Comparison of Noise Test Codes when Applied to air Compressors

Michael J. Lucas, INCE Bd. Cert., Ingersoll-Rand Company, Davidson/NC

INTRODUCTION

Beginning January 2004, ISO-2151 became the international noise test code used for testing compressors and vacuum pumps. Before January 2004, the test code European compressor manufacturers followed was PN8NTC2.3 and in the United States compressor manufacturers followed S5.1. ISO 2151 is very similar to PN8NTC2.3 with the following three main differences: (1) noise measurements can now be made using either a parallelepiped or hemispherical reference surface; (2) noise labeling is now declared as a dual number, specifically the sound power and the measurement uncertainty; and (3) sound intensity measurements are no longer limited to production checking and testing large machines in-situ. Sound intensity can now be used for labeling the sound power of a machine.

ISO 2151 provides the methods for the measurement, determination, and declaration of the noise from portable and stationary compressors and vacuum pumps. The standard specifies that sound power shall be determined according to either ISO 3744, ISO 9614-1, or ISO 9614-2 with Grade 2 accuracy. The sound power in ISO 2151 is declared as a dual number. The A-weighted sound power level rounded to the nearest decibel referenced to 10^{-12} Watts and the uncertainty. The measurement uncertainty represents the maximum value of the standard deviation of reproducibility. If the manufacturer has no experience data at measuring the standard deviation of reproducibility, then as an alternative, the manufacturer may use +3 dB for measurements that follow Grade 2 accuracy.

ISO 3744 describes the measurement of sound power using sound pressure. The reference surface can be either a parallelepiped or a hemisphere. Measurements can to be made in a free-field condition having low background noise level on a hard reflecting plane. The only instrument required to determine the sound power level is a sound level meter. One of the goals of this paper was to try different microphone configurations for the same compressor to see if these changes could produce a difference in the sound power level.

ISO 9614-1 and ISO 9614-2 are measurement standards that specifically apply to the determination of sound power using a sound intensity probe. The first standard applies to measurements made at discrete points while the second standard applies to measurements made using the scanning technique. This paper will concentrate on the measurement of sound intensity using the scanning approach and compare these test results to measurements made with sound pressure.

The compressor that is used in this study is an air-cooled oil-flooded screw compressor that has a reported sound pressure level in the marketing literature of 74 dBA at 1 meter. As this report will describe we were unable to measure the advertised sound level, in fact our measurements indicate the actual sound level is 6 dB greater. Since ISO-2151 is a new standard used by the compressor industry, it is important to understand the strengths and weaknesses of the standard.

The paper begins with a brief summary on the three main normative reference standards, the test equipment used in the comparison study, the findings of the study, and examines some of the issues and concerns with each of these normative reference standards.

DETERMINATION OF SOUND POWER USING SOUND PRESSURE

ISO 3744 is used for any environment approximating free field conditions over a reflecting plane. In our study, the testing was done in an open-air sound pad located far away from any nearby reflecting objects. The test site is made from concrete and an outdoor weather station located nearby records the temperature, humidity, and most importantly the wind speed at the time of the measurement. The background noise level must be at least 15 dB(A) lower in each octave band than when the machine is running. When the differences are not less than 15 dB(A) and greater than 6 dB(A), then the standard provides procedures for obtaining a correction factor. The maximum correction factor applied to any single measurement is 1.3 dB.

The reference surfaces described in ISO 3744 can be either a parallelepiped (see Figure 1) or hemisphere (see Figure 2). The measurement distance d used for the parallelepiped reference surface is the distance from the surface of the compressor to the sides of the reference surface. The measurement radius r is the radius of a hemispherical measurement surface. In our testing the distance d is 1 meter and the radius r is 4 meters.

The number of microphones used in the test depends on the largest dimension of the compressor package. For most compressors that have two of the dimension less than 1 meter (L< 1 meter and W < 1 meter) and a height less than 2 meters, only 9 microphones are required, see Figure 1. If however any one of these dimensions are greater, then ISO 3744 provides additional examples for adding more microphones to the reference surface. Hemispherical measurements typically use 10 microphones at a distance r, which is at least 3 meters. When additional microphones are needed, instructions for adding microphone positions are provided in ISO 3744. The compressor tested had an approximate width of 1 meter, a length of 2.5 meters, and a height of 2 meters.

ISO 3744 specifies that additional microphone positions should be added when the difference between the highest and the lowest sound pressure level measured at all microphone positions exceeds the total number of microphone positions. ISO 3744 also states that additional microphone positions should be added when the noise from the source is highly directional, or the noise radiates only from openings in the enclosure.

The calculations involved in determining the sound power from sound pressure, is

$$L_W = \overline{L}_{pf} + 10\log_{10}\left(\frac{S}{S_o}\right)$$

where $\overline{L}_{pf}$ represents the energy average sound pressure level measured at all microphone positions. The recorded sound pressure levels are time average A-weighted levels that have been corrected for background noise and environmental influences. S represents the area of the reference surface in square meters and S_o is equal to 1 meter squared. From this simple formula, the A-weighted L_W sound power level is directly determined using sound pressure measurements.

One of the test procedures described in ISO 3744 is an “Absolute Comparison Test”. The procedure can only be used if the source under test (i.e. air compressor) can be removed from the center of the reference surface. This technique calls for mounting a reference sound source at the center of the reference surface to determine the environmental correction factor that would need to be applied. The environmental correction factor is determined by taking the difference between the measured uncorrected sound power level and the calibrated sound power level determined for the sound source. With any open test site consisting of a hard reflecting plane that is distant from any hard reflecting objects, the environmental correction factor is typically equal to or less than 0.5 dB and is therefore said to be negligible.

DETERMINATION OF SOUND POWER USING ACOUSTIC INTENSITY

ISO 9614-1 describes the measurement of sound power by acquiring sound intensity measurements at discrete points on a grid and ISO 9614-2 describes sound intensity measurements using the scanning technique. It is important when making sound intensity measurements using either standard, to verify if the measurement achieves the desired grade of accuracy. ISO 9614-2 contains three test criterions to test measurement accuracy. A discussion of these criterions follows.

The Pressure-Residual Intensity Index is the arithmetic difference between the pressure and intensity when the probe is oriented in a sound field such that the acoustic intensity is zero. Pressure-Residual Index is denoted in the literature as δ_{pI_o}. The Dynamic Capability Index is determined from the Pressure-Residual Index according to the following equation $L_d = \delta_{pI_o} - K$. In this equation, K is equal to 10 dB for grade 2 accuracy.

The Surface Pressure-Intensity Indicator is defined as the average sound pressure minus the sound power plus ten-logarithm of the total surface area in meters squared. Symbolically the Surface Pressure-Intensity Indicator is written as $F_{pI} = \lfloor L_p \rfloor - L_W + 10\log_{10}(S/S_o)$. For any measurement surface required to be suitable for the determination of the sound power level, the Dynamic Capability Index must be greater than the Surface Pressure-Intensity Indicator ($L_d > F_{pI}$). In all cases tested in this study, this criterion was satisfied.

As a second criterion that must be satisfied, the sum of the negative partial power must be less than or equal to 3 dB. The negative partial power is an energy summation as shown below

$$F_{+/-} = 10\log_{10}\left[\frac{\sum |P_i|}{\sum P_i}\right] dB\ ,$$

where P_i is the time-averaged rate of flow of sound energy through an element. All of the acoustic intensity testing had a negative partial power equal to zero.

A third criterion is to check on the partial-power repeatability. This is done by making two separate scans: one scan in the vertical direction and the other scan in the horizontal direction. The sound power L_{Wi} passing through each segment i is calculated by $L_{Wi} = 10\log_{10}\left[P_i / P_o\right]$. In this equation, P_o is the reference sound power, its value is assumed to be 10^{-12} Watts. The difference in sound power must be ≤ 1.5 dB between one-third octave bands from 500 Hz to 5000 Hz.

DESCRIPTION OF TEST EQUIPMENT

All of the equipment used in the test was Bruel & Kjaer instruments and calibrated at annual intervals. The data acquisition system was a PULSE Type 2816 populated with Type 3022 and 3028 microphone modules and a Type 3017 acoustic intensity module. Pressure microphones used in the test were prepolarized free field microphones Type 4189. The intensity probe was a Type 3595 using ½ inch microphone pair Type 4197. All acoustic intensity measurements were made with a UC5269 12 mm spacer that has an operational frequency range between 250 Hz to 5 kHz. The acoustic calibrator used in conjunction with the intensity probe is a Type 3541.

COMPARISON OF TEST RESULTS

Table 1 presents the results from five different tests. The difference between the highest and lowest sound power level measured according to ISO 3744 is 0.7 dB, which is within the acceptable range of 1.5 dB standard deviation for a grade 2 engineering method. The Max/Min deviation, which is the difference between the sound pressure level for the highest microphone minus the sound pressure level for the lowest microphone, exceeds the number of microphones in two of the three tests. According to the standard, additional microphones should have been added to the reference surface, but the results show that the net sound power was the same when 14 microphones were used.

Absolute Comparison Test was made with a calibrated sound power source. The sound source is rated at 94 dB(A), but was calibrated at an independent test laboratory to be 93.6 dB(A). After completion of noise test with the 14 microphone parallelepiped reference surfaces, the compressor was removed from the center of the microphone array and replaced with the sound source. The sound pressure level we obtained was 94.4 dB(A) when the source was positioned on the reflecting plane and 94.2(A) when the source was positioned 1 meter above the reflecting plane.

Two separate intensity measurements were made using different size reference surfaces and scan times. Both measurements satisfied the three criterions described in 9614-2. The difference in the levels is 1.9 dB, and the difference between the highest sound power level measured using the nine-microphone techniques and the intensity scanning technique is 2.6 dB. These differences are greater than would be expected and illustrate the variability that can be achieved when applying different measurement techniques on the same compressor.

Three manual scans were made for Scan I and Scan II. In total, there were six manual scans. The first and second scans were horizontal and vertical sweeps with the probe facing normal to the reference surface. The third scan was a horizontal sweep with the probe parallel to the reference surface. Table 2 presents the results for the pressure and intensity measured on each side of the compressor. Side 1 is the instrument panel side, moving in the counterclockwise direction looking down from the top, and side 2 is the air intake side. Side 3 is the back side of the compressor, and side 5 is the top of the compressor. Side 5 has a rooftop ventilator that discharges package cooling air that has been heated by an air and oil coolers.

Table 2 shows that the difference in the time average pressure and intensity are within expectations for all the measurements. Pressures measurements made when the probe is pointing normal and parallel to the reference surface are almost equal. A problem identified in the measurements is the intensity did not decrease when the probe was pointing in the parallel position on side 5. The rooftop ventilator is responsible for this behavior.

ISSUES AND CONCERNS

Acoustical enclosures used with air compressors have openings for cooling air to enter and leave the package. It is through these openings that most of the noise escapes from the package. The sound field near these openings is the greatest contributor to the overall noise level. The sound fields near these openings are highly directional. On the discharge side, the air is usually heated and the air flow velocity may vary between 2 to 15 m/sec.

Sound pressure measurements are limited to an air speed of 5 m/sec. Heated airflow in the vicinity of a microphone can alter a microphones acoustical performance. Sound intensity has a greater sensitivity to airflow than sound pressure. Both ISO 9614-1 (paragraph 5.3) and ISO 9614-2 (paragraph 5.3 and Annex C) describe the adverse effects when making measurements near airflow. These standards specify that acoustic intensity measurements should not be made if the air speed exceeds 2 m/sec. The standards also contain cautionary notes on avoiding sound intensity methods where temperatures are significantly greater than the ambient temperature (ISO 9614-2 paragraph 5.4).

The best approach for overcoming this problem is to move the reference surface further away from the compressor discharge. Increasing the size of the reference surface with pressure measurements is easily done with microphone stands; but with intensity measurement, this can become logistically difficult to accomplish.

At greater distances from the compressor, other problems arise due to propagation effects. Factors that complicate the measurement of noise at greater distances between the compressor and the microphone are acoustic directivity, atmospheric refractions in wind and temperature, and the ground effect from the reflecting plane. To clarify some of the issues with acoustic measurements made on a sound pad, a propagation model was developed.

The propagation model assumes spherical spreading, air absorption, and excess ground attenuation. The air absorption coefficients are determined using methods described in American National Standards Institute (ANSI) S1.26-1978 [6]. Excess ground attenuation is the interference of the acoustic rays with the ground. The basic problem can be envisioned as a source near the ground that is radiating sound and a receiver represented as a microphone, 1.5 meters above the ground level. The geometric configuration shown in Figure 3 leads to a grazing angle of ϕ for the reflected acoustic ray. When the direct and reflected waves interact at the receiver position, the two wave fronts are either amplified or attenuated. The exact nature of the interaction is dependent upon the path length of the direct and the reflected rays, the grazing angle ϕ, and the acoustic impedance of the ground. The difference in path lengths between the direct and the reflected sound waves is usually small, but can be of the order of a wavelength. The acoustical properties of the ground are very important in determining the interaction of the reflected ray and the resultant recombination at the receiver position. The algorithms used in the model are based on studies made by Chien and Soroka [7] and then later by Chessell[8] with corrections made by Daigle[9].

The model assumes a spherical wave front emanating from a point source at the center of a sound pad and a sound pad made of concrete. The specific acoustic impedance of the concrete pad can be expressed in terms of the flow resistance factor, which is assumed to be $1x10^6$ cgs rayls. The height of the source (h_s) and the receiver (h_r) are both assumed to be 1.5 meters above the ground plane. The source is an omni-directional broadband point source that has a sound power of 111 dB or a sound pressure at one meter of 100 dB. Results of the model, showing the sound pressure level at the receiver position located 7 meters from the source (d=7 meters), are shown in Figure 4. The sound levels range from a high of 88 dB to a low of 62 dB depending on the frequency. Figure 5 shows contour plots for selected pure tones when the source and receiver positions are at 1.5 meters above the reflecting plane. Plotted are the contours of the un-weighted sound level for frequencies of 250 Hz, 500 Hz, 1 kHz, and 2 kHz tones. These figures illustrate that depending on the receiver position and the frequency, the sound levels do not drop off at a uniform rate as would be expected when the distance between the source and the receiver are increased.

As demonstrated by the computer model, one of the difficulties with making any kind of measurement on a hard reflecting plane, such as a sound pad, is accounting for ground effects. Situations where the microphone is located several meters from the source are most susceptible to this problem. The problem can occur with hemispherical and the parallelepiped reference surfaces, but it is more problematic with the hemispherical reference surface because the distance d between the source and the receiver is often greatest. These effects are known to occur when the sound field is localized to a specific area on the exterior of the compressor package. For example, this problem is known to occur with the tail pipe emission of a diesel driven portable compressor. The tail pipe acts as a point source that can give results similar to those shown in Figure 6 with the overhead microphone. Most electrically driven compressors do not suffer from this problem because the compressor is enclosed in an acoustical enclosure that is lined on the inside with an adhesive type of acoustical foam. Acoustical enclosures tend to distribute the radiant sound preventing ground effects from becoming a problem. But the problem still exists especially with the overhead microphone, as shown in Figure 7. Fortunately, the process of averaging the sound pressure level over all microphone positions reduces this entire effect. Increasing the number of microphones used in the test is one method of decreasing the effects of excess ground attenuation. When excess ground attenuation is observed in the data, adding more microphone positions can help eliminate the problem.

CONCLUSION

Noise labeling of compressors is a very important both to the manufacturers and the customers. Often, the noise of the compressor can be one of the major deciding points to a customer when making a purchase. The compressor that we tested is an air cooled machine that discharges a significant amount of heated air from the package. The opening from the package where the air is discharged produces the greatest sound levels. The overall package sound power level is mainly determined by the measurement of the package discharge sound level. Scanning the package discharge with acoustic intensity can easily produce inaccurate results due to the high flow rates and the heated air that blows across the microphone pair. If compressor manufactures are using acoustic intensity, they need to exercise extreme care when measuring the acoustic intensity level at the package discharge. Perhaps they need to validate their results using sound pressure techniques. This may explain why the compressor we tested was advertised at 74 dB(A) and not 80 dB(A) as tested on our sound pad.

ACKNOWLEDGMENTS

This work could not have been possible without the expert advice of Dr. Steve Sharp and Rob Haseley.

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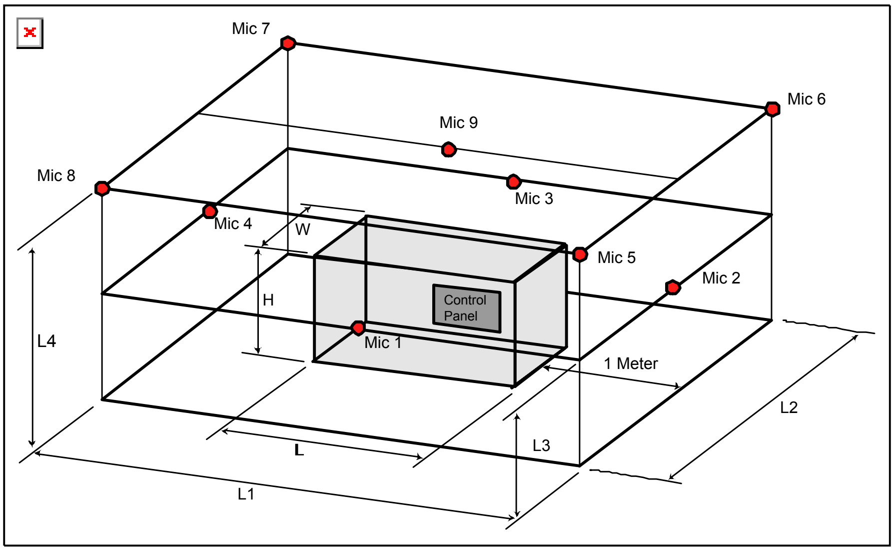

Figure 1. Parallelepiped method for 9 microphone positions.

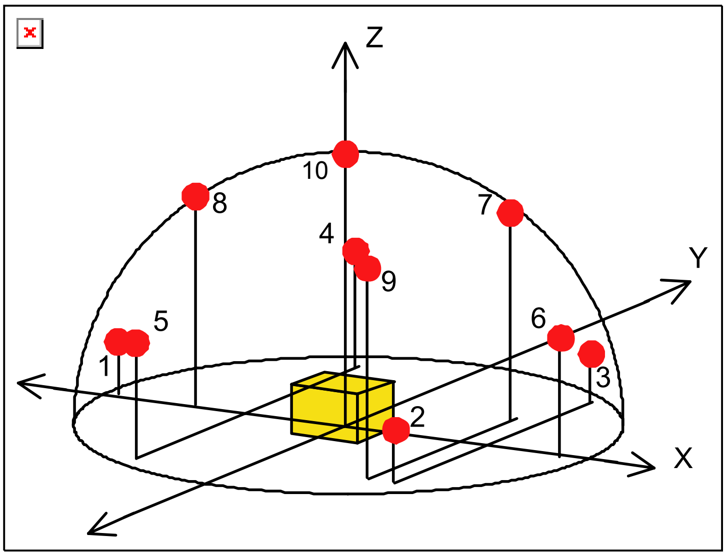

Figure 2. Hemispherical method for 10 microphone positions.

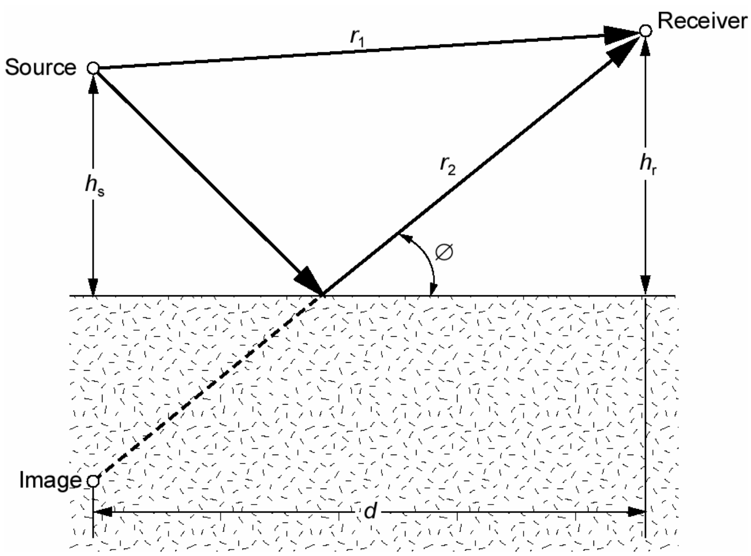

Figure 3. Geometry of source and receiver on sound pad.

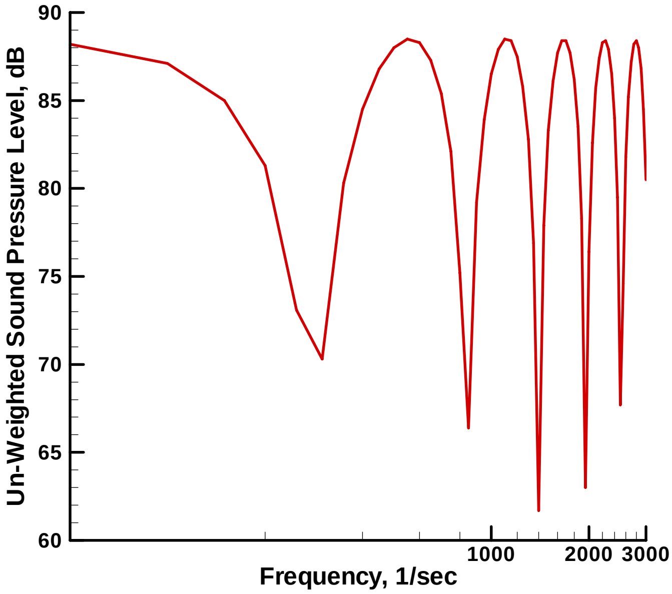

Figure 4. Model results of sound level on sound pad. Source sound power is 111 dB at a height if 1.5 meters, receiver height is 1.5 meters, and distance between source and receiver is 7 meters.

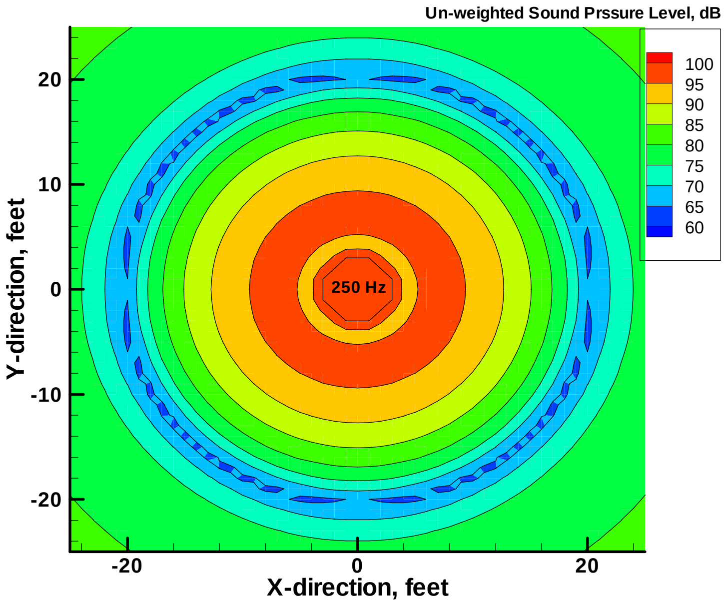

Figure 5A. Unweighted sound pressure map for pure tone, 250 Hz source, at a height of 1.5 meters and receiver contour plane height at 1.5 meters.

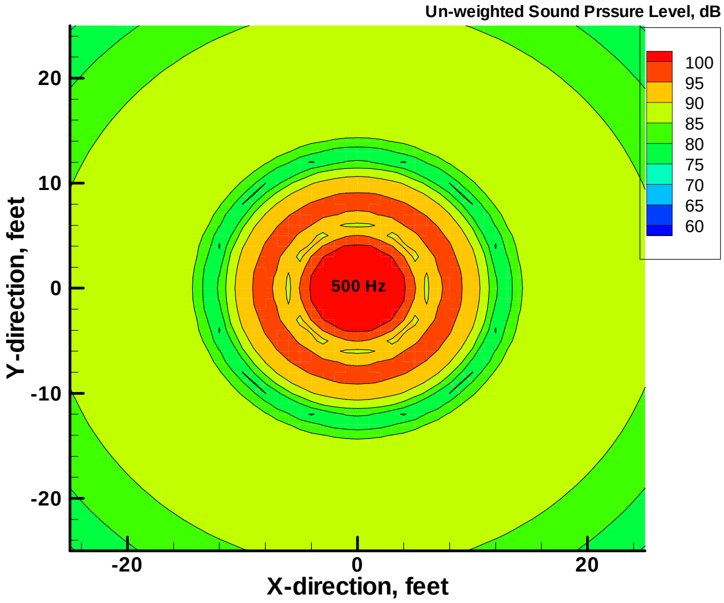

Figure 5B. Unweighted sound pressure map for pure tone, 500 Hz source, at a height of 1.5 meters and receiver contour plane height at 1.5 meters.

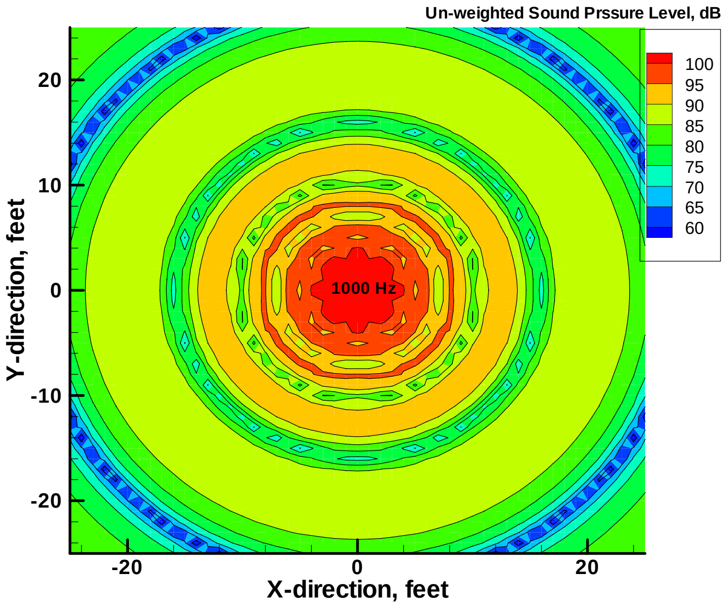

Figure 5C. Unweighted sound pressure map for pure tone, 1000 Hz source, at a height of 1.5 meters and receiver contour plane height at 1.5 meters.

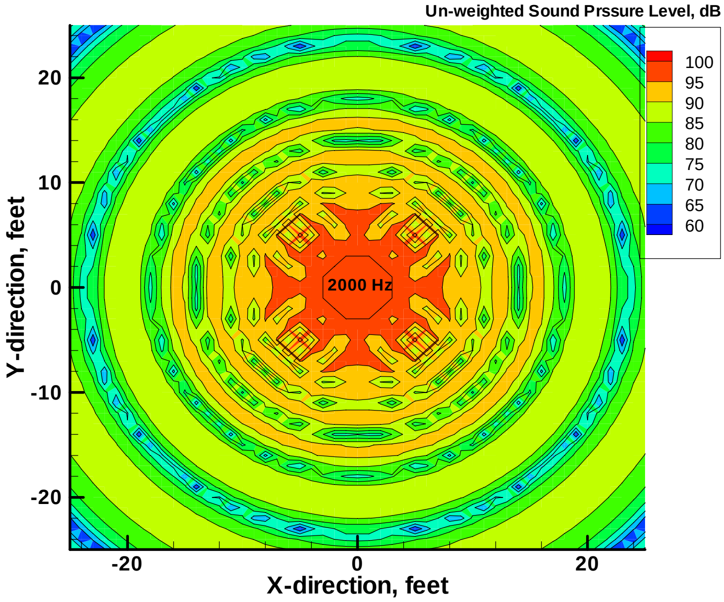

Figure 5D. Unweighted sound pressure map for pure tone, 2000 Hz source, at a height of 1.5 meters and receiver contour plane height at 1.5 meters.

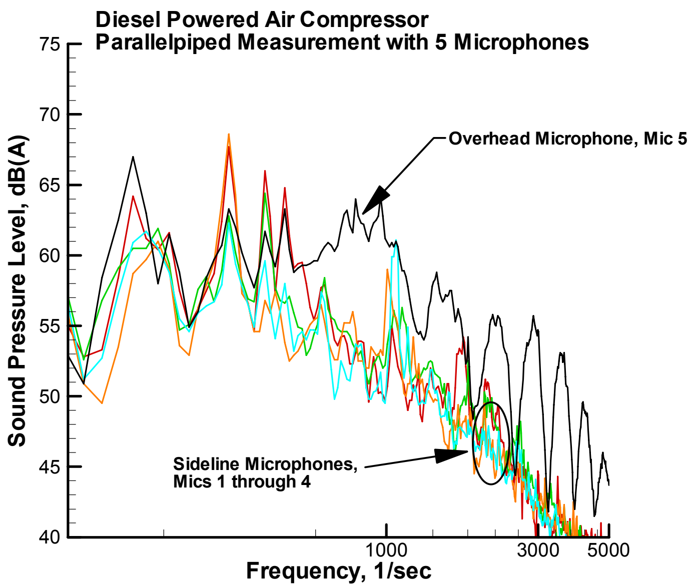

Figure 6. Parallelepiped Measurements for Diesel Driven Air Compressor, r = 7 meters.

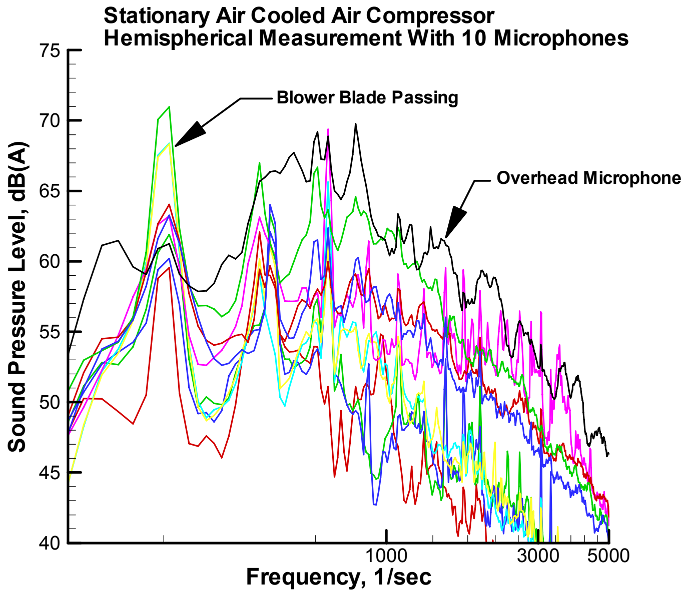

Figure 7. Hemispherical Measurements for Stationary Air Compressor, r = 4 meters.

Table 1. Summary of noise measurements made using five different approaches.

Test Code ISO 3744				
Parallelpiped or Hemisphere	Number of Mics	Max/Min Deviation dB	Measured at 1 Meter From Surface of Compressor dB(A)	Sound Power dB(A)
Parallelpiped	9	13.7	80.6	98.2
Parallelpiped	14	12.3	80.2	97.9
Hemisphere	10	13	79.8	97.5

Test Code ISO 9614-2				
Test	Distance to Measurement Surface meters	Scan time in seconds per side	Sound Level Measured at 1 Meter From Surface of Compressor dB(A)	Sound Power dB(A)
Scan 1	0.5	30	77.9	95.6
Scan 2	0.25	60	79.8	97.5

Table 2. Summary comparison when intensity probe is oriented in sound field normal to reference surface and parallel to reference surface.

		Probe Normal to Surface			Probe Parallel to Surface		
		Pressure dB(A)	Intensity dB(A)	Difference dB	Pressure dB(A)	Intensity dB(A)	Difference dB
Scan I	**Side 1**	80.5	78.3	2.2	81.8	74.2	7.6
	Side 2	82.5	80.4	2.1	83.2	74.5	8.7
	Side 3	79.8	77.8	2	80.6	72.2	8.4
	Side 4	78.2	76.8	1.4	79.5	67.3	12.2
	Side 5	85.8	**83.9**	1.9	86.9	**82.4**	4.5
	Surface Avg.	82.2	80.2	2	83.2	77.1	6.1
Scan II	**Side 1**	81.5	78.9	2.6	81.3	69.5	11.8
	Side 2	85.2	83.3	1.9	85.4	76.8	8.6
	Side 3	81	78.5	2.5	81.5	73.3	8.2
	Side 4	80	78.4	1.6	79.7	67.4	12.3
	Side 5	90.5	**89**	1.5	90.2	**83.9**	6.3
	Surface Avg.	85.2	83.5	1.7	85.1	77.8	7.3
Side 2 - Package Air Intake				Side 5 - Package Air Discharge (rooftop blower)			