Assessment of Errors in Sound Pressure Measurement in a Large Anechoic Chamber

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Introduction
A large acoustical anechoic chamber has recently been put into operation at the Canadian Radiation Protection Bureau. The walls, floor and ceiling of the anechoic chamber are lined with flat-tipped fibreglass wedges designed for a cut-off frequency of 50 Hz. The interior (wedge tip to wedge tip) is 13 m long, 9 m wide and 8 m high.

In order to create well-defined noise exposures and measurements of sound power and sound pressure in the chamber, its free-field performance must be quantified. This provides baseline estimates for errors in sound pressure measurements and a technique for error estimation as measurement configurations change. This paper describes characterization of the free field performance from 50 to 5000 Hz along the chamber axis. Implications for measurement uncertainties in the anechoic chamber are discussed.

Method and Apparatus
The technique used was similar to that recommended in ISO[1] and ANSI[2] standards and used to characterize other large anechoic chambers[3, 4].

Free-field performance was characterized by measured deviations from the $1/r$ dependence of pressure, p, on distance, r, for a point source in a free field (inverse square law). This can be expressed as:

$$1/p = r/A \qquad (1)$$

where A is proportional to the source strength.

The deviation, $\epsilon(r)$, from the inverse square law was obtained from:

$$\epsilon(r) = 20\log\frac{p_{meas}(r)}{p_{fit}(r)} \qquad (2)$$

where p_{meas} was the measured pressure at position r. The quantity p_{fit}, at any value of r, was the pressure given by a linear least squares fit to equation (1) of the pressures measured over a limited range of r values.

The data range to be fitted was arrived at as a compromise between several competing criteria. Ideally, to reduce the effects of echoes, the least squares fit should be determined from data measured as close to the source as possible. However, the measurement also has to be far enough away that the field is omnidirectional within ±1 dB[1, 2]. This limit on source directivity means that estimation of the maximum measurement error (ϵ_{max}) can be determined experimentally within ±0.2 dB, for ϵ_{max} values less than 2 dB[3]. In addition, the measurement has to be far enough away that, to a good approximation, the free-field pressure field due to the source varies with 1/r. This was diagnosed by measurements of sound source directivity as a function of distance as described below. Finally the range must be large enough to sufficiently reduce statistical uncertainties in the linear least squares fit.

Generation of the acoustic pressures to be measured was done with two novel sound sources; a low frequency dodecahedral array of speakers for 50 to 500 Hz[5] and a higher frequency piezoceramic sphere for 500 to 5000 Hz. Both sources were symmetric on three axes, about a reference point. The low frequency source was constructed from twelve, 6 inch, 100 watt loudspeakers set in the faces of a dodecahedron with an average spherical radius of 19 cm. The higher frequency source was a lead zirconate sphere with a 96.52 mm O.D. and a 4.92 mm wall thickness (Channel Industries, Santa Barbara, CA).

Each sound source was supplied with a simultaneous mix of 11 computer generated sinusoids at 1/3 octave band centre frequencies spanning the range appropriate to each source. For the low frequency measurements, the signal was supplied from a Nagra IV-SJ tape recorder through a Brüel & Kjær (B&K) 2706 power amplifier. The driving signal for the higher frequency source was output by computer through a National Instruments AT-DSP2200 digital signal processor board and amplified using a Yamaha PC 5002 M 1000 W power amplifier.

For directivity measurements, the low frequency source was rotated by mounting it on a tripod centred on a B&K 3922 turntable. The higher frequency source was rotated by supporting it in the end of a nylon stocking, hung 2 m below the spindle of a B&K 3923 rotating microphone boom. The sources rotated about their geometric centres, and measurements were taken every 4 degrees. Repeated revolutions gave a total averaging time of 4 seconds per 4 degree sector. Nine directivity measurements were made at distances between 31.5 and 200 cm from the centre of each source.

Deviations from the inverse square law were obtained with the sources hung from the ceiling and centred vertically in the chamber. Measurements were made along a horizontal line parallel to the long axis of the chamber. The mid point of this measurement traverse was near the centre of the chamber. Low frequency measurements were taken from 50 cm to 560 cm in 2 cm to 10 cm steps using 64 second linear time averaging. Measurements of the higher frequency source were averaged for 8 seconds at each position. At frequencies above 2500 Hz the microphone was positioned from 50 to 530 cm in 1 cm steps. For frequencies from 500 Hz to 2500 Hz, the microphone was positioned from 50 to 545 cm in 5 cm steps.

All measurements of the dodecahedron were made using a B&K 3545 intensity probe, with 12 mm 4181 microphones and a 50 mm spacer. Microphone calibrations were made before and after measurements using a B&K 3541 system (with pistonphone). For the piezoceramic sphere, all directivity measurements and deviation measurements above 2500 Hz were made with a B&K 4165 1/2" microphone, attached to a nosecone, and powered by a B&K 2807 microphone power supply. A B&K 4228 pistonphone was used for microphone calibration for this latter system. To obtain an adequate signal to noise ratio at frequencies from 500 Hz to 2500 Hz with the piezoceramic sphere, deviation measurements were made with a 1" diameter B&K 4179 low noise microphone with nose cone. All pressure measurements were made with a signal to noise ratio of at least 30 dB.

All positioning of the measuring microphone was controlled using a B&K 9654 robot. A B&K type 2133 1/3 octave band frequency analyzer was used for data analysis.

For both directivity and deviation measurements, all ancillary structures within the anechoic chamber that could act as acoustical reflectors, were carefully wrapped with fibreglass batts.

Results and Conclusions

The least squares fit to equation **(1)** was made over the range r=0.5 to 1 m, where r was taken as the separation between the microphone and the source geometric centre. This was justified by the spatial symmetry of the sources described above.

Measurements suggested that the minimum source receiver separation for the least squares fit should be 50 cm. At distances greater than 50 cm, the change in directivity with distance was 0.1 to 0.4 dB for the dodecahedron and 0.2 to 0.5 dB for the piezoceramic sphere. In most frequency bands, the inverse square law was validated to within ±0.4 dB for the sources used in this work. Furthermore, at distances greater than 50 cm, the maximum deviation from omnidirectionality was less than 0.8 dB.

The results shown in Fig. 1 are of maximum absolute deviations versus frequency for four source-receiver separation distances up to 1, 2, 4 and 5.5 m. In the frequency range from 100 to 5000 Hz, the maximum deviations from free field ranged from 0.4 dB at 100 Hz to 1.0 dB at 5 kHz. At 50 Hz the maximum deviation rose to 3.6 dB. Below 100 Hz, the source receiver separation must be reduced to about 2 metres in order to reduce errors to 1 dB.

The maximum deviations described above, gave a "worst case" error estimate for pressure measurements in the anechoic chamber. These errors could only occur for a source with strong tonal components. The maximum deviation, or error (ϵ_{max}) can be calculated by the summation of pressure amplitudes of direct and reflected sound[6]:

$$\epsilon_{max} = \left| 20\log\left(1 \pm Rr\sum_{i=1}^{6}\frac{1}{d_i}\right)\right| \qquad (3)$$

where R is the chamber wall reflection coefficient (<0.1 above the cutoff frequency for an anechoic chamber), r is the distance between source acoustic centre and microphone, d_i is the distance travelled from source to microphone by a wave reflected from the ith wall. The deviations presented here were consistent with the chamber being anechoic down to 50 Hz. Measured deviations only reach the deviations calculated using equation **(3)** (with R=0.1) at the chamber cutoff frequency of 50 Hz.

The error estimate in equation **(3)** is conservative for spatially averaged measurements, a broadband source using a large analysis bandwidth (i.e., A-weighted totals), or a large device containing multiple incoherent sources. In these cases the cross terms in equation **(3)** tend to cancel and in the limit the deviations are reduced to an energy type summation of the direct and reflected sound.

$$\epsilon_{max} = 10\log\left(1 + R^2 r^2\sum_{i=1}^{6}\frac{1}{d_i^2}\right) \qquad (4)$$

The difference between the two measurement situations is seen, for example, when the deviation from equation **(3)** is 1 dB. Then the estimated error in equation **(4)** will be in the range 0.02 to 0.1 dB (the latter value is associated with a source or receiver position close to a single wall).

For an omnidirectional source, initial estimates of expected errors can be made using the data from figure 1. For example, using equation **(3)**, R can be estimated as 0.1 at 50 Hz, and ranges from 0.02 to 0.06 above 100 Hz. Substituting values for d_i's in equations **(3)** and **(4)** can give upper and lower bounds on pressure measurement errors in any position in the chamber. If the source is not omnidirectional, the d_i's in equations **(3)** and **(4)** must be weighted to obtain an error estimate.

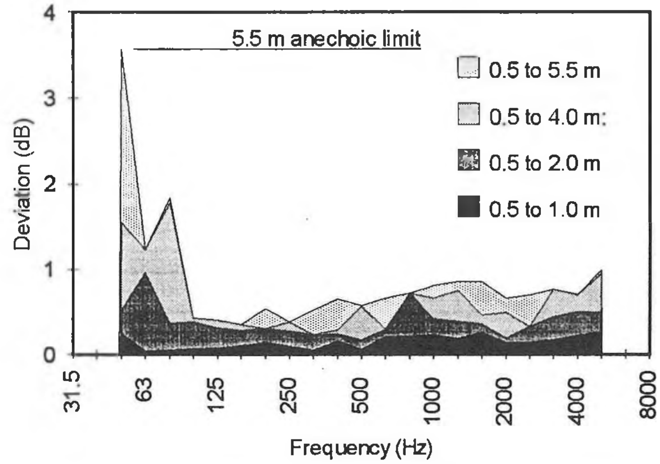

Figure 1: Measured maximum deviations from inverse square law for four source-receiver separation distances.

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