2aEA6. Characterization of directional microphones in an arbitrary sound field

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An acoustic characterization method for directional microphones is presented that does not require an anechoic chamber to provide a controlled plane-wave sound field. Measurements of a directional microphone under test are performed in a nearly arbitrary sound field for several angles of sound incidence, and the corresponding sound pressure and pressure gradients in the vicinity of the test microphone are measured using an automated probe microphone scanning system. From these measurements the total acoustic frequency response of the directional microphone can be decomposed into its sensitivities to sound pressure and pressure gradient using a least squares estimation technique. These component responses can then be combined to predict the directional response of the microphone to a plane-wave sound field. This technique is demonstrated on a commercially available pressure gradient microphone and also on a combination sound pressure-pressure gradient microphone. Comparisons with the plane-wave responses measured in an anechoic environment show that the method gives reasonable results down to 100 hertz.
INTRODUCTION

Directional microphones are characterized by their acoustic response to plane sound waves. A plane-wave sound field can be generated in an anechoic chamber or in a large room, at a distance from a loudspeaker greater than the sound wavelength, and away from acoustically reflective surfaces. Unfortunately, this testing environment is not always available because of room size or the presence of necessary test equipment in the sound field.

Methods for improving the quality of acoustic measurements have their limitations. Time domain windowing of the impulse response can reduce the effects of reflections in acoustic measurements [1], but the reflections cannot be windowed out without biasing the response at lower frequencies [2] or without modifying the measured response for lightly damped systems with settling times greater than reflection reverberation times. The effects of reflections can be reduced by placing the sound source close to the microphone, but near-field or proximity effects result in higher response measurements for pressure gradient microphones at lower frequencies than the responses obtained from acoustic plane waves [3]. Corrections for near-field effects can be made using theoretical expressions if measurements are performed in an anechoic chamber at known distances from a monopole source and the type of directional acoustic sensor is known [2]. A theoretically based near-field correction would be difficult to perform for a directional microphone that depends on an unknown combination of sound pressure and pressure gradient.

In the acoustic testing method described here, measurements of the directional microphone under test are performed in a nearly arbitrary sound field for several angles of sound incidence, and the corresponding sound pressure and pressure gradients in the vicinity of the test microphone are measured using an automated probe microphone scanning system. From these measurements, the total acoustic frequency response of the directional microphone can be decomposed into its sensitivities to sound pressure and pressure gradient using a least squares estimation technique. These component responses are then combined to predict the directional response of the microphone to a plane-wave sound field. This method is verified with the plane-wave responses measured in anechoic environments.

TEST SETUP

The test setup is illustrated by the schematic in Figure 1. A loudspeaker is mounted to a rotation stage (Newport URS150BPP rotation stage) and the test microphone is positioned at the center of the stage. The sound incidence angle, $\phi$, is changed by moving the loudspeaker with the rotation stage while leaving the test microphone in a fixed position. Measurements of the sound pressure are obtained using a custom probe microphone scanning system. A probe microphone (Brüel & Kjær probe microphone type 4182) is tethered to a rod that is fixed to a computer-controlled XYZ motorized positioning system (Newport custom system: (3) ILS250PP linear stages, (1) EQ120 right-angle bracket, (1) ESP300 motion controller/driver). A dynamic signal analyzer (Spectral Dynamics SigLab Model 50-21) generates an analog output signal for a power amplifier (Techron 5515 Power Supply Amplifier) that drives the loudspeaker (Morel MDM55 mid-range speaker). The loudspeaker is fitted with a 1.5-inch diameter tube that serves as a wave guide. The test microphone is positioned close to the opening of the tube. The test microphone and probe microphone signals along with the speaker excitation signal are sampled and processed with the dynamic signal analyzer to obtain complex transfer functions. Data acquisition and motion control are coordinated using custom programs written in MATLAB. The test setup is on a vibration isolation table (Newport Research Series Vibration Isolation Table RS 4000, 3’x6’x8”), situated within a small sound-isolation chamber (Eckel audiometric booth, inside dimensions (LxWxH) 7’-4” x 9’-8” x 6’-6”). A photograph of the test setup is provided in Figure 2.

SOUND FIELD CHARACTERIZATION

The sound field is measured in order to obtain the relationship between pressure gradient and sound pressure in the vicinity of the test microphone. Using the probe microphone scanning system described in the previous section, the sound pressure is sampled over an equally spaced linear array of 41 measurement locations centered over the middle of the test microphone, with measurement steps of 1 [mm]. Complex transfer functions of the sound pressure with respect to the loudspeaker excitation signal are obtained at the measurement points using a continuous random excitation signal with 20-kHz bandwidth, which is amplified and broadcast from the loudspeaker. The probe microphone output and excitation signal are
simultaneously sampled at a rate of 51.2 kHz, and processed using 10 record averages to get transfer functions with 6.25-Hz resolution bandwidth. Coherence squared functions are also estimated to monitor data quality. The sound pressure transfer functions are normalized to the transfer function measured at the center position. Then, at each frequency bin, the real and imaginary parts of the sound pressure transfer functions are numerically differentiated to obtain estimates of the pressure gradients with respect to sound pressure. A third-order polynomial is fit to the data to smooth the data prior to differentiation.

To verify the sound field characterization procedure, the measured transfer function of pressure gradient to sound pressure is compared to theoretical transfer functions for ideal sound fields. For a plane wave with the pressure gradient at an angle $\phi$ from the direction of wave propagation, the transfer function of pressure gradient to sound pressure is

$$H_{ppx}^{(pw)}(\omega) = -ik\cos(\phi)$$  \hspace{1cm} (1)

where $k = \omega/c$ is the wave number, $\omega$ is frequency in radians per second, $c$ is the wave propagation speed, and $i = \sqrt{-1}$. The sound field near a small monopole source may be approximated as spherical waves radiating from a point. For a pressure gradient at an angle $\phi$ from the radial direction of the spherical wave, the transfer function of pressure gradient to sound pressure is

$$H_{ppx}^{(sw)}(r, \omega) = \left(-\frac{1}{r} - ik\right)\cos(\phi)$$  \hspace{1cm} (2)

where $r$ is the distance from the point source in [m]. Equations (1) and (2) are obtained by differentiating the plane-wave and spherical-wave sound pressure expressions that satisfy the acoustic wave equation and normalizing to sound pressure.
The measured and theoretical transfer functions of pressure gradient to sound pressure are compared in Figure 3. The curves in the top plot are the magnitudes of the transfer functions plotted versus frequency, and the bottom plot has the corresponding phase angles. Frequencies below 100 Hz are not displayed because of the poor data quality in the measurements due to the limited frequency response of the loudspeaker. The third-order polynomial model used to fit the data for differentiation of the measured sound pressure provided $R^2$ values close to 1 for the measurement frequencies up to 10 kHz. Data is excluded from the plots above 10 kHz because the order of the polynomial model was too low to accurately fit the data at these higher frequencies. The distance from the theoretical point source for the spherical wave is $r = 0.038\, [m]$ and is chosen to provide the best fit with the measured data. The magnitude and phase curves of the measured transfer function have periodic fluctuations over frequency that are not accounted for using the simple models of the sound field. These fluctuations are most likely due to reflections and standing waves in the test setup. The comparison shows that the test sound field is not a plane wave, but more closely matches a spherical wave.

**Figure 3:** Comparison of measured and theoretical transfer functions of pressure gradient to sound pressure. The top plot shows the magnitudes of the transfer functions, and the bottom plot contains the corresponding phase angles. The sound field is not a plane wave, but more closely matches that for a spherical wave at a distance $r = 0.038\, [m]$ from the point source. The measured transfer function curves have periodic fluctuations over frequency which are most likely due to standing waves and reflections in the test setup.

**PLANE-WAVE ACOUSTIC RESPONSE ESTIMATION METHOD**

We would like to obtain the directional response of the microphone for faraway sound sources where sound is propagating as acoustic plane waves. To estimate the plane-wave response, the sound field is characterized using the method described in the previous section for varying sound incidence angles. The transfer functions of the test microphone output with respect to sound pressure are also measured for the different sound directions. It is assumed that these microphone responses can be expressed as a linear combination of sound pressure and pressure gradient components. A least squares method is used to identify these microphone component responses. The far-field directional response of the microphone is then simulated using the theoretical plane-wave expressions for pressure and pressure gradient.

The Fourier transform of the directional microphone output voltage for sound incident at angle $\phi_i$ is approximated as

$$V^{(i)}(\omega) = P^{(i)}(\omega)G_{pv}(\omega) + \frac{P^{(i)}(\omega)}{X}G_{px}(\omega)$$  \hspace{1cm} (3)

where $P^{(i)}(\omega)$ and $P^{(i)}(\omega)$ are the Fourier transforms of the pressure and pressure gradient, respectively, near the test microphone at sound incidence angle $\phi_i$. The microphone response has a sound-pressure component $G_{ps}(\omega)$, and a pressure gradient component $G_{px}(\omega)$. Our goal is to obtain estimates of these component transfer functions from the microphone response and sound-field measurements acquired for various sound incidence angles.

Normalizing equation (3) by the measured sound pressure amplitude $P^{(i)}(\omega)$, the transfer function of the microphone output voltage to sound pressure at $\phi_i$ is

$$H^{(i)}_{pv}(\omega) = G_{pv}(\omega) + \frac{P^{(i)}(\omega)}{P^{(i)}(\omega)}G_{px}(\omega) + \epsilon_i(\omega)$$  \hspace{1cm} (4)
where $\epsilon_i(\omega)$ is the equation error. The measurements at $n$ incidence angles can be written as

$$
\begin{pmatrix}
H_{pp}^{(1)}(\omega) \\
H_{pp}^{(2)}(\omega) \\
\vdots \\
H_{pp}^{(n)}(\omega)
\end{pmatrix}
= 
\begin{pmatrix}
1 & H_{pp}^{(1)}(\omega) \\
1 & H_{pp}^{(2)}(\omega) \\
\vdots & \vdots \\
1 & H_{pp}^{(n)}(\omega)
\end{pmatrix}
\begin{pmatrix}
G_{pv}(\omega) \\
G_{pv}(\omega)
\end{pmatrix}
+ 
\begin{pmatrix}
\epsilon_1(\omega) \\
\epsilon_2(\omega) \\
\vdots \\
\epsilon_n(\omega)
\end{pmatrix}
$$

This has the form

$$
Z = [Y]\beta + \xi
$$

where

$$
\beta = \begin{pmatrix}
G_{pv}(\omega) \\
G_{pv}(\omega)
\end{pmatrix}
$$

are the microphone component responses. With $n > 2$, the least squares solution for these complex transfer functions is

$$
\hat{\beta} = ([Y]^T[Y])^{-1}[Y]^T Z
$$

where $^T$ is the complex conjugate transpose.

From $G_{pv}(\omega)$ and $G_{pv}(\omega)$, the plane-wave response of the microphone is estimated by

$$
H_{pv}^{(pw)}(\omega) = G_{pv}(\omega) + H_{pp}^{(pw)}(\omega)G_{pv}(\omega)
$$

where $H_{pp}^{(pw)}(\omega)$ is the theoretical transfer function of pressure gradient to pressure for a plane wave calculated with equation (1).

**PLANE-WAVE RESPONSE VERIFICATION**

The plane-wave acoustic response identification method was performed on a pressure differential microphone (Knowles NR23160) and also on a combination sound pressure-pressure gradient microphone (Panasonic WM-55A103). These results are compared with the acoustic responses measured in anechoic test environments.

**Pressure Differential Microphone Test Results**

The plane-wave acoustic response for the pressure differential microphone was calculated using equations (1) and (9). Verification of these results was obtained by testing the differential microphone in a large room. For these measurements, the loudspeaker was positioned 3 meters from the test microphone, and the microphone was rotated to obtain the directivity. A reference microphone (Brüel & Kjær 1/8" type 4138) was used to sample the sound pressure near the test microphone. Figure 4 shows the test microphone sensitivities at 0 and 90 degrees sound incidence. The results from both methods match reasonably well. The simulated plane-wave responses were based on measurements acquired within the near field of the sound source but do not show the boost at lower frequencies which is seen with the sound-field characterization data in Figure 3.

The directivity of the microphone was obtained from the responses at sound incidence angles from 0 to 180 degrees with increments of 10 degrees. Octave band averaging was performed and the data was normalized to the maximum value. The directivity indexes [4] were calculated with the reference angle at 0 degrees. A comparison of the directivity patterns from both methods along with the corresponding directivity indexes is shown in Figure 5, where the data was mirrored for the incidence angles 180 to 360 degrees in the polar plot. The directivity patterns obtained from both methods agree well.

**Pressure-Pressure Gradient Combination Microphone Test Results**

The plane-wave acoustic response for the combination pressure-pressure gradient microphone was also calculated using equations (1) and (9) and verified with measurements taken in an anechoic chamber. For these measurements, the loudspeaker was again positioned 3 meters from the test microphone and the microphone was rotated to obtain the directivity. A larger 1/2"-reference microphone (Brüel & Kjær 1/2" type 4130) was used to sample the sound pressure near the test microphone. Figure 6 shows the
FIGURE 4: Acoustic sensitivities for a differential microphone obtained from the plane-wave response estimation method and from direct measurements performed in a large room agree.

FIGURE 5: Differential microphone directivity patterns at 4000-hertz octave band from the plane-wave response estimation method and from direct measurements performed in a large room agree.

sensitivities for the combination microphone at 0 and 180 degrees sound incidence. The results from both methods match reasonably well, although the presence of the 1/2” reference microphone has influenced the anechoic chamber measurements.

The directivity of the combination microphone was obtained using the same procedure as described above. Figure 7 shows a comparison of the directivity patterns from the two methods. The directivity patterns obtained from both methods agree well.

CONCLUSIONS

A technique for obtaining the plane-wave response for directional microphones using a nearly arbitrary sound field has been demonstrated on a commercially available pressure-gradient microphone, and also on a combination sound pressure-pressure gradient microphone. Comparisons with the plane-wave responses measured in an anechoic environment show that the method gives reasonable results down to 100 hertz.
FIGURE 6: Acoustic sensitivities for a combination pressure-pressure gradient microphone obtained from the plane-wave response estimation method and from direct measurements performed in an anechoic chamber agree.

FIGURE 7: Combination pressure-pressure gradient microphone directivity patterns at 1000 hertz octave band from the plane-wave response estimation method and from direct measurements performed in an anechoic chamber agree.

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REFERENCES


