The Phone-Or 3D Optical Energy Density Probe: calibration test report of the modified/re-calibrated probe

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Abstract

This report discusses the results from the second calibration test performed on the Phone-Or 3D optical Energy Density probe. The first calibration test found several performance issues associated with high level of noise in the Phone-Or probe. Since then, the Phone-Or manufacturer has addressed those issues by modifying and re-calibrating the probe. To investigate the current performance of modified/re-calibrated probe, a second calibration test was performed in the Anechoic chamber at the University of Adelaide. The test results show that the Phone-Or probe's performance has improved considerably with its self-noise level, particularly due to 50 Hz harmonics, been reduced significantly.

1 Phone-Or 3D optical Energy Density probe

The Phone-Or Energy Density probe (Figure 1) is a set of fibre-optical based sensors for measuring a single omni-directional pressure and 3-axis pressure gradients (black, red and green channels) in an acoustic field. Its nominal nominal frequency range is between 10 Hz and 4 KHz with +/- 2 dB variations [1]. It has a dynamic range of 80 dB with 3.5 Vrms maximum output level. In this second calibration test, Brüel & Kjær PULSE system signal analyzer was used for measurements up to 6.4 KHz, with 800 frequency bins in the FFT and 8 Hz bin width.

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

2 Back-to-back pressure test

The calibration tests were performed in an Anechoic chamber at the University of Adelaide. The Phone-Or omni-directional pressure sensor was calibrated with a calibrated 0.25" Brüel & Kjær (B&K) microphone from a B&K Sound Intensity probe Type 3519 [2]. For this particular test, both sensors were placed back-to-back at a distance of about 2m from the sound source (a speaker). Two tests were conducted in which the sound source was coming from the front and the back of the sensors respectively, i.e. forward and backward wave tests. In the tests, the Phone-Or pressure sensitivity used was 100 mV/Pa, as provided by the manufacturer. The test results are described below:

Figure 2 shows the frequency response from the B&K microphone pressure reading to the Phone-Or pressure reading. The results show that measurements from both sensors are relatively similar, particularly for frequencies between 80 Hz and 2.8 KHz (with up 3 dB variation). In addition, the average result (see Figure 2) shows up to 3 dB variation between 80 Hz and 6.4 KHz. Differences between the Phone-Or probe and Brüel & Kjær microphone are larger at higher frequencies due to higher sensitivities to sensor misallignment. The phase delay associated with the Phone-Or amplifier was estimated from the forward and backward wave tests to cancel out the phase delay due to misalignment of B&K microphone relative to the Phone-Or sensor. The estimated time delay between 180 Hz and 6.4 KHz is found to vary between 62 and 100 μs with almost constant average time delay of 75-80 μs, i.e. a linear phase delay. The time delay ΔT was calculated from the phase delay $\Delta\phi$ as follows:

$$\begin{aligned} \Delta T &= \frac{\Delta\phi(^o)}{360^o} T \\ &= \frac{\Delta\phi(^o)}{360^o} \frac{1}{f} \end{aligned} \tag{1}$$

where T and f is the soundwave period and frequency respectively.

3 Pressure gradient test

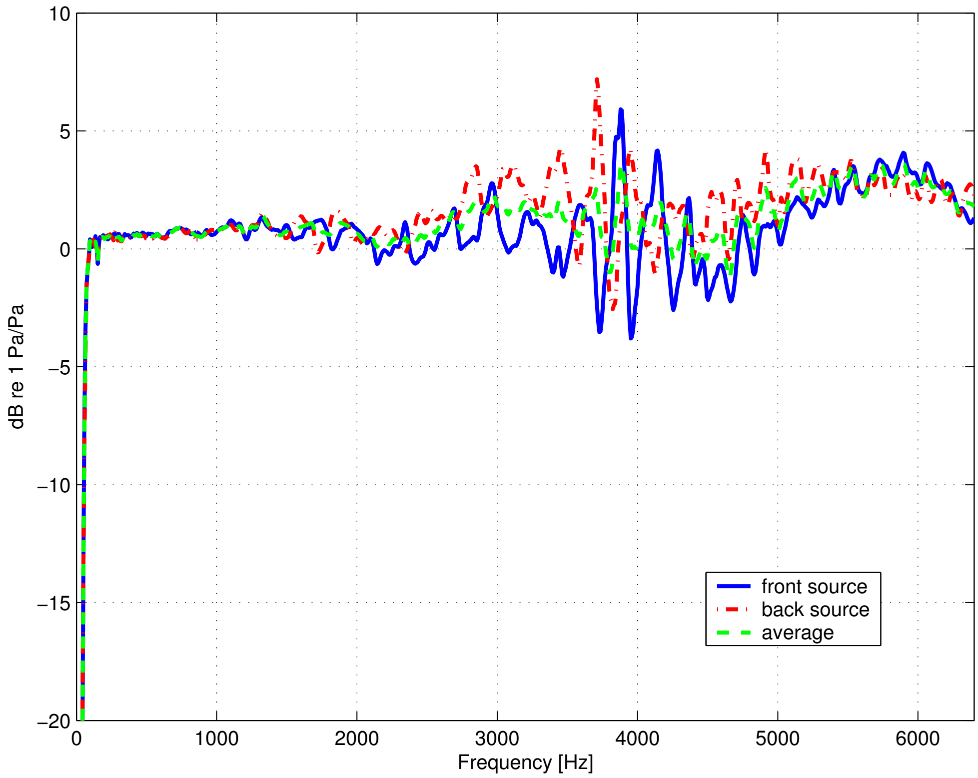
The pressure gradient tests were undertaken for the purpose of re-calibrating the three Phone-Or pressure gradient sensors. A B&K Sound Intensity probe Type 3519 with two 0.25" phase-matched microphones and a 11mm spacer were used for pressure gradient measurements. Far-field and near-field conditions were tested inside the Anechoic chamber.

3.1 Far field test

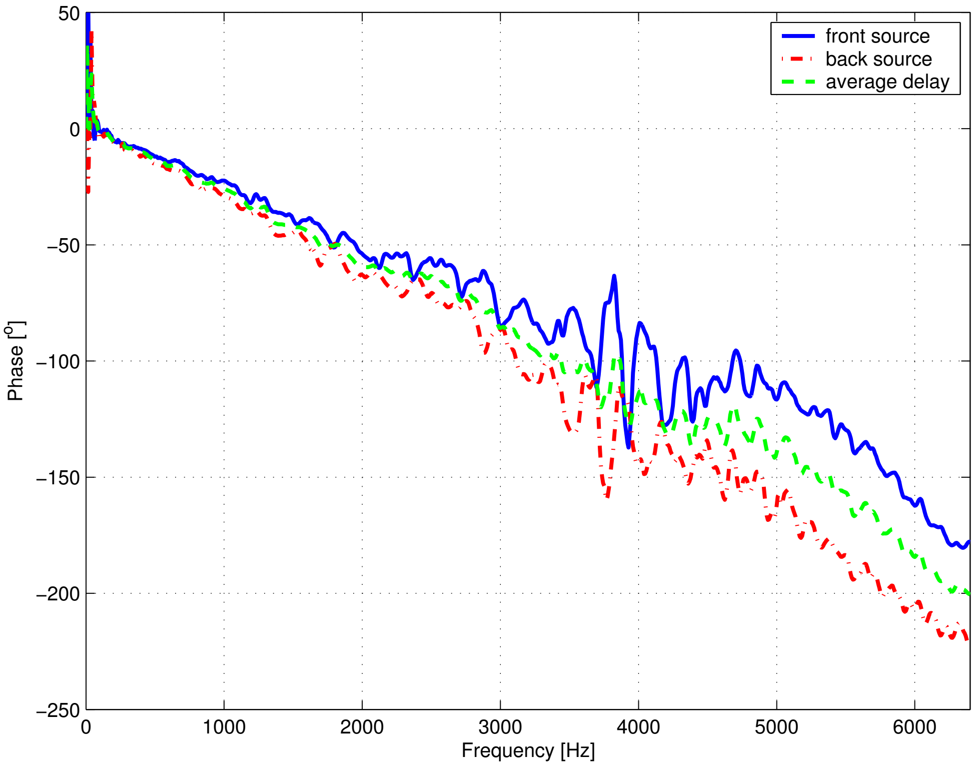
The Phone-Or sensitivity provided by the specifications is 35.5 mV/Pa, for the condition of 1" distance from the sound source, sensor facing the source at 1 KHz and 1 Pa [3]. The following derivations have been described in the first report [3], but will be repeated here for clarity.

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 $\Delta\phi = 9.1^o$. The estimated pressure gradient $\Delta p/\Delta x$ can be obtained from pressure measurements at two adjacent points, p_1 and p_2:

$$\begin{aligned} \frac{\Delta p}{\Delta x} &= \frac{p_2 - p_1}{\Delta x} \\ &= \frac{1}{\Delta x}\left(p - pe^{-j\Delta\phi}\right) \\ &= \frac{1}{\Delta x} p\left(1 - (\cos\Delta\phi - j\sin\Delta\phi)\right) \\ \left|\frac{\Delta p}{\Delta x}\right| &= \frac{0.159\mathrm{Pa}}{0.0087\mathrm{m}} = 18.3\frac{\mathrm{Pa}}{\mathrm{m}} \end{aligned} \tag{2}$$



(a) Magnitude



(b) Phase

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

where $p = 1$ Pa and 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).

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

$$\frac{p}{v} = \rho c \tag{3}$$

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

The particle velocity is related to the pressure gradient by

$$j\omega v = -\frac{1}{\rho}\frac{\partial p}{\partial x}. \tag{4}$$

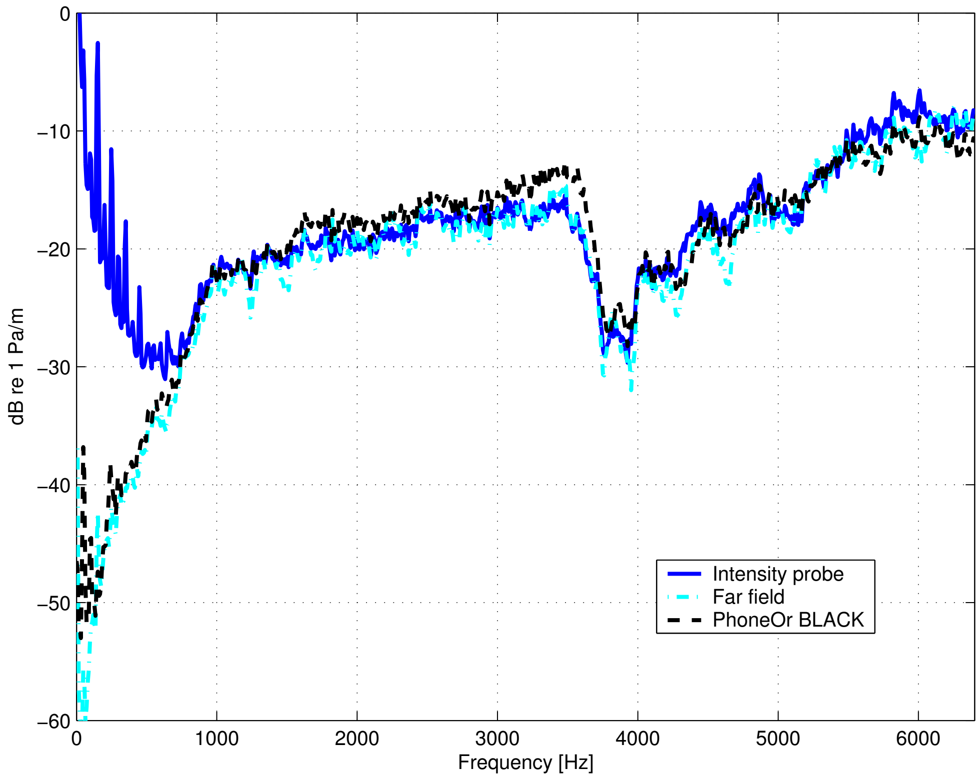
The estimated far-field pressure gradient is obtained by substituting (3) into (4):

$$\frac{\partial p}{\partial x} = -\frac{j\omega p}{c}. \tag{5}$$

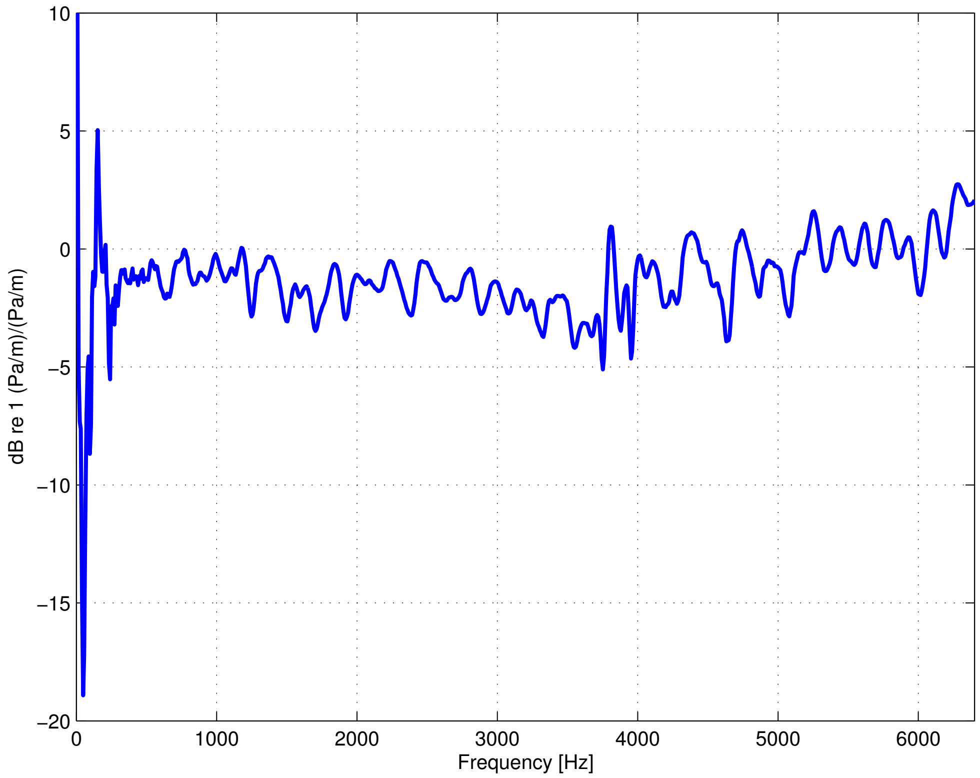
Figures 3, 4 and 5 show the auto-spectra measurements for calibration of black, red and green channels respectively. The Phone-Or measurements are compared to the measurements from the B&K Sound Intensity probe and from the far-field assumption. The results show that all three different methods of measurements are relatively similar up to 6.4 KHz, except for the Intensity probe measurement below 500 Hz. The discrepancy might be caused by the low-frequency limitation because of the spacer used for the Intensity probe.

In the previous calibration tests [3], it was observed that a high-level electric noise at 50 Hz harmonics that corrupted the measurements at frequencies below 400 Hz. Based on the results from the above figures, the noise level of the new calibrated Phone-Or has now been reduced by more than 30 dB, occuring below 200 Hz, at which the pressure gradient signal is relatively small. It should be noted that the highest level of noise in the measurements corresponds to approximately 44 μV since the Phone-Or sensitivity is 1.94 mV/(Pa/m).

Frequency responses between the measurements from the Phone-Or and far-field assumption are illustrated in Figures 6, 7 and 8 for calibration of black, red and green channels respectively. Between 160 Hz to 6.4 KHz, the Phone-Or measurements are within 5 dB of measurements using the far-field assumption. The phase delays associated with the Phone-Or amplifier can be seen from the results, where the results for black, red and green channels vary up to 68 μ s. However, the phase delays are considerably less than those measured before the Phone-Or was modified/re-calibrated by the manufacturer [3].

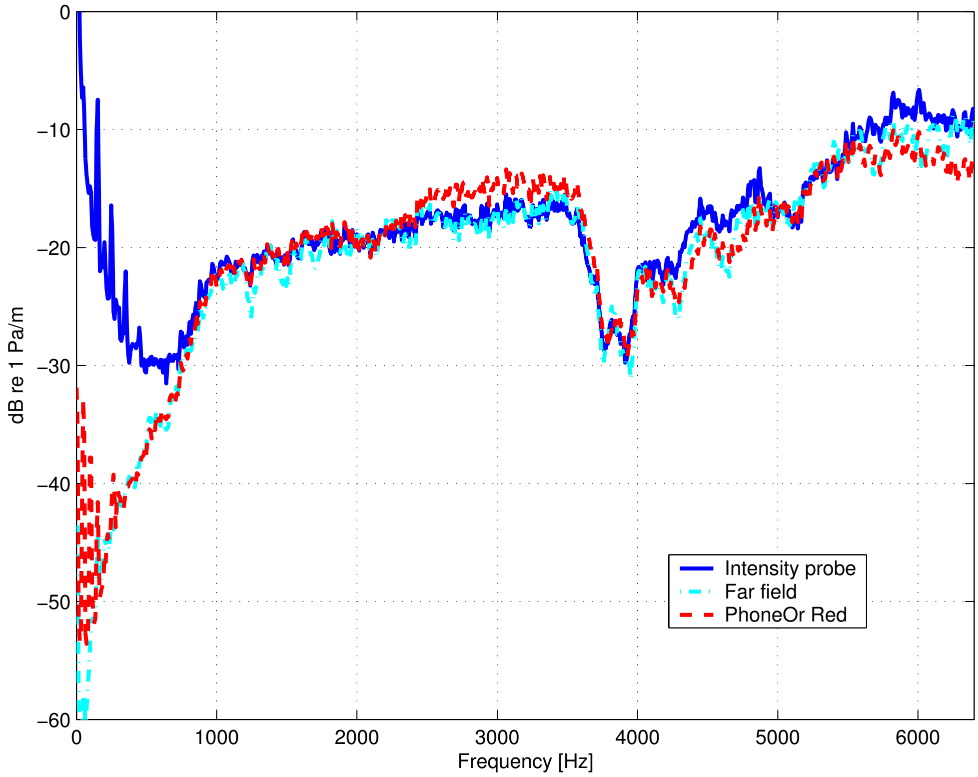


(a) Pressure gradient auto-spectra

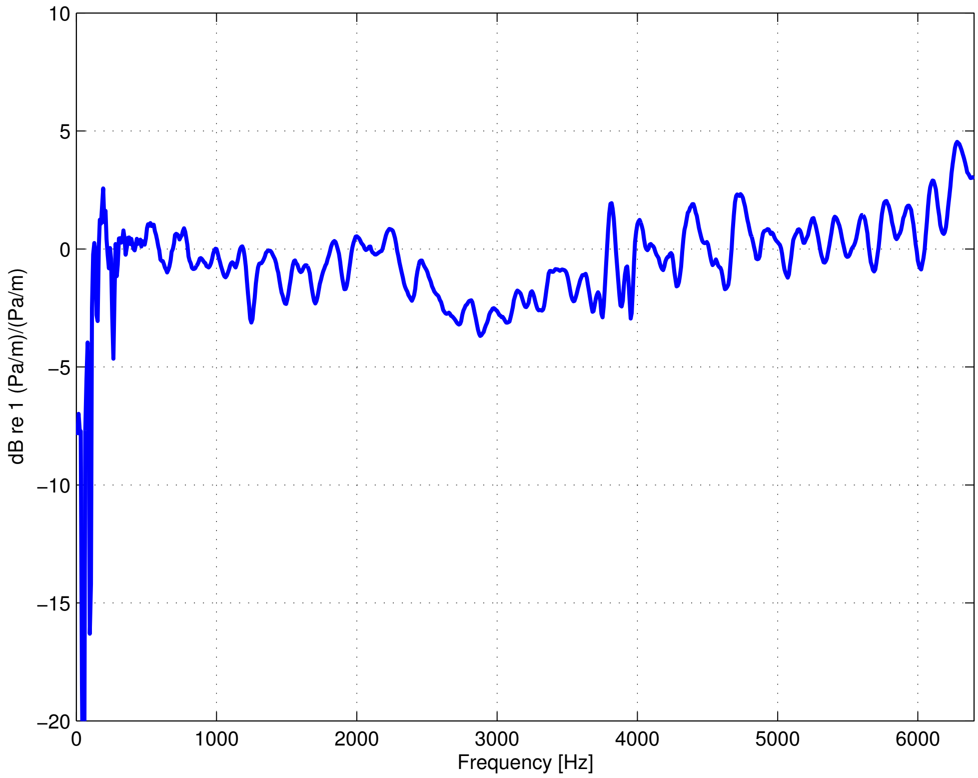


(b) The difference between the Phone-Or and far-field auto-spectra

Figure 3: Black channel calibration.

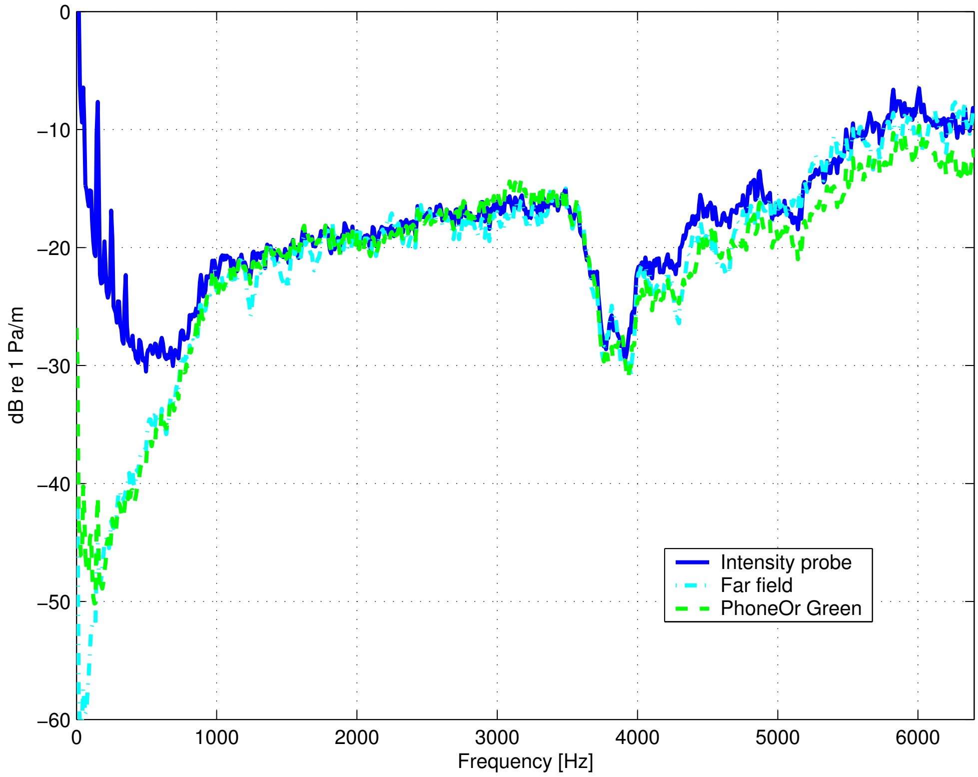


(a) Pressure gradient auto-spectra

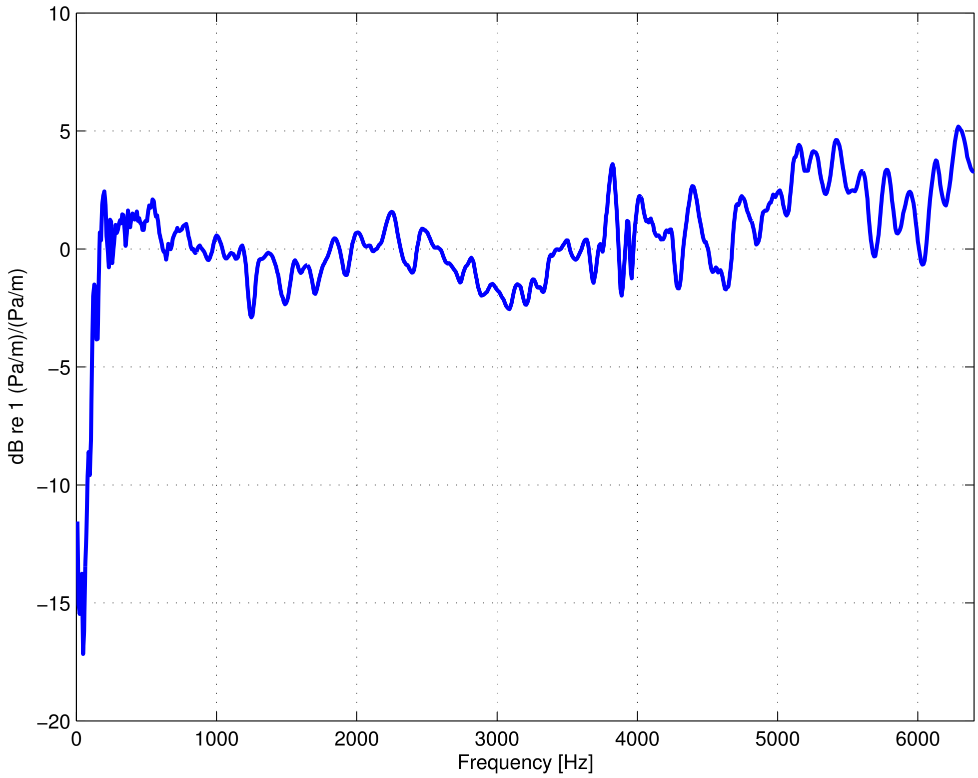


(b) The difference between the Phone-Or and far-field auto-spectra

Figure 4: Red channel calibration.

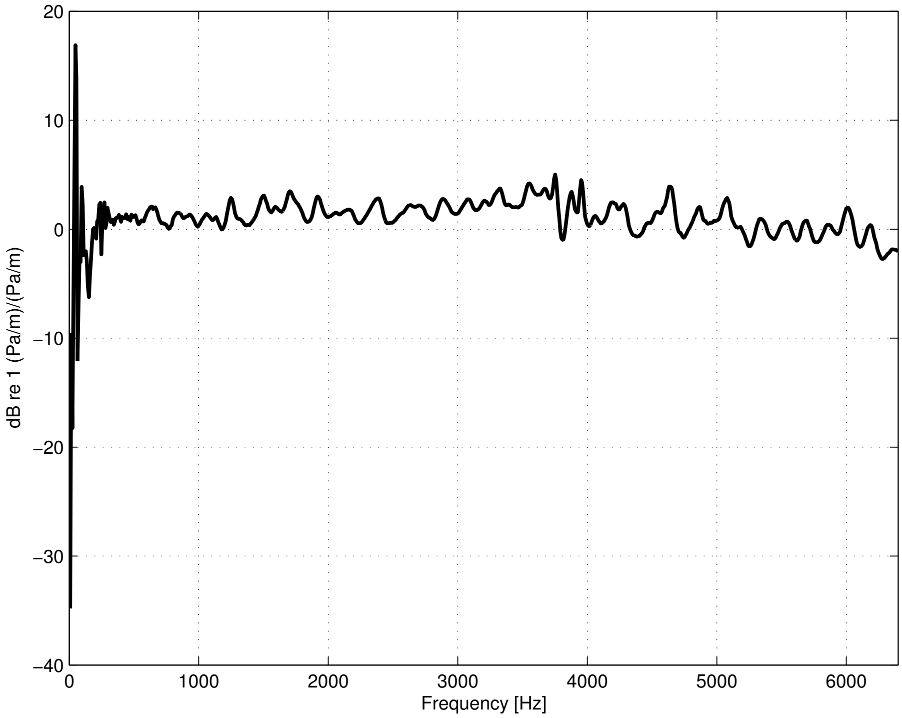


(a) Pressure gradient auto-spectra

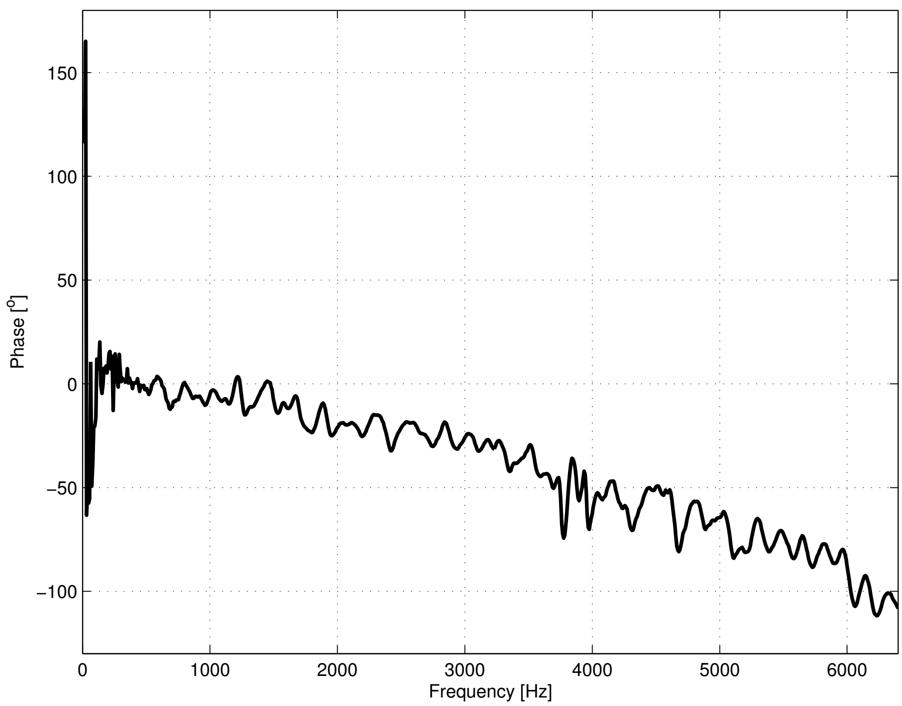


(b) The difference between the Phone-Or and far-field auto-spectra

Figure 5: Green channel calibration.

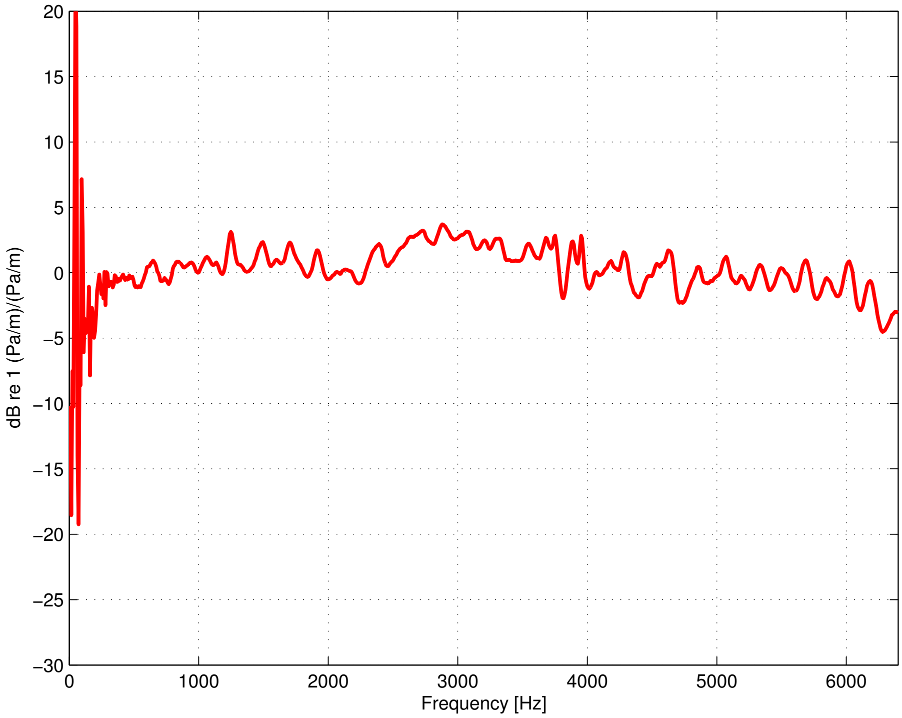


(a) Magnitude

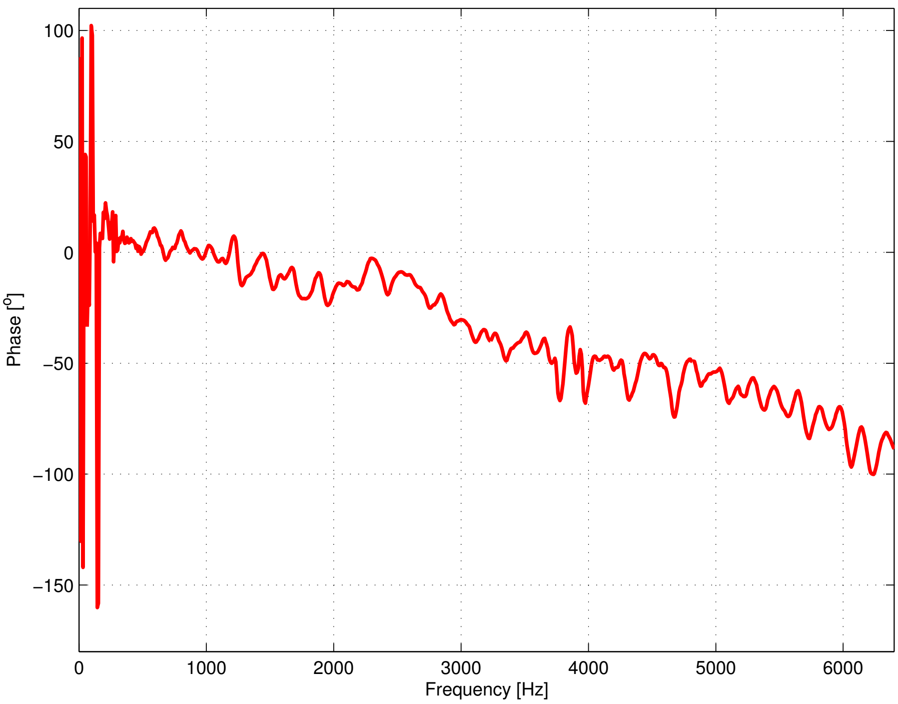


(b) Phase

Figure 6: Frequency response: Black channel.

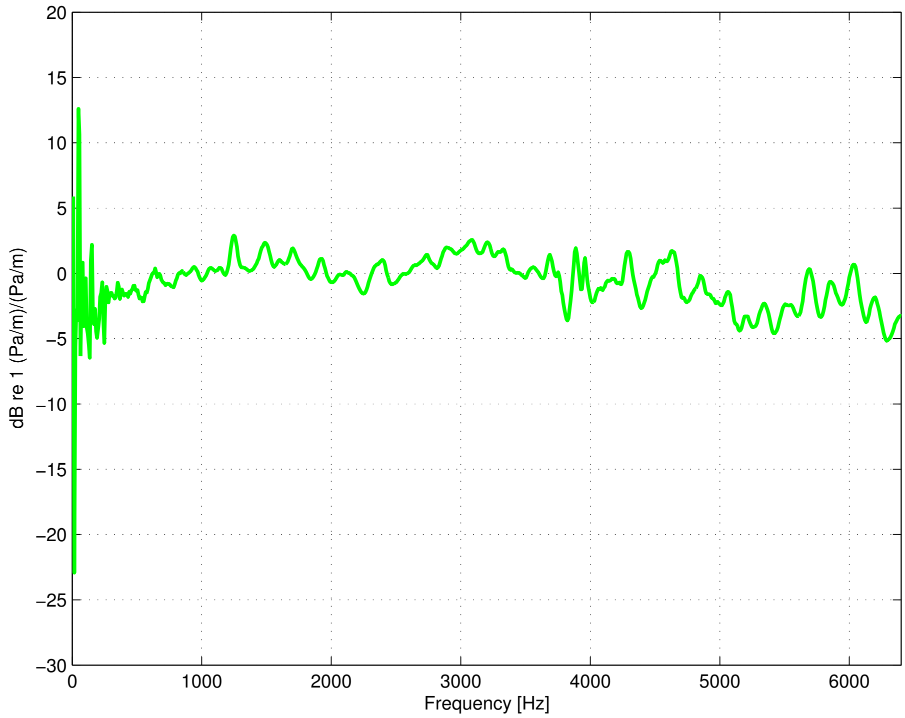


(a) Magnitude

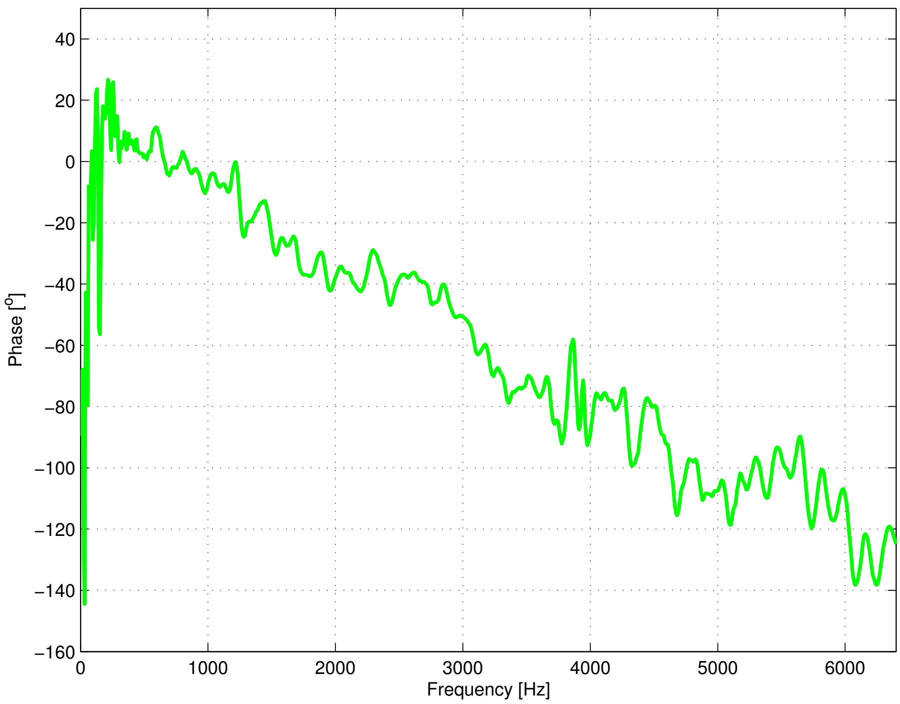


(b) Phase

Figure 7: Frequency response: Red channel.



(a) Magnitude



(b) Phase

Figure 8: Frequency response: Green channel.

3.2 Near field test

For the near field test, the Sound Intensity Phone-Or probe was positioned at a distance of about 100 mm from the sound source, similar to the first calibration test described in the first report [3]. The Phone-Or pressure gradient sensitivity used has been calculated previously in Section 3.1, i.e. 1.94 mV/(Pa/m). The auto-spectra from the measurements on the red pressure gradient channel and the Sound Intensity probe are shown in Figure 9. The results show that both measurements have good agreement, particularly at frequencies above 800 Hz. At lower frequencies, more discrepancies are expected since the near-field measurements were more sensitive to location mismatch of the two sensors. It is observed that the current results have a better agreement compared to the near-field test results in the first report. The difference in the measurements are within 3 dB for frequencies between 500 Hz and 6.4 KHz as illustrated in Figure 10.

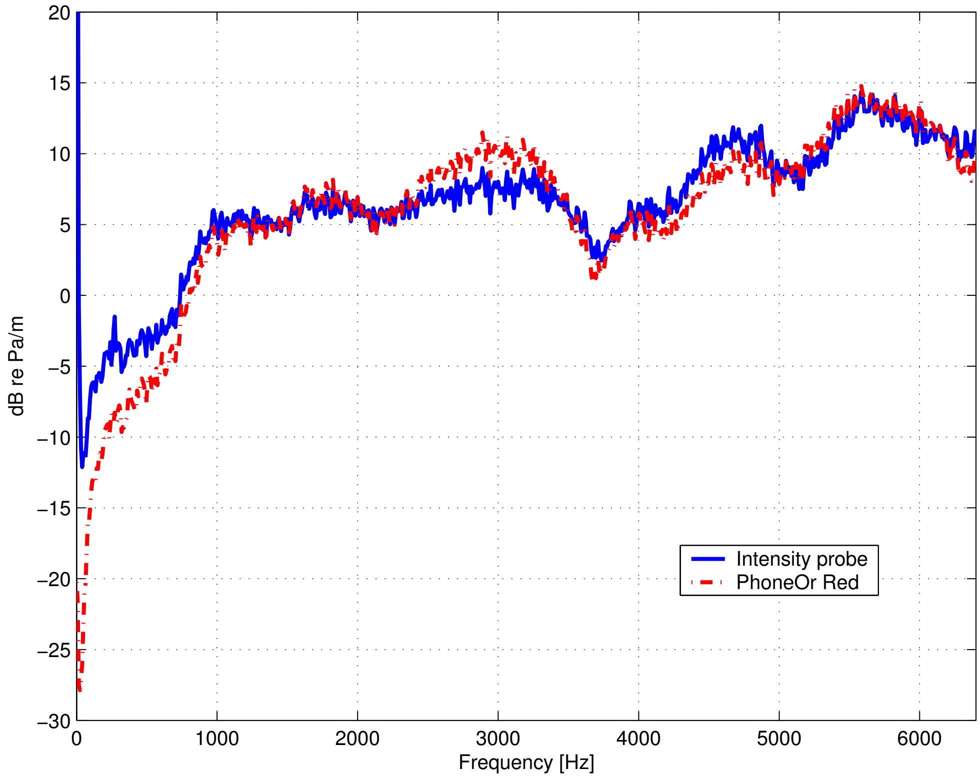


Figure 9: Pressure gradient auto-spectra at near-field: red channel.

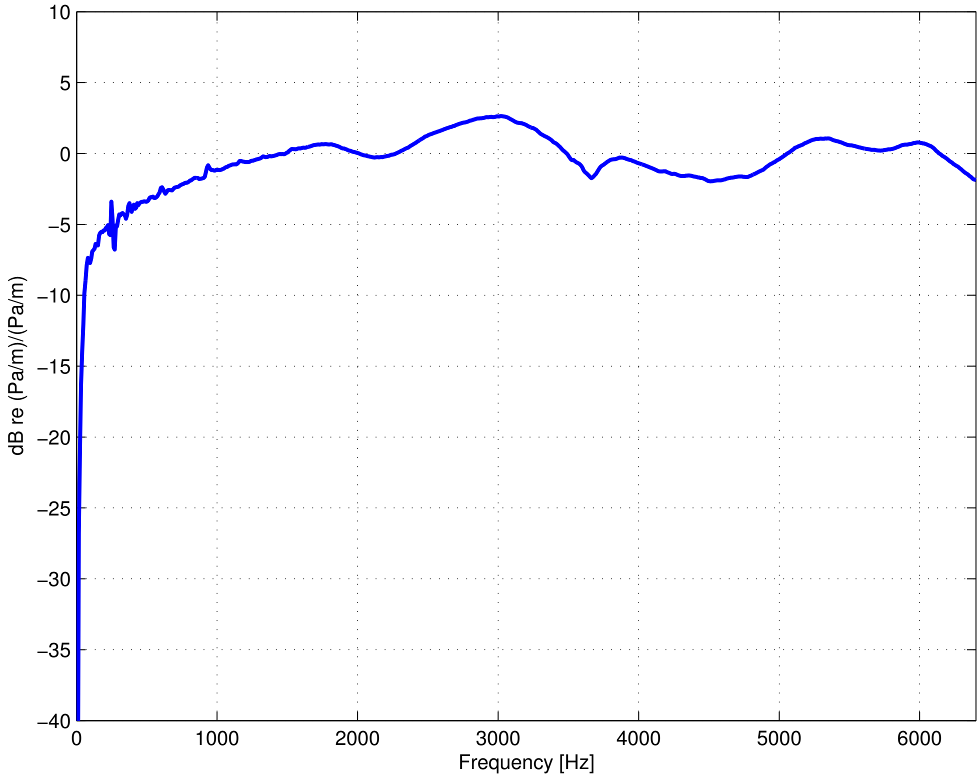
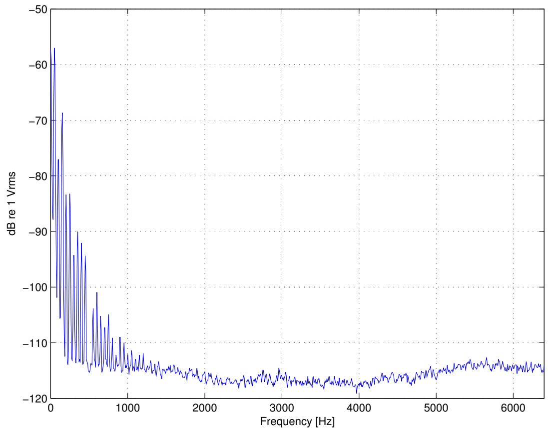


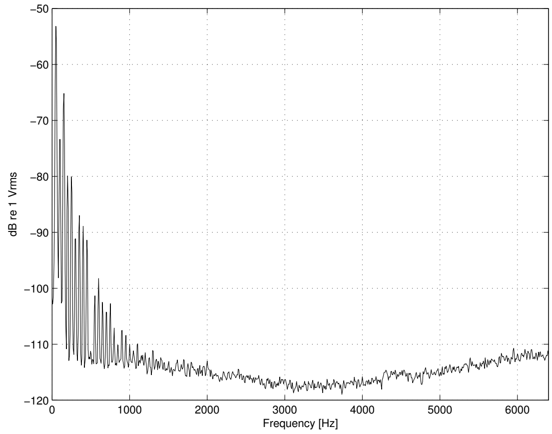
Figure 10: The difference of auto-spectra: Phone-Or probe vs Intensity probe.

4 Phone-Or self-noise level test

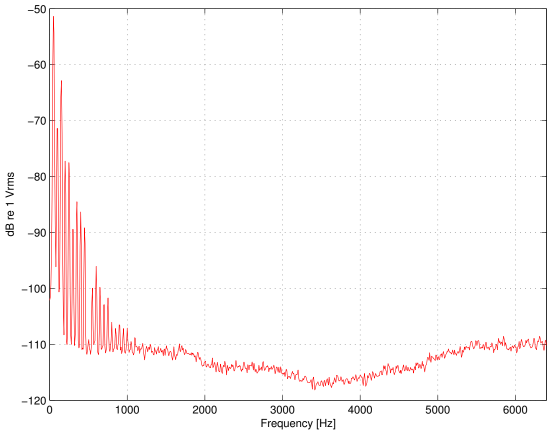
Finally, the self-noise test is performed to see if the noise-level of the modified Phone-Or probe has improved in all channels. Figures 11 and 12 compare the self-noise level of the Phone-Or probe up to 6.4 KHz, for the original un-modified Phone-Or probe and the recently modified and re-calibrated Phone-Or probe respectively. It is obvious that the noise levels at low frequencies due to 50 Hz harmonics have been reduced considerably at all channels. The self-noise levels for omni-directional pressure and the three pressure gradient (black, red, and green) channels are 0.54, 0.64, 0.82 ands 0.79 mVrms respectively. The results can be compared with the self-noise levels of the un-modified Phone-Or probe of 2.1, 2.6, 2.9 and 2.4 mVrms for those 4 channels. In addition, the problem with the excessive high frequency self-noise level at the black channel, which was observed at the first calibration test [3], has now been rectified.



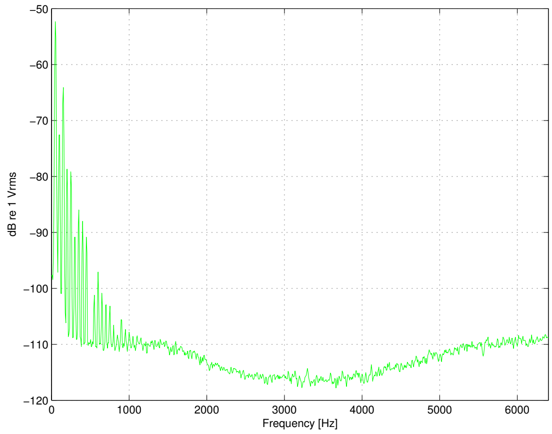
(a) Omni-directional



(b) Black - pressure gradient

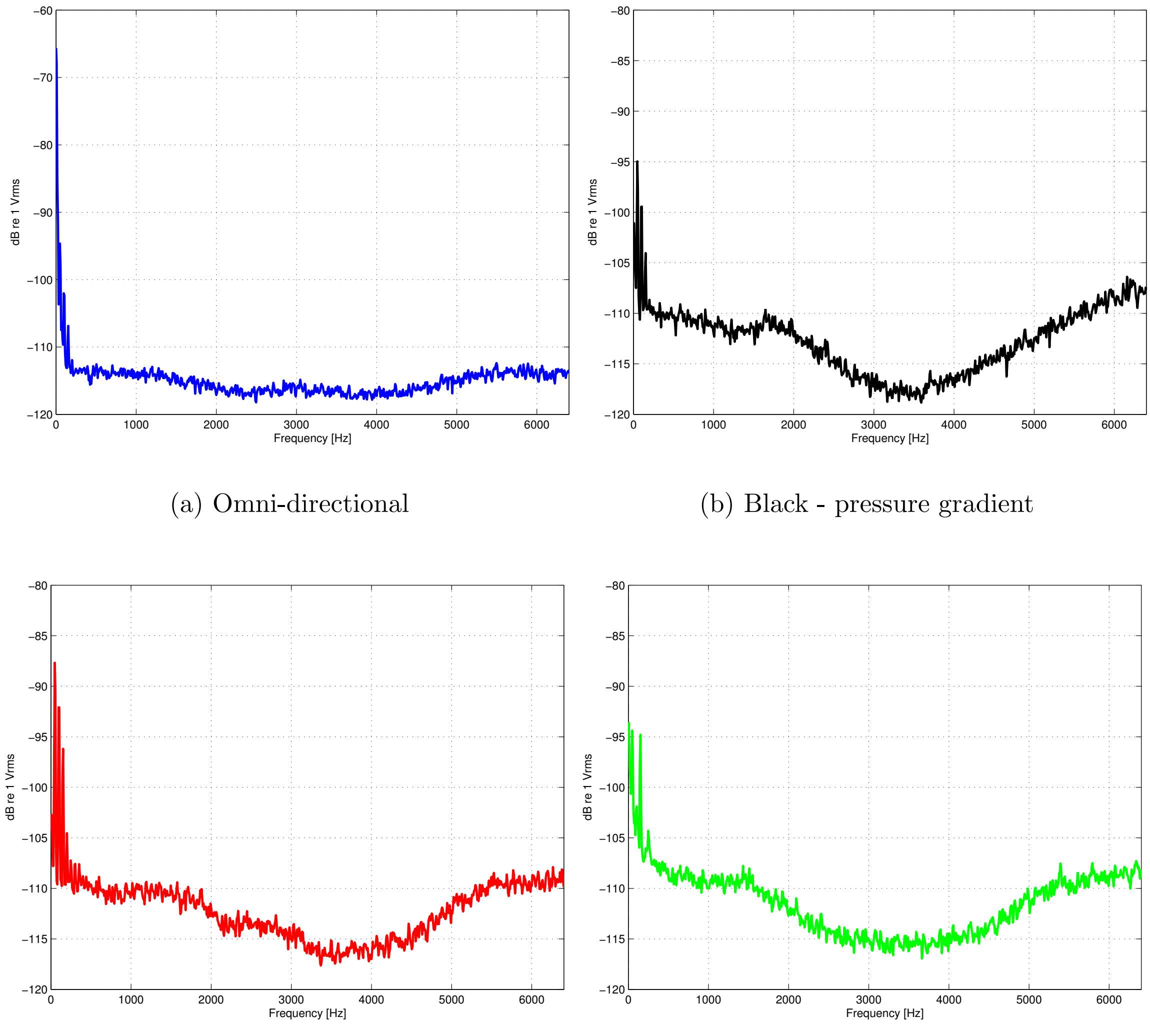


(c) Red - pressure gradient



(d) Green - pressure gradient

Figure 11: Auto-spectra of self-noise level for 4 channels: original Phone-Or probe [3].



(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: modified Phone-Or probe.

5 Conclusions

The second calibration tests for the modified/re-calibrated Phone-Or 3D optical Energy Density probe have been completed. 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 test results showed that the noise level from the Phone-Or probe has been reduced significantly, allowing more accurate measurements from the probe. The calibration test results demonstrate the potential of the Phone-Or probe to be used for efficient acoustic sensing for active noise control.

References

[1] 3D sound field optical microphone system for EMI/RFI environments. *Phone-Or manual, www.phone-or.com, Israel*, 2003.

[2] Brüel & Kjær sound intensity analysing system type 3360 - instruction manual. 1983.

[3] D. Halim, D. Petersen, and B. Cazzolato. *Calibration test report for the Phone-Or 3D Optical Energy Density Probe.* School of Mechanical Eng., Uni. of Adelaide, SA, Australia, July 2004.