Acoustics'08
Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Acoustical Design Margins: Uncertainty in Prediction and Measurement of Community Noise

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ABSTRACT Compliance with regulatory requirements for sound levels in communities adjacent to industrial or power generating facilities is typically a contractual commitment with the potential for significant financial penalties in the event of non-compliance. Uncertainties at any stage of the design, specification or prediction of plant sound level may be accounted for as part of the overall plant acoustical design margin. There are also additional uncertainties in terms of compliance sound measurement surveys that are commonly referred to as either "test tolerance", or "instrumentation tolerance and measurement uncertainty". From the viewpoint of the plant equipment supplier all of the uncertainties associated with equipment design and specification are simply additive to all of the uncertainties of compliance measurements since they all contribute to or affect the selection of the overall plant acoustical design margin. The discussion will address the types of uncertainties in source sound power levels and measurement error, tolerances, and confidence limits of field sound surveys, highlighting some seldom-treated aspects of uncertainty. Measurement uncertainties and the applicable combinatorial rules will be treated

1 Introduction

Uncertainties in the design, specification, prediction or measurement of industrial or power plant sound level directly affect the overall plant acoustical design margin. Whether classified as "confidence interval;", "error", "test tolerance", "instrumentation tolerance and measurement uncertainty", or something similar, from the viewpoint of the plant acoustical designer all of the foregoing uncertainties are in some fashion additive and all affect the overall plant acoustical design margin. Ray [1] has summarized the uncertainties related to measurement error, tolerances, and confidence limits of field sound survey measurements. Per ISO 3746 [2], the A-weighted measurement uncertainty for far field environmental noise from gas turbine installations, including those discussed by Ray [1], is 3 dB. Parzych [3] has dealt with several significant sources of uncertainty in predictive acoustical modeling for outdoor far field sound levels. Peppin and Putnam [4] have demonstrated the quantifiable uncertainty of assigning source sound power levels with confidence. Uncertainty, in the broadest sense, encompasses all of the elements of relative imprecision, absolute inaccuracy, test tolerances, instrumentation tolerances, modeling simplifications and other variables whether known or unknown.

2 Categories of Uncertainty

2.1 Predictive Uncertainty

When applied to computer modeling, predictive uncertainty is used to describe the degree to which an analytically predicted level differs from the level that would be predicted if all input parameters were perfectly known and perfectly modeled. Predictive uncertainty includes the inability to define any source sound power level with an accuracy any better than that reported by Peppin and Putnam [4] and also relates to the method of sound source modeling.

2.2 Measurement Uncertainty

Measurement uncertainty refers most commonly to measurement surveys and will be used here both in the context of laboratory measurement of calibrated sound sources and field sound measurements. Measurement uncertainty encompasses the statistical sampling error in any measurement, the instrumentation tolerance and all of the other sources of error in any measurement set.

2.3 Instrumentation Accuracy

Instrumentation accuracy refers to the difference between the true value of the sound level and the value indicated by the instrument train. It is one component of measurement uncertainty. For the sound level meter, this is the accuracy commonly prescribed in instrumentation standards ANSI S1.4 [5] and ANSI S1.43 [6].

3 Modeling Uncertainties

3.1 Source Sound Power Level Uncertainty

Peppin and Putnam [4] reported on a series of round robin laboratory tests conducted using four (4) calibrated sound sources at seven (7) different National Voluntary Laboratory Accreditation Program (NVLAP)-certified testing laboratories, run by the United States National Institute of Standards and Technology (NIST). The 95% confidence interval for precision was calculated for the 125 Hz through 4,000 Hz octave bands. Table 1, from Peppin and Putnam [4], summarizes the uncertainty for the 95% confidence interval for precision.

SOUND POWER LEVELS IN DECIBELS RE. 1 PICOWATT						
95% Confidence Interval for Precision	OCTAVE BAND CENTER FREQUENCY, HZ					
	125	250	500	1K	2K	4K
	2.4	1.0	1.0	1.2	1.2	1.0

TABLE 2. SOURCE SOUND POWER LEVEL UNCERTAINTY: THE 95% CONFIDENCE INTERVAL FOR THE PRECISION OF SOUND POWER LEVEL

If all other aspects of an analysis or prediction or measurement possess zero uncertainty, the values summarized in Table 1 represent the best that current sound technology can deliver. In other words, these values represent the very best laboratory precision to be expected in quantifying the sound power level from even a relatively simple calibrated sound source. No claim is made as to the absolute *accuracy*, or true value, of the sound power level. However, we cannot reasonably expect any greater *precision* in assigning source sound power levels than found in Table 1.

Consider the import of Figure 1 uncertainties in terms of one of the favorite tools of sound prediction technology: graphical sound level contours. By transposing the uncertainties of Figure 1 into a Figure 2 format, we see the uncertainty band relative to a predicted radial trend representing, in this case, a predictive model's calculated A-weighted sound level as a function of distance.

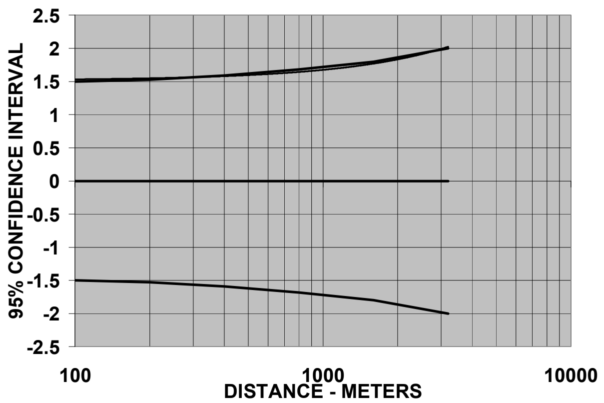

Figure 1: Applying the 95% C.I. uncertainties of Table 2 to an example case of a simple cycle 100MW class gas turbine far field A-weighted sound levels.

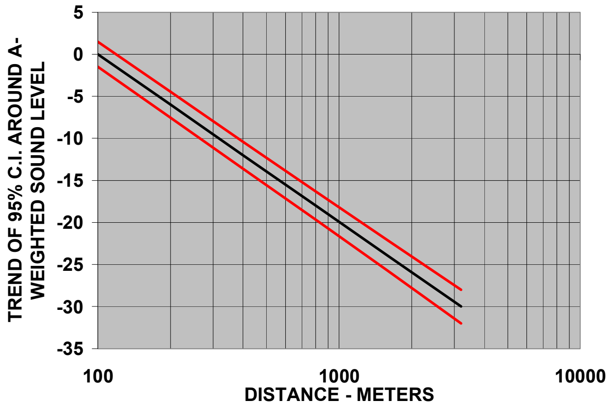

Figure 2: Radial Trend of the example simple cycle gas turbine far field A-weighted sound levels with the 95% C.I. of Figure 1 based upon the Table 2 uncertainties.

Figure 3 demonstrates the uncertainty of locating a given far field sound level contour at a certain distance from the source. Illustrating the A-weighted sound level uncertainty in this manner is more dramatic than the simple ±1.5 dB to ±2 dB errors suggested by Figures 1 and 2, at any given receiver. For example, Figure 3 shows that the predicted location of a sound level contour at a distance of one (1) kilometer from the sound source acoustical center can be as much as ± 200 meters in error. This is, note once again, the best precision that laboratory sound power determination can expect to yield, while the reality of any actual industrial or power generation facility will be much worse. Stated another way, the range of the unknown, that is, the position within which the true contour will lie, will never be better than 40% of the one-kilometer distance from the source to the receiver. Recall that considerations of all other additional uncertainties are not yet included and will only compound the imprecision of this estimate of contour location.

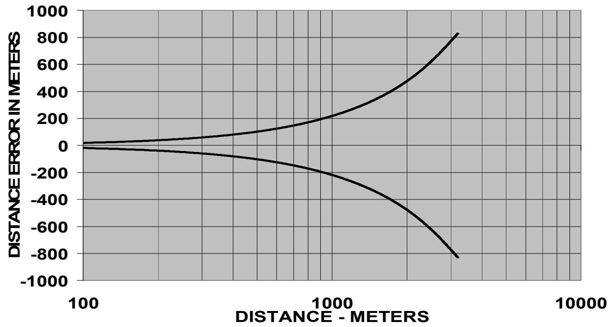

Figure 3: The 95% C.I. from Figure 2, as derived from Table 2 uncertainties, for the example case, presented in terms of the error of estimating the distance to a given sound level isopleth.

3.2 An Unanticipated Atmospheric Effect

Apart from the myriad of atmospheric effects that have been studied, consider the effect of the temporal instabilities of the instantaneous sound pressure level measured at any given far field position. As the far field measuring position is moved progressively farther from an otherwise steady state sound source, any sound level histogram of instantaneous sound source levels will typically exhibit increasing standard deviations (assuming the sampling rate is a few seconds or less). Whatever the driving mechanisms for this effect, be they wind gradients, temperature gradients or other atmospheric turbulence, the net result of an increasingly divergent histogram of sound level as a function of distance will relate directly to the matter of uncertainty, including modeling uncertainty.

The reason for this lies in the difference between the calculated (predicted) or analytically expected sound level and the actual measured, long-term equivalent sound level derived from the histogram or directly measured by a sound level meter. The metric predicted by most computer models is the mean sound level, that is: L_{50}. The metric most commonly measured at far field locations of interest is the average time-weighted sound level, otherwise known as the equivalent level, or L_{eq} . Whenever this is the case, it must be understood that a broadening of a sound level histogram (by whatever means) introduces an increasingly larger difference between L_{50} and L_{eq}. Such a difference must be recognized as a source of predictive uncertainty, shown in Figure 4.

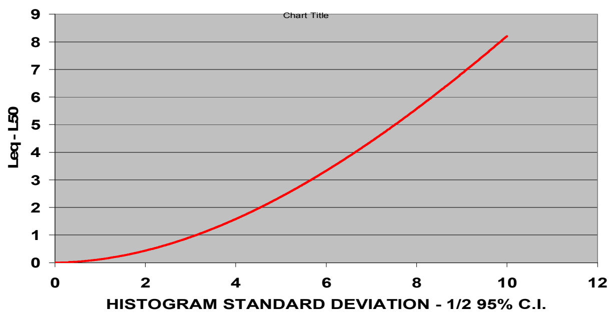

Figure 4: Atmospheric Diffusion Effect: Difference between the mean, L50, and the equivalent, Leq, sound level of any given normal distribution histogram as a function of the standard deviation of the histogram.

Figure 4 presents the calculated difference between L_{eq} and L_{50} as a function of the standard deviation, in decibels, of a histogram of sound levels, with normal distribution, measured at a given position. An actual case history is presented in Figure 5 to illustrate the phenomenon.

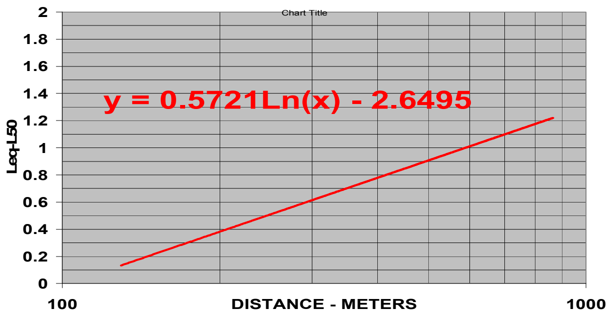

Figure 5: Atmospheric Diffusion Effect: Log-Trend line of an actual case history showing the result of a progressive broadening of a histogram with increasing distance from the source. The trend line is for the difference, in decibels, between measured Leq and measured L50 for the 25 Hz one-third octave band from a pair of simple cycle gas turbines. The distance is from the approximate acoustical center of the turbines.

3.3 Computer Model Algorithms

To test the hypothesis that computer models utilizing similar though slightly different algorithms yield "substantially similar" results, a simple case was submitted to six different volunteer users [7]. Classical spherical diffusion theory should yield identical results in all cases over a flat reflecting surface. Modeling real world situations, however, requires the added consideration of actual ground absorption, excess air absorption and barrier effects, at a minimum. Therefore some small differences might be expected.

The results depicted in Figure 6 are hardly "substantially similar". These differences should be regarded as uncertainties in the same sense as any other source of error in sound level predictions. These results suggest that computer model algorithm uncertainties (i.e. differences) are as large, or larger, than other elements considered here. To be clear, this analysis does not suggest any particular computer model contains uncertainties of this magnitude, but rather different users, using different models, will obtain differing results.

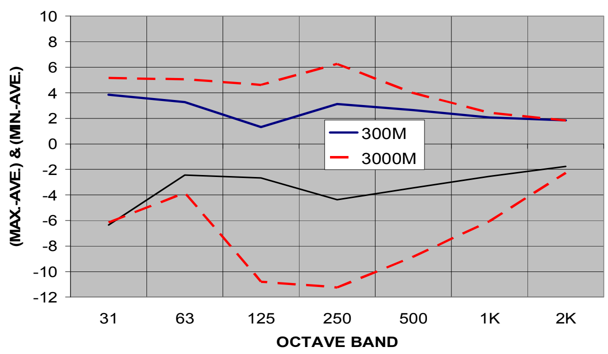

Figure 6: Range of results for a recent ASTM Round Robin far field propagation modeling test. The test case was a point source and a receiver, each at 1.5 meters above a flat, grassy ground plane with the receiver located at either 300 or 3,000 meters from the source. An infinitely long perpendicular 3-meter high barrier wall was located 10 meters from the source. Ambient conditions were assumed to be calm (for some models light downwind conditions), 65 degrees Fahrenheit and 50% relative humidity. No other special wind or thermal gradients were specified.

3.4 Point Source versus Distributed Source Modeling

An often overlooked aspect of uncertainty is whether to treat stationary sound power sources as idealized points or attempt to model their three-dimensional configurations. Consider an actual industrial installation that consists of a 200 MW class simple cycle gas turbine generator. As an illustration of the effect that three-dimensional modeling can have, a 10 meter high barrier wall is modeled at a distance of 33 meters from the centerline of the gas turbine. The investigation will consider the differences, at far field positions beyond the barrier wall, between the model results using single point sources for each of the components and the model results using three-dimensional 'distributed' sources approximating the physical shapes of the sources. For the distributed source case, the sound power level of each of the 14 sources used in the example is divided equally among 54 points distributed around the exterior surfaces of the respective components.. Three specific aspects comparing these modeling approaches are presented in Figures 7, 8 and 9, with explanations provided in the figure captions.

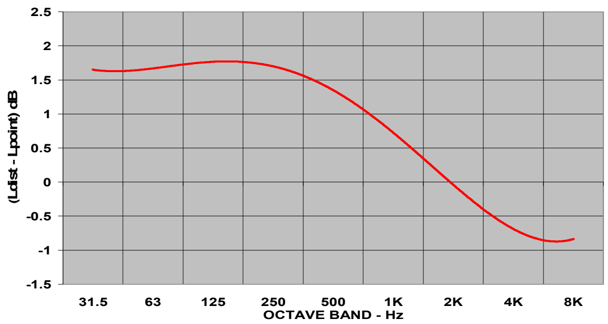

Figure 7 – Distributed vs. Point Source Evaluation: Differences in octave band sound pressure level, plotted as the difference between the level for the distributed source model (each of 14 components modeled as 54 points) minus the level with each of the 14 components modeled as an individual point, at a far field position 1.5 meters above grade and 240 meters from the source, with a 10 meter high barrier located 33 meters from the source.

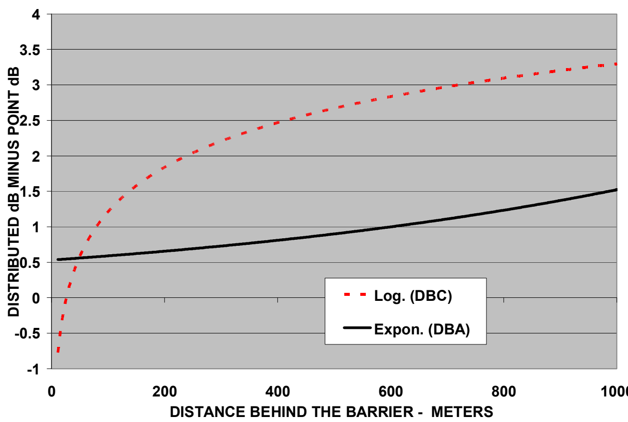

Figure 8 – Distributed vs. Point Source Evaluation: Differences in A-weighted (bottom curve) and C-weighted (top curve) sound level, plotted as the difference between the level for the distributed source model (each of 14 components modeled as 54 points) minus the level with each of the 14 components modeled as an individual point, at far field positions 1.5

meters above grade, with a 10 meter high barrier located 33 meters from the source.

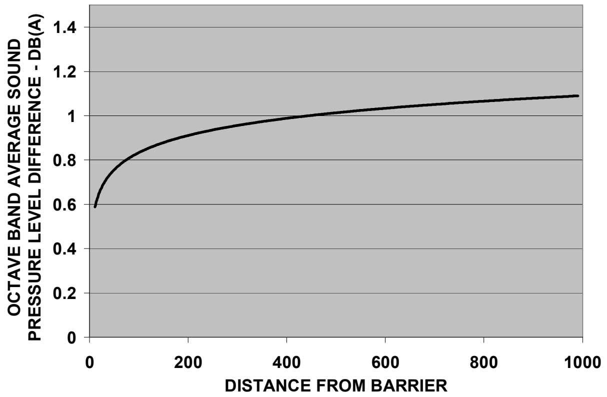

Figure 9 – Distributed vs. Point Source Evaluation: The trend of the differences in the average of the nine standard octave bands, plotted as the difference between the average for the case of the distributed source model (each of 14 components modeled as 54 points) minus the average for the case of each of the 14 components modeled as an individual point, as a function of the distance from the source, in meters, with a 10 meter high barrier located 33 meters from the source.

4 Combining Uncertainties

4.1 ASME Performance Test Code Combinatorial Rule

The AMSE Performance Test Code (PTC) 19.1 [8] contains a thorough assessment of uncertainty, the elements of which have been incorporated into an updated revision of ASME PTC 36 [9]. The constituents of uncertainty, as applied strictly to acoustical measurements, are denoted Type A and Type B. The Type A components are all those evaluated using statistical methods on a series of repeated measurements, such as the 95% confidence interval of a measurement sample. The Type B components are all those other elements that lead to an imprecision in the determination of a true sound level. In order to evaluate the overall uncertainty of a given measurement, the known or estimated uncertainties are combined using the classic *square root of the sum-of-the-squares* (SRSS) method as shown in Eq.(1).

$$U_C = (U_A^2 + U_{B1}^2 + U_{B2}^2 + \ldots)^{1/2} \quad (1)$$

where: U_C = combined uncertainty

U_A = Type A uncertainty

U_{Bn} = Type B uncertainties

Example Type B acoustical uncertainties, per AMSE PTC 36 [9], are shown in Table 2.

Element	Definition	"Best Expected" Uncertainty	Typical Uncertainty
U_A	Standard Error of Estimate	0.5 dB	1.5 dB
U_{B1}	Calibration of the Instrument	0.2 dB	0.3 dB
U_{B2}	Tolerances on the Instrumentation Train	0.2 dB	0.4 dB
U_{B3}	Uncertainty of Microphone Mounting	0.3 dB	0.9 dB
U_{B4}	Uncertainty of Distance from the Acoustic Center	0.1 dB	0.2 dB
U_{B5}	Uncertainty of Air Impedance	0.1 dB	0.3 dB
U_{B6}	Uncertainty of Source Sound Power Level (L_W)	0.4 dB	0.9 dB
U_{B7}	Background Noise Influence	0.1 dB	0.8 dB
U_C	**Combined Uncertainty**	**0.8 dB**	**2.2 dB**

TABLE 2. EXPECTED RANGE OF UNCERTAINTIES

Suggested "Best" and "Typical" uncertainties for the eight uncertainty elements, one for Type A and seven for Type B, are shown. Calculated combined uncertainty values for each of the example cases are 0.8 dB (Best) and 2.2 dB (Typical). These must still be combined (via SRSS) with other uncertainties to be expected from, for instance, prevailing atmospheric conditions commonly encountered. The resultant total measurement uncertainty will be about 3 dB, or even greater, which might be considered as consistent with ISO 3746 [2] for general purpose surveys. Thus, an appropriate A-weighted sound level test tolerance for all far field power plant compliance tests should be on the order of 3 dB.

4.2 Alternative Combinatorial Rule

The discussion above regarding the various components of measurement uncertainties in terms of ASME PTC 19.1 [8] (utilizing elements of ISO Guide 98:1995 [10]) instructs us to combine uncertainties via "square root sum of the squares" (SRSS). This will not always be valid. Probst and Donner [11] have provided a rationale for an important exception to the SRSS combinatorial rule. Their work was directed toward the uncertainty to be expected from a specific computer model's prediction of far field sound levels, and is not to be confused with the treatment in 3.3 above of the variations among unrelated modeling programs.

For the case of a complex sound source being modeled as a distinct set of separate sources, when the uncertainty of the estimated sound power levels for the various component sources can be assigned, a logarithmically weighted ensemble uncertainty is justified, and will take the form of a weighted root-mean square (rms) expression as shown in Eq.(2):

$$\sigma = \frac{\sqrt{\sum\left(\sigma_n \cdot 10^{0.1 \cdot L_n}\right)^2}}{\sum 10^{0.1 \cdot L_n}} \quad (2)$$

where: σ = standard deviation of the ensemble

σ_n = standard deviation of the nth source

L_n = Sound Power, in decibels, of the nth source

The requirements for this expression are merely that the sources themselves are incoherent and that the sound at the receiver be statistically uncorrelated. Probst and Donner [11] present an example case in which five sound power sources with standard deviations ranging from 2.2 dB to 3.6 dB combine to yield an ensemble standard deviation of uncertainty equal to 1.4 dB. Note that the ensemble standard deviation is always less than the average of the standard deviations is such a case. A generalized form of Eq.(2) for n sources of equal sound power level is shown in Eq.(3):

$$\sigma = \frac{\sigma'}{\sqrt{n}} \quad (3)$$

where: σ = standard deviation of the ensemble

σ' = standard deviation of each of the sources

As may be seen, this implies that the standard deviation of the ensemble of a large number of similar component sources within the ensemble is progressively reduced for a larger and larger number of constituent components. Therefore, the uncertainty of an increasingly complex source, theoretically at least, tends toward the negligible. Conceptually, we may regard this tendency as being due to the various individual uncertainties offsetting one another.

5 Summary

From among a large number of potential sources of uncertainty in predictive modeling or measurement, several elements of uncertainty in acoustical modeling (source sound power level, atmospherics and computer model algorithms), as well as elements of uncertainty in sound measurements (per PTC 19.1 [8]) have been discussed. It has been shown that uncertainties such as are shown in Table 3 may be commonly encountered and must be anticipated.

Uncertainty Class	Affecting		Magnitude
	Measure ments	Model	
Type A and Type B	X		Up to 2 dB
Source Sound Power Level		X	1 to 2 dB
Atmospherics	X	X	Up to 8 dB
Computer Model Algorithms		X	2 to 5 dB
Point vs. Distributed Source		X	1 to 2 dB

TABLE 3. A SUMMARY OF THE RANGE OF EXPECTED UNCERTAINTIES DISCUSSED IN THIS PAPER

The sources and magnitudes of all potential uncertainties, including the specific types discussed here, most of which are commonly ignored, must always be considered. Specifically:

- Sound measurement surveys should be regarded as having A-weighted uncertainties on the order of 3 dB per ISO 3746 [2]. Whether to consider such uncertainties as Test Tolerances is a contractual matter among the parties involved.
- Plant acoustical design programs must anticipate the expected uncertainties of source sound power definition and modeling demonstrated here (a prudent A-weighted margin of 2dB to 3 dB is recommended).
- Sound level predictions at distances greater than 300 meters (1,000 feet) from any source should only be performed with the utmost care and qualifications.
- Sound level commitments at distances greater than 150 meters (500 feet) from the source may be inadvisable.
- Distributed source models should always be used.
- It is important to note that there are circumstances in which it is appropriate to evaluate combined uncertainties in terms of rms rather than SRSS.

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