Reno, Nevada
NOISE-CON 2007
2007 October 22-24

Elevated sources under hemispherical arrays for product noise testing in hemi-anechoic chambers

Einar G. Ristroph[a]
Ankit Chadha[b]
Acoustic Systems Acoustical Research Facility / ETS-Lindgren
415 East Saint Elmo Road
Austin, Texas 78745

Douglas F. Winker[c]
ETS-Lindgren
1301 Arrow Point Drive
Cedar Park, Texas 78613

ABSTRACT

Consumer product noise emission testing is often conducted using standardized test methods such as ISO 3744 or ISO 3745. Both standards outline a method of averaging sound pressure levels over a known surface area enveloping the specimen in a free-field environment to determine sound power levels. When the device under test is small (the case for many consumer products), a hemispherical measurement surface in a hemi-anechoic chamber is often used. An assumption is made that the source location is the center of the hemisphere and thus only direct sound energy encounters the measurement surface. In practice, the actual center of measurement surface is located *in* the floor plane, and the actual product to be tested is placed *above* the floor plane. When a product emits noise from an upper portion of its form factor, the distance is increased. Measured sound pressure levels are thus affected by combination of direct signal and reflected signal from the floor. (The term "image source" is often used.) The effect of combination of the direct and reflected signals on a hemispherical measurement surface is evaluated here through presentation of theoretical and laboratory data.

1. INTRODUCTION

Perhaps the most common microphone array seen inside acoustic hemi-anechoic chambers used to conduct product noise control engineering today is an array forming a hemispherical measurement surface over the reflecting floor plane, with microphones sampling the surface area, from which we calculate surface average sound pressure level for determination of sound power level of a prototype device. Some such arrays employ a specimen turntable or microphone traversing mechanism to sample sound pressure levels in paths along the measurement surface, but it is also common to utilize simple fixed microphone arrangements. Hemispherical measurement surfaces are specified in sound power level determination standards such as ISO 3744[1] (engineering grade) and ISO 3745[2] (precision grade).

---

[a] Email address: einar.ristroph@ets-lindgren.com
[b] Email address: ankit.chadha@ets-lindgren.com
[c] Email address: douglas.winker@ets-lindgren.com

ISO 3744 requires correction for small (less than 2 dB) reflections in a hemi-anechoic chamber, and ISO 3745 requires correction factors for time-of-test meteorological conditions, but both standards specify determination of uncorrected sound power levels from surface average sound pressure levels using:

$$L_{Wf} = \overline{L_{pf}} + 10 Log_{10} \frac{S_1}{S_0} \qquad (1)^{d}$$

where L_{Wf} is the so-determined sound power level in a given frequency band (or overall or A-weighted power level), in dB re 1 pW, $\overline{L_{pf}}$ is the surface-average of the measured band sound pressure levels, in dB re 20 µPa, S_1 is the area of the measurement surface in m^2, and S_0 = 1 m^2. Of interest here is the effect of distance between a sound source and the reflecting plane on the so-determined sound power levels. This distance can be due to physical elevation, such as specified for "sub-assemblies" in the test code for IT equipment[4], or can be unavoidable in the common case of a product which emits noise from an upper portion of its form factor.

When a source is raised under a microphone array, the measured sound pressure levels are affected by the change in distance between source and microphone, but can also be affected by sound reflected off the floor reaching the microphone. The reflected sound energy can (due to a phase offset attributable to the difference in distances between the direct and reflected sound paths) combine constructively or destructively with the direct sound energy, affecting the measured surface sound pressure levels. Different wavelengths will have different phase offsets, so the sound pressure level disturbance is far more of a concern when bandwidth is limited (in terms of emission *or* signal analysis, such as in narrowband data often acquired for sound quality analysis.)

Here we discuss these effects from a theoretical view by showing predicted sound pressure levels over the measurement surface for a sinusoid-emitting point source, and then present actual sound power level determinations using test method in ISO 3744 with loudspeakers emitting pure tone signals raised to various heights.

The reader wishing only to get an idea of expected errors in sound power level determinations is encouraged to skip ahead to the presentation of laboratory data.

2. THEORETICAL DISCUSSION

A. "Close Enough to the Floor"

Consider a monopole point source at distance of h_s from an origin O on the reflecting plane in a hemi-anechoic space, radiating a constant sinusoid of wavelength λ. Further consider a hemispherical measurement surface of radius r and of origin O. If the source height h_s is sufficiently small, i.e., if

$$\frac{2\pi}{\lambda} h_s << 1 \qquad (2)^{e}$$

---

[d] We do not consider herein, yet wish to direct the readers attention to, the missing *cos(θ)* in Equation 1 when applied to raised sources, recently elucidated by Nobile, Fiore, and Boyes[3].

[e] We use Blackstock's conditional evaluation.[5]

then the radiation can be considered omnidirectional about the hemi-anechoic space[5], thus the measurement surface. In such a case, the directivity index *DI* is constant for all directions about the hemi-anechoic space and is approximately 3 dB[5,6]. Then the sound pressure level *Lp* is the same for any point on the hemispherical measurement surface. As a function of “true” sound power level L_{W0}, the sound pressure level is then predicted as

$$L_p \approx L_{W0} - 20Log_{10}(r) - 8\text{ dB}$$ (3)[6]

For example, a source with “true” sound power level of 80 dB re 1 pW and a measurement surface with radius of 1.4 meters would result in a measured sound pressure level of 69.1 dB re 20 μPa at any point on the measurement surface. Equation 1 would yield the “true” sound power level for any microphone arrangement. The conditional term in Equation 2, for one-third octave band center frequencies and various heights above the floor is shown in Table 1. It exceeds 1 at higher frequencies for all heights shown.

h_s (meters)	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**
f (Hz)					
100	0.1	0.2	0.3	0.4	0.5
125	0.1	0.2	0.3	0.5	0.6
160	0.1	0.3	0.4	0.6	0.7
200	0.2	0.4	0.5	0.7	0.9
250	0.2	0.5	0.7	0.9	1.1
315	0.3	0.6	0.9	1.2	1.4
400	0.4	0.7	1.1	1.5	1.8
500	0.5	0.9	1.4	1.8	2.3
630	0.6	1.2	1.7	2.3	2.9
800	0.7	1.5	2.2	2.9	3.7
1000	0.9	1.8	2.7	3.7	4.6
1250	1.1	2.3	3.4	4.6	5.7
1600	1.5	2.9	4.4	5.9	7.3
2000	1.8	3.7	5.5	7.3	9.2
2500	2.3	4.6	6.9	9.2	11.4
3150	2.9	5.8	8.7	11.5	14.4
4000	3.7	7.3	11.0	14.7	18.3
5000	4.6	9.2	13.7	18.3	22.9
6300	5.8	11.5	17.3	23.1	28.9
8000	7.3	14.7	22.0	29.3	36.6
10000	9.2	18.3	27.5	36.6	45.8
12500	11.4	22.9	34.3	45.8	57.2
16000	14.7	29.3	44.0	58.6	73.3
20000	18.3	36.6	55.0	73.3	91.6

Table 1: Values of product of wavenumber k and source height h_s for one-third octave band center frequencies at various heights.

B. Direct and Reflected Signal Combinations over Measurement Surface

Now consider a point source above the reflecting plane, but assume that source height is large with respect to a wavelength. Consider sound arriving at a given point on the measurement surface as having two component signals: the direct signal and the reflected signal. For a sinusoidal point source, (and perhaps some consumer products with tonal emissions having an effective acoustic center sufficiently high enough) there will be heights on a hemispherical measurement surface where the direct and reflected signals are out of phase and combine destructively, and other heights where the signals are in phase and combine constructively.

To combine these signals at any given receiver *R* on the measurement surface, we will first need to find their amplitudes (specifically, rms pressures) at the surface, and the phase shift between the two signals at the receiver. Determination of the path lengths is necessary.

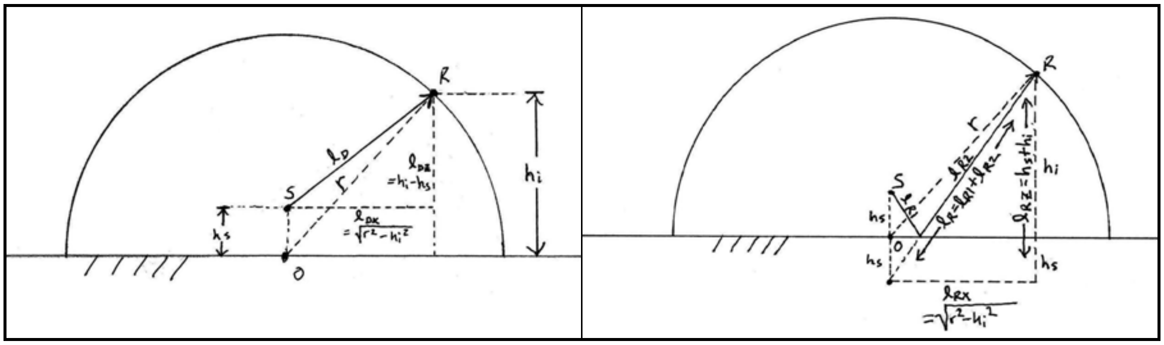

Figure 1: Geometric solutions for direct path length l_D (left) and reflected path length l_R (right)

We can geometrically show in Figure 1 that the direct path length l_D, from source to receiver at height h_i, on the measurement surface is

$$l_D = \sqrt{-2h_i \times h_s + h_s^2 + r^2} \tag{4}$$

and similarly show that the reflected path length l_R for the same receiver is

$$l_R = \sqrt{2h_i \times h_s + h_s^2 + r^2} \tag{5}$$

The rms pressure resulting from the direct signal at the receiver p_D is predicted as

$$p_D = \sqrt{10^{\left(\frac{L_{pD}}{10}\right)} \times p_{REF}^2} \approx \sqrt{10^{\left(\frac{L_{W0}-20Log(l_D)-11}{10}\right)} \times p_{REF}^2} \qquad (7)^{f}$$

and rms pressure resulting from the reflected signal at the receiver p_R is predicted as

$$p_R = \sqrt{10^{\left(\frac{L_{pR}}{10}\right)} \times p_{REF}^2} \approx \sqrt{10^{\left(\frac{L_{W0}-20Log(l_R)-11}{10}\right)} \times p_{REF}^2} \tag{8}$$

Assuming no phase change upon reflection from the rigid plane, the phase difference between the two traveling sinusoids at the receiver is then the absolute difference in their traveled distances in wavelengths, or in radians

---

[f] We use Equation 6.29 from Beranek[6] with zero directivity for point source.

$$\theta = \frac{|l_D - l_R|}{\lambda} \times 2\pi \tag{9}$$

The total sound pressure level L_{pT} at the receiver is predicted as

$$L_{pT} = 20Log_{10}\left(\frac{p_T}{p_{REF}}\right) = 20Log_{10}\left(\frac{\sqrt{{p_D}^2 + {p_R}^2 + 2p_D p_R \cos(\theta)}}{p_{REF}}\right)\text{dB} \tag{10}$$

This predicted sound pressure level is a function of "true" sound power level, wavelength, radius, and source and receiver heights, but is independent of compass angle, thus we can graphically show predicted sound pressure levels on the hemispherical surface in two dimensions about a single quadrant of a polar plot, as shown in Figure 2.

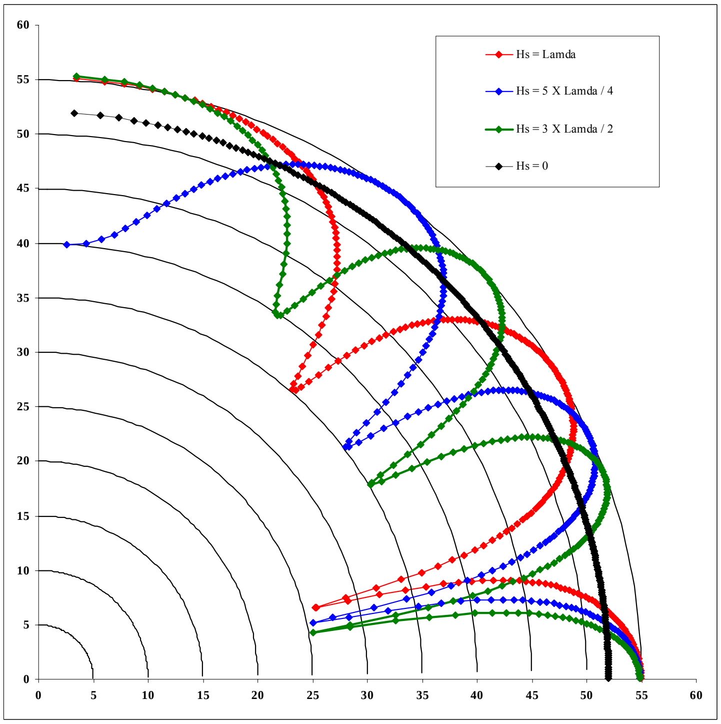

Figure 2: Predicted 250 Hz discrete frequency sound pressure levels on an imaginary 10-meter radius 250- coaxial paths array, for a $L_{W(250Hz)}$ = 80 dB re 1pW source at three different heights selected as functions of wavelength.

C. Discussion

Expectedly, the predicted radiation patterns shown in Figure 2 match those for two simple sources[7] spaced at a distance of *twice* the source height (the distance between the actual source and it's "image source").

It is important to note that the theoretical data presented in Figure 2 for $h_s=0$ were not calculated using the equations presented for combination of direct and reflected signals in Section B, as this prediction assumes that the distance between the floor and the source is sufficiently large with respect to a wavelength (for $h_s=0$, we certainly meet the condition of Equation 2 and thus apply Equation 3 from Section A). As source height approaches zero, application of the predictions in Section B would yield a 3 dB difference in surface average sound pressure levels compared to the prediction in Section A. For real-world sources, no discontinuity (i.e., sudden jump or decrease) in sound pressure level is aurally observed as one moves the source up and down over the floor in a hemi-anechoic chamber. We admittedly provide computationally ambiguous guidelines for applicability of these predictions. We encountered difficulty in our efforts to more clearly define and validate computational predictions through laboratory measurements for two reasons: we did not have a monopole, and, we did not know the "true" sound power of even our best approximations of a point source[g]. Regardless, the *relative* measured sound pressure levels roughly matched with the predicted radiation patterns for a tapered cone approximation of a point source placed at various heights under an arch microphone array.

3. DETERMINED SOUND POWERS FROM LOUDSPEAKERS AT INCREMENTAL HEIGHTS

A. Hemidodecahedron loudspeaker cabinet

A small loudspeaker cabinet constructed of ½" oak panels, with 2"-diameter loudspeakers on each of the six faces (all wired in-phase) of a hemidodecahedron (shown in Figure 3) was tested at incremental heights above the floor of the Acoustic Systems 49 cubic-meter hemi-anechoic chamber, using a 1.4 meter radius microphone array per ISO 3744 Table B.2. Testing was in accordance with ISO 3744, with the exception that only 10 microphone positions were used, as is common for non-accredited prototype testing when low frequency emissions are being evaluated. Incremental heights were accomplished by using stacks of aluminum tape rolls, creating non-dissipative incremental-height cylindrical mounting stands (contributions from possible tube resonances were determined to be negligible by comparing levels with and without foam insulation stuffed inside of cylinder prior to testing). The loudspeaker cabinet's maximum outer dimensions are about 15 cm by 15 cm by 8.5 cm height. The signal consisted of pure tones at each one-third octave band center frequency from 100 Hz to 20 kHz (inclusive) at levels well above background levels. Based on the source size, it was expected to approximate a monopole *for the lower few frequencies tested*, although experimental free-field directivity indexes were not determined. The range in determined sound power levels at each frequency for incremental heights is shown in Figure 4.

---

[g] We are also concerned with whether or not sound power of a source should be theoretically constrained for predictive computations when it's surrounding environment (proximity to floor plane) is not, based on previous work.[8]

Figure 3: small loudspeaker cabinet raised underneath 1.4 meter radius ISO 3744 Table B.2 microphone array for “engineering method / grade 2” laboratory sound power determination.

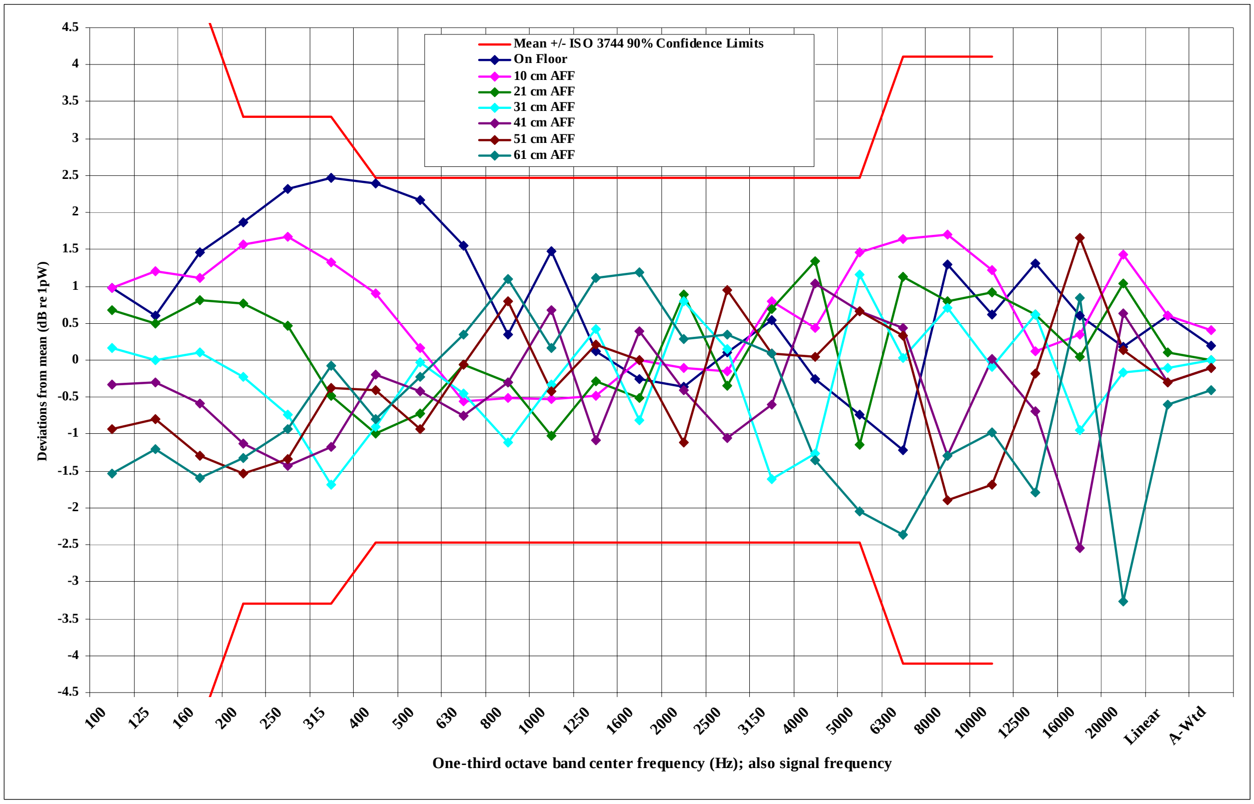

Figure 4: Range in determined sound power levels (using test method in ISO 3744) for a loudspeaker cabinet at various heights. The loudspeaker was supplied a signal consisting of pure tones at each one-third octave band center frequency. (“Characteristic source dimension”[1] slightly exceeded standard limit of *r/2* for the “61 cm AFF” test.)

B. Tapered-cone tweeter

A tapered-cone tweeter loudspeaker assembly (shown in Figure 5) with an opening approximately 5 mm in diameter was suspended at incremental heights above the floor of the Acoustic Systems 49 cubic-meter hemi-anechoic chamber and tested in accordance with ISO 3744, using a 1.4 meter radius microphone array per ISO 3744 Table B.2. The tip of the cone was centered over the center point of the floor. The source was rotated 180° to provide 10 additional sampling points in accordance with the standard. The signal consisted of pure tones at each one-third octave band center frequency from 800 Hz to 20 kHz (inclusive) at levels well above background levels. This was expected to approximate a monopole source in the limited frequency range of 800 Hz to 5 kHz, although experimental free-field directivity indexes were not determined. The range in determined sound power levels at each frequency is shown in Figure 6.

Figure 5: Tapered-cone loudspeaker suspended underneath 1.4 meter radius ISO 3744 Table B.2 microphone array for "engineering method / grade 2" laboratory sound power determination.

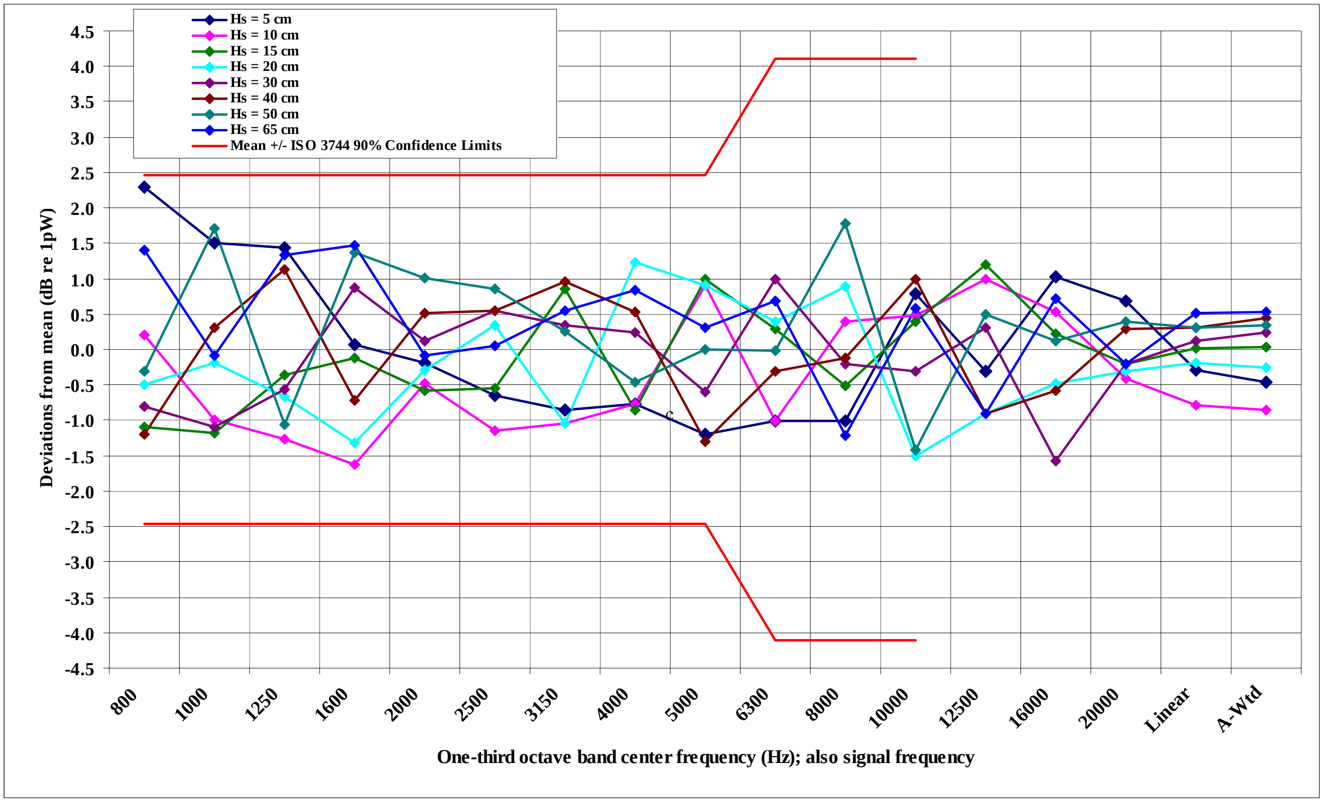

Figure 6: Range in ISO 3744-determined sound power levels for a tapered-cone loudspeaker at various heights. The loudspeaker was supplied a signal consisting of pure tones at each one-third octave band center frequency.

4. CONCLUSIONS

Additional work is required to determine if the prediction methodology presented here could be used to estimate potential errors in sound power level determinations. The low frequency variations in determined sound power shown in Figure 4 are concerning with respect to the predictive calculations: the assumption for application of the signal-combination prediction method is that the source height is large compared to a wavelength – not so at low frequencies for the heights tested. Further examination of the individual microphone sound pressure levels from these tests and refinement of predictive methods is left to future work.

The ranges presented in the laboratory data represent somewhat "worse-case scenario" contributions from reflections causing errors in sound power determinations conducted in accordance with ISO 3744. (Iterative predictive calculations or narrowband measurements for discrete frequencies other than those coinciding with one-third octave band center frequencies were not conducted, however; such an exercise may produce particular frequency/source height combinations which give larger errors.) The range in determined sound power levels seen in Figures 4 and 6 are presented to give an idea of expected errors in sound power determinations of tonal devices, as well as expected error in surface-averaged narrowband data for both tonal and broadband products.

ACKNOWLEDGEMENTS

Acoustic Systems, a division of ETS-Lindgren, for financial support of this work. Michael C. Black, John A. Phillips, and Jeff G. Schmitt for continual guidance and assistance.

REFERENCES

[1] *Acoustics — Determination of sound power levels of noise sources using sound pressure -- Engineering method in an essentially free field over a reflecting plane*, International Standard ISO 3744:1994 (International Organization for Standardization, Geneva, Switzerland, 1994).

[2] *Acoustics — Determination of sound power levels of noise sources using sound pressure -- Precision methods for anechoic and hemi-anechoic rooms*, International Standard ISO 3745:2003 (International Organization for Standardization, Geneva, Switzerland, 2003).

[3] Matthew A. Nobile, Felicia Fiore, and Robert N. Boyes, "Measurement of sound power level using enveloping surfaces: Investigation of the cos(θ) error", *Proceedings of Inter-noise 2006*, edited by Courtney Burroughs and George Maling (International Institute of Noise Control Engineering, available at http://www.inceusa.org)

[4] *Acoustics — Measurement of airborne noise emitted by information technology and telecommunications equipment*, International Standard ISO 7779:1999 (International Organization for Standardization, Geneva, Switzerland, 1999).

[5] David T. Blackstock, "Monopole next to a rigid plane", Example 15.1 (page 497) in *Fundamentals of Physical Acoustics* (John Wiley and Sons, New York, 2000).

[6] Leo L. Beranek, "The Measurement of Power Levels and Directivity Patterns of Noise Sources", Chapter 6 in *Noise and Vibration Control*, edited by Leo L. Beranek (McGraw-Hill, New York, 1971).

[7] Leo L. Beranek, "Directivity Patterns", Part X in *Acoustics* (Acoustical Society of America, New York, 1996)

[8] Einar G. Ristroph, "Comparison of two test methods for determination of broadband sound power levels emitted by products: a reverberation chamber method versus a hemi-anechoic chamber method", *Proceedings of Inter-noise 2006*, edited by Courtney Burroughs and George Maling (International Institute of Noise Control Engineering, available at http://www.inceusa.org)