Noise in Induction Motors—Causes and Treatments

William R. Finley, *Member, IEEE*

Abstract—**In order to reduce the overall noise level around an induction motor effectively, it is first necessary to understand the motor's many noise sources and how noise is transmitted from the motor. In addition, it must be understood how noise is additive and how the surrounding area will affect the overall noise level. Determining the noise level of a fully loaded motor is especially difficult when the ambient noise is louder than the motor. However, it is possible to estimate when the noise source and associated frequencies are understood. Only then can the proper recommendation be made as to what type of noise treatment, if any, to apply to the motor. Time and effort is better spent treating the equipment that is the primary source of the noise.**

INTRODUCTION

THERE ARE three sections to this paper. Section I identifies causes and frequencies of windage and magnetic noise in an induction motor. Specific problems that are unique to various motors are also identified. In Section II, a testing procedure is established that can be followed to determine the full-load noise level of an induction motor. Also included is a testing procedure to determine the nature and origin of the noise so that it can be treated in the proper manner. Section III discusses the most effective methods of reducing motor noise levels in the field and at the factory.

I. CAUSES AND FREQUENCIES OF NOISE IN AN INDUCTION MOTOR

A. Windage Noise

Windage noise is generated by the interaction of the moving parts of the rotor with the cooling air that passes through the motor. Noise is also generated by the interaction of the moving air with stationary parts of the motor. Windage noise is airborne and will not produce vibration of the yoke as does structure-borne magnetically generated noise (see Figs. 1 and 2). The primary sources of air flow and windage noise in an induction motor are the fans and the rotor bars in the vents areas and at the rotor ends.

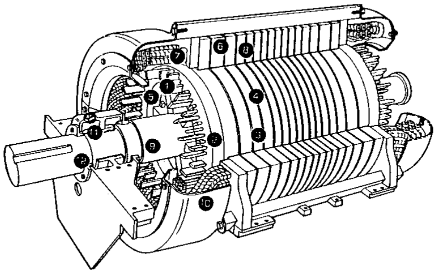

Fig. 1. View of a typical open motor that has the bars extended to act as fans.

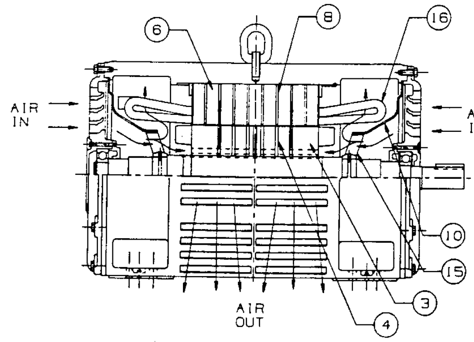

Fig. 2. Air-flow pattern with fans forcing air through rotor.

Open Motors: These have a free exchange of internal and external air as shown in Figs. 1 and 2. The numbers on the figure refer to the parts of the motor: 1) Extended rotor bars, 2) rotor end rings, 3) rotor laminations, 4) rotor vents, 5) rotor spider, 6) stator laminations, 7) stator winding, 8) stator vents, 9) rotor shaft, 10) air deflector, 11) bearings, 12) labyrinth seal, 13) air in, 14) air out, 15) rotor fans, 16) stator coils, 17) core and enclosure.

The two internal fans or extended bars draw in ambient air from each end of the motor. This air cools the coil ends of the stator winding. On vented rotors the rotor bars act like fans and draw ambient air into the motor and through the a xial and radial vents in the rotor. This air is then blown through radial vents in the stator. It then mixes with the air coming through the coil ends and is exhausted from the motor. Exiting with the air out of the motor is any airborne noise generated inside the motor.

On some open two-pole motors, the rotor fans assist in forcing the air simultaneously through the rotor and coil ends. This method of cooling is more efficient because it forces more air through the rotor and stator where the majority of the losses are generated and the cooling air is needed. This type of fan design will also generate less noise and lower windage losses. However, it is more costly to install these separately mounted fans (see Fig. 2).

Totally Enclosed Fan-Cooled Motors (TEFC): A fin-cooled motor has an external fan that blows air over the

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The author is with Siemens Energy and Automation, Inc., Norwood, OH 45212.

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external fins, whereas on a totally enclosed air to air-cooled motor (TEAAC), an external fan is used to blow air through tubes in the air to air heat exchanger as shown in Fig. 3. There is little concern with any internally generated windage noise. No exchange of internal and external air takes place; therefore, very little noise can escape the motor enclosure. The main source of windage noise on a TEFC motor is the external fan.

B. Frequency of Windage Noise

The frequency of windage noise is equal to the passing frequency of the fan blades or rotor bars. The passing frequency is the frequency at which the bars or fan blades pass by a fixed reference point. The passing frequency in Hertz is calculated by the following equations:

$$\text{Passing frequency of fan blades} = \frac{(\text{no. of fan blades})\ \text{r/min}}{60} \tag{1}$$

$$\text{Passing frequency of rotor bars} = \frac{(\text{no. of bars})\ \text{r/min}}{60} \tag{2}$$

where r/min = revolutions per minute of rotor.

The noise generated is virtually the same at full load and no load since there is little change in rotational speed. Table I shows typical passing frequencies for induction motors.

Frequencies may vary with manufacturers and machine size. It is important to note that the passing frequency and noise for the rotor bars are at a higher and more irritating frequency than that of the fans. When correcting for A weighting, which takes into account the sensitivity of the human ear to various frequencies, noise levels at the above fan frequencies would be reduced by 3-16 dB, whereas noise levels at the above rotor-bar frequencies would not be reduced at all, and in the 2000-Hz band levels would be increased by 1 dB. In general, the high levels of windage noise on an open motor will come from the rotor bar fan action, not from the fans.

C. Magnetic Noise

Magnetic noise should be minimized in the original design as it is extremely difficult to reduce in an existing motor. Magnetic noise is primarily structure borne, and cannot be reduced by internal sound lining. Structure-borne noise results from the vibration of the stator core or teeth. There are no practical ways of isolating the stator core laminations from the enclosure. Therefore, this noise is transmitted out of the motor by the enclosure structure and then becomes airborne from the vibration of the outer surface.

Constant-Level Magnetic Noise: This is a result of the forces and vibration that are generated by the interaction of the fundamental magnetic flux wave with the rotating magnetic parts of the rotor. This noise does not change in magnitude with load but can be minimized by the proper rotor and stator slot combination. Many rules for the proper slot combination were established years ago by Kron [1] and motor manufacturers have added to these rules over the years. It has been proven that if these rules are followed, constant-level magnetic noise will not be a problem. In addition, this noise exists at no load, which makes it easy to detect during a routine factory test. A new rotor with a change in slot quantity would be required to reduce the noise.

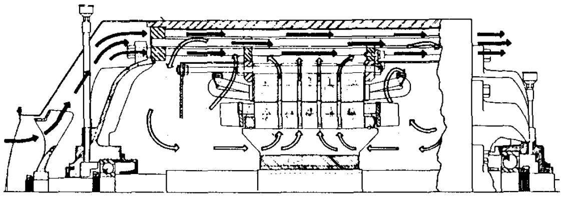


Fig. 3. View of totally enclosed motor with air-to-air heat exchanger (TEAAC). ⇒ Internal air. → External air.

TABLE I
TYPICAL PASSING OR FORCING FREQUENCIES (HERTZ)

Pole	Fan	Rotor Bars
2	300-540	2340-3060
4	210-510	1380-1740
6	180-340	1120-1380
8	135-255	870-1035

Load-Related Magnetic Noise: This is generated when current is induced into the rotor bars under an increasing load. The electrical current in the bars creates a magnetic field around the bars that applies an attracting force on the stator teeth. These radial and tangential forces, which are applied to the stator teeth, create vibration and noise (Fig. 4).

The forces applied to the stator teeth are not evenly distributed to every tooth at any instant in time; they are applied with different magnitudes at different teeth, depending on the relative rotor- and stator-tooth location. This results in force waves over the stator circumference that will produce flexural modes m of vibration, as shown in Fig. 5.

The mode shape is a result of the difference between the number of rotor and stator slots as shown in (3). If the resonant frequency of the core is close to the forcing frequency, a high level of magnetic noise will result. The lower modes of vibration may produce resonant frequencies that are close to the forcing frequencies.

$$m = (N_s - N_r) +/- KP \tag{3}$$

where

N_s number of stator slots
N_r number of rotor slots
P number of poles
K all integers 0, 1, 2, 3, etc.

To understand the resonant frequency of the core at a mode of vibration, the core can be represented as a beam, which is simply supported on both ends and flexes about the ends due to forces applied on the beam. The length of the beam is equal to the circumferential length of the mean diameter of the stator core for one-half the mode wave length (see Fig. 6) [2].

$$f_0 = \frac{36\,700\, m(m^2 - 1)h}{D_s^2\left[R(m^2 + 1)\right]^{1/2}} \tag{4}$$

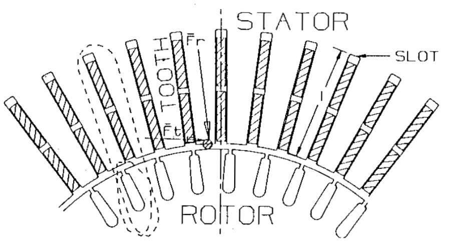


Fig. 4. Magnetic field around rotor bar and resulting forces.

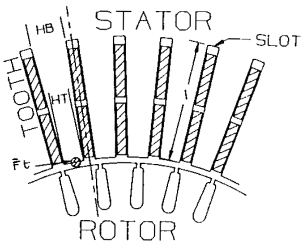
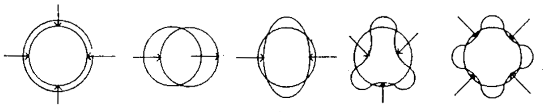
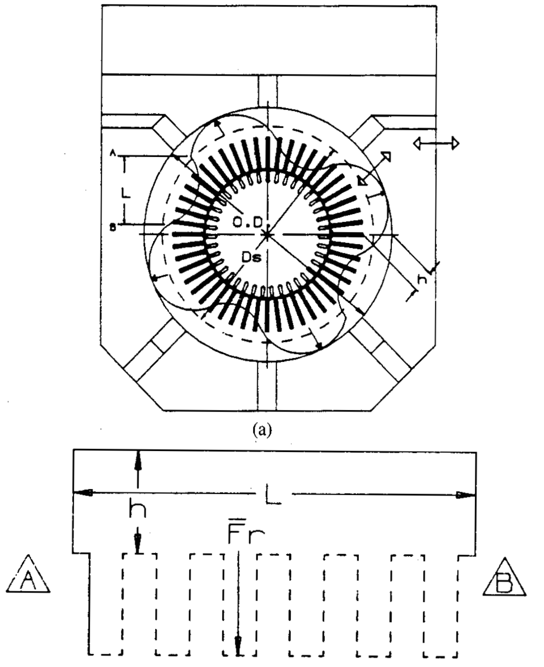


Fig. 7. View of tooth and forces.



(a) (b) (c) (d) (e)

Fig. 5. Mode shapes: (a) $m = 0$; (b) $m = 1$; (c) $m = 2$; (d) $m = 3$; (e) $m = 4$.



(a)

(b)

Fig. 6. (a) Fourth mode of vibration and (b) linear representation of core for a one-half wavelength of force.

where

h	depth of stator core behind slot in inches
R	$\frac{\text{weight of core plus teeth}}{\text{weight of core}}$
D_s	O.D. − h in inches
m	mode of vibration.

Fig. 6(b) is a linear representation of the stator core for one-half a wave length of the fourth mode force wave shown in Fig. 6(a). Points A and B are points of zero displacement about which the beam is flexing. It is the resonant frequency of this beam length that is of concern and must not coincide with the frequencies of the forces being applied:

$$L = \frac{3.14 D_s}{2m} = \frac{3.14 D_s}{2 \times 4}.$$

The frequency of stator tooth resonance is also a concern. A resonant condition in the tooth can be excited by the tangential forces applied to the teeth. The tooth is a cantilever beam supported at the root by the core. The resonant frequency of the cantilever beam as calculated in (5) is a function of the beam length and width. It is normally preferred to keep the resonant frequency of the tooth above the forcing frequencies. A longer and narrower beam will produce a lower resonant frequency. Therefore, it is necessary to limit the stator slot depth and width [7], [9].

$$F_{0(\text{tooth})} = \frac{F_{0(\text{Rect})} X_{(\text{Rect})}^{1/2}}{X_{(\text{Trap})}^{1/2}} = \frac{32825\, HB\left[1.5(HT + HB)\right]^{1/2}}{l^2\left[2HT + HB\right]^{1/2}} \tag{5}$$

where

$$F_{0(\text{Rect})} = \frac{32825\, HB}{l^2}$$

is the natural frequency of an iron rectangular cantilever beam.

$$\frac{X_{(\text{Rect})}}{X_{(\text{Trap})}} = \frac{1.5(HT + HB)}{2HT + HB}$$

is the ratio of moment per area between a rectangular and trapezoidal beam. This ratio will give the approximate resonant frequencies of a tapered cantilever beam knowing the resonant frequency of a rectangular beam:

l	tooth length
HB	tooth width at root
HT	tooth width at tooth tip.

The frequencies of the load-related magnetic forces, applied to the stator teeth and core, they equal the passing frequency of the rotor bars plus side bands at +/− $2f$, $4f$, $6f$, and $8f$ Hz. A fundamental force is generated at the passing frequency of the rotor slot. The side bands are created when the amplitude of this force is modulated at two times the frequency f of the power source. On a 60-Hz system, this 120 Hz modulation produces the side bands.

The force applied to each tooth produces displacement of the tooth and the core, which translates directly into noise. The displacement and noise will have a greater amplification the closer the forcing frequency is to the resonant frequency of the core or tooth [5]:

$$\text{Amplification factor} = \frac{1}{1 - (f/f_0)^2}. \tag{6}$$

Knowing the frequency and the displacement of the core or teeth, we calculate the noise as follows [2], [5]:

$$\text{dB} = 20\log\left[1.13 \times 10^6 f(p-p)\right] = 121 + 20\left[\log(p-p)f\right] \tag{7}$$

where

$$p-p = \frac{19.56[\text{No. of } g\text{'s}]}{f^2} = \frac{v}{3.14 \times f}$$

$p-p$ displacement peak to peak, in.
v velocity, in./s
f line frequency
f_0 resonant frequency of the core
g acceleration, in./s^2.

Load-related magnetic noise is the most difficult noise to identify because it does not exist at no load and will not be present during a routine factory test. If a complete factory test, including a load test is performed, the test stand loading equipment may have noise levels in excess of that of the motor making the motor noise difficult to detect. In addition, slight manufacturing variations can cause a major change in the amplification factor. Therefore, load-related magnetic noise may vary greatly between duplicate machines when operating close to a resonant condition.

Variable frequency drives (*VFD*) will cause an increase in magnetic noise. This increase is a result of the additional magnetic forces that are generated in the motor by the higher frequency voltage harmonics coming from the VFD.

Six-pulse inverter drives can increase the noise level by up to 2-6 dB, whereas a pulse-width-modulated (PWM) drive can increase the noise level by as much as 5-9 dB.

There may also be speeds within the operating speed range where the core or enclosure is resonant at the frequency of the force being produced by the voltage harmonics. In order to avoid excessive noise, the speeds where the resonance occurs must be blocked out.

The additional magnetic noise created in the motor due to VFD can be minimized by the following:

1) The noise can be minimized by filtering the incoming voltage from the VFD.
2) The noise can be minimized by reducing the magnetic field in the motor's air gap. Forces in the gap applied to the stator teeth are a function of the square of the gap density. This can be reduced by increasing the core length and/or frame size and diameter.
3) On a PWM be especially careful to avoid a core resonance at the commutation frequency.

D. Unique Windage Noise Problems

Two-pole motors are prone to the generation of excessive windage noise. Windage noise can also become a problem on large-diameter four- and six-pole machines. Windage noise varies as a function of the rotor or fan diameter. Equation (8) shows how sound pressure Lp will vary with r/min or diameter [6].

$$Lp_1 = Lp_2 + 50\log\frac{\text{r/min}_1}{\text{r/min}_2} + 70\log\frac{\text{diameter}_1}{\text{diameter}_2}. \tag{8}$$

On a TEFC motor it is difficult to attenuate the noise generated by the external fan. Therefore, to minimize noise generation, a careful fan design is required.

E. Unique Magnetic Noise Problems

Stator Tooth Resonance: This is a major concern on two- and four-pole, small- and medium-horsepower (hp) motors. Two- and four-pole motors are built on smaller stator bore diameters and have deeper stator slots than the higher pole machines. These deep-stator slots cause the stator teeth to be long and have a relatively low resonant frequency. This, along with the higher forcing frequencies associated with two- and four-pole motors, can cause the tooth-resonant frequency to be very close to the forcing frequency. When this happens, the noise level can increase 10 dB or more under load. The stator slot is normally sized to produce a tooth-resonant frequency much higher than the forcing frequency. Note the relative tooth height and core depth in figure 8.

Excessive Stator Core Load-Related Noise: This is more common on six-pole and slower motors. The stator core back iron has less depth and will vibrate at a greater magnitude with smaller forces. It is also more difficult to avoid the resonant conditions of the many different modes of vibration. Compare the relative core depths in Fig. 8.

II. FIELD-TESTING PROCEDURE FOR NOISE

The following outlines a test procedure that can be performed on any induction motor. From this procedure, the nature and the magnitude of noise under load can be determined. The following testing procedure requires the use of a handheld octave band-noise analyzer and a discrete frequency (narrow-band) spectrum analyzer with noise pickup.

Step 1: While the motor is running at no load, turn the power off and monitor the noise.

a) If the noise goes away as soon as the power is turned off, the noise is magnetically generated. This could be either constant-level magnetic noise or the motor could be operating very close to a resonance, causing some load-related magnetic noise. Even at no load, there will be a small amount of current in the rotor bars, producing small forces that may excite a resonant condition.
b) If the noise does not decrease immediately but reduces gradually as the motor coasts down, the noise is mechanical, or windage in nature. Excessive mechanical-bearing noise can be generated by antifriction bearings. The use of precision bearings can help minimize the noise. Normally, bearing noise can be identified due to the location and frequencies of the noise. In this paper only mechanical windage noise will be discussed. See [10] for more information on bearing noise.

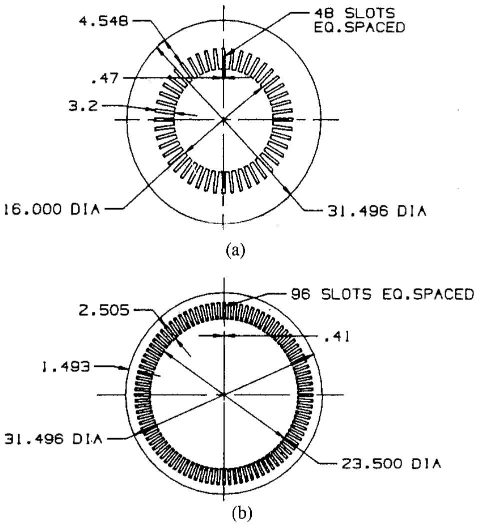


Fig. 8. Comparison of (a) two-pole and (b) six-pole punching.

Step 1 will only determine the noise source at no load. To determine if there is a significant increase in magnetic noise under load, steps 2, 3, 4, and 5 must be followed.

Step 2: Determine the overall no-load sound pressure Lp_{NL} at 3 ft in a free field over a reflective plane as defined in IEEE 85 and NEMA MG 3 (3 and 4). For this $Lp(n)_{\mathrm{NL}}$, $Lp(n)_{\mathrm{amb}}$, and $L(n)_C$ must be tested for and equations (9) and (10) solved.

$Lp(n)_{\mathrm{NL}}$ = No load noise at test point n corrected for free field and other noise sources (ambient noise)
$Lp(n)_{\mathrm{amb}}$ = Sound pressure ambient at point n.
$L(n)_C$ = Free-field dB correction at point n per MG 3.
$Lp(n)_{\mathrm{NL}@df(x)}$ = No-load sound pressure at point n at discrete frequency x.
$Lp(n)_{\mathrm{FL}@df(x)}$ = Full-load sound pressure at point n at discrete frequency x

where

NL	No load
FL	full load
n	test point location. There are 11 points for a medium-sized machine. It becomes very time consuming to handle too many points in a field test, and it may be impossible to get the 3 readings above the motor, and the one on the drive end. For the purpose intended here, 7 or 11 points will achieve the needed results, but for a more accurate estimate of overall noise, try to get all 11 points. When working on a larger machine and greater accuracy is required, increase the number of test points as stated in IEEE 85.
C	corrected for free-field and ambient-noise sources.
$Lp(n)$	sound pressure at point n.
$df(x)$	discrete frequency x. There are nine frequencies in total.

Note, log and antilog are base 10.

For this overall no-load test, the motor must be located in a quiet area with no reflective surfaces except the floor within 5 ft of the motor. Some motor manufacturers may use a reverberant room and test in accordance with IEEE 85, but this is not practical for a field test. In the field, it is necessary to take overall dB A readings 3 ft or greater from the outer surface of the motor $Lp(n)_{\mathrm{NL}}$. These readings must be taken at test points n as shown in Fig. 9 around and over the top of the motor while the motor is running at no load NL.

Now a test must be performed to determine the correction for free-field $L(n)_C$. This correction is typically 2–3 dB but could be much greater in a highly reverberant field. To test for this correction, similar readings must be taken at double the distance from the center of the motor, as were the first set of no-load readings. Note that this distance is from the center of the motor and not from the outer surface. Knowing the change in sound pressure at the two test locations, the room constant R can be determined from graph 2 in Fig. 10. With this room constant, use the graph 1 in Fig. 10 and find the difference in noise at the distance in question, due to the R of the room versus an R equal to infinity. This difference will be the free-field correction $L(n)_C$. For more details on this, see the example in the later field test.

Next, with the motor not running, take overall readings in dB A of the background ambient noise $Lp(n)_{\mathrm{amb}}$. These readings are to be taken at the same 11 points. This information will be used to make the correction for other noise sources as shown in (9).

Solve (9) to find the free-field no-load noise at each test location around the motor:

$$Lp(n)_{\mathrm{NL}} = 10\log\left[\operatorname{antilog}\frac{Lp(n)_{\mathrm{NL}}}{10} - \operatorname{antilog}\frac{Lp(n)_{\mathrm{amb}}}{10}\right] - L(n)_C. \quad (9)$$

Solve (10) to find the average no-load noise around the motor:

$$Lp_{\mathrm{NL}} = 10\log\frac{1}{n}\left[\operatorname{antilog}\frac{Lp(1)_{\mathrm{NL}}}{10} + \cdots + \operatorname{antilog}\frac{Lp(n)_{\mathrm{NL}}}{10}\right]. \quad (10)$$

If the noise levels are within 4 dB of each other, it would introduce little error to make a simpler arithmetic average of the dB A levels instead of the calculation in (10). This also applies to the later averages calculated in (11) and (13).

Step 3: While the motor is operating at full load, take noise readings at the nine discrete frequencies that are associated with load-related magnetic noise. This test will require the use of a spectrum analyzer. These frequencies are the rotor-bar passing frequency, and the side bands $+/-\ 2f$, $4f$, $6f$, and $8f$. This is similar to what will be done in step 4 at no load. Note that the rotor slot passing frequency at full load is lower than that at no load by the ratio of (full-load r/min)/(no-load r/min).

In addition, take octave band readings in the one or two

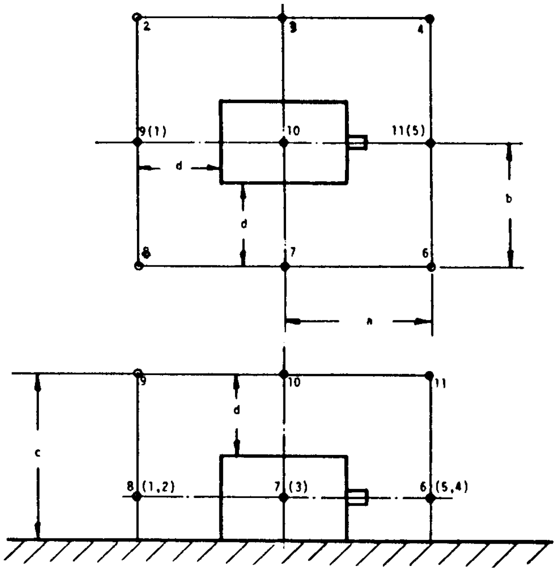
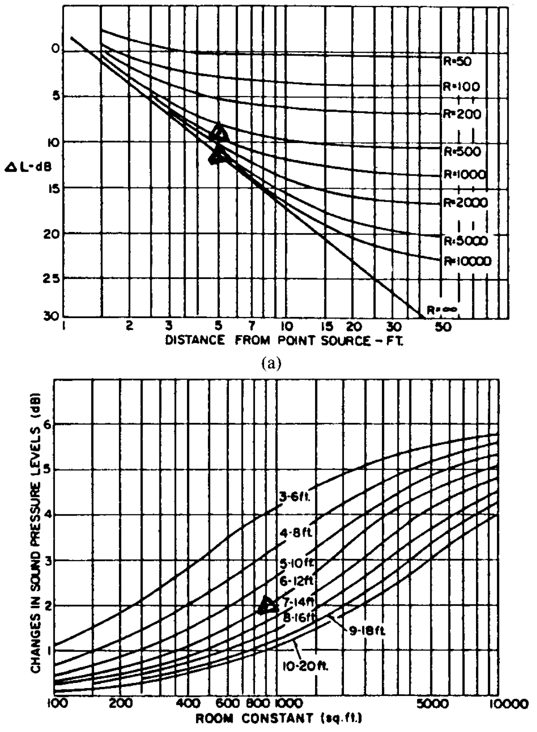


Fig. 9. Prescribed points, medium machine. (All points of measurement shall be located on the rectilinear planes prescribed where d is equal to 1 m or greater.) (Reproduced from IEEE Std. 85-1973, IEEE Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery, © 1973 by the Institute of Electrical and Electronics Engineers, Inc. Reproduced with permission).



(a)

(b)

Fig. 10. Graphs from MG 3. (a) Graph 1: attenuation of sound level $\triangle L$ as a function of distance and room constant over a reflection floor; (b) graph 2: estimation of room constant from sound pressure level measurements at two points. Reproduced with permission of the National Electrical Manufacturers Association from NEMA Standards Publication MG 3 1974 (R 1979, 1984), "Sound level prediction for installed rotating electrical machines," © 1974 by NEMA.

octave bands that contain the frequencies of magnetic noise. Take these readings at the points shown in Fig. 9 and at twice the distance from the center of the motor. This will be used to determine the value for $L(n)_C$ needed in (11). Determine $L(n)_C$ for each test point in a similar manner to that done in step 2.

For each of the nine discrete frequencies, take the averages of the readings tested at each location n and correct for the free field as shown in (11):

$$Lp_{\mathrm{FL}@df(x)} = 10\log\frac{1}{n}\left[\text{antilog}\,\frac{\left(Lp(1)_{\mathrm{FL}@df(x)} - L(1)_C\right)}{10} + \cdots + \text{antilog}\,\frac{\left(Lp(n)_{\mathrm{FL}@df(x)} - L(n)_C\right)}{10}\right]. \quad (11)$$

Now, make a logarithmic addition of the average noise levels at each discrete frequency calculated in (11). This calculation shown in (12) will give the total noise at full load at the frequencies of load-related magnetic noise:

$$Lp_{\mathrm{FL}@df} = 10\log\left[\text{antilog}\,\frac{Lp_{\mathrm{FL}@df(1)}}{10} + \cdots + \text{antilog}\,\frac{Lp_{\mathrm{FL}@df(x)}}{10}\right]. \quad (12)$$

Step 4: While the motor is running at no load, measure the noise levels at the discrete frequencies of load-related magnetic noise. (This information is needed so it can be determined how much noise exists at no load at these frequencies.) Take all no load readings in dB A, 3 ft from the motor at the same points defined in Fig. 9. Record the noise levels $Lp(n)_{\mathrm{NL}@df(x)}$ at the nine discrete frequencies that are associated with load noise. These frequencies are the rotor-slot-passing frequency, and the side bands $+/-\ 2f$, $4f$, $6f$, and $8f$ Hertz. Note that the rotor slot frequency here is based on synchronous speed, and will vary in frequency from readings taken in step 3 under load.

In addition, determine $L(n)_C$ for each test location in the same way as previously done in step 3. If the motor is located in the same area, then the same correction may be used here.

For each of the nine discrete frequencies take the averages of the readings taken at the test locations and correct for free field as shown in (13):

$$Lp_{\mathrm{NL}@df(x)} = 10\log\frac{1}{n}\left[\text{antilog}\,\frac{\left(Lp(1)_{\mathrm{NL}@df(x)} - L(1)_C\right)}{10} + \cdots + \text{antilog}\,\frac{\left(Lp(n)_{\mathrm{NL}@df(x)} - L(n)_C\right)}{10}\right]. \quad (13)$$

Now, make a logarithmic addition of the average noise levels at each discrete frequency calculated in (13). This calculation shown in (14) will give the total noise at no load at the frequencies of load-related magnetic noise:

$$Lp_{\mathrm{NL}@df} = 10\log\left[\text{antilog}\,\frac{Lp_{\mathrm{NL}@df(1)}}{10} + \cdots + \text{antilog}\,\frac{Lp_{\mathrm{NL}@df(x)}}{10}\right]. \quad (14)$$

Correcting for ambient noise is normally not necessary in step 3 or 4. It is reasonable to assume that there will not be other noise sources at these exact discrete frequencies. To verify this while the motor is not running, take noise readings around the motor at the same discrete frequencies. Then while the motor is driving the load, verify that the discrete frequency noise levels are higher near the motor than they are near the driven equipment.

Step 5: Calculate the total overall full-load noise Lp_{FL} in a free field. This is shown in (15) using the results from (10), (12), and (14):

$$Lp_{\mathrm{FL}} = 10 \log \left[\text{antilog} \frac{Lp_{\mathrm{NL}}}{10} + \text{antilog} \frac{Lp_{\mathrm{FL}@df}}{10} - \text{antilog} \frac{Lp_{\mathrm{NL}@df}}{10} \right]. \quad (15)$$

An Example of a Field Test: Recently in a field test of four duplicate motors, one motor was found to be generating a much higher level of noise at a very irritating frequency. It was noted that although the noise levels were considerably lower on three of the motors, the noise being generated was at exactly the same discrete frequencies. The following tests were performed on the motor which was generating the excessive noise. Equipment used was a 2215 B & K Octave Band Analyzer, and a Nicolet Spectrum Analyzer.

Step 1: A no-load noise test was performed with the motor uncoupled from the compressor it was intended to drive. The overall noise level measured was less than 85 dB A and it was reported that the noise decreased gradually with speed after the power was turned off. As was outlined in step 1 of the testing procedure, this would establish the noise to be windage in nature.

Previously, in a loaded noise test, the user was measuring overall noise levels in excess of 97 dB A. The user did not understand that the motor noise could increase under load. Therefore, an incorrect assumption was made that the noise was not coming from the motor.

Step 2: The following overall no-load test data was the result of a factory test. There was inadequate time to uncouple and relocate the motor to rerun this test. The same results would have been achieved by following the field test procedure in step 2.

	Frequency Bands								
	63	125	250	500	1000	2000	4000	8000	Lp_{NL}
dB A at 3 ft	45	65	72	73	76	83	76	64	84.9

Step 3: In the following test, the motor was loaded by the compressor it was driving. Noise levels were measured with a spectrum analyzer at the nine discrete frequencies as outlined in step 3. The passing frequency is equal to 2330 Hz, as calculated by (2) for a 39-slot rotor rotating at 3585 r/min. The test showed that the noise levels at the passing frequency and at the +/− 120 Hz side bands were much greater than the higher order side bands. Noise levels 15 dB A or more below the highest peak may be ignored to reduce testing time as was done here. This will introduce less than a 0.75-dB error.

Next, the free-field correction must be determined by a test. Since the calculated rotor slot frequency and the +/− 120 Hz side bands fell within the 2000-Hz band, the test for the free-field correction was accomplished by taking readings in the 2000-Hz octave band on rectilinear planes 6 and 12 ft from the center of motor. The noise levels were found to drop approximately 2 dB when moving from 6–12 ft. Because this was fairly consistent at all locations around the motor, only one free-field correction needed to be calculated. If it had not been consistent, a different correction at each test point would have been required. Looking at graph 2 of Figure 10, a 2-dB drop on the 6–12 curve would represent a room constant of 900. Note, 5 ft from the center of this motor equals 3 ft from the outer surface, since this motor has a maximum dimension of 4 ft. As shown in graph 1 of Fig. 10 for a distance of 5 ft from the center of the motor and using the R equal to the 900 curve, the drop is equal to -9 dB. This can then be compared to -12 on the R equal to the infinity curve. As is shown in the following calculation, this would give a free-field correction of 3 dB:

$$\begin{aligned} \mathrm{dB} &= 12 && \text{for } R = \text{infinity(free field)} \\ -\ \underline{\mathrm{dB} = 9} & && \text{for } R = 900 \\ L(n)_c &= 3 && \text{for } n = 1 \text{ through } 11. \end{aligned}$$

Taking the average of the readings, and subtracting 3 dB at each point per (11), the results are as follows:

Full load r/min 3585				2000 Hz Octave band	
Frequencies	2210	2330	2450		Overall
$Lp_{\mathrm{NL@df(x)}}$ uncorrected	85.9	90	94.5	96.2	99.5
$Lp_{\mathrm{NL@df(x)}}$	82.9	87	91.5	93.2	

All other noise levels at other discrete frequencies were below 75 dB A and not recorded. The following is the sum of the noise levels at the discrete frequencies at full load:

$$Lp_{\mathrm{FL}\cdot f} = 10 \log \left[\text{antilog} \frac{82.9}{10} + \text{antilog} \frac{87}{10} + \text{antilog} \frac{91.5}{10} \right] = 93.2 \text{ dB } A. \quad (12)$$

It appeared that most of the noise in the 2000-Hz octave band was coming from the motor and was load-related magnetic noise.

Step 4: In the following test the motor was in the same location as in step 3 but uncoupled from the compressor. Noise levels were recorded at the rotor-slot frequency of 2340 Hz and the +/− 120 Hz side bands. Equation (13) calculates the average of the discrete frequency no-load noise levels measured around the motor. The results of this equation are as follows and have already been corrected for a free field:

Frequencies	2220	2340	2460
$Lp(n)_{\mathrm{NL}@df(x)}$	75.2	74.6	73.9

$$Lp_{\mathrm{N}_L@df} = 10\log\left[\text{antilog}\frac{75.2}{10} + \text{antilog}\frac{74.6}{10} + \text{antilog}\frac{73.9}{10}\right]$$
$$= 79.4\ \mathrm{dB}A \text{ at 3 ft in a free field.} \quad (14)$$

Step 5: Now determine the overall full-load noise level corrected for a free field and ambient noise as shown in (14):

$$Lp_{\mathrm{FL}} = 10\log\left[\text{antilog}\frac{84.9}{10} + \text{antilog}\frac{93.2}{10} - \text{antilog}\frac{79.4}{10}\right] = 94.0\ \mathrm{dB}\,A. \quad (15)$$

This test showed the noise level to increase 9 dB under load and proved it to be magnetically generated load related noise.

Similar Test on One of the Three Quiet Motors: This test result is included here as a comparison. It is interesting to see how noise levels can vary between duplicate machines when operating too close to a resonance.

	2210 Hz	2330 Hz	2450 Hz
$Lp_{\mathrm{FL}@df(x)} =$	76.8	78.2	80.9

$$Lp_{\mathrm{FL}@df} = 83.7 \quad (12)$$
$$Lp_{\mathrm{NL}@df} = 79.0 \quad (14)$$
$$Lp_{\mathrm{FL}} = 10\log\left[\text{antilog}\frac{84.9}{10} + \text{antilog}\frac{83.7}{10} - \text{antilog}\frac{79}{10}\right]$$
$$= 87.9\ \mathrm{dB\,A}. \quad (15)$$

The noise on this motor only increased 3 dB under load as compared to the first motor, which increased 9 dB.

III. Methods of Reducing Noise

Only a few years ago, 90 dBA at no load was considered a low noise level for an induction motor. Now, many users are requiring motor manufacturers to limit the motor noise to 85, or even 82 dBA. In the past, these noise levels were typically achieved by either 1) adding sound insulation, 2) some type of enclosure change or baffle arrangement, 3) fan-diameter reduction. In the future, motor manufacturers can expect to see noise limitations drop to 80 dBA or below. Many times, windage noise is not the main concern, even on the higher speed motors. On many motors, the magnetic noise will tend to exceed these levels even when they are not operating close to a resonant condition.

It is also important to understand that the noise level measured around a motor will be much higher than the free-field no-load noise level. When adding other noise sources, and the reverberant room effects, the results could be as follows:

dBA of motor no load, free field	85
Typical increase in motor noise under load	3
dBA for equipment motor is driving	88
Typical addition for room ambient noise	1
Typical addition for semireverberant effects of room	3

$$Lp_{\text{total}} = 10\log\left[\text{antilog}\frac{(85+3)}{10} + \text{antilog}\frac{(88)}{10}\right] + 1 + 3$$
$$= 95.0\ \mathrm{dBA}.$$

As is shown here, though the free-field noise of the motor may increase less than 3 dB under load, the noise level around the motor could possibly be 10 dB above the no load level of the motor.

A. Windage Noise Reduction

Windage noise is airborne, which makes it easier to reduce in an existing motor than magnetically generated structure-borne noise. The generation of windage noise can be reduced, or existing noise can be attenuated in the following ways:

1) By reducing the fan diameter, which will reduce the generation of windage noise by the following calculations:

$$\mathrm{dB\ reduction} = 70\log\left(\text{diameter}_2/\text{diameter}_1\right)$$

where

diameter_2 = New fan diameter
diameter_1 = Original fan diameter.

2) By using a fan that has an air foil or backward bent-blade design that will reduce the generation of windage noise.
3) By reducing the number of rotor vents.
4) By band taping the bar extensions on fabricated rotors between the rotor core and the end connector.
5) By lining the existing air chambers with sound-absorbent insulation.
6) By the use of lined baffles to deflect the air at the intakes or exhausts. The line of sight, from the exhaust and/or intake to the noise-producing source, should be blocked. When designed properly this can be done without any significant cooling reduction.

Items 1, 2, 3, and 4 must be performed at the factory or service shop and should be considered in the original design. Modifications in items 5 and 6 can be handled in the field, but are more cost effective and technically correct if included in the original design.

Most of the windage noise of open motors comes from the fan action of the rotor bars, not the fans. Therefore, a fan-diameter reduction will not always cause a significant reduction in noise. The cause of the noise can be determined by comparing the frequency of the noise to the passing frequency of the bars and fans. If the rotor fans on the open motor are assisting in forcing the air through the rotor, then the fan reduction may have a significant effect, but it will not follow the fan laws. On TEFC motors, an external fan-diameter reduction is very effective. Any fan or vent reduction will cause the motor to run hotter. This will have to be compensated for by either reducing horsepower output or by increasing frame size and cost.

Installing sound insulation in the top covers where space allows and/or the introduction of baffles will reduce windage noise significantly. It is not unusual to be able to reduce noise level by as much as 10 dB without increasing the motor temperature.

When using baffles or sound insulation, caution must be taken to avoid restricting the air flow. To accomplish this, the air flow requirement must be known and baffles located in such a way that the air speed and pressure drop is not excessive. A general rule for the maximum air velocity in a short straight run of ducts is given in the following formulas. The CFM required to cool a motor can be measured on an existing motor or estimated by the following:

$$CFM = P\,(kW_{\text{loss}}) \tag{16}$$

where

$$P = 60\text{–}100.\ \text{Use 100 to be safe.}$$

$$kW\ \text{loss} = \frac{(0.746\ \text{hp})}{\text{efficiency}} - 746\ \text{hp}$$

$$\text{maximum air velocity} = (0.15)(D_F)(3.14)(\text{r/min}) \tag{17}$$

where

$$D_F = \text{diameter of fan or rotor in feet}$$

$$\text{velocity} = \text{feet per minute}.$$

If there are bends in the ducts, substitute (0.10) for (0.15) in (17).

Noise levels can be minimized on new designs by the use of enclosures with increasing weather protection as seen in Fig. 11.

B. Magnetic Noise Reduction

In the first example given, the motor was found to have excessive noise in the 2000-Hz band. It was proved to be magnetically generated load-related noise. Magnetic noise is the most difficult noise to reduce, since it is structure borne and difficult to isolate from the external surface of the motor. The following are ways that magnetic noise can be controlled or reduced:

1) Change the stator slot design or rotor-slot quantity to achieve a greater margin between the forcing frequencies and the resonant frequencies of the core or teeth. By changing the stator-slot size the resonant frequencies of the core and tooth will be changed, whereas changing the quantity of rotor slots will change the forcing frequencies and mode of vibration.
2) Build the rating on a large core length or frame size to reduce the magnetic field density in the air gap. The force applied to the stator teeth is proportional to the square of the flux density. In addition, a larger machine will also increase the strength of the teeth and core thereby reducing vibration and noise.

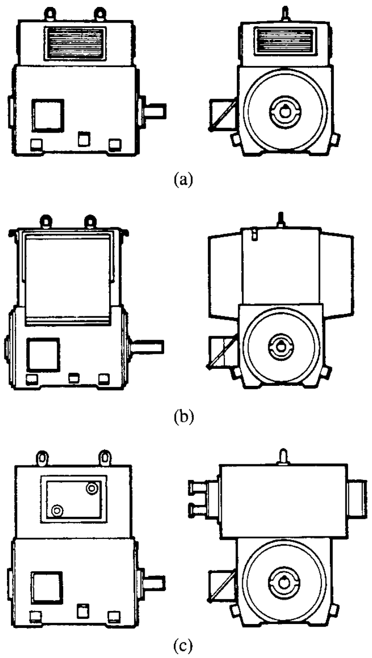

(a)
(b)
(c)

Fig. 11. Enclosures with increasing weather protection: (a) Open drip proof: least control of windage noise; (b) weather-protected type II: has a much greater control of windage noise since the air must make multiple bends, which can all be lined with sound insulation; (c) totally enclosed water cooled: has the greatest control of windage noise since there is no exchange of internal and external air. Enclosure is made of thick-enough steel to minimize transmission of noise.

3) Install magnetic wedges in the stator slot. This will reduce the tangential forces being applied to the teeth.
4) Build an enclosure around the motor to stop the transmission of structure-borne noise. The enclosure and air ducting must be isolated from the motor, either by air space or through isolation bushings. The bushings must be designed not to transmit the frequencies in question. The enclosure can be made of any material thick enough to effectively attenuate the transmission of sound. It should be lined on the inside with 2–4 in. of sound insulation to prevent the buildup of noise inside the enclosure. The air ducts must be sized so that air flow is not restricted. They must also be sealed to prevent the exhaust air from mixing with the intake air. The temperature of the cooling air entering the motor must not exceed the design ambient. Although most open motors do not rely on heat radiation from the yoke to cool the motor, they may require cool ambient air around the bearing capsules to cool the bearings. The enclosure should be vented to keep the air inside the enclosure around the bearings at ambient temperature.

Only the modification in item 4 can be performed in the field. The other items will require extensive work at the factory or service shop. Items 1, 2, and 3 should be considered in the original design where it would be more cost effective and technically correct.

Reducing the Noise on the Motor in the Field-Test

Example: When reviewing the design of the motor presented here, the stator tooth resonance was calculated to be 2585 Hz. This is too close to the forcing frequencies of 2210, 2330, and 2450 Hz and may periodically cause excessive noise. Several manufacturing variations can affect the tooth resonance or dampen the vibration including core pressure, steel grade, coil placement in slot, tightness of slot wedges, and penetration of the VPI insulation.

A test on a modified design, which had a higher calculated resonant frequency of 2975 Hz, showed a considerable improvement in the noise level. This higher resonant frequency is due to a reduction in the stator slot height from 3.5–3.2 in.

Tested no load noise

Octave band	63	125	250	500	1000	2000	4000	8000	Lp_{NL}
dB A at 3 ft	60	64	70	73	71	76.6	70.8	52.3	79.7.

Under load the following noise levels were found:

	2210 Hz	2330 Hz	2450 Hz	2570 Hz
$Lp_{\mathrm{FL}\cdot f(x)}$	70.6	70.4	75.8	72.0

$Lp_{\mathrm{FL}\cdot f}$ = noise at full load at discrete frequencies = 78.8
$Lp_{\mathrm{NL}\cdot f}$ = noise at no load at discrete frequencies = 74.1
Lp_{FL} = total full-load noise level = 81.6.

This motor tested 5 dB A lower at no load than the best of the previous motors and only increased 2 dB from no load to full load.

IV. CONCLUSIONS

1) When trying to reduce induction motor noise, first determine the noise source within the motor. This must be established before the proper treatment to the motor can be determined.
2) Estimate the actual overall full-load noise level of the motor; this will help determine whether or not applying noise treatment to the motor is beneficial. If the motor is not the primary noise source, a large reduction in motor noise may not achieve a significant reduction in the overall noise level.
3) Further noise reductions that may be required in the future to achieve levels below 80 dB A will be accomplished by frame-size increases and/or isolation-type enclosures built around the motor.
4) If low noise is required, it is better to consider it in the original motor design than to make modifications in the field.

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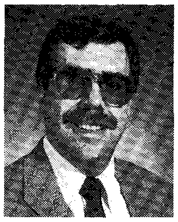

William R. Finley (M'89) was born in 1954. He received the B.S. degree in electrical engineering from the University of Cincinnati, Cincinnati, OH, in 1977.

From 1977 to 1985 he worked in the design of induction motors for production and quotations with Siemens Energy & Automation, Inc. (formerly Allis Chalmers, Inc.). During this time he was also project manager on developments of new product lines. Since 1985 he has supervised electrical engineering for the design and quotation of medium and large induction motors in the United States.

Mr. Finley is currently a member of the IEEE 85 working group on noise. He is also a member of the NEMA International Standardization Sub-Section, Motor and Generator Section, the NEMA Motor Rerate Group, Motor and Generator Section, and the NEMA Joint Sections Committee on Motor Inrush.