Audio Engineering Society

Convention e-Brief 230

Presented at the 139th Convention
2015 Oct 29–Nov 1, New York, USA

A Database of Loudspeaker Polar Radiation Measurements

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ABSTRACT

Anechoic directivity data for a variety of loudspeakers have been measured and compiled into a freely available online database, which may be used to evaluate these loudspeakers based on their directivities. The measurements are illustrated through four types of plots (frequency response, polar, contour, and waterfall) and are also given as raw impulse responses. Two sets of directivity metrics are defined and are used to rank the loudspeakers. The first set consists of full and partial directivity indices that isolate sections of the loudspeaker's radiation pattern (e.g., forward radiation alone) and quantify its directivity over those sections. The second set quantifies the extent to which the loudspeaker exhibits constant directivity. Measurements are taken, in an anechoic chamber, along horizontal and vertical orbits with a (nominal) radius of 1.6 m and an angular resolution of five degrees.

1 Introduction

The directivity of a loudspeaker (i.e., the extent to which the loudspeaker's acoustic radiation is biased toward a given direction) can have a significant influence on the physical interactions of the emitted sound with the environment and, consequently, the perception of that sound. It is an important characteristic to consider, for instance, when predicting the behavior of a loudspeaker in a room, and detailed information about the directivity of the loudspeaker is often required to make such predictions. For example, the average frequency response over a listening area (i.e., a "room curve") can be estimated using anechoic directivity data and absorption coefficients for the room's surfaces [1].

In order to quantify the directivity of a loudspeaker, the first step is to measure acoustical radiation for multiple directions. Davis et al. [2] summarize an early method that involves making sound power measurements at various points around a loudspeaker, where each point represents an equal area on the surface of an imaginary sphere enveloping the loudspeaker. However, many loudspeaker manufacturers make such measurements at discrete points only along horizontal and vertical "orbits" to simplify the measurement process [1, 2]. The measured data are often visualized using different types of plots, such as frequency response, polar, and contour plots [1, 2]. Additionally, these data are used to compute directivity metrics, such as loudspeaker coverage angle and directivity index (DI), which provide convenient and meaningful measures of the directivity of a loudspeaker. These metrics, however, are only defined for complete sets of directivity measurements, some of which may not be relevant in certain applications, and no standardized metrics exist to quantify constant directivity. Furthermore, limited resources exist which facilitate the evaluation of various kinds of loudspeakers based on their directivities.

The objective of this work is to provide polar radiation measurements of a wide variety of loudspeaker types (e.g., electrostatic, concentric, horn-loaded, etc.), and to present a database of plots and directivity metrics by which to evaluate and compare them. In Sections 2 and 3, we describe the measurement procedure and signal processing, respectively, used to generate the database. In Section 4, we present two sets of directivity metrics, the first of which quantifies the loudspeaker's directivity over isolated sections of its radiation pattern, while the second quantifies the extent to which the loudspeaker exhibits constant directivity. Finally, in Section 5, we describe the different plots used to visualize the data. The database is available online from the 3D Audio and Applied Acoustics Laboratory at Princeton University.[1]

2 Measurement Procedure

We conduct measurements in accordance with the prescriptions of the AES standard on loudspeaker polar radiation measurements [3], with one exception: instead of measuring impulse responses (IRs) over the entire sphere, we measure IRs only along horizontal and vertical orbits around the loudspeaker, as is commonly done by loudspeaker manufacturers [1]. These measurements are conducted in an anechoic chamber, which has dimensions of $3.6 \times 2.35 \times 2.55$ m ($l \times w \times h$) and anechoic wedges 8 inches deep, which corresponds to one quarter-wavelength at ~ 425 Hz.

In general, we measure IRs along two full orbits around the loudspeaker. However, due to the limited size of the anechoic chamber, for some larger loudspeakers, we are only able to make measurements along the horizontal orbit. Furthermore, due to the evolution of the measurement procedure, some past measurements were conducted only along front halves of these orbits. For laterally symmetric loudspeakers, we make measurements only along one side of the horizontal orbit.

We place, in the anechoic chamber, the loudspeaker on a computer-controlled turntable (Outline ET250-3D), aligned such that the point of rotation coincides with the center of the high-frequency transducer, by default. The loudspeaker is placed upright on the turntable for the horizontal orbit, and sideways for the vertical orbit. We then place the measurement microphone (B&K Type 4189-A-021) at a (nominal) distance of 1.6 m from the loudspeaker, and align the barrel of the microphone with the measurement axis.[2] We then adjust the microphone gain (using a B&K Type 4231 calibrator) such that -11 dBFS corresponds to 94 dBSPL, and we set the loudspeaker gain such that the microphone reads as close to 94 dBSPL as possible (at 1 kHz), provided that the loudspeaker does not audibly distort.

With the loudspeaker initially on-axis with the microphone, we send to the loudspeaker an exponential sine sweep (ESS) [4] generated in Plogue Bidule, and record the resulting microphone signal.[3] All measurements are conducted at a sampling rate of 96 kHz and the ESS signals are generated with a nominal frequency range of 20 Hz to 48 kHz and a duration of 5 seconds. The loudspeaker is then rotated in 5° increments and the above steps are repeated until the orbit is completed.

3 Signal Processing

We process the measured data in two phases: first, we detect and extract the IRs, and second, we window the IRs and smooth the sound pressure level (SPL) data.

3.1 Impulse Response Extraction

We first deconvolve, in Mathematica, the recorded sweep by the input sweep, via the fast Fourier transform (FFT), to yield the measured IR. For each IR, we detect the onset via thresholding, with the threshold level set to the smallest multiple of 5% (of the peak amplitude) which exceeds the peak noise amplitude of the IR. Once the threshold-crossing (onset) is found, we compute the relative delay between the onsets of the current and on-axis IRs, and then time-align the current IR to the on-axis IR. These IRs, the threshold levels, and the delay values are provided in the database.

3.2 Time-Windowing and Spectral Smoothing

To isolate the direct sound of the IR, we apply a tapered cosine (Tukey) window with default parameters set to a 3 ms rectangular (flat) portion and 0.5 ms cosine fade-in and fade-out,[4] and aligned such that the start of the flat portion of the window coincides with

[1] http://www.princeton.edu/3D3A/Directivity.html

[2] The measurement axis is defined as the line that passes through the measurement microphone and the point of rotation [3].

[3] More recently, we have adopted the phase-controlled ESS [5].

[4] The window may be narrowed, for example, in cases where strong early reflections corrupt the direct sound and lead to a comb-filtering effect, or widened to increase frequency resolution.

the onset of the IR. We then zero-pad these windowed IRs to ~ 170.67 ms ($16,384$ samples at 96 kHz) and transform into the frequency domain via the FFT. Since the output level of the microphone is calibrated as described in Section 2, to convert the measured power spectra to SPL, we multiply by $10^{5.25}$ (i.e., add 105 dB). Finally, we smooth the SPL spectra using fractional-octave power smoothing, as described by Hatziantoniou and Mourjopoulos [6], with a 1/24$^{\text{th}}$-octave rectangular window by default.

4 Directivity Metrics

We compute *directivity index* (DI) spectra to quantify the directivity of a loudspeaker as well as several metrics which quantify the extent to which a loudspeaker exhibits *constant directivity*.

4.1 Directivity Index Spectra

For highly directive loudspeakers, the on-axis radiation accounts for a large fraction of the total output power. Accordingly, we compute the (full-sphere) DI spectrum [1] and define several partial DI spectra, each of which is given by the ratio between the on-axis power spectrum and an average power spectrum over a certain subset of measurements. In general, DI spectra are given (in dB) by

$$\mathrm{DI}(f) = 10\log_{10}\frac{|H_0(f)|^2}{\sum_n w_n |H_n(f)|^2 / \sum_n w_n}, \quad (1)$$

where f is frequency, H_0 is the on-axis frequency response, H_n is the n^{th} frequency response, and w_n is its weight, which is proportional to the surface area of the portion of the unit sphere represented by the n^{th} measurement [1, 2]. In addition to the full-sphere DI spectrum, for which the average power spectrum (also called the *sound power* curve [1]) is computed over all directions of both orbits, we compute 1) the frontal-hemisphere DI spectrum, for which the average is taken only over the front halves of each orbit, 2) the horizontal (vertical) DI spectrum, for which the average is taken over the entire horizontal (vertical) orbit, and 3) the frontal horizontal (vertical) DI spectrum, for which the average is taken only over the front half of the horizontal (vertical) orbit. These partial DI spectra allow certain sections of the radiation pattern (e.g., forward horizontal radiation) to be isolated when evaluating directivity. We also compute logarithmically-weighted averages of these spectra over 100 Hz to 20 kHz, by default.[5] More precise definitions of these DI spectra and of the logarithmically-weighted average can be found in the documentation of the database [7].

4.2 Metrics of Constant Directivity

Constant directivity loudspeakers exhibit a polar radiation pattern that is invariant with frequency. For such loudspeakers, a contour plot of relative SPL, normalized by the on-axis frequency response, will consist of contours (i.e., lines of constant relative SPL, see Fig. 1 for example) that are everywhere parallel and horizontal. Consequently, we define one metric of constant directivity which quantifies the extent to which the contours are parallel. We begin by computing the gradient of relative SPL at every frequency-angle point. The unit-vector that is orthogonal to the gradient would then be tangent to a contour passing through that point. We then compute a matrix of dot-products with a reference unit vector, $(1,0)$, where the first component is in the frequency direction, for each frequency-angle point. The average (logarithmic over a specified frequency range, linear over a specified angular range) of the absolute values of this set then yields a non-negative number, which is less than or equal to unity. Values closer to unity indicate highly parallel contours and therefore nearly constant directivity. Additional metrics for constant directivity will be discussed in a future publication.

For all loudspeakers in this survey, we compute all possible directivity metrics given the available data. These values are tabulated and provided in the database.

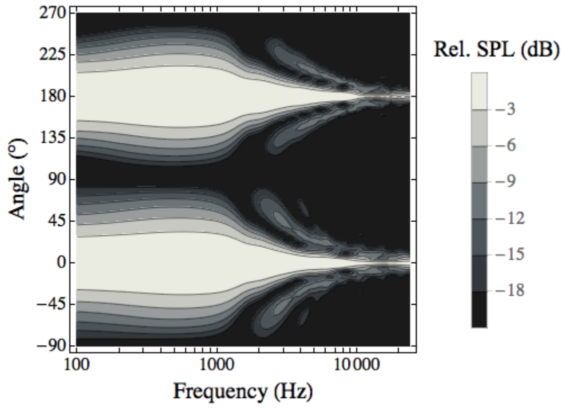
5 Data Visualization

The processed SPL data described in Section 3.2 are presented with four types of plots: frequency response, polar, contour, and waterfall. Frequency response plots show the SPL as a function of frequency, without normalization and separated by quadrant (and orbit). Polar plots show relative SPL, normalized by the on-axis frequency response value at 1 kHz, for a single orbit as a function of angle, with curves drawn for six discrete frequencies: 100 Hz, 500 Hz, 1 kHz, 5 kHz, 10 kHz, and 20 kHz. Contour plots (shown in Fig. 1) show relative

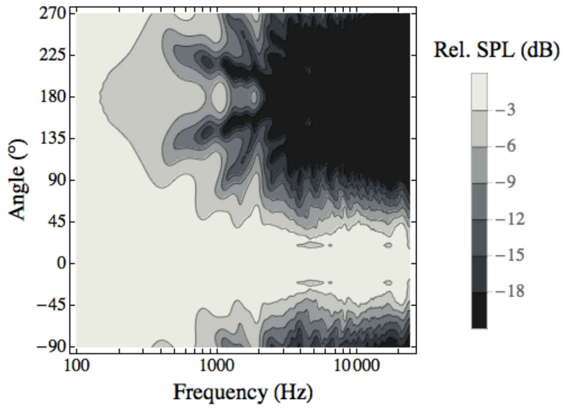
[5] The standard deviations of the DI spectra also suggest necessary (although not sufficient) conditions for constant directivity, as small values indicate that the DI is constant with frequency.

SPL, normalized by the on-axis frequency response, for a single orbit as a function of both frequency and angle, with contours drawn every 3 dB. Finally, waterfall plots show the SPL, normalized by the on-axis frequency response and separated by quadrant, as a 3-D surface plotted over frequency and angle. Furthermore, each DI spectrum is plotted as a frequency response, along with the corresponding average power spectrum and the on-axis response.

As illustrative examples, we present the contour plots for the horizontal orbits of two loudspeakers: the Sanders Sound Systems Model 11 (a flat electrostatic panel with a transmission-line woofer) and the KEF LS50 (a two-way coaxial dynamic). The highly directive but dipolar nature of the electrostatic transducer is readily seen in Fig. 1a. We note that the dipole radiation pattern is maintained even at low frequencies (< 1 kHz), although the width of the main lobe increases significantly below ~ 2 kHz. In contrast, the radiation of a more typical closed-box dynamic transducer, shown in Fig. 1b, exhibits a clear bias towards forward radiation (i.e., very little energy is radiated from the rear), although its main lobe is much wider than that of the electrostatic, especially at high frequencies (> 1 kHz).



(a) Sanders Sound Systems Model 11



(b) KEF LS50

Fig. 1: Contour plots of relative SPL values, normalized by the respective on-axis responses.

Acknowledgements

This project is sponsored by the Sony Corporation of America. The authors would like to thank L. Mosakowski, T. Matchen, T. Jin, G. Colombi, and M. Hamati for their contributions to this project.

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