OPTIONS FOR CONVERTING SOUND POWER LEVELS TO SOUND PRESSURE LEVELS AT 3 FEET

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Abstract - Active motor sound level limit specifications NEMA MG1-2016 & IEC 60034-9 require that motor manufacturers meet noise levels in terms of sound power levels in decibels. Prior to the last couple of decades, the maximum permissible sound levels were determined based on sound pressure levels typically at three feet or one meter from the motor's surfaces per outdated sound specification IEEE 85-1973. Subsequently, and contrary to what they had done for decades, motor manufacturers may no longer record sound pressure levels, or they may record them at a distance other than 3 feet, or with a measurement surface other than a rectangular box. To accommodate customers that still request noise tests in terms of sound pressure at 3 feet / 1 meter, and also to compare with decades of legacy motor noise test data, two traditional methods and two alternate methods for converting sound power to sound pressure at three feet have been compared to the measured noise test results of ten medium AC motors. One traditional conversion method and one of the two alternate methods yield the closest sound pressure levels compared to the measured values at 3 feet. The half-cylinder conformal surface method and the average distance to each rectilinear surface method underestimate the sound pressure at 3 feet by less than 1 dB on average.

Index Terms — Sound Power Level, Sound Pressure Level, Sound Conversion Method Comparison, Sound Conversion Equations

I. INTRODUCTION

Sound Power Level (SWL) is a measure of the acoustic power emitted from a source of noise, expressed in decibels, as in a 20W home audio speaker or a powerful 50kW radio station. The Sound Pressure Level (SPL) is the pressure disturbance in the atmosphere measured using predefined conditions such as the location of the equipment, the environmental conditions, and the distance of the measurement from the measurement point. SPL is also expressed in decibels. SPL is the value resulting from precisely instrumented and controlled tests that ultimately represent what our ears hear. The SPL is the value that is typically presented by a handheld sound meter.

For more than two decades maximum sound level standards, such as NEMA MG 1-2016 Table 9-1 [1] and IEC 60034-9 Tables 1 & 2 [2], have been based on overall, A-weighted sound power levels (SWLs). Previously, the maximum sound levels were determined based on overall, A-weighted, sound pressure levels (SPLs) at various distances from the motor's surfaces such as 3 feet, or 5 feet or 1 meter per obsolete sound specification IEEE 85-1973 [3]. The traditional methods of converting from overall, average sound pressure levels at 1 meter/3 feet to overall sound power levels or vice versa were to add or subtract the term (10 x log (Area/1m^2) [4] relating to the noise measurement surface area to the overall sound pressure level or the overall sound power level depending on which conversion was being undertaken. The noise measurement surface for a horizontally mounted, electric motor could be a rectangular box (Fig. 1) or a conformal surface (Fig. 2). When mounted horizontally, motors with round frames, such as TEFC motors, a half-cylinder, conformal measurement surface is likely to yield a more accurate calculated result than the more widely used rectilinear box, especially when there are a relatively small number of microphones, such as five, or alternatively stated, just one per rectilinear measurement surface.

The issue involved with using rectilinear surface areas to convert from the average sound pressure level at 3 feet to average sound power level or vice versa is that one microphone set up at shaft height in the "middle" of the rectilinear surface is unlikely to capture the average sound pressure level for the whole surface thereby the resultant average, overall sound power level is overestimated by up to a few decibels when sound pressure level is measured and conversely the sound pressure level at 3 feet is underestimated by up to a few decibels when calculated from the overall sound power level of the motor.

As will be shown later in this paper, besides the conformal surface area method yielding relatively accurate calculated average sound pressure level results to what has been measured during the past several decades, there are two other independent calculation methods that are possible due to the ISO 3744/ANSI S12.54 [7] defined origin of sound from a sound power source.

II. SWL-SPL CONVERSION METHODS

A. Method 1 – Rectilinear Surface Area

For horizontally mounted motors, the traditional noise measurement surfaces for converting sound power to sound pressure at 3 feet or vice versa are rectilinear boxes [5] or conformal surfaces [6]. As shown in Fig. 1, the rectilinear box has a width and length that extends 3 feet or 1 meter beyond each side of the motor, plus a height (h_s) that is 3 feet or 1 meter above the motor.

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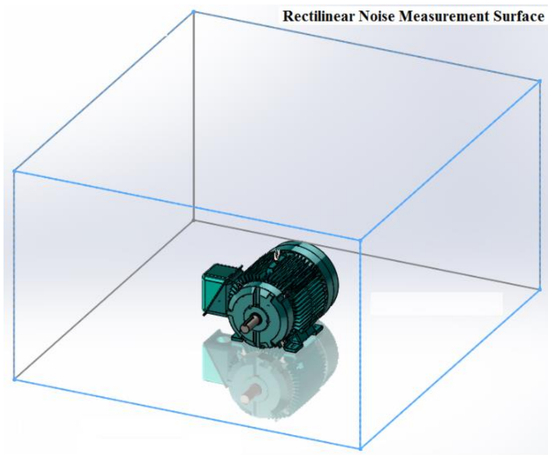

Fig. 1 Rectilinear Noise Measurement Surface

The surface area of the rectilinear box is:

$$Area = 2(L_s h_s + w_s h_s) + (L_s w_s) \quad (1)$$

where

w_s	rectilinear measurement surface width;
L_s	rectilinear measurement surface length;
h_s	rectilinear measurement surface height.

The conversion from sound power to sound pressure level is:

$$SPL = SWL - 10 \log (Area/1m^2) \quad (2)$$

B. Method 2 – Conformal Surface Area

For a horizontally mounted, round frame motor, a half-cylinder, conformal noise measurement surface is as shown in Figure 2. The radius of the half-cylinder is 3 feet or 1 meter greater that the motor's radius. The length of the measurement surface is also 3 feet longer or 1 meter longer on both ends compared to the length of the motor. An open, 4-sided rectilinear box up to shaft height is also part of the noise measurement surface.

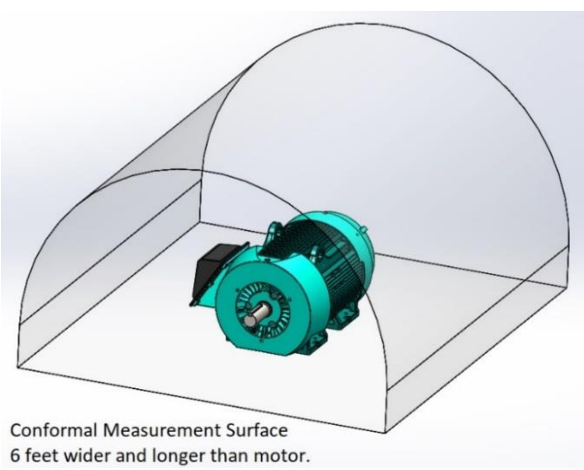

Fig. 2 Conformal Noise Measurement Surface

The half-cylinder, conformal measurement surface area formula is:

$$Area = \pi D L_s/2 + \pi D^2/4 + 2h_{sh}(L_s + w_s) \quad (3)$$

where

D	diameter of conformal measurement surface;
h_{sh}	motor shaft height.

C. Method 3 – Distance from the Origin to the Shaft Height, Rectilinear Surface Center

ANSI S12.54 and ISO 3744 [7] are the noise test procedure standards designated by NEMA MG 1-2016 and IEC 60034-9. These test procedure standards put the origin of the motor at the bottom, center of the motor, as shown in Fig. 3.

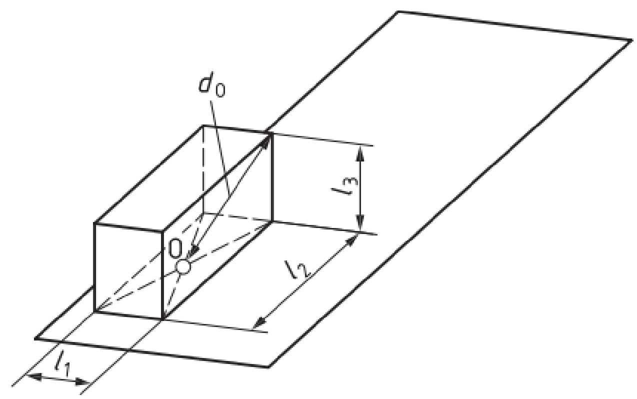

Fig. 3 Noise Origin Relative to Motor Dimensions

Where l_1, l_2 and l_3 are the width, length, and height dimensions of the motor respectively. The d_0 dimension is defined by standards ANSI S12.54 and ISO 3744 as the motor's characteristic dimension. It is not used in this paper.

Since sound is considered by standards ISO 3744 and ANSI S12.54 to propagate from a point source, the surface of advancing sound from the origin is a hemisphere. Thus, the area in the SWL-to-SPL conversion equation is the surface area of a hemisphere. The formula for the SPL at 3 feet (1 meter) is derived from (1), as follows.

$$SPL = SWL - 10 \log \left(\frac{Area}{m^2}\right)$$

$$= SWL - 10 \log (2\pi r^2/m^2) \quad (4)$$

which reduces to:

$$SPL = SWL - (20 \log(r) + 7.98) \quad (5)\ [8]$$

where

r	distance from the origin to the measurement location.

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The general equation for averaging SPLs in decibels is:

$$SPL_{avg} = 10 \log \left(\frac{1}{n} \cdot \sum_{i=1}^{n} 10^{SPL_i/10} \right) \tag{6}$$

where

n number of SPLs to be averaged.

As shown in Fig. 4, given that a rectilinear noise measurement box has 5 surfaces and that the two sides are equal from a calculation standpoint as are the two ends, the overall SPL average formula reduces to:

$$SPL_{avg} = 10 \log \{\frac{1}{5} [2 (10^{SPL_s} + 10^{SPL_e}) + 10^{SPL_t}]\} \tag{7}$$

where

SPL_s SPL determined using (5) with r as the distance from the origin to the shaft height center of the side measurement surfaces;

SPL_e SPL determined using (5) with r as the distance from the origin to the shaft height center of the end measurement surfaces;

SPL_t SPL determined using (5) with r as the distance from the origin to the center of the top measurement surface height.

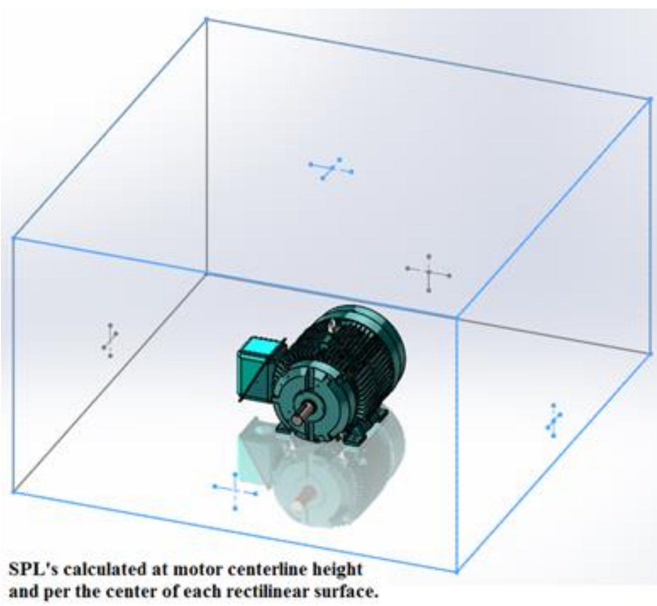

Fig. 4 Shaft Height Center of Each Noise Measurement Surface

D. Method 4 – Average Distance to Each Rectilinear Surface

Method 4 uses (5) to calculate the average SPL of each rectilinear surface after the theoretical average distance to rectilinear surface is determined. Considering that (5) utilizes the distance from the origin to any measurement point of interest to determine the SPL at that point, it follows that the average distance to each of the five rectilinear measurement surfaces provides the key to determining the average SPL of those surfaces. Thus, for Method 4, r in (5) is the average distance to the surface.

How is the average distance from the motor's origin to each of the rectilinear surfaces found? One way to determine the average distance from the bottom, center of the motor to any rectilinear surface is to divide the measurement surface into two areas such that all the points inside the dividing line between the two subsurface areas have a smaller distance to the origin than the average distance while all the points outside the dividing line have a greater distance to the origin than the average distance. As displayed by equal length vectors in Fig. 5, to be equidistance from the origin the points forming the dividing line between the two equal area subsurfaces must be on an arc.

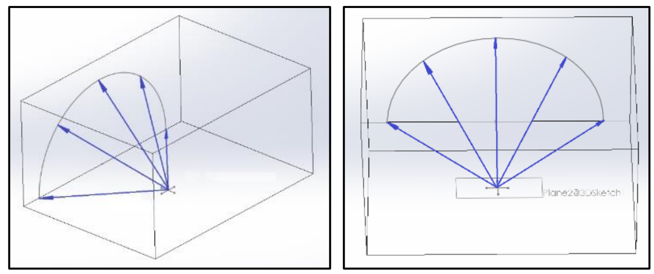

Fig. 5 Equal Distances from Origin to Measurement Surface

In accordance with (5) all points outside the arc have a longer distance and a lower SPL than the average distance to the surface and the average SPL, while all points inside the arc have a shorter distance and a higher SPL than the average distance from the origin to the surface and average SPL. As shown in Fig. 6, for the vertical surfaces the arc is a semicircle. For the top measurement surface the arc is a full circle.

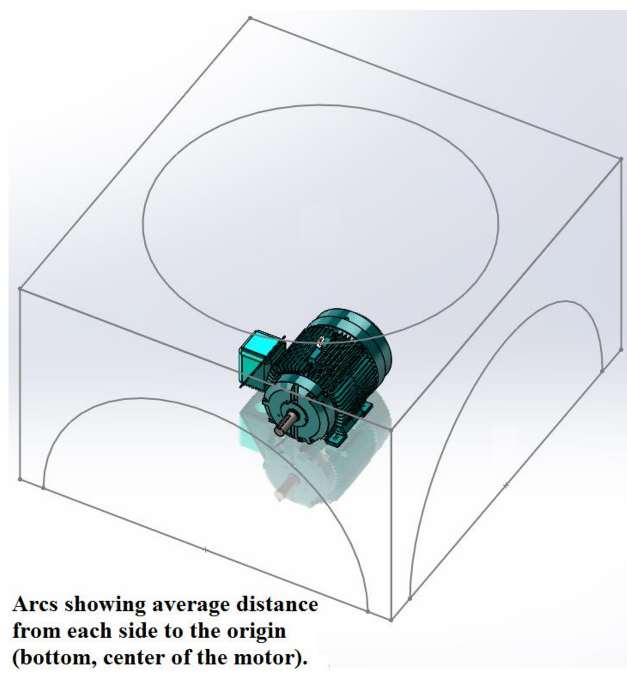

Fig. 6 Average Distance to Surface Leads to the Average SPL

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The equations for the rectilinear side surfaces are:

$$r_{arc.t} = \sqrt{L_s h_s/\pi} \quad (8)$$

$$r_s = \sqrt{r_{arc.s}{}^2 + (w_s/2)^2} \quad (9)$$

where

- $r_{arc.s}$ radius of arc on the side measurement surface;
- r_s distance from the origin to the average SPL arc on the side measurement surface.

The equations for the noise measurement surface ends are:

$$r_{arc.e} = \sqrt{w_s h_s/\pi} \quad (10)$$

$$r_e = \sqrt{(r_{arc.e}{}^2 + (L_s/2)^2} \quad (11)$$

where

- $r_{arc.e}$ radius of arc on the side measurement surface;
- r_e distance from the origin to the average SPL arc on the end measurement surface.

The equation to determine the average to the top measurement surface is:

$$r_{arc.t} = \sqrt{w_s L_s/2\pi} \quad (12)$$

$$r_t = \sqrt{(r_{arc.t}{}^2 + h_s{}^2} \quad (13)$$

where

- $r_{arc.t}$ radius of arc on the side measurement surface;
- r_t distance from the origin to the average SPL arc on the side measurement surface.

After determining the average distance via (8-13), and SPL for each of the five measurement surfaces per (5), the overall SPL is calculated with (7).

III. TEST SET-UP AND EQUIPMENT

Noise tests were conducted in a hemi-anechoic chamber located in Greenville, South Carolina. For the measured portion of the comparison between the measured vs. calculated methods 1-4, a single channel, handheld sound level meter with integral preamplifier, microphone, software and display (shown in Fig. 7) was utilized to record the overall SPLs at 3 feet from each of 5 motor surfaces, as shown in Fig. 4.

Before moving onto the calculated portion of the comparison it is important to acknowledge that there are two methods of obtaining overall SWLs. One method is to record sound intensity levels (SILs), i.e., sound power per unit area, using a sound intensity probe. Like measuring SPL, SIL is measured at several locations that are representative of the average sound level of the surrounding area, then the overall, average sound power is determined by first multiplying the SILs by the areas they represent to obtain the average SWL for that area and then logarithmically averaging the SWLs from all the measured locations/areas. The formula for overall SWL using SILs is shown in (14).

$$SWL_{avg} = 10 \cdot \log\left(\frac{1}{n} \cdot \sum_{i=1}^{n} 10^{SIL_i \cdot Area_i/10}\right) \quad (14)$$

Fig. 7 Handheld Sound Meter

The second method of determining overall SWL is to measure SPLs at a convenient distance using a recommended or approved measurement surface. Noise test procedure standards ISO 3744 and ANSI S12.54 allow horizontally mounted small and medium size motors to be tested using a hemispherical surface with the radius up to 16 meters. Working within these parameters and the available hemi-anechoic chamber dimensions a convenient radius for the author to permanently position 10 microphones with which to record the sound pressure of small and medium-size motors is 9 feet (2.743 meters).

Moving onto the calculated portion of the comparison, sound pressure was recorded using 10 microphones positioned on a hemispherical measurement surface with radius equal to 2.743 m (9 ft) and in accordance with locations provided by ANSI S12.54/ISO 3744 (see Appendix A). Sound power levels were then calculated using (15), as shown below. From the calculated SWLs, SPLs at 3 feet were calculated using the four aforementioned SWL-SPL conversion methods via (1) to (5) and (7) to (13).

$$SWL = SPL + 10 \cdot \log\left(\frac{Area}{1\,m^2}\right) = SPL + 16.75\,\text{dB} \quad (15)$$

where

$$Area = 2\pi\,(2.7432\,m)^2 = 47.28 \cdot m^2$$

IV. TEST RESULTS & ANALYSIS

Ten medium AC motors were sound tested. The results are shown below in Table I. To make easier the comparison of conversion methods 1-4 with that of the measured values, Table 2 displays the difference between the calculated and measured values for each of the 10 motors. Table 2 also presents the average calculated difference from the measured values for each of the four SWL-SPL conversion methods.

As shown in Table 2, on average SWL-SPL conversion

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Method 1 (rectilinear surface area) underestimates the SPL at 3 feet by a minimum of close to ½ dB and at maximum almost 2 dB. A closer calculated approximation of SPL at 3 feet is obtained by utilizing Method 2 (conformal surface area) whereby the average difference is near 1/3 dB and the maximum and minimum differences with measured values are 0.20 dB and 1.00 dB respectively. Those differences are underestimated values and there is one overestimated value of near ½ dB with the 150HP, NEMA 445TNZ frame motor.

TABLE I
SOUND PRESSURE LEVELS – MEASURED VS. CALCULATED

	NEMA Frame Size	Measured SPL @ 3ft	Calculated - Overall SPL @ 3 feet in dB(A)			
			Method	Method	Method	Method
		0	1	2	3	4
1	445TNZ[1]	79.29	78.83	79.78	81.72	79.60
2	405TSD[2] (S.N.'s 2002-2009)	78.10	76.95	77.90	79.67	77.52
3		78.30	76.97	77.92	79.69	77.54
4		78.03	76.73	77.68	79.45	77.30
5		78.53	76.99	77.94	79.71	77.56
6		78.02	76.56	77.51	79.28	77.13
7		78.02	77.04	77.99	79.76	77.61
8		78.49	76.93	77.88	79.65	77.50
9		78.21	76.92	77.87	79.64	77.49
10	365T[3]	67.44	65.50	66.44	68.41	66.25

[1] 150HP, 2 pole, 60 Hz, TEFC

[2] 100HP, 2 pole, 60 Hz, TEFC

[3] 75HP, 4 pole, 60 Hz, TEFC

TABLE 2

SOUND PRESSURE LEVELS – DISPLAYING THE DIFFERENCE BETWEEN MEASURED AND CALCULATED VALUES

	NEMA Frame Size	Measured SPL @ 3ft	Difference - Overall SPL @ 3 feet in dB(A)			
			Method	Method	Method	Method
		0	1	2	3	4
1	445TNZ[1]	79.29	-0.46	0.49	2.43	0.31
2	405TSD[2] (S.N.'s 2002-2009)	78.10	-1.15	-0.20	1.57	-0.58
3		78.30	-1.33	-0.38	1.39	-0.76
4		78.03	-1.30	-0.35	1.42	-0.73
5		78.53	-1.54	-0.59	1.18	-0.97
6		78.02	-1.46	-0.51	1.26	-0.89
7		78.02	-0.98	-0.03	1.74	-0.41
8		78.49	-1.56	-0.61	1.16	-0.99
9		78.21	-1.29	-0.34	1.43	-0.72
10	365T[3]	67.44	-1.94	-1.00	0.97	-1.19
	Average Difference		-1.30	-0.35	1.46	-0.69

The least accurate, but also most conservative SWL-to-SPL conversion method, is the one that if the theory were correct would be the most accurate method. Method 3 attempts to calculate the SPL at 3 feet in exactly the same locations as where the SPL's were measured using a handheld sound meter. The result is that Method 3 overestimates the SPL at 3 feet by near 1 dB to over 2.4 dB with the average rounding out to approximately 1-1/2 dB. The question as to why the measured and calculated values are not the same since they were both based on the same locations relative to the motor-under-test most likely is explained by the fact that the sound origin and the motor origin are two different locations. According to sound testing standards ISO 3744 and ANSI S12.54, the motor origin and sound origin is at the bottom, center of the motor. However, for an idling, totally enclosed, fan cooled (TEFC) motor the origin of the motor's dominant sound source is the opposite drive end cooling fan. For very small TEFC motors the cooling fan and the motor origin are insignificantly just a few inches apart, but for medium-size AC motors the difference grows to 1-2 feet apart which is a much more significant figure relative to the 3 feet measurement distance from each motor surface.

Method 4, calculating the average distance to each noise measurement surface, is worthy of consideration. The minimum and maximum differences between measured and calculated values are 0.3 dB and 1.2 dB with the average difference of 10 motors being 0.7 dB. Since the measured SPL @ 3 feet values are only measured in one location per each of the 5 rectilinear surfaces, it is not likely that the measured values achieve the ideal of the average SPL for the measurement surface. Although the half-cylinder, conformal measurement surface (Method 2) appears to approximate decades of measured data more accurately than calculating SPL based on the average distance to each measurement surface (Method 4), with the measured data taken only at the shaft-height, "middle" of each rectilinear surface, it is beyond the scope of this paper to ascertain which method most closely represents the actual overall SPL at 3 feet.

Three of the four SWL-SPL conversion methods appear to under-estimate the SPL at 3 feet compared to measured values. Underestimating the SPL can mean that a customer or customer's representative that sound tests the motor is likely to measure a higher overall SPL which can result in an unhappy customer and/or possibly a lost customer. For motor manufacturers that prefer to present their customers with a conservative SPL at 3 feet or 1 meter, Method 3 is the best option. For OEM's that want to quote a SPL value that is close to a measured value, Methods 2 or 4 are the best options.

V. CONCLUSION

Given that the World's most referred to noise limit standards are NEMA MG 1-2016 and IEC-60034-9, and that these standards specify noise limits in SWLs, for those customers who are accustomed to noise limits in terms of SPLs at 3 feet or 1 meter it is imperative to have a relatively accurate means of calculating the SPL at 3 feet/1 meter particularly for motor manufacturers that no longer measure SPLs, or for those who measure SPLs at a different distance or on a different measurement surface than that of a rectangular box surface.

Four SWL-to-SPL calculation methods have been presented and the results have been compared to noise measurements recorded using a handheld sound meter 3 feet from 5 motor surfaces of 10 horizontally, foot-mounted, medium-size AC

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TEFC motors. The two calculation methods that provide the closest results to those that are measured are Method 2 which uses a half-cylinder, conformal measurement surface as the means to convert SWLs to SPLs at 3 feet and Method 4 which determines the theoretical average SPL of each of 5 rectilinear surfaces, then logarithmically averages the SPLs from the 5 rectilinear surfaces. Those two methods underestimate the SPL at 3 feet by less than 1 dB on average but could possibly provide a more accurate overall SPL considering the measured values using 1 microphone location per rectilinear surface most likely did not capture exactly the average SPL for the whole surface. Perhaps a future paper could explore the inaccuracy of using just one microphone location per rectilinear surface at shaft height as the average SPL for the whole rectilinear surface.

Commonly used SWL-to-SPL conversion method rectangular box (Method 1) underestimates the SPL at 3 feet by an average of 1.3 dB, thereby presenting the situation whereby a motor customer could unhappily miss the noise requirement of their customer, the end-user. Theoretically Method 3 calculates the SPL level at the exact, same location where the handheld sound meter recorded the SPL. Although this method is the most conservative for medium AC, TEFC motors, it is also the least accurate, most likely because the source of sound for calculation per noise test standards ISO 3744/ANSI S12.54 (bottom, center of the motor) differs from the actual source of sound (opposite drive end cooling fan).

VI. NOMENCLATURE

SPL	Sound Pressure Level (dB).
SWL	Sound Power Level (dB).
SIL	Sound Intensity Level (dB).
SPL_{all}	Overall sound pressure level (dB).
SPL_{side}	Average SPL of rectilinear side surfaces (m).
SPL_{end}	Average SPL of rectilinear end surfaces (m).
SPL_{top}	Average SPL of rectilinear top surface (m).
l_1	Motor width (m).
l_2	Motor length (m).
l_3	Motor height (m).
w_s	Rectilinear measurement surface width (m).
L_s	Rectilinear measurement surface length (m).
h_s	Rectilinear measurement surface height (m).
D	Diameter of conformal measurement surface (m).
h_{sh}	Motor shaft height (m).
r	Distance - motor origin to measurement location (m).
r_s	Average distance - motor origin to rectilinear side measurement surfaces (m).
r_e	Average distance - motor origin to rectilinear end measurement surfaces (m).
r_t	Average distance - motor origin to rectilinear top measurement surface (m).
$r_{arc.s}$	Arc radius – equates rectilinear side measurement surface areas inside and outside the radius (m).
$r_{arc.e}$	Arc radius – equates rectilinear end measurement surface areas inside and outside the radius (m).
$r_{arc.t}$	Arc radius – equates rectilinear top measurement surface areas inside and outside the radius (m).

VII. ACKNOWLEDGEMENTS

Bill Martin and Tyler Womack performed the noise tests of the ten motors used for comparison in this paper.

VIII. REFERENCES

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VITAE

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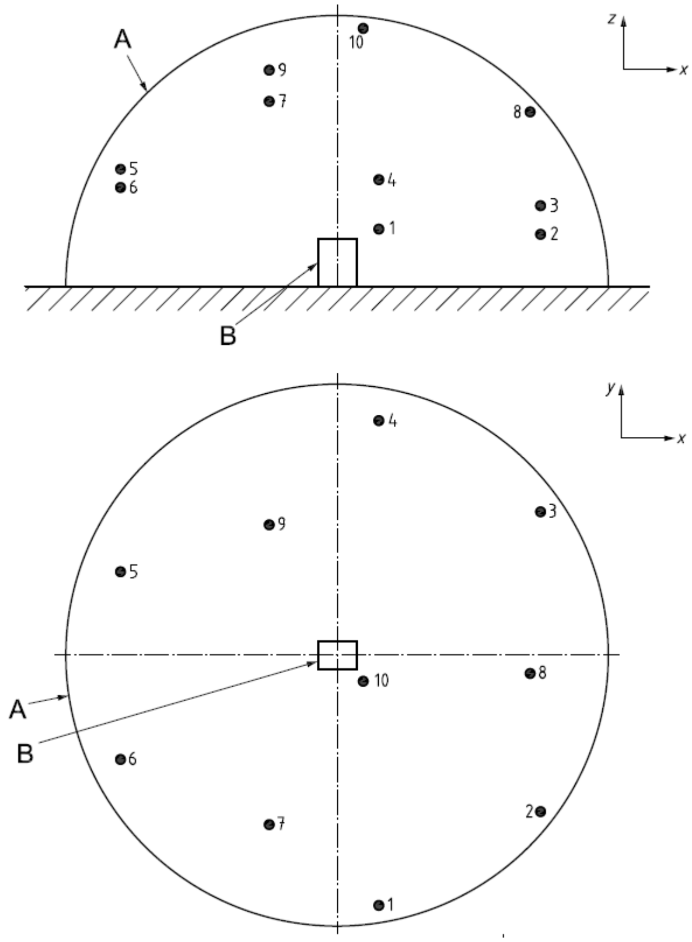
APPENDIX A

ANSI/ASA S12.54-2011 / ISO 3744:2010 Preferred Microphone Locations



Key

● key microphone positions (1, 2, 3, 4, 5, 6, 7, 8, 9, 10)
A measurement surface B reference box

Figure B.1 — Preferred microphone positions on the hemispherical measurement surface for all noise sources
(The co-ordinates of the positions are given in Table B.1)

Table B.1 — Preferred microphone positions for all noise sources

Position number	x/r	y/r	z/r
1	0.16	− 0.96	0.22
2	0.78	− 0.60	0.20
3	0.78	0.55	0.31
4	0.16	0.90	0.41
5	− 0.83	0.32	0.45
6	− 0.83	− 0.40	0.38
7	− 0.26	− 0.65	0.71
8	0.74	− 0.07	0.67
9	− 0.26	0.50	0.83
10	0.10	− 0.10	0.99

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