistent with the calibration specifications provided by the manufacturer.

1 Phone-Or 3D optical Energy Density probe

The Phone-Or Energy Density probe (shown in Figure 1) is a set of fibre-optical based sensors for measuring a single omni-directional pressure and 3-axis pressure gradients in an acoustic field. The four sensors are packed into a transparent acoustic housing and each sensor is connected to a pair of optical fibres.

The principle of operation of the Phone-Or optical sensor is explained in [1]. The light from an LED (Light Emitting Diode) is sent through one optical fibre to illuminate a membrane that contains a reflecting spot. The reflected light (modulated in its intensity) is sent to a Photo-detector inside the electro-optic box through another fibre. The modulated light intensity can be correlated to the dynamics of the membrane and its reflecting spot. This allows the acoustic pressure experienced at the transducer's membrane to be measured.

The Phone-Or specifications [2] provide a nominal frequency range between 10 Hz and 4 KHz with +/- 2 dB variations. Its dynamic range is 80 dB with 3.5 Vrms maximum output level.

Figure 1: Phone-Or Energy Density probe [2].

2 Back-to-back pressure test

A Phone-Or 3D optical Energy Density probe was tested in an Anechoic chamber at the University of Adelaide. Initially, the Phone-Or omni-directional pressure sensor was calibrated by comparing the Phone-Or pressure reading with the pressure reading of a calibrated Brüel & Kjær(B&K) microphone. The Phone-Or pressure sensitivity provided by the manufacturer is 100 mV/Pa. A calibrated B&K 0.5" microphone was positioned back-to-back with the omni-directional pressure sensor at far-field conditions, where the sound source was located about 2m from both sensors. Two tests were conducted in which the sound source was coming from the front and the back of the sensors respectively, ie. forward and backward wave tests. The frequency response from the B&K microphone pressure reading to the Phone-Or pressure reading is shown in Figure 2. Figure 2b shows that there is a phase delay associated with the Phone-Or amplifier, estimated at 45 μs. The Phone-Or phase delay was obtained from the average of the phase delay from the forward and backward wave tests in order to cancel out the phase delay due to misalignment of B&K microphone relative to the Phone-Or sensor.

3 Pressure gradient test

The next tests involved the calibration of the three Phone-Or pressure gradient sensors. A B&K Sound Intensity probe Type 3519 with 2 phase-matched microphones were used for pressure gradient measurements. The test included the far-field and near-field conditions inside an Anechoic chamber.

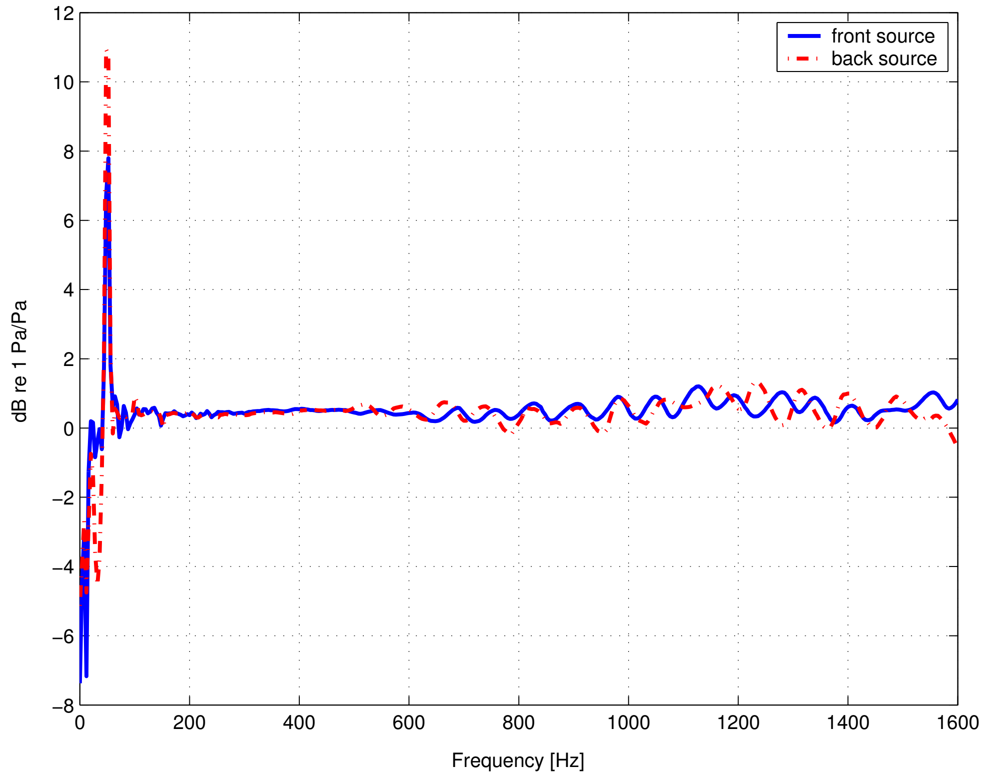
3.1 Far field test

The first test used the B&K Sound Intensity probe with two B&K Type 4165 0.5" microphones with a spacing of 50 mm. The Phone-Or sensitivity provided by the specifications is 35.5 mV/Pa which was obtained for 1" distance from the sound source, sensor facing the source at 1 KHz and 1 Pa. For far-field calibration, the actual pressure gradient sensitivity was calculated based on the Phone-Or separation distance of $\Delta x = 8.7$ mm. At 1 KHz, this corresponds to a phase delay of $\Delta\phi = 9.1^o$. Hence, the estimated pressure gradient $\Delta p/\Delta x$ can be obtained from pressure measurements at two adjacent points, p_1 and p_2:

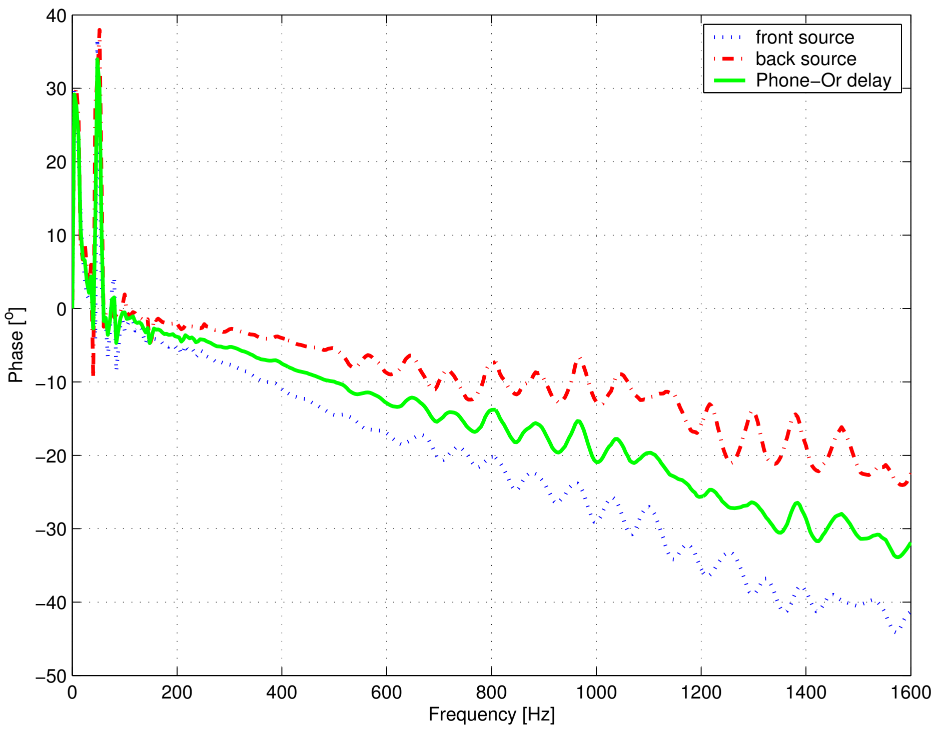
$$\begin{aligned}
\frac{\Delta p}{\Delta x} &= \frac{p_2 - p_1}{\Delta x} \\
&= \frac{1}{\Delta x}\left(p - pe^{-j\Delta\phi}\right) \\
&= \frac{1}{\Delta x} p\left(1 - (\cos\Delta\phi - j\sin\Delta\phi)\right) \\
\left|\frac{\Delta p}{\Delta x}\right| &= \frac{0.159\text{Pa}}{0.0087\text{m}} = 18.3\frac{\text{Pa}}{\text{m}} \qquad (1)
\end{aligned}$$

where $p = 1$ Pa. Note, it has been assumed that the pressure amplitude is equal, which is approximately true in the far field. Thus, the Phone-Or pressure gradient sensitivity used for calibration is (35.5 mV/Pa) / (18.3 Pa/m) = 1.94 mV/(Pa/m).

During the tests, it was observed that the Phone-Or black channel had a relatively high noise level so only calibration results from red and green channels will be presented in this



(a) Magnitude



(b) Phase

Figure 2: Frequency response of back-to-back pressure test.

report. It is suggested that the Phone-Or probe is to be returned for further inspection by the manufacturer. More details on the noise level will be discussed in Section 4. The pressure gradient measurements from the Sound Intensity and Phone-Or probes were also compared to the pressure gradient estimation assuming a far-field condition. In this case, the pressure p is related to the particle velocity v by

$$\frac{p}{v} = \rho c \tag{2}$$

where $\rho = 1.2\,\mathrm{kg/m^3}$ and $c = 343$ m/s are the air density and speed of sound respectively.

Since the particle velocity is related to the pressure gradient by

$$j\omega v = -\frac{1}{\rho}\frac{\partial p}{\partial x}, \tag{3}$$

then the estimated far-field pressure gradient is obtained by substituting (2) into (3):

$$\frac{\partial p}{\partial x} = -\frac{j\omega p}{c}. \tag{4}$$

Figures 3a and 4a show the auto-spectra for red and green channels respectively, compared to the measurements from the B&K Sound Intensity probe. The auto-spectra from the Intensity probe and far-field assumption were similar up to about 2.5 KHz but started to differ at higher frequencies. This result is expected since the 50mm spacer used for the probe has a useful frequency range of only between 31.5 Hz and 1.25 KHz [3]. Differences between the Phone-Or and far-field auto-spectra measurements are shown in Figures 3b and 4b for red and green channels respectively. It can be observed that from 400 Hz to 2.5 KHz the Phone-Or measurements are similar to those using far-field assumption. At frequencies higher than 2.5 KHz, the Phone-Or pressure gradient sensor measured a higher level of pressure gradient by 3-4 dB.

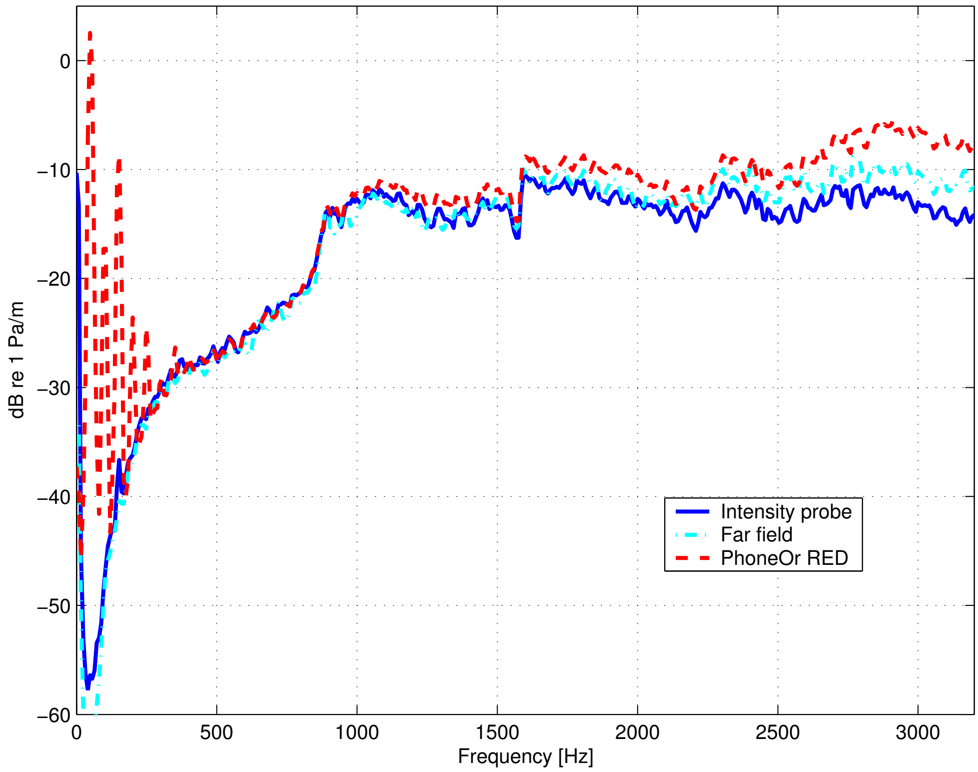
At lower frequencies below 400 Hz, a high level of 50 Hz harmonics from electrical noise is apparent from the Phone-Or's pressure gradient auto-spectra. The high noise level is partly caused by the fact that the acoustic pressure gradient is significantly lower at lower frequencies, providing a low signal-to-noise ratio. The signal-to-noise ratio can be improved either by simply increasing the strength of the sound field or by increasing the Phone-Or set-up gain.

The tests were repeated using B&K Type 4135 0.25" microphones and a 12mm spacer (a useful frequency range of 125 Hz to 5 KHz [3]). The Phone-Or pressure gradient measurements were compared with those using far-field assumption. Figure 5 shows the auto-spectra from both measurements for red channel calibration. The frequency response from the far-field measurement to the Phone-Or measurement is shown in Figure 6 with the phase delay for forward wave test (ie. sound source at the front of the sensor) shown in Figure 6b. It is observed that between 250 Hz to 3.2 KHz, the Phone-Or measurement is within 4-5 dB of the measurement using the far-field assumption.

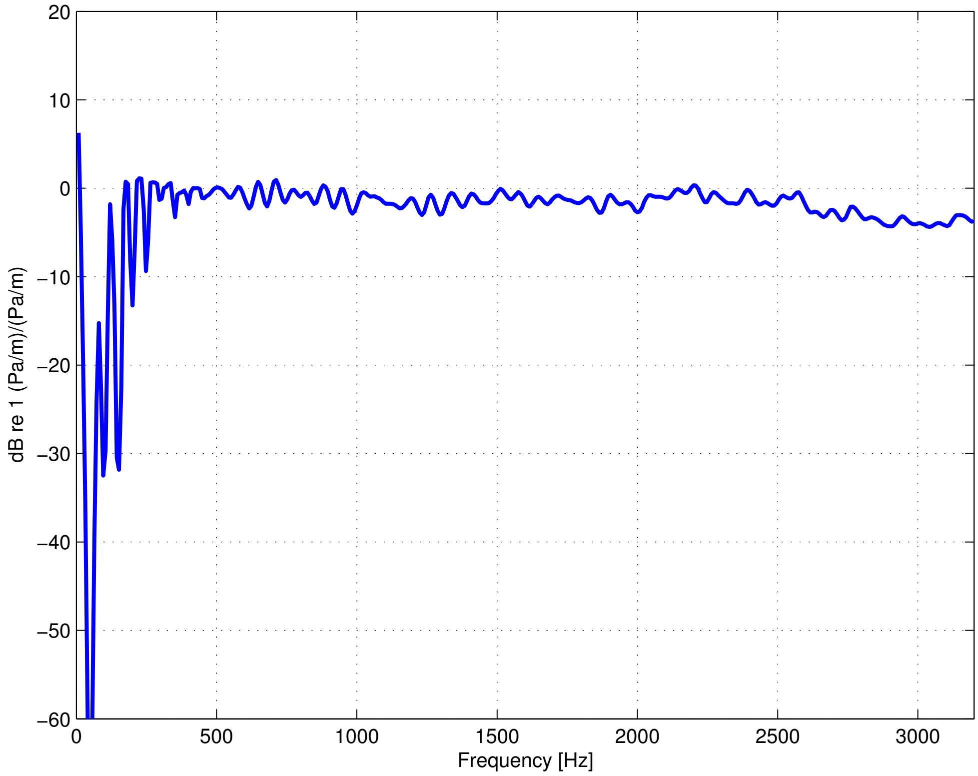
Similar results are also observed for the green channel as illustrated in Figures 7 and 8.

3.2 Near field test

The Sound Intensity probe and Phone-Or probe were positioned at a distance of about 100 mm from the sound source for measurements at near-field conditions. In the tests,

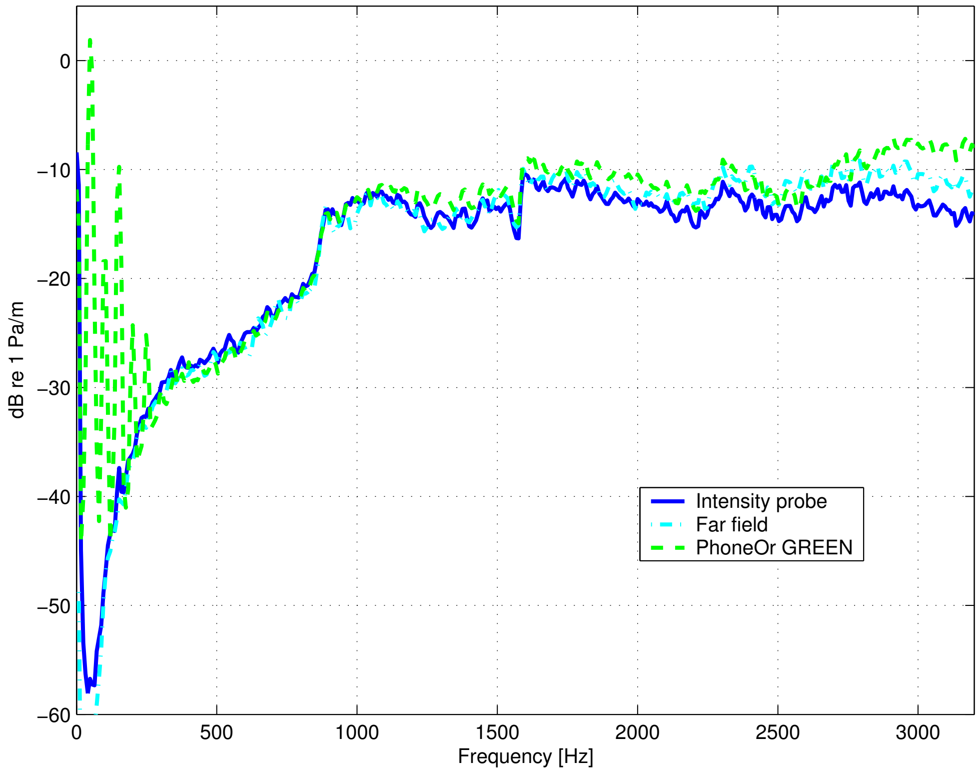


(a) Pressure gradient auto-spectra

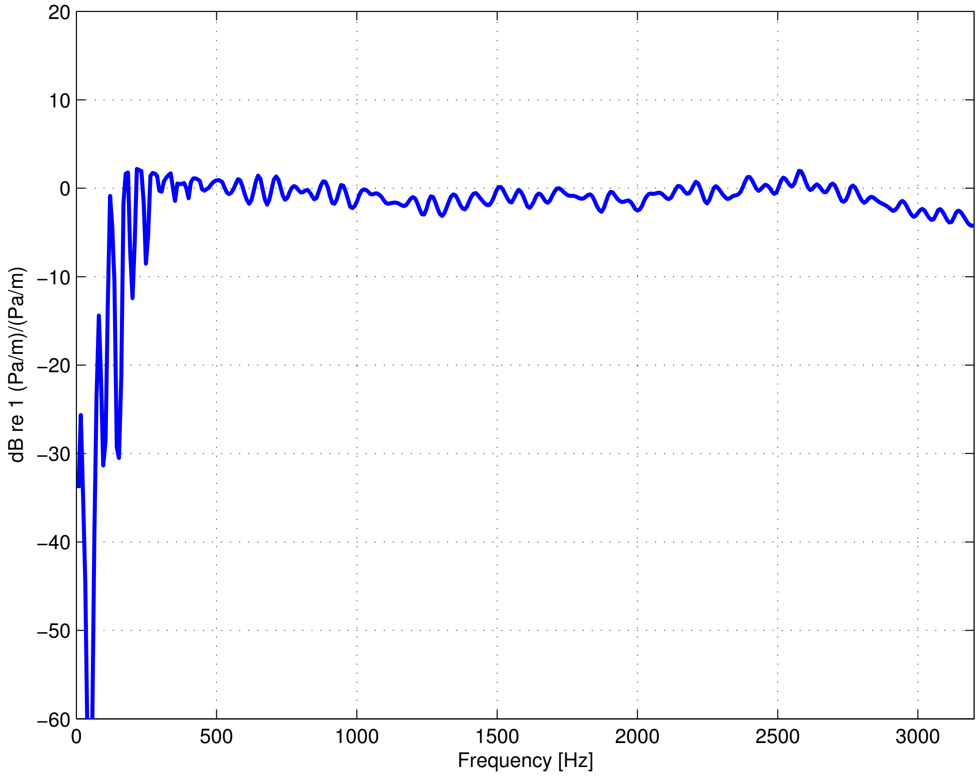


(b) The difference between the Phone-Or and far-field auto-spectra

Figure 3: Red channel calibration.



(a) Pressure gradient auto-spectra



(b) The difference between the Phone-Or and far-field auto-spectra

Figure 4: Green channel calibration.

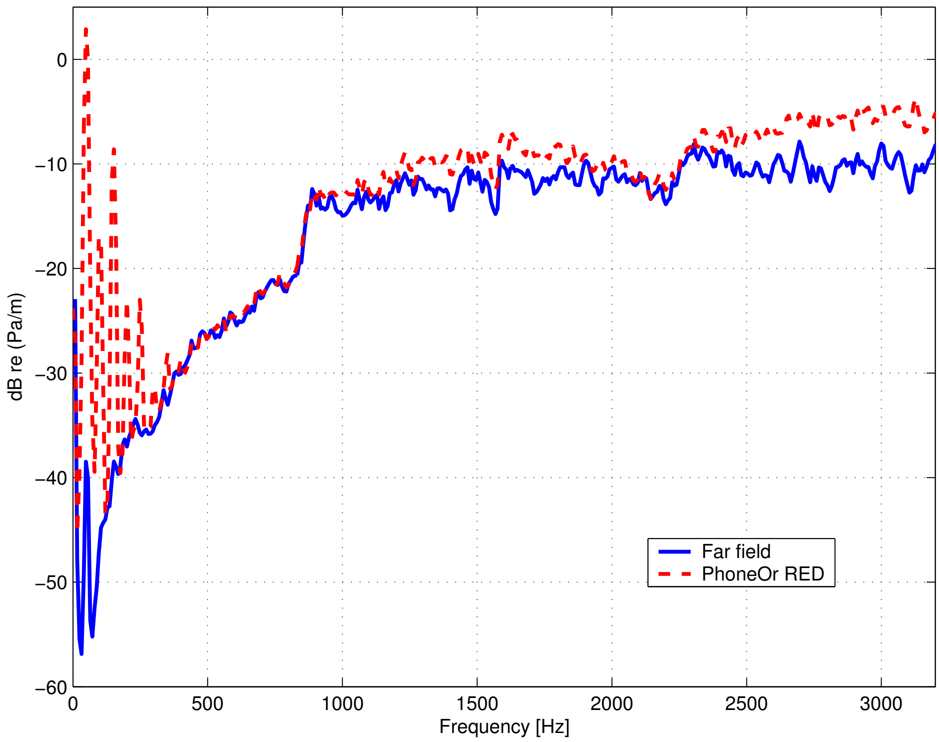


Figure 5: Pressure gradient auto-spectra at far-field: red channel.

the Phone-Or pressure gradient sensitivity used is still based on the far-field assumption disccused in Section 3.1, which is 1.94 mV/(Pa/m). The red pressure gradient channel was tested and the auto-spectra from the Phone-Or and Sound Intensity probe measurements are shown in Figure 9. It is observed that the Phone-Or measurements using the far-field assumption is about 3-4 dB larger than the measured pressure gradient by the Intensity probe, illustrated in Figure 10. Part of the discrepancy could be attributed to the near-field measurement sensitivity to errors in sensor placement.

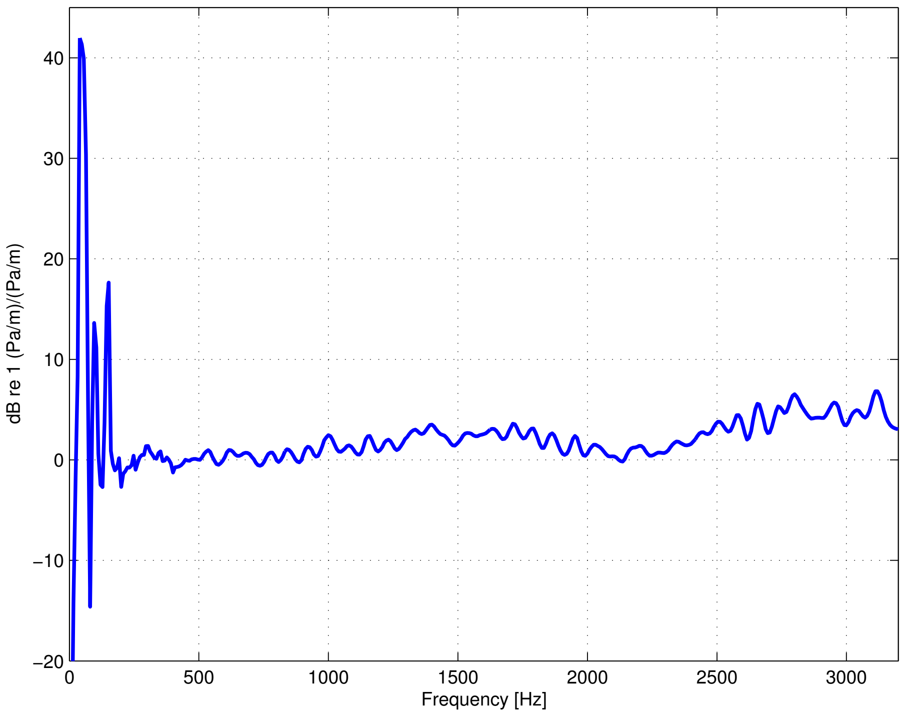
Based on the results, assuming the misplacement error is sufficiently small, the sensitivity required by the Phone-Or would be about 40%-60% smaller than the one calculated based on the far-field assumption. Thus, the sensitivity based on the near-field results should be between 1.2-1.4 mV/(Pa/m).

4 Phone-Or self-noise level test

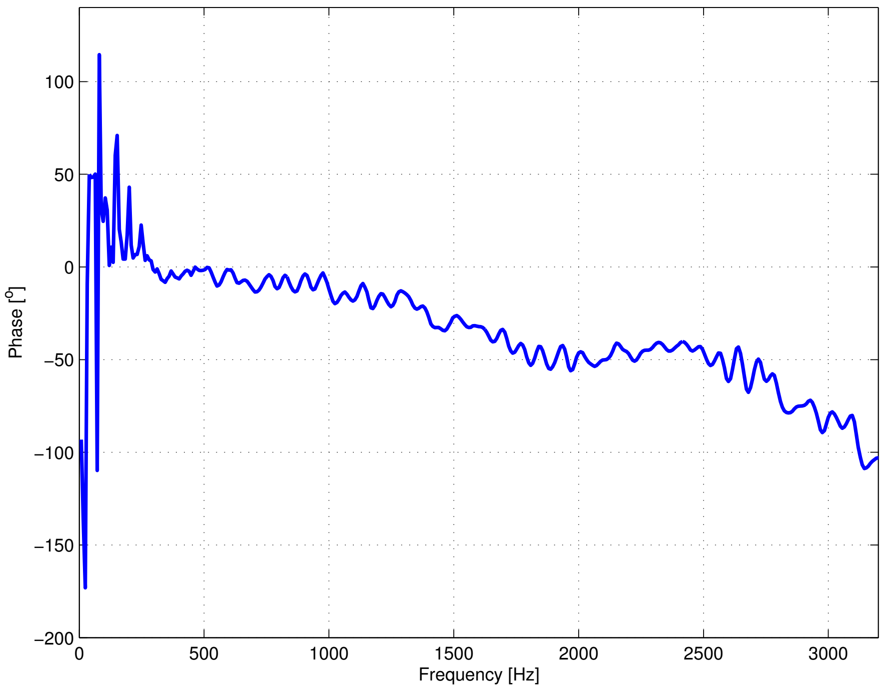
Figure 11 shows the self-noise level of the Phone-Or probe up to 6.4 KHz, where the self-noise level is 2.1, 2.6, 2.9 and 2.4 mVrms for omni-directional pressure, black, red and green channels respectively.

A National Instruments Data Acquisition Card, with a sampling frequency of 1.5 MHz, was used for obtaining the high-frequency self-noise measurements. The self-noise auto-spectra are shown in Figure 12. It is concluded that the black channel has a relatively high self-noise level compared to the other three channels, especially at 63.9 and 322.35 KHz.

The Phone-Or self-noise signals are shown in Figure 13 which compares the noise level



(a) Magnitude



(b) Phase

Figure 6: Frequency response: red channel (forward wave test).

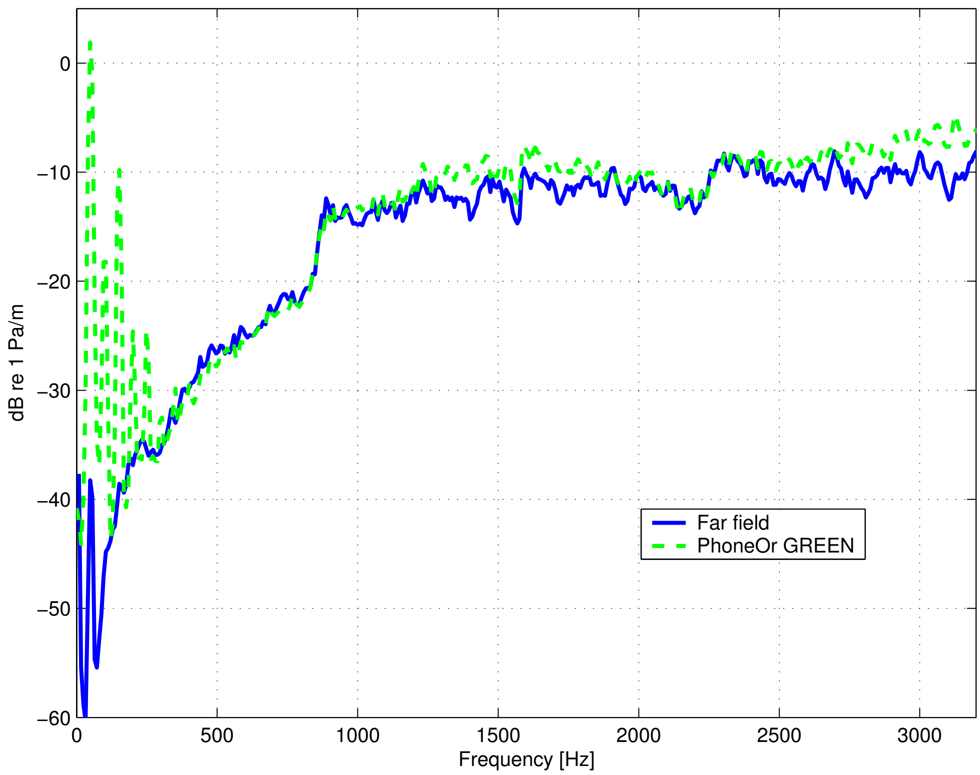


Figure 7: Pressure gradient auto-spectra at far-field: green channel.

of the black channel with that of the rest.

5 Conclusions

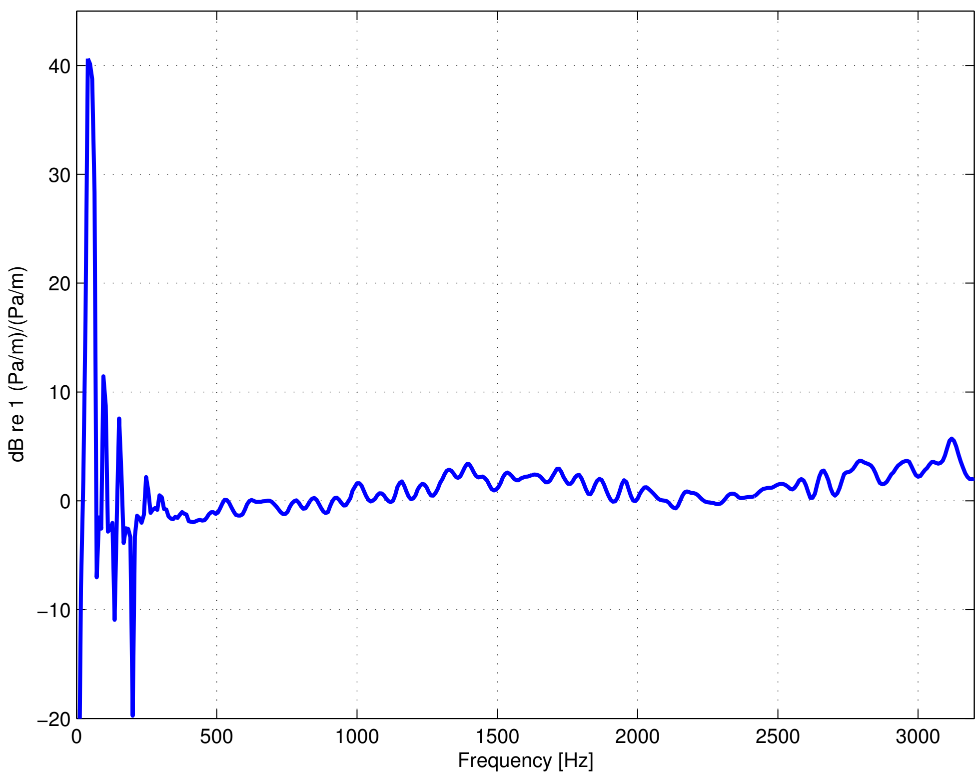
The calibration tests for Phone-Or 3D optical Energy Density probe have been performed. The Phone-Or's single omni-directional pressure and 3-axis pressure gradient (black, red and green) sensors were tested in the Anechoic chamber. The calibration results showed similar results with the calibration provided by the manufacturer. A relatively high noise level was observed at the black channel of the Phone-Or's pressure gradient sensors and it was suggested that the Phone-Or probe was to be checked further by the manufacturer.

6 Recommendation

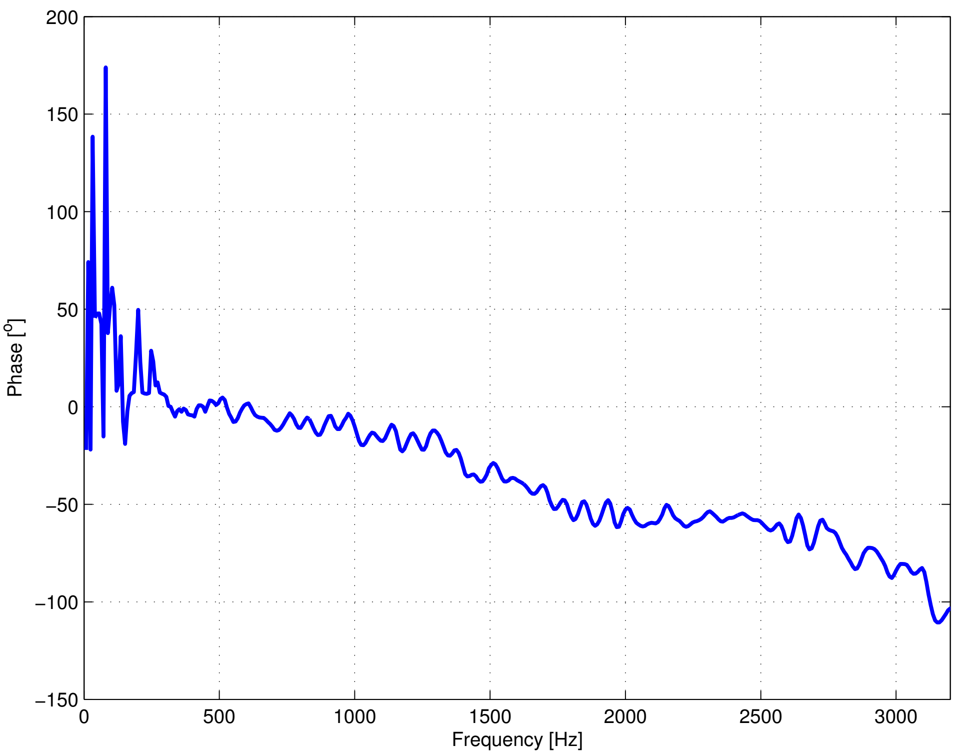
Due to the low sensitivity of the pressure gradient sensors at low frequencies, it is recommended that the overall gain of all 4 channels be increased by 20 dB. This will make the system less sensitive to electrical noise.

7 Acknowledgments

The assistance from Carl Howard, Colin Hansen, Anthony Zander and Rick Morgans in providing suggestions for the testings is gratefully acknowledged.



(a) Magnitude



(b) Phase

Figure 8: Frequency response: green channel (forward wave test).

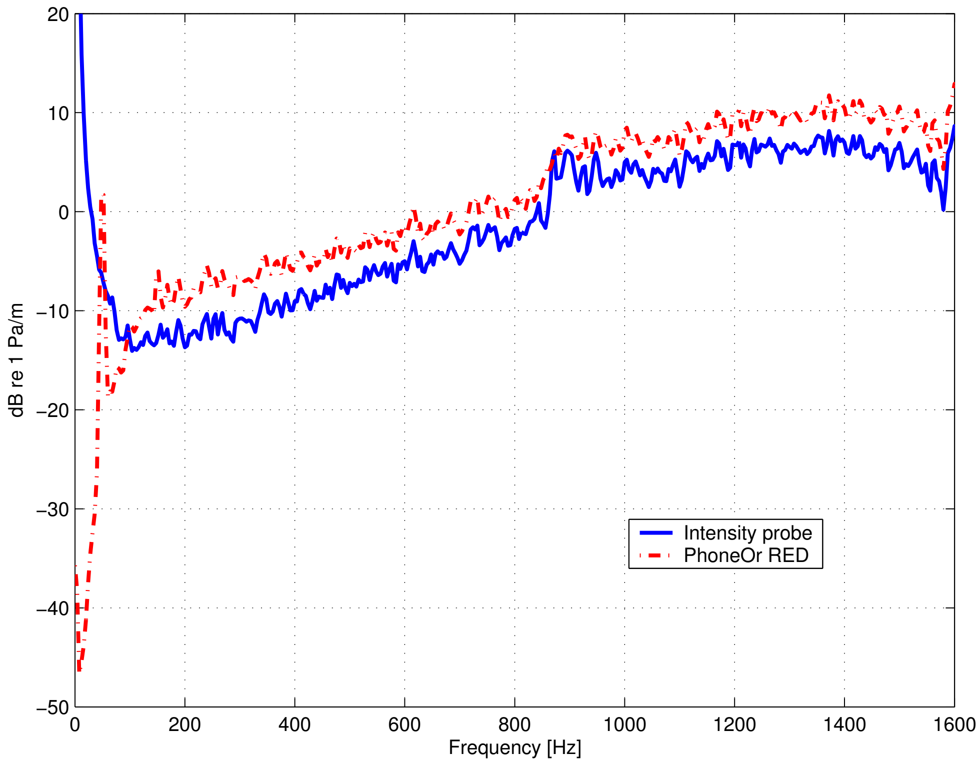


Figure 9: Pressure gradient auto-spectra at near-field: red channel.

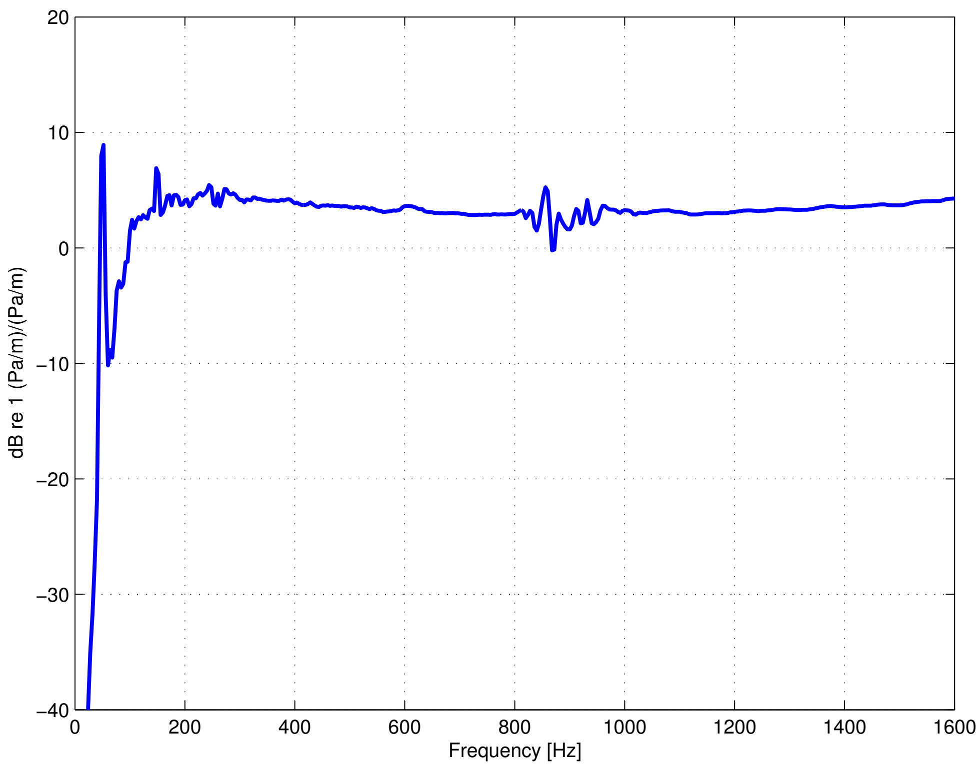
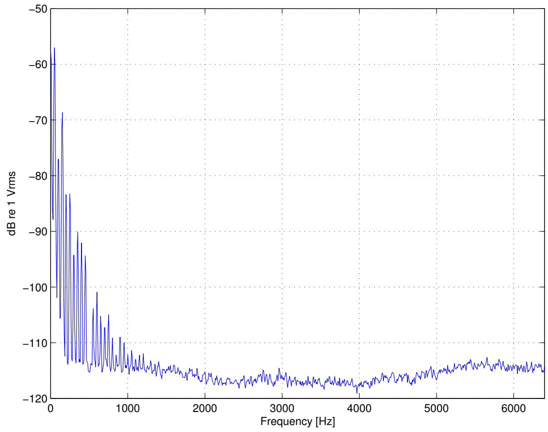
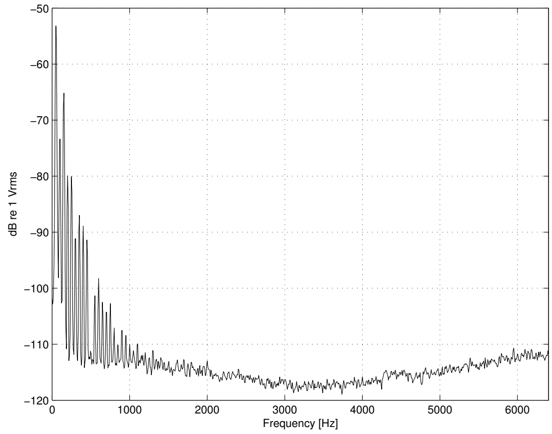


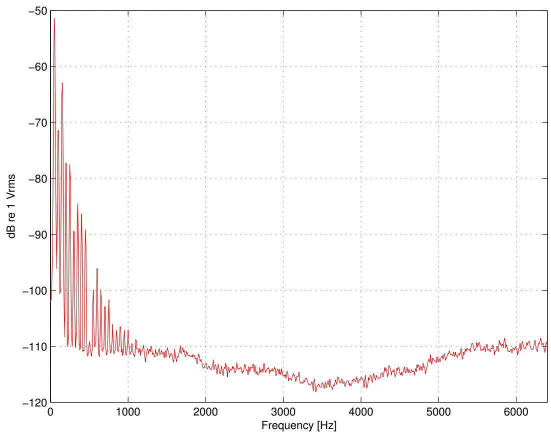
Figure 10: The difference of auto-spectra: Phone-Or probe vs Intensity probe.



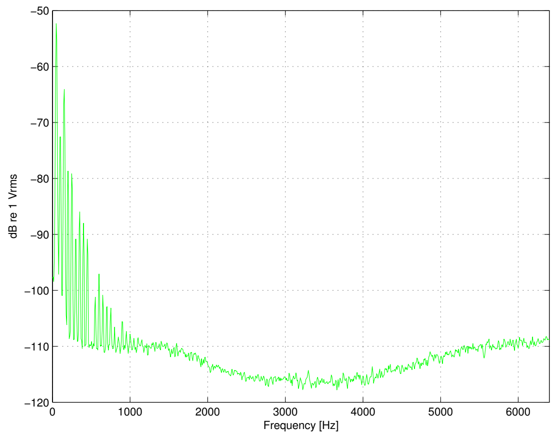
(a) Omni-directional



(b) Black - pressure gradient

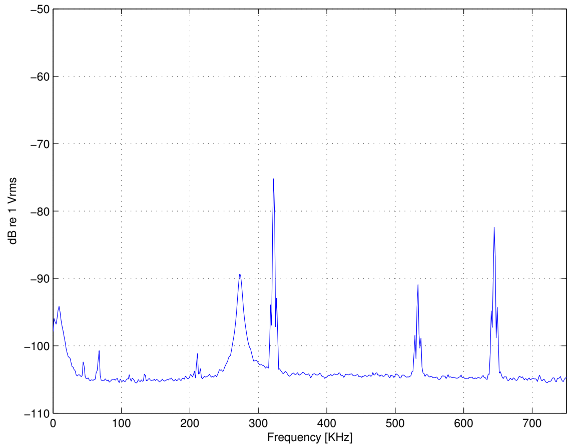


(c) Red - pressure gradient

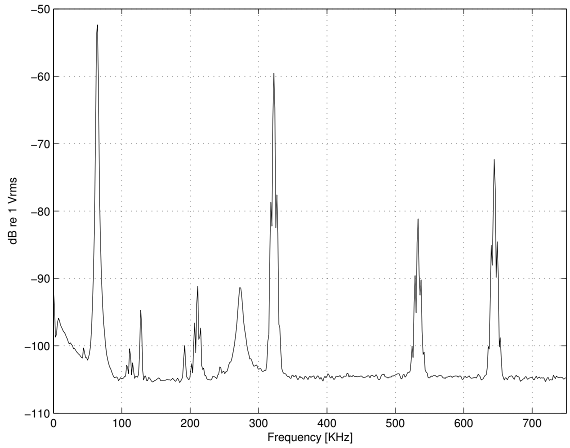


(d) Green - pressure gradient

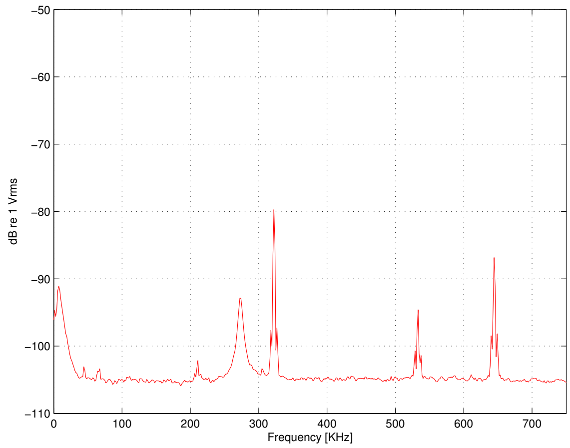
Figure 11: Auto-spectra of self-noise level for 4 channels.



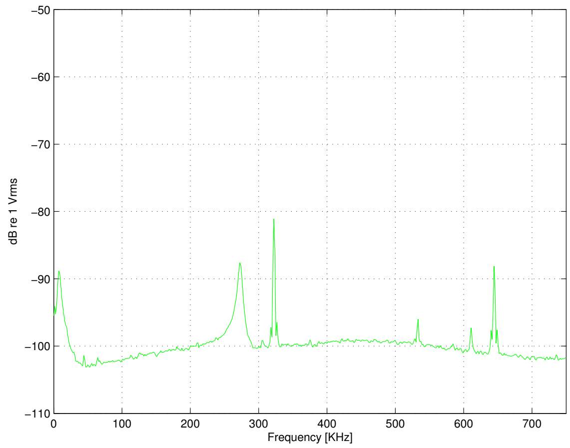
(a) Omni-directional



(b) Black - pressure gradient

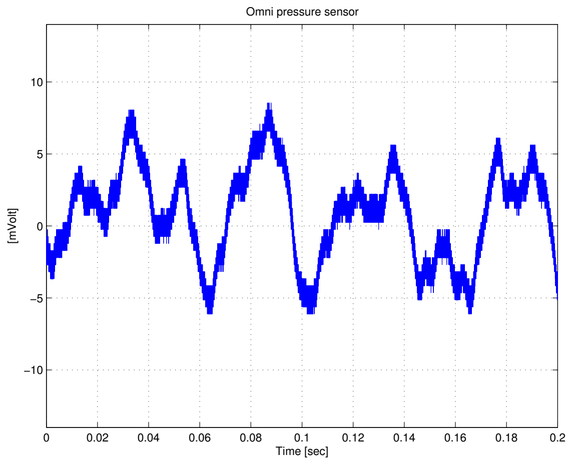


(c) Red - pressure gradient

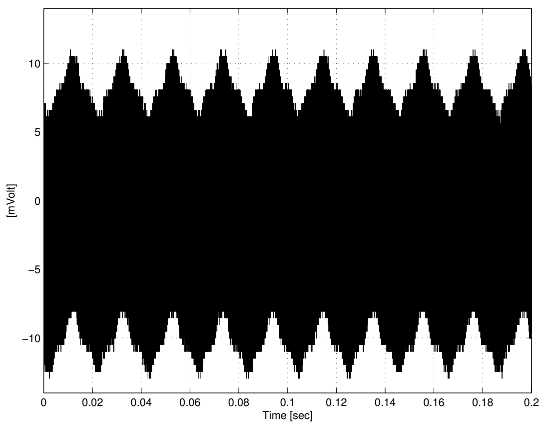


(d) Green - pressure gradient

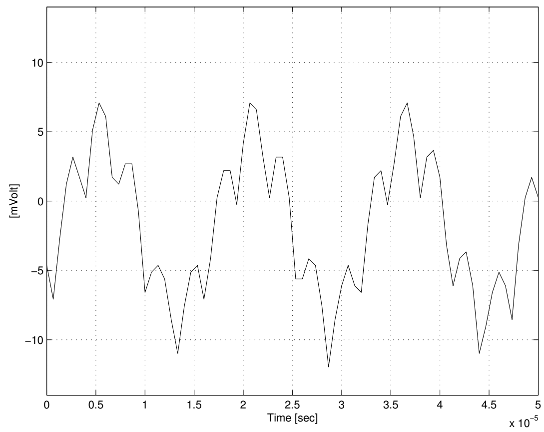
Figure 12: Auto-spectra of self-noise level for 4 channels.



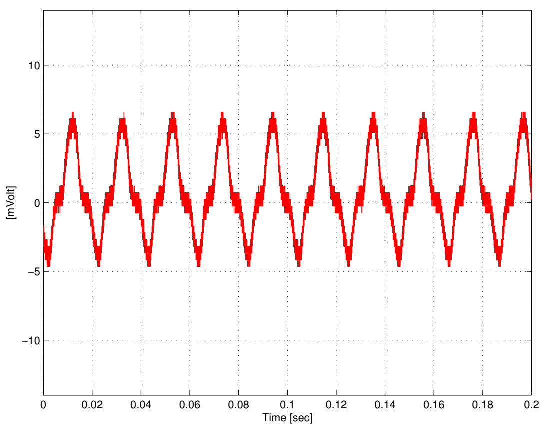
(a) Omni-directional



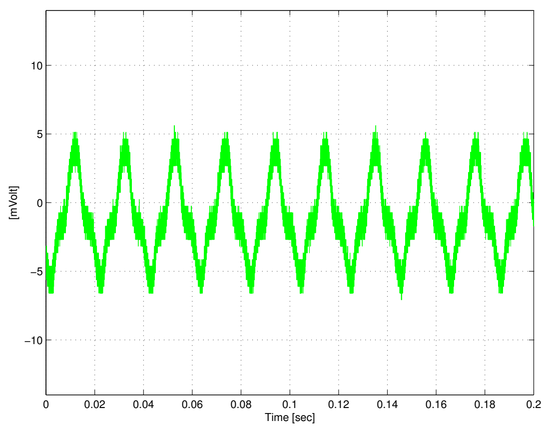
(b) Black - pressure gradient



(c) Black - high frequency noise



(d) Red - pressure gradient



(e) Green - pressure gradient

Figure 13: Self-noise level in time domain for 4 channels.

References

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