Estimating Community Sound Levels of Large Industrial Equipment

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ABSTRACT

A simple acoustic radiation computer model based on the ISO 9613 parts 1 and 2 standards is applied with enhancements to address the effects of the large source size of industrial equipment. Large equipment modeled as a point source is discussed and how a point noise model can be adapted to accurately estimate sound from large sources. Often, industrial facility noise models ignore obvious factors, such as partial screening or partial reflections from large sound sources, directivity effects and the physical source dimensions as well. This paper addresses these typically ignored effects that are uniquely important to large industrial equipment by exercising the SPM9613™ computer model to estimate the inaccuracy of simple point source models. The paper also presents comparisons of predicted and measured sound pressure levels of a simple cycle gas turbine power generation facility using the large source model.

INTRODUCTION

Obtaining good agreement between community noise predictions and sound measurements is imperative when designing optimized noise control features or predicting the impact an industrial facility can have on the environment. Under predicting sound levels relative to the actual operational sound level of a facility can be very costly to the facility's owner in terms of retrofit design time, financial outlay, and cost of "downtime" while a facility is being retrofit with additional noise abatement. In a worse case scenario, a facility may be forced to shut down if it exceeds the levels set by local noise ordinances or state regulations. This typically leads the acoustical designer to add substantial margins to his design calculations. Yet, overly conservative prediction methods, or predicting far field sound levels significantly higher than those measured of the operational facility, not only place an unnecessary financial burden on the initial noise abatement, but can also affect the long term efficiency of the equipment when the noise control contributes to larger than necessary pressure drops, mechanical losses and maintenance issues.

Community noise prediction models of large industrial facilities are most often based on point source radiation models. Large industrial facilities begin with sound power levels of the equipment components. The sound power levels are input to far field sound radiation models to account for attenuation due to atmospheric absorption, ground effects, barrier effects and sound reinforcements from specular reflections. In many instances, sound pressure levels can be over or under predicted by several decibels. While much of the noise prediction inaccuracy can be blamed on inaccurate equipment sound power levels, other factors inherent to the large size of the equipment are often ignored. Understanding and accounting for the uniqueness of the large noise sources is imperative in obtaining accurate noise predictions.

BASIS OF SOUND RADIATION MODEL

The basis of the SPM9613™ sound radiation model is the ISO standards 9613 Parts 1 (1993) and 2 (1996). ISO 9613-1:1993(E) specifically addresses atmospheric attenuation while ISO 9613-2:1996(E) specifies an engineering method for calculating environmental noise from a variety of noise sources by prescribing methods to determine the various attenuation effects observed during outdoor sound propagation. The equations are simple and primarily empirically based. ISO 9613-2 assumes the user wishes to evaluate outdoor noise propagation during meteorological conditions favorable to sound propagation; downwind from the sound source with wind velocities between 1 and 5 m/s at 3 to 11 m above the ground. The standard does not provide a means for evaluating sound emission under non-favorable conditions but does provide guidance for estimating long term average sounds levels over a long period of time (a year for example) due to a variety of environmental conditions.

Basic Equation

The basic equation used in ISO 9613-2 to define the downwind sound pressure level (Lp) at a receiver is:

$$Lp = Lw_{point} + D - A$$

where

Lw_{point} is the point source sound power level, in dB re 1 picowatt
D is the directivity indices, in dB
A is the attenuation of various effects defined by:

$$A = A_{div} + A_{atm} + A_{ground} + A_{screen} + A_{misc}$$

A_{div} is geometrical divergence attenuation
A_{atm} is atmospheric absorption
A_{ground} is ground effect attenuation
A_{screen} is screening attenuation
A_{misc} is the attenuation due to miscellaneous effects, such as propagation through industrial sites or foliage

Divergence

The spherical spreading, or divergence term A_{div}, is calculated as follows:

$$A_{div} = 20Log_{10}(d) + 11, \text{ dB}$$

where d is the source to observer distance, in meters.

Atmospheric Absorption

The atmospheric absorption term, A_{atm}, is mainly a high frequency sound attenuator, dependent on distance, relative humidity and temperature. Table 1 illustrates an example of the amount of attenuation observed at a distance of 1000 meters.

Table 1. Atmospheric Absorption at 1000 meters, 20 degrees C, 70% relative humidity

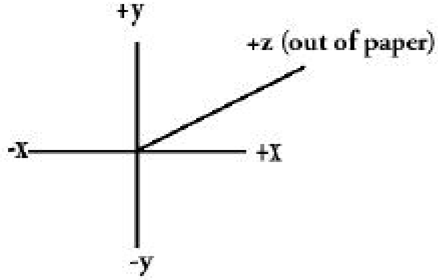
Octave Band Center Frequency, Hertz									
16	31.5	63	125	250	500	1000	2000	4000	8000
0	0	0.1	0.3	1.1	2.8	5.0	9.0	22.9	76.6

The above coefficients (or coefficients as calculated by ISO 9613-1) are multiplied by the actual distance then divided by 1000 meters to obtain atmospheric attenuation at other distances. Other temperature and humidity conditions can be estimated with the ISO 9613-1 standard.

Coordinate System

The coordinate system used in a computer prediction method can be arbitrary since only the distances need to be known in ISO 9613-2 equations. However, defining sound sources, barriers and observers spatially within a coordinate system are required to determine these distances. The coordinate system, as shown in Figure 1, is selected as follows: x and y correspond to locations in the horizontal plane. Positive z is above the horizontal plane.

Figure 1. Coordinate System Reference



Ground Effects

Ground reflection effects can reduce sound observed at a receptor when the ground is "soft", or increase the sound at a receptor when the ground is "hard". Predicting the effect requires the knowledge of the ground composition near the source, between the source and receiver (middle ground) and near the receiver. The ground attenuation is frequency dependent. The main parameters are the heights above the ground plane for the source, hs, and the receiver height, hr, a number defining the ground hardness or absorption coefficient, {Gs, Gm or Gr}, and the ground plane distance, dp.

The ISO 9613-2 standard assumes that the ground has a more-or-less constant slope between the source and the observer. When the slope between the source and observer is other than zero, the coordinate system must be transformed to define the projected distance and "apparent height" above the ground plane as shown in Figure 2.

The determination of the transformed projected ground plane distance, dp, and the source and observer heights above the ground plane are defined as follows:

Three terms along the ground plane are defined:

$$x'g = [(xs - xo)^2 + (ys - yo)^2 + (zgs - zgo)^2]^{1/2}$$
$$x's = h's \cdot \sin(\theta)$$
$$x'o = h'o \cdot \sin(\theta)$$

where

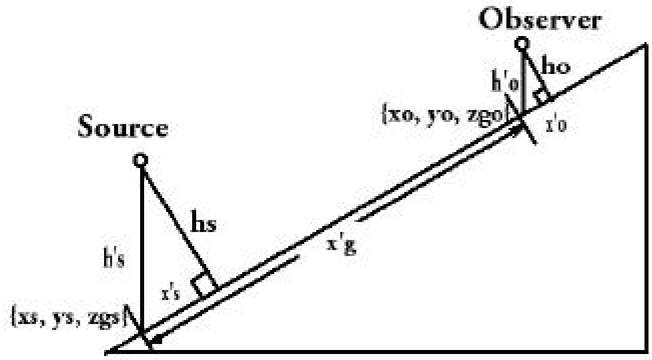
xs, ys the source x and y coordinates
zgs is the ground elevation at the source
xo, yo the observer x an y coordinates
zgo is the ground elevation at the observer
h's is the vertical source height above the ground
h'o is the vertical observer height above the ground

$$\sin(\theta) = (zgo - zgs) / x'g$$

The transformed ground plane distance, dp, and transformed heights above the ground plane hs & hr are defined below:

$$dp = x'g - x's + x'o$$
$$hs = h's \cdot \cos(\theta)$$
$$ho = h'o \cdot \cos(\theta)$$

Figure 2. Coordinate Transformation to the Ground Plane



The terms defining the frequency dependence of the ground effect are shown in Table 2.

Table 2. Frequency Dependant Ground Attenuation Terms

O.B.C.F, Hertz	Source or Receiver Attenuation A_s or A_r	Mid Ground Attenuation A_m
31.5*	-1.5	-3q
63	-1.5	-3q
125	-1.5 + {Gs or Gr} · a'(h)	-3q · (1 - Gm)
250	-1.5 + {Gs or Gr} · b'(h)	-3q · (1 - Gm)
500	-1.5 + {Gs or Gr} · c'(h)	-3q · (1 - Gm)
1000	-1.5 + {Gs or Gr} · d'(h)	-3q · (1 - Gm)
2000	-1.5(1 - {Gs or Gr})	-3q · (1 - Gm)
4000	-1.5(1 - {Gs or Gr})	-3q · (1 - Gm)
8000	-1.5(1 - {Gs or Gr})	-3q · (1 - Gm)

*extension of the ISO 9613-2 Standard

where

a'(h) $= 1.5 + 3.0 \exp(-0.12 \cdot (h-5)^2)\, p' + 5.7\exp(-0.09h^2)\, [1-\exp(-2.8\cdot 10^{-6} \cdot dp^2)]$
b'(h) $= 1.5 + 8.6 \exp(-0.09 \cdot h^2)\, p'$
c'(h) $= 1.5 + 14.0 \exp(-0.46 \cdot h^2)\, p'$
d'(h) $= 1.5 + 5.0 \exp(-0.9 \cdot h^2)\, p'$
p' $= 1-\exp(-dp/50)$
dp = ground plane distance from source to receiver
q $= 0$, for $dp \leq 30(hr + hs)$ or
q $= 1 - 30(hr + hs)/dp$, when $dp > 30(hr + hs)$

Generically, the value G is defined as the ground hardness indicator, or absorption coefficient, 0 for hard ground, 1 for very soft ground. Values range between 0 and 1 for mixed ground.

Specifically,

Gs	is the ground hardness at the source
Gm	is the ground hardness at the middle ground
Gr	is the ground hardness at the receiver

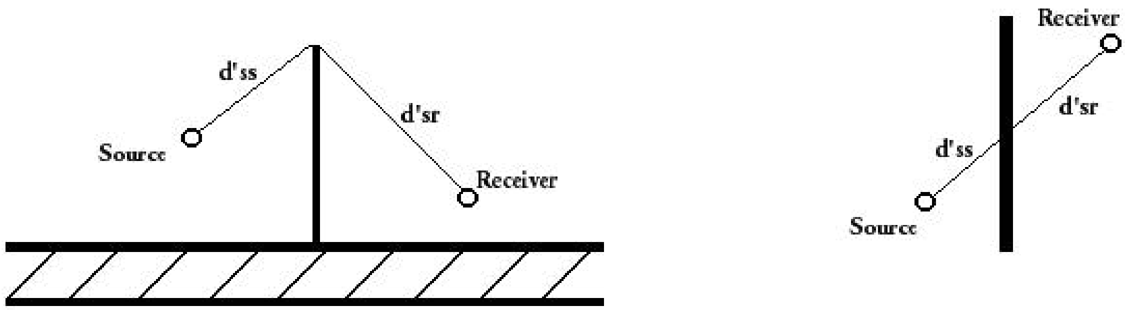
$A_{ground} = A_s + A_m + A_r$

ISO 9613-2 provides no guidance on limiting the attenuation of the ground effect. However, "*Noise and Vibration Control Engineering*", by Beranek and Ver[2], shows the "Practical Limit" to be about 20 dB relative to hard ground, and a "Conservative Limit" of 10 dB relative to hard ground.

Screening (Sound Barriers)

The sound barrier is one of the most important tools the noise control engineer has in controlling noise. Figure 3 defines the barrier geometry.

Figure 3. Barrier Geometry Definition



Elevation View of Screen (Barrier) **Plan View of Screen (Barrier)**

The screening attenuation (D_z) is calculated with the following equations:

$D_z = 10 \log_{10} (3 + (20 / \lambda) C_3 \; z \; Kmet)$, in dB

where

λ	is the wavelength of the sound
z	is the difference between the direct and refracted path lengths
C_3	is frequency dependant and ranges from 1 to 3 for multiple screens, or = 1 for single screens

e' is the distance between the screens in the direction of the source and receiver, accounting for the distance component parallel with the screen.

Kmet is the correction factor for meteorological influences, defined as

Kmet $= \exp(-(1/2000)((dss \cdot dsr \cdot d) / 2z)^{1/2}))$ for $z > 0$
or
Kmet = 1 for other values of z or lateral diffraction

dss perpendicular distance from source to plane of screen.
dsr perpendicular distance from plane of screen to receiver.
d'ss distance from source to screen in the direction of the source and receiver, accounting for the distance component parallel with the screen.
d'sr distance screen to receiver in the direction of the source and receiver, accounting for the distance component parallel with the screen.

d distance source to receiver

z $= d'ss + d'sr + e' - d$

The value of z is given a negative value if the observer is in the bright zone of the screen.

In simplistic terms, the Screen Attenuation is defined as the larger of either the Screen Attenuation alone or the Ground Attenuation. Mathematically, the screening term, A_{screen}, is defined as follows:

For top edge attenuation due to the screen:
$A_{screen} = D_z - A_{ground}$
If $A_{screen} < 0$, A_{screen} is set equal to 0.

For side edge attenuation due to the screen:
$A_{screen} = D_z$

The A_{ground} term will then cancel when it is added in the basic attenuation equation.

The horizontal dimension of the screen, perpendicular to the line connecting the source to receiver, must be greater than one wavelength of the center frequency of interest to be considered a screen.

Although not addressed in the ISO9613-2 standard, an additional requirement has been added to the SPM9613™ computer model such that the barrier's height must be greater than ½ wavelength. The ½ awelength height limit is necessary to eliminate attenuation of sources in the "bright zone" from short screens. Without this limitation, the equation's shown above would allow parking lot speed bumps to provide substantial attenuations.

Single screens include multiple paths for sound propagation. The following propagation paths are considered; around each of the vertical sides and over the top of the barrier. The path attenuation is summed and the final attenuation determined. The maximum attenuation allowed by a single screen is 20 dB.

Multiple screens assume the attenuation around the barrier is adequate and estimate only the path over the top of the barrier. All combinations of screens existing between the source and observer are computed first singularly, then in pairs. When computed in pairs, the barrier combination providing the largest attenuation is used in the screening term. If the distance between the first screen and second screen is greater than or equal to one wavelength, the maximum attenuation allowed by the double screen is 25 dB.

Miscellaneous Attenuation

For the purposes of this document, miscellaneous attenuation is defined as the attenuation from industrial sites, foliage and housing. The details of the attenuation concepts and values can be found in the ISO 9613-2 standard.

$$A_{misc} = A_{industrial} + A_{foliage} + A_{housing}$$

Reflections

To simplify the calculation, only first reflections from any surface are considered. The calculation logic is as follows: An image source is created from the real source. The point of intersection with the reflector and the line connecting the image source to observer is found. The sound is propagated from the real source to the point of intersection on the reflector, accounting for barriers and other miscellaneous noise attenuation along the way. The sound is then propagated from the point of reflection to the receiver, again looking for barriers and other miscellaneous noise attenuation. All attenuation effects follow that of the reflected source to observer path. The directivity used is that in the direction of the intersection point with the surface.

ANALYSIS

Sound Source Definition

Many times the engineer or consultant is asked to calculate the noise from an industrial facility at a position closer to the source than a point source model would justify. Various guidelines, such as those provided in ISO 9613 part 2[1], clearly state that a source should be broken up into multiple “sub-point-sources” if the calculation distance is ≤ 2 times the largest source dimension. As an example, a 50 meter long cooling tower would need to be broken down into 4 sub-sources if a prediction is to be made at an observer distance of 25 meters from the tower’s surface. While most engineers understand the need to break sources up into such multiple semi-sources, time constraints and computer resources can limit their ability.

To evaluate the effect of using the single point source over simplification, a numerical investigation was performed by the author[4]. A large source was simulated by breaking it down into multiple point-sources distributed on it's surface. The results of various densities of points representing the surface were then compared to a single point source calculation.

Figure 4 shows four different point source distributions selected to model a finite plane sound source (90 meter long by 30 meter tall building wall). The 6x18 grid was chosen to meet the ISO 9613-2 recommended number of sub sources.

Figure 4. Distributions of Point Sources Modeled

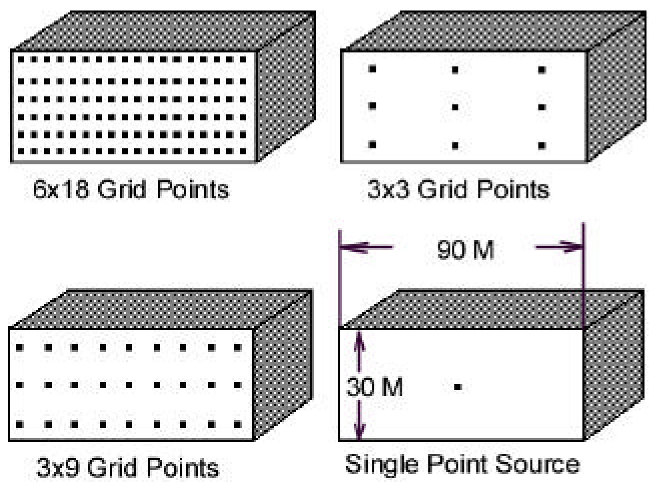


Figure 5 presents the results of the calculated sound pressure level (Lp) as a function of the perpendicular distance from the center of the finite plane sound source.

At distances closer than about 1.8 times the largest source dimension, the point source significantly departs from the 6x18 "standard" grid. The simple 3x3 grid approximates the 6x18 grid within 1 dB at of about 1/9 (10 meters) of the largest source dimension.

Shown in Figure 6 is the calculated sound pressure level as a function of distance parallel to the face of the source for four different point source distributions. An observer was modeled in the plane of the surface source 10 m, 20 m, 40 m, 80 m, 160 m and 320 m from the source's edge. It appears that an accuracy of ±1 dB can be obtained with a simple 3x3 surface grid to distances as close as 1/9 the source's largest physical dimension. The required source dimensions are consistent with Rathe[3]'s findings for representing finite plane sources points.

Figure 5. Lp As A Function Of Perpendicular Distance From A 90 M x 30M Wall

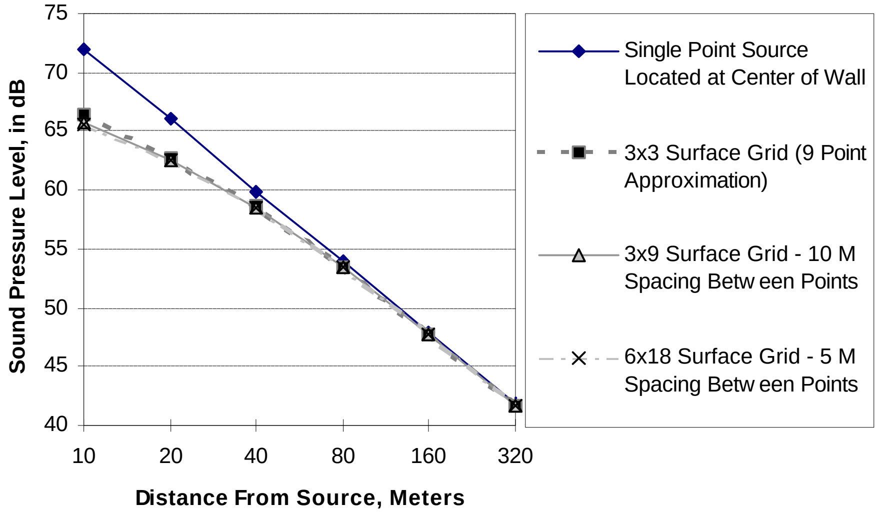
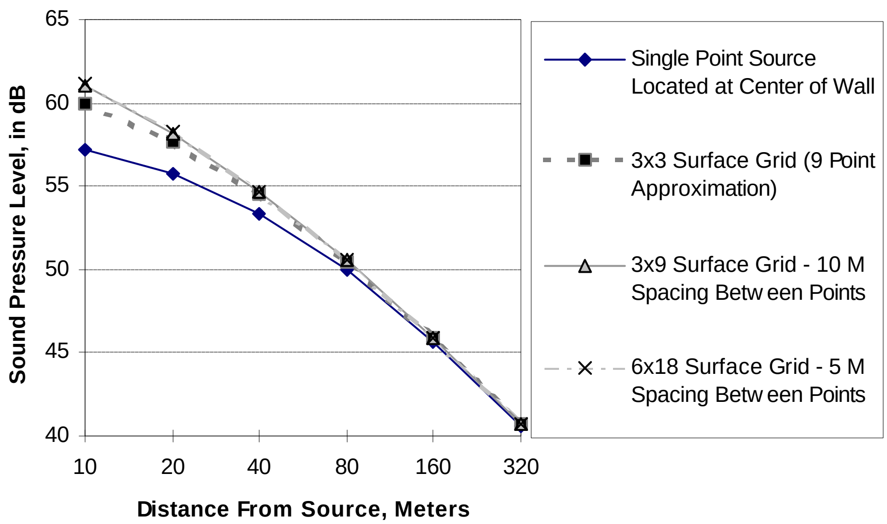


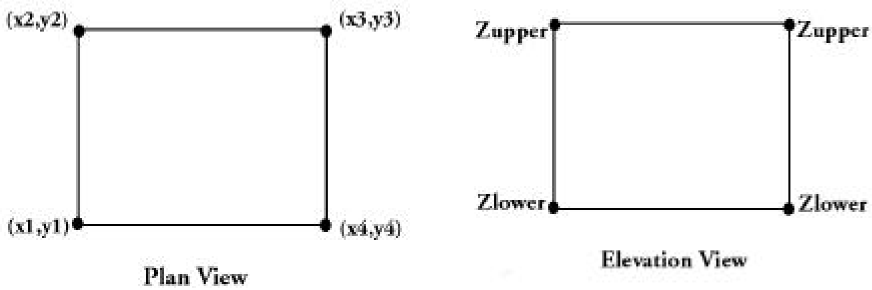
Figure 6. Lp As A Function Of Parallel Distance From A 90 M X 30 M Wall



The ISO 9613-2 engineering method requires that all sound sources must be defined as point sources. For large sound sources that are closer to the receiver than twice the diameter of the relevant area of sources, or when the source is partially blocked by a barrier, the standard says the source must be broken down into several points.

The SPM9613™ code represents the sound source as a three dimensional "box". Four corners {(x1,y1), (x2,y2), (x3,y3), (x4, y4)} of the physical source and the upper and lower surface elevations {(Zupper, Zlower)}

Figure 7. Source Coordinates



The 3-D distribution of points for surface sources is determined as follows:

The areas of each of the vertical "walls" is calculated by:

$$S_{(1>2)} = i_{(1>2)}(Zupper - Zlower) * [(x2-x1)^2 + (y2-y1)^2]^{1/2}$$
$$S_{(2>3)} = i_{(2>3)}(Zupper - Zlower) * [(x3-x2)^2 + (y3-y2)^2]^{1/2}$$
$$S_{(3>4)} = i_{(3>4)}(Zupper - Zlower) * [(x4-x3)^2 + (y4-y3)^2]^{1/2}$$
$$S_{(4>1)} = i_{(4>1)}(Zupper - Zlower) * [(x1-x4)^2 + (y1-y4)^2]^{1/2}$$

For the upper and lower surfaces, the average length of opposite sides is calculated by:

$$L_1 = ½\{[(x2-x1)^2 + (y2-y1)^2]^{1/2} + [(x4-x3)^2 + (y4-y3)^2]^{1/2}\}$$

$$L_2 = ½\{[(x3-x2)^2 + (y3-y2)^2]^{1/2} + [(x1-x4)^2 + (y1-y4)^2]^{1/2}\}$$

The areas of each of the upper and lower surfaces is calculated by:

$$S_{(lower)} = i_{(lower)} L_1 L_2$$
$$S_{(upper)} = i_{(upper)} L_1 L_2$$

where the values of "i" are either 0 or 1 indicating if a side of the source radiates sound.

0 indicates the side does <u>not</u> radiate sound, while 1 indicates the side <u>does</u> radiate sound.

The representation of the upper and lower surface areas requires that the shapes should be nearly rectangular to assure the upper and lower surface areas are estimated with reasonable accuracy.

The total 3-D area $S_{(total)}$ is calculated by:

$$S_{(total)} = S_{(1>2)} + S_{(2>3)} + S_{(3>4)} + S_{(4>1)} + S_{(lower)} + S_{(upper)}$$

And the power level of the side defined by points x1,y1 and x2,y2 is calculated by:

$$Lw_{(1>2)} = Lw_{(total\ source)} + 10Log_{10}(S_{(1>2)} / S_{(total)})$$

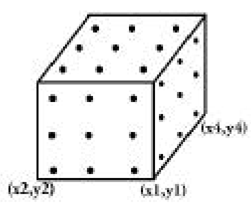
This equation is repeated substituting the corresponding area term for the other 5 sides.

A grid of 9 evenly spaced points (3 rows of 3 columns) are placed on each side. The grid of points are spaced at 1/6, 1/2 and 5/6 the length or height from the edge of the side. The total number of points representing the total large source is equal to the number of sides of a source radiating sound multiplied by 9.

The sound power defined for a single point (one of the nine (9) points on the side) is shown by example for side x1,y1 and x2,y2 as;

$$Lw_{point} = Lw_{(1>2)} + 10Log_{10}(1/9)$$

Figure 8. Point Source Distribution



Source Directivity

Accounting for a source's directivity can be accomplished in two ways:

- Directivity indices
- Radiation pattern changes by reflections and barriers

The directivity indices, D, is a frequency and direction dependent term. To simplify the application of including source directivity indices they can be tied to the 3-dimensional shape of the source and not the selected coordinate system of the model.

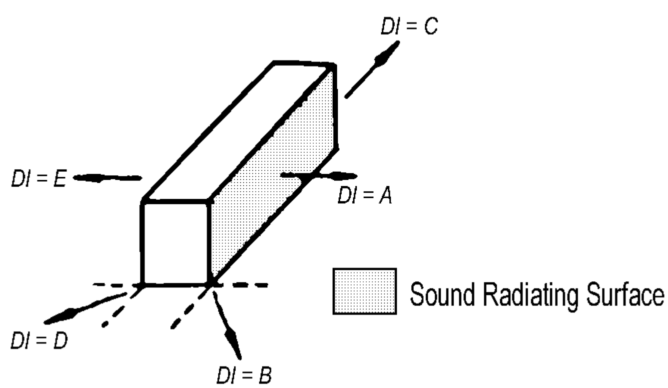
The large size of some industrial equipment enclosures, boilers and other equipment can justify modeling them as "buildings." However, many far field noise calculations ignore the size implications and model this "building" as a point source radiating from the center of the enclosure.

The directivity indices (DI) of sound sources radiating from building facades and roofs is generalized by the VDI 2714 standard[5]. Limitations are provided that the corrections are for A-weighted sound with "predominantly mid frequency dependence" No guidance is giving for building size considerations. Assuming the majority of the indices are dominated by shielding effects, the user would expect significant frequency dependence. The generalization does not leave the user with a strong feeling of confidence that his calculations will be accurate. No guidance is provided for determining the appropriateness of these simplified indices.

To estimate the impact of the actual size of a building, a computer simulation was designed to model surface sources on one wall of a typical building. The sources were located approximately 2 centimeters off the physical front wall surface. Each of the four building walls was modeled as a barrier. The barrier attenuation (including multiple barriers) was modeled in accordance with ISO 9613-2. All observer directions were located 200 meters from the geometric center of the wall surface modeled.

Shown in Figure 9 is the directional frame of reference used in the data presentation.

Figure 9. Directivity Reference



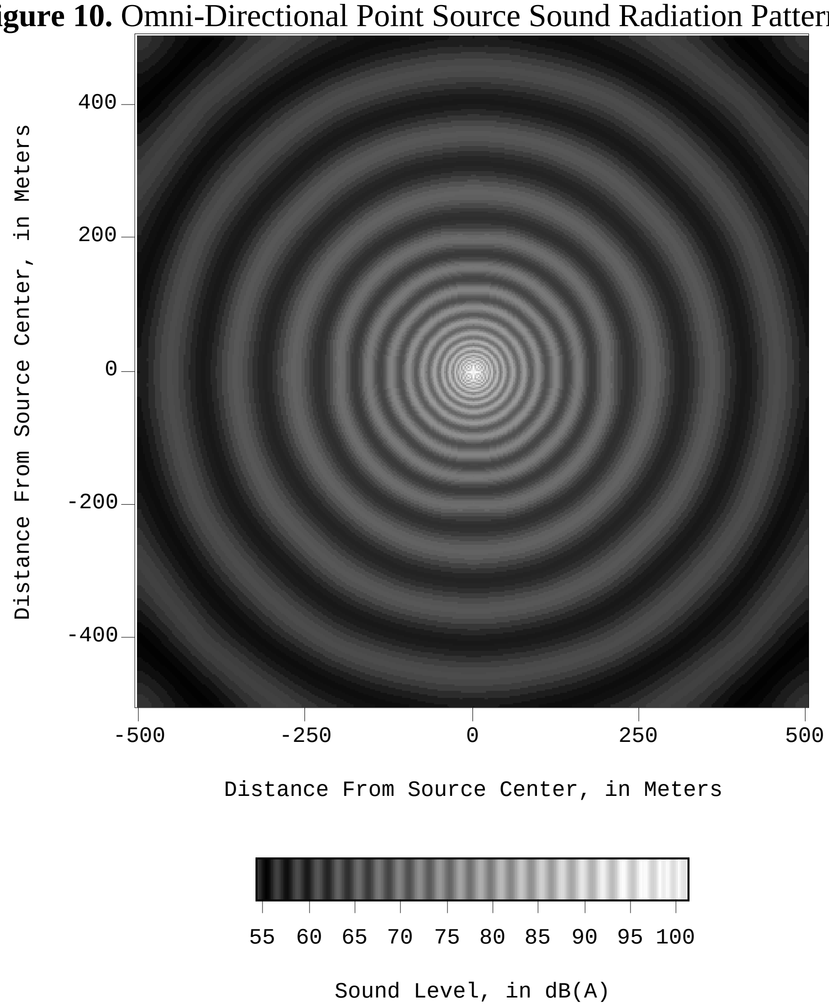
The results are compared to the non-frequency dependent results of VDI 2714 in Table 3. While directivity indices of the front surface (directions A and B) are similar to the indices presented in the VDI 2714 standard, the other directions depart from the generalization rapidly. Directivity indices are significant once the line of sight is broken to the source. Reference 4 shows significant dependence on building size can exist. As the building or enclosure approaches negligible size, such that the wavelength of interest is much larger than the largest source dimension, the directivity indices would approach 0 dB in all directions.

Further investigation was done to define the directivity pattern of a 10 meter “cube” relative to a simple omni-directional point noise source often used to define large sound sources. Shown in Figure 10 is a typical omni-directional point source radiation pattern.

Table 3. Estimated frequency dependent DI, in dB, of a 12 meter long x 4 meter wide x 4 meter tall building wall compared to frequency independent indices

	VDI 2714 Frequency Independent	**Octave Band Center Frequency, Hertz**								
		32	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**
DI = A	0 dB	0	0	0	0	0	0	0	0	0
DI = B	0 dB	0	0	0	0	0	0	0	0	0
DI = C	-5 dB	0	0	-1	-2	-3	-4	-4	-4	-4
DI = D	-10 dB	0	-6	-8	-13	-19	-24	-25	-25	-25
DI = E	-20 dB	0	-6	-8	-13	-19	-24	-25	-25	-25

Figure 10. Omni-Directional Point Source Sound Radiation Patterns



Presented in Figure 11 is the plan view of a sound source represented by 3x3 arrays of points located on the surface of the "cube" with barriers behind them. The results of the directivity analysis of the 3-D representation are shown in Figure 12.

Figure 11. Large Sound Source Representation

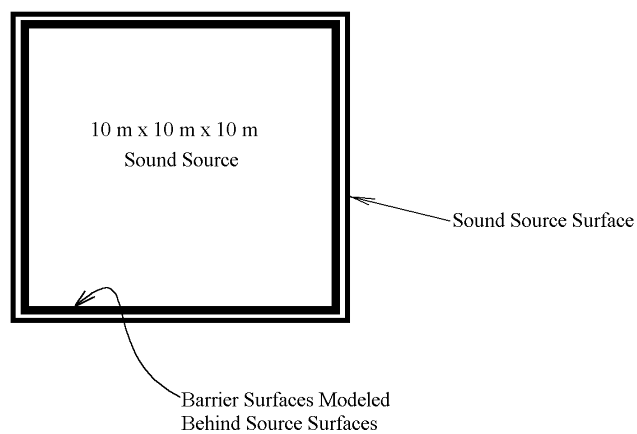
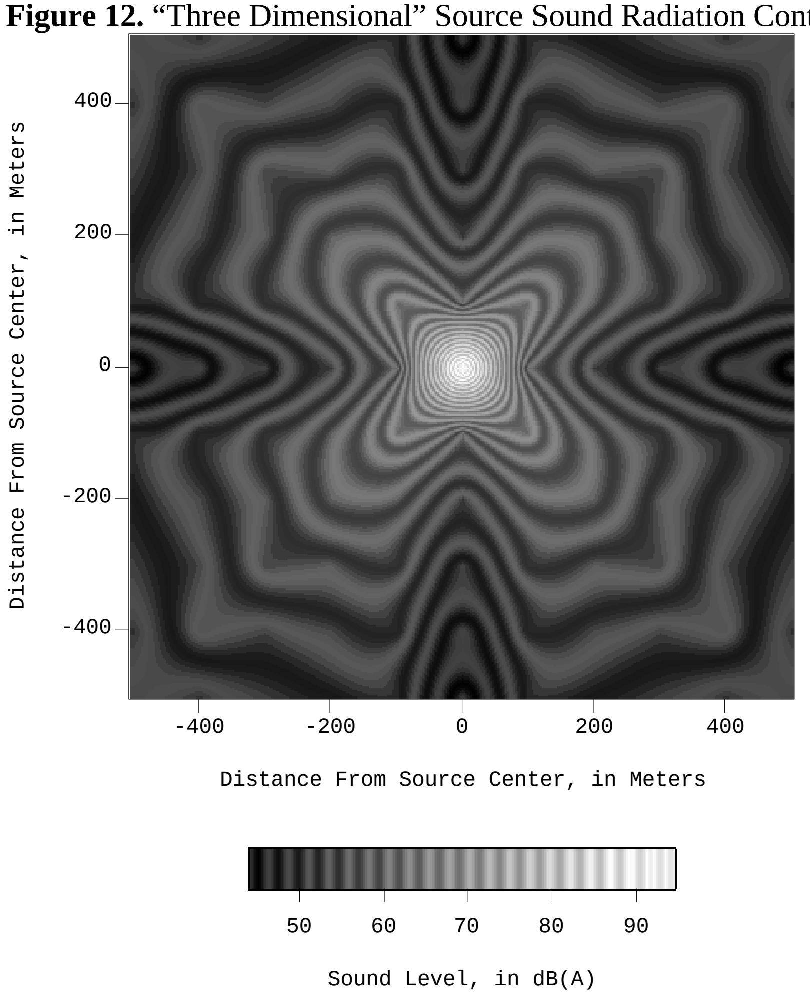


Figure 12. "Three Dimensional" Source Sound Radiation Contours

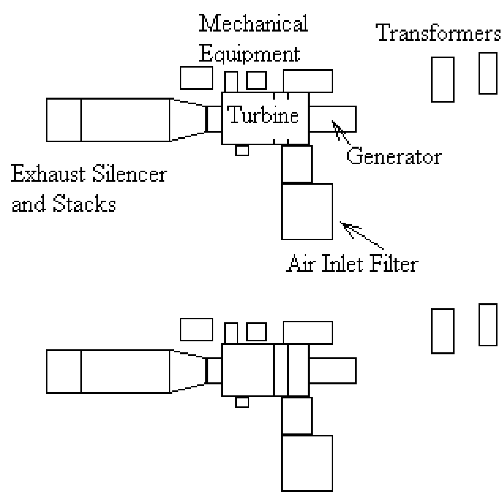


The substantial departure from the results observed in the omni-direction point model are clear. The strong bands of sound radiated toward the corners of the cube (45, 135, 215 and 305 degrees) are related to largest observable surface area at the sound receptor (two wall surfaces are visible by the sound receptor) while less of the source area is observable in other directions.

Comparison of Calculations with Measurements Made of a Gas Turbine Power Generation Facility

To evaluate the accuracy of the SPM9613™ acoustical prediction model, sound level measurements made downwind of a large 2 unit simple cycle gas turbine facility were compared to the analytical predictions of the facility. A sketch of the gas turbines is shown in Figure 13.

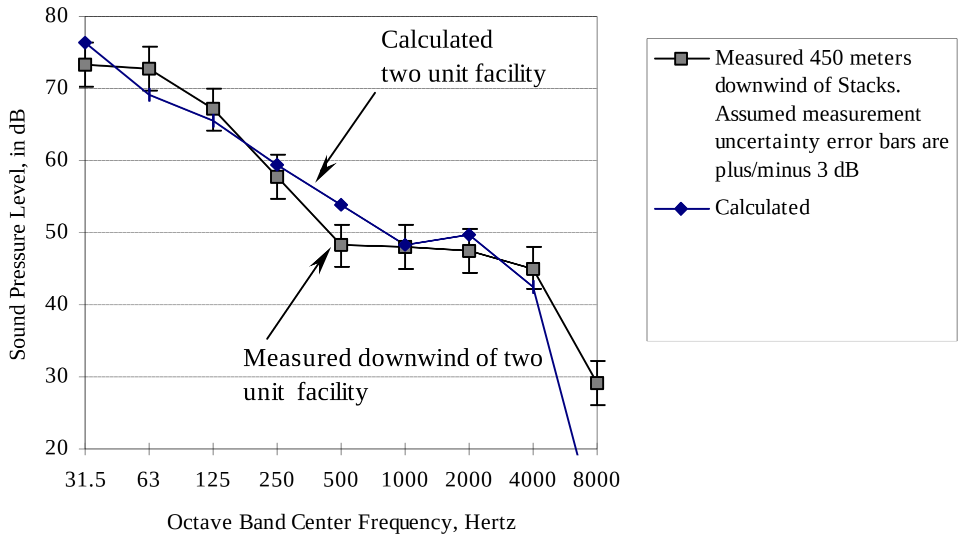
Figure 13. Gas Turbine Simple Cycle Power Generation Facility



The sound power level data used in the calculations were provided by the gas turbine manufacturer. The results of the estimated versus measured sound pressure levels of the facility can be seen in Figure 14.

The correlation between predictions and estimates is very good considering measurement uncertainty/prediction uncertainty of at least ±3 dB in any given octave band. The measured 8,000 Hz octave band noise is dominated by ambient sources and can't be used for prediction method evaluation purposes. The good correlation provides reasonable assurance that the SPM9613™ model can be used with confidence in predicting environmental sound of large industrial equipment and as a diagnostic tool for use in evaluating various noise control options.

Figure 14. Calculated versus Measured Sound Pressure Levels of a 2 Unit Simple Cycle Gas Turbine Facility



CONCLUSIONS

A community noise computer prediction model, SPM9613™, based the ISO 9613 part 2 standard has been developed to enable the accurate prediction of large industrial noise sources. Significant departures in directivity and sound pressure levels were observed relative to single point source radiation models. Predictions based on the SPM9613™ large source radiation model were found to be accurate to approximately ±3 dB over an octave band frequency range of 31.5 Hz to 8000 Hz.

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Key Words

Community noise
Sound Prediction
Barriers
Directivity
Source noise modeling
Building noise
Computer modeling
ISO 9613
SPM9613

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The proceeding paper was prepared and presented in the Air and Waste Management Conference in Orlando Florida in 2001 and authored by **Dave Parzych, Principal Acoustical Consultant and Noise Control Consultant of Power Acoustics, Inc.**

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