1

Generation and Radiation of Noise in Electrical Machines

1.1 Vibration, sound, and noise

Vibration is a limited reciprocating motion of a particle of an elastic body or medium in alternately opposite directions from its position of equilibrium, when that equilibrium has been disturbed. In order to vibrate, the body or system must have two characteristics: elasticity and mass. The *amplitude of vibration* is the maximum displacement of a vibrating particle or body from its position of rest.

Sound is defined as vibrations transmitted through an elastic solid, liquid, or gas with frequencies in the approximate range of 20 to 20,000 Hz, capable of being detected by human ears. *Pitch* is the perceived tone of a sound which is determined by the sound wave frequency. A sound with a high frequency (short wavelength) has a high pitch, while a sound with low frequency (long wavelength) has a low pitch.

Noise is disagreeable or unwanted sound. Distinction is made between airborne noise and noise traveling through solid objects. *Airborne noise* is the noise caused by the movement of large volumes of air and the use of high pressure. *Structure-borne* noise is the noise carried by means of vibrations of solid objects.

1.2 Sound waves

A *sound wave* is generated by a vibrating object and can be defined as a mechanical disturbance advancing with a finite speed through a medium. Sound waves are small-amplitude adiabatic oscillations characterized by wavespeed, wavelength, frequency, and amplitude (Appendix A). In air, sound waves are *longitudinal waves*, that is, with displacement in the direction of propagation. In other words, the motion of the individual particles of the medium is in the direction that is parallel to the direction of the energy transport. *Transverse waves* are those with vibrations perpendicular to the direction of travel of the wave an exist in the elastic medium. Examples of transverse waves include waves on a string and electromagnetic waves.

Only transverse waves can be polarized, i.e., can have orientation. Polarized waves oscillate in only one direction perpendicular to the line of travel. For example, the polarization of an electromagnetic wave is defined as the orientation of the electric field vector. The electric field vector is perpendicular to both the direction of travel and the magnetic field vector. Polarized waves can be formed from unpolarized waves by passing them through some polarizing process, e.g., a train of unpolarized waves in a rope can be polarized by passing them through a narrow physical gap.

Sound waves cannot be polarized. Unpolarized waves can oscillate in any direction in the plane perpendicular to the direction of travel and have no preferred plane of polarization.

All sound waves have common behavior under a number of standard situations and exhibit:

- reflection, i.e., the phenomenon of a propagating wave being thrown back from a surface between two media with different mechanical properties;
- refraction, i.e., the change in direction of a propagating wave when passing from one medium to another;
- diffraction, i.e., the process of spreading out of waves, e.g., when they travel through a small slit or go around an obstacle;
- scattering, i.e., the change in direction of motion;
- interference, i.e., mutual influence of two waves, e.g., the addition of two waves that come in to contact with each other;
- absorption, i.e., the incident sound that strikes a material that is not reflected back;
- dispersion, i.e., the splitting up of a wave depending on frequency.

Sound amplitude can be measured as sound pressure level (SPL), sound intensity level (SIL), sound power level (SWL), and sound energy density (SED) (Appendix A).

A human ear can perceive sound waves of sufficient intensity whose frequencies are approximately within the limits from 16 to 20, 000 Hz (audio-frequency range). There is a minimum sound intensity for a given frequency at which the sound can be perceived by the human ear. The minimum sound intensity is different for different frequencies and is called the *threshold of audibility*. Figure 1.1 shows the audibility zone for the whole audio-frequency range. The range of the sound intensity that can be perceived by the ear is from 10^{-12} to 1 W/m^2 corresponding to 20 μPa sound pressure. The maximum sound intensity at which the ear feels a pain is called the *threshold of pain*. Sound amplitudes that are extremely loud (at the threshold of pain) have pressure amplitudes of only 100 Pa. Some environmental noise levels are compared in Figure 1.2. Typical sound power levels for common sounds are also given in Table 1.1

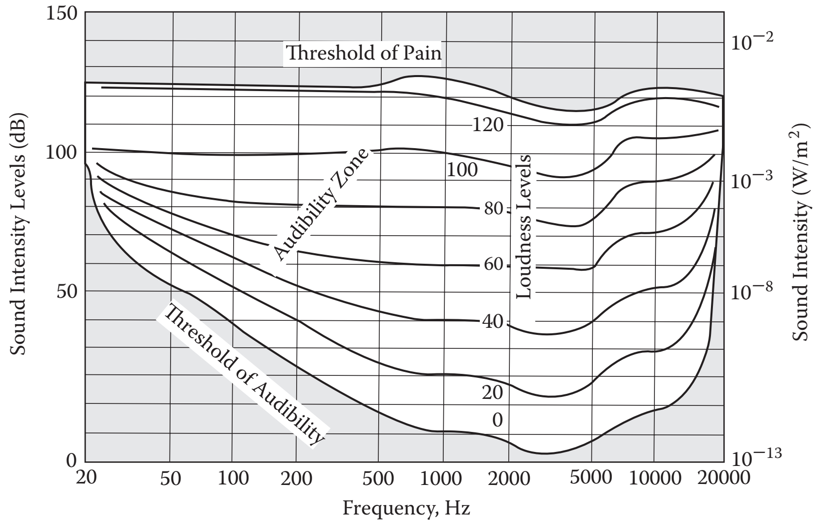

Figure 1.1 Sound intensity and audibility zone as a function of frequency.

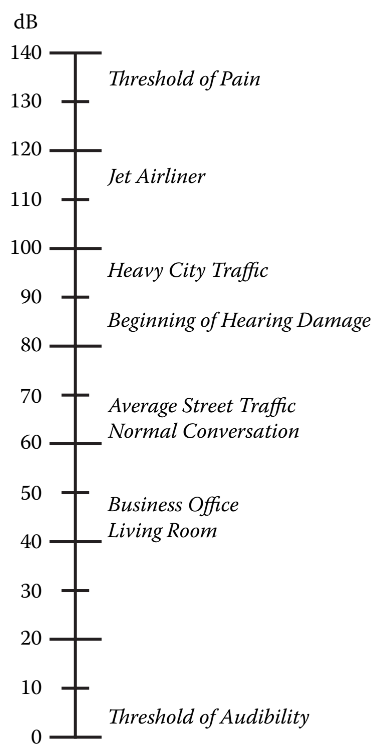

Figure 1.2 Comparison of some environmental noise levels.

Table 1.1 Typical sound power levels.

Source of noise	Sound power level, dB(A)
Quietest audible sound for persons under normal conditions	10
Rustle of leaves	15
Soft whisper, room in a quiet dwelling at midnight	30
Voice, low	40
Mosquito buzzing	45
Department store, clothing department	48
Modern elevator propulsion motor	50
Normal conversation	55
Bird singing Large department store Busy restaurant or canteen	60
Voice, conversation	70
10-kW, 4-pole cage induction motor Normal street traffic	75
Pneumatic tools Alarm clock ringing Buses, trucks, motorcycles	80
Small air compressors Loud symphonic music Lawn mower Your boss complaining	90
Heavy city traffic Air compressor Heavy diesel vehicle	92
Permanent hearing loss (exposed full-time)	95
Car on highway	100
Steel plate falling	105
Magnetic drill press	106
Vacuum pump	108
Hard rock music	110
Jet passing overhead	115
Jackhammer	120
Jolt squeeze hammer	122
Jet plane taking off	150
Saturn rocket	200

1.3 Sources of noise in electrical machines

The frequency of interest for vibration is generally within 0 to 1000 Hz, and for noise is over 1000 Hz. Vibration and noise produced by electrical machines can be divided into three categories:

- electromagnetic vibration and noise associated with parasitic effects due to higher space and time harmonics, eccentricity, phase unbalance, slot openings, magnetic saturation, and magnetostrictive expansion of the core laminations;
- mechanical vibration and noise associated with the mechanical assembly, in particular bearings;
- aerodynamic vibration and noise associated with flow of ventilating air through or over the motor.

The load induced sources of noise include:

- noise due to coupling of the machine with a load, e.g., shaft misalignment, belt transmission, elevator sheave with ropes, tooth gears, coupling, reciprocating compressor;
- noise due to mounting the machine on foundation or other structure.

The noise from its source is transmitted through the medium (structure, air) to the recipient (human being, sensor) of the noise. The process of noise generation and transmission in electrical machines is illustrated in Figure 1.3. Basics of acoustics are explained in Appendix A.

1.3.1 Electromagnetic sources of noise

Electromagnetic vibration and *noise* are caused by generation of electromagnetic fields (Chapter 2). Both stator and rotor excite magnetic flux density waves in the air gap. If the stator produces $B_{m1}\cos(\omega_1 t + k\alpha + \phi_1)$ magnetic flux density wave and rotor produces $B_{m2}\cos(\omega_2 t + l\alpha + \phi_2)$ magnetic flux densisty wave, then their product is

$$0.5B_{m1}B_{m2}\cos[\omega_1 + \omega_2)t + (k+l)\alpha + (\phi_1 + \phi_2)] \\ + 0.5B_{m1}B_{m2}\cos[\omega_1 - \omega_2)t + (k-l)\alpha + (\phi_1 - \phi_2)] \qquad (1.1)$$

where B_{m1} and B_{m2} are the amplitudes of the stator and rotor magnetic flux density waves, ω_1 and ω_2 are the angular frequencies of the stator and rotor magnetic fields, ϕ_1 and ϕ_2 are phases of the stator and rotor magentic flux desnity waves, $k = 1, 2, 3, \ldots$, and $l = 1, 2, 3, \ldots$. The product expressed by Equation 1.1 is proportional to magnetic stress wave in the air gap with amplitude $P_{mr} = 0.5B_{m1}B_{m2}$, angular frequency $\omega_r = \omega_1 \pm \omega_2$, order $r = k \pm l$ and phase $\phi_1 \pm \phi_2$. The magnetic stress (or magnetic pressure) wave acts in radial directions on the stator and rotor active surfaces causing the deformation and hence the vibration and noise.

The slots, distribution of windings in slots, input current waveform distortion, air gap permeance fluctuations, rotor eccentricity, and phase unbalance give

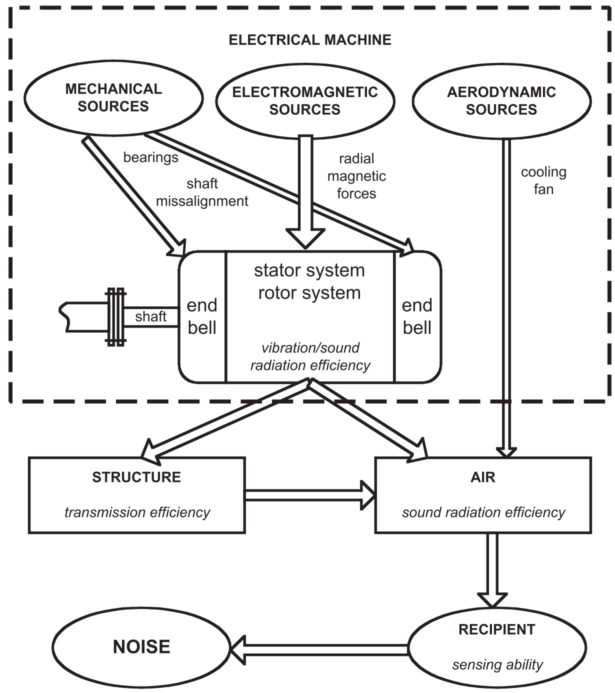

Figure 1.3 Noise generation and transmission in electrical machines.

rise to mechanical deformations and vibration. Magnetomotive force (MMF) space harmonics, time harmonics, slot harmonics, eccentricity harmonics, and saturation harmonics, produce parasitic higher harmonic forces and torques. Especially, radial force waves in a.c. machines, which act both on the stator and rotor, produce deformation of the magnetic circuit.

The stator-frame (or stator-enclosure) structure is the primary radiator of the machine noise. If the frequency of the radial force is close to or equal to any of the natural frequencies of the stator–frame system, resonance occurs, leading to the stator system deformation, vibration, and acoustic noise.

Magnetostrictive noise of electrical machines in most cases can be neglected due to low frequency $2f$ and high order $r = 2p$ of radial forces, where f is the fundamental frequency and p is the number of pole pairs. However, radial forces due to the magnetostriction can reach about 50% of radial forces produced by the air gap magnetic field.

In inverter fed motors, parasitic oscillating torques are produced due to higher time harmonics in the stator winding currents. These parasitic torques are, in general, greater than oscillating torques produced by space harmonics. Moreover, the voltage ripple of the rectifier is transmitted through the intermediate circuit to the inverter and produces another kind of oscillating torque [200].

1.3.2 Mechanical sources of noise

Mechanical vibration and noise (Chapter 7) is mainly due to bearings, their defects, journal ovality, sliding contacts, bent shaft, rotor unbalance, shaft misalignment, couplings, U-joints, gears etc. The rotor should be precisely balanced as it can significantly reduce the vibration. The rotor unbalance causes rotor dynamic vibration and eccentricity which in turn results in noise emission from the stator, rotor, and rotor support structure. Both rolling and sleeve bearings are used in electrical machines.

The noise due to *rolling bearings* depends on the accuracy of bearing parts, mechanical resonance frequency of the outer ring, running speed, lubrication conditions, tolerances, alignment, load, temperature, and presence of foreign materials.

The noise level level due to *sleeve bearings* is generally lower than that of rolling bearings. The vibration and noise produced by sleeve bearings depends on the roughness of sliding surfaces, lubrication, stability and whirling of the oil film in the bearing, manufacture process, quality, and installation.

1.3.3 Aerodynamic noise

The basic source of *noise of an aerodynamic nature* (Chapter 7) is the fan. Any obstacle placed in the air stream produces noise. In nonsealed motors, the noise of the internal fan is emitted by the vent holes. In totally enclosed motors, the noise of the external fan predominates.

According to the spectral distribution of the fan noise, there is broad-band noise (100 to 10, 000 Hz) and siren noise (tonal noise). Siren noise can be eliminated by increasing the distance between the impeller and the stationary obstacle.

1.4 Energy conversion process

Figure 1.4 shows how the *electrical energy* is converted into *acoustic energy* in an electrical machine. The input current interacts with the magnetic field producing high-frequency forces that act on the inner stator core surface (Figure 1.5). These forces excite the stator core and frame in the corresponding frequency range and generate mechanical vibration and noise. As a result of vibration, the surface of the stator yoke and frame displaces with frequencies corresponding to the frequencies of forces. The surrounding medium (air) is excited to vibrate, too, and generates acoustic noise.

The radiated acoustic power is very small, approximately 10^{-6} to 10^{-4} W for an electrical motor rated below 10 kW. It is therefore not easy to calculate the acoustic power with reasonable accuracy.

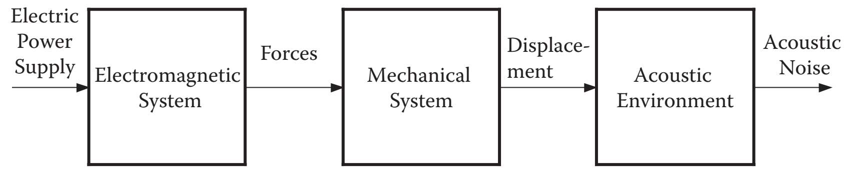

Figure 1.4 Conversion of electric energy into acoustic energy in electrical machines.

The stator and frame assembly, as a mechanical system, is characterized by a distributed mass M, damping C, and stiffness K. The electromagnetic force waves excite the mechanical system to generate vibration. The amplitude of vibration is a function of the magnitude and frequency of those forces (Appendix D).

The mechanical system can be simply described by a lumped parameter model with N degrees of freedom in the following matrix form

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{F(t)\} \tag{1.2}$$

where q is an $(N, 1)$ vector expressing the displacement of N degrees of freedom, $\{F(t)\}$ is the force vector applying to the degrees of freedom, $[M]$ is the mass matrix, $[C]$ is the damping matrix and $[K]$ is the stiffness matrix. Equation 1.2

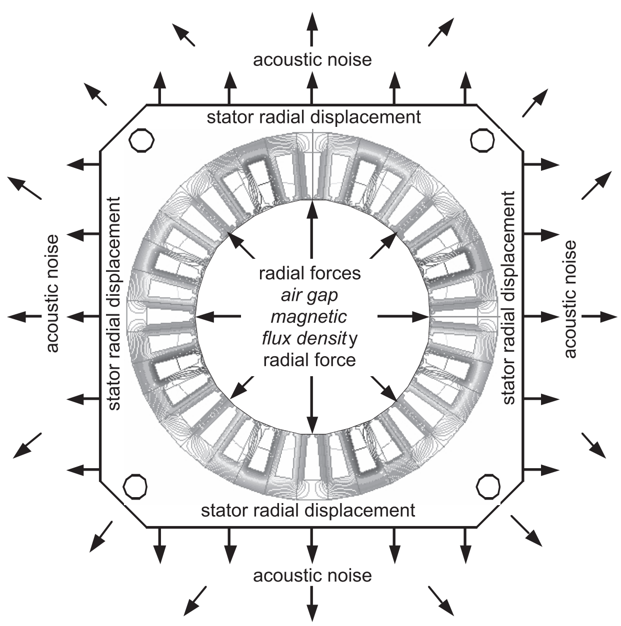

Figure 1.5 Mechanism of generation of vibration and noise in electrical machines.

can be solved using a structural finite element method (FEM) package. In practice, there are difficulties with predictions of the $[C]$ matrix for laminated materials, physical properties of materials, and errors in calculation of magnetic forces [213].

1.5 Noise limits and measurement procedures for electrical machines

Acoustic quantities (Appendix A) can be expressed in terms of the *sound pressure level* (SPL) or *sound power level* (SWL). The sound pressure level is the most common descriptor used to characterize the loudness of an ambient sound level. In general, it is more complicated to measure the sound power level than the sound pressure level. The sound power level measurement is independent of the surface of the machine and environmental conditions. According to National Electrotechnical Manufactured Association (NEMA) [162], the sound pressure level L_{pA} can be related to the sound power level L_{WA} in dB(A), as follows

$$L_{pA} = L_{WA} - 10\log_{10}\left(\frac{2\pi r_d^2}{S_0}\right) \tag{1.3}$$

where L_{pA} is the average sound pressure level in a free-field over a reflective plane on a hemispherical surface at 1 m distance from the machine, $r_d = 1.0 + 0.5 l_m$, l_m is the maximum linear dimension of the tested machine in meters, and $S_0 = 1.0\,\text{m}^2$.

The noise of electrical machines depends on the type of the machine, its topology, size, design, construction, enclosure, materials, manufacturing, rated power, speed, tolerances, mounting, support, foundation, coupling, bearings, supply, load, etc. Some consequences of noise as, for example, manufacturing, mounting or support are very difficult to predict.

In general, the equations for sound pressure level or sound power level as functions of rotational speed n, rated output power P_{out}, or torque T have the following forms:

$$L_{p1} = A_1 + B_1 \log_{10} n \tag{1.4}$$

$$L_{p2} = A_2 + B_2 \log_{10} P_{out} \tag{1.5}$$

$$L_{p3} = A_3 + B_3 \log_{10} T \tag{1.6}$$

where A_1, A_2, A_3, B_1, B_2, and B_3 are constants.

When a motor is tested at no load under conditions specified by [162], the sound power level of the motor shall not exceed values given in Tables 1.2 and 1.3. The enclosures of motors are an open drip proof machine (ODP) type, totally enclosed fan cooled machine (TEFC) type, and weather protected type II machine (WPII) type. The WPII machine is a guarded machine with its ventilating passages at both intake and discharge so arranged that high velocity air and airborne particles blown into the machine by storms or high winds can be discharged without entering

Table 1.2 Maximum A-weighted sound power levels L_{wA} in dB(A) at no load for motors with rated speeds 1200 rpm and less according to NEMA [162].

Rated power		900 rpm and less			901 to 1200 rpm		
kW	hp	ODP	TEFC	WPII	ODP	TEFC	WPII
0.37	0.5	67	67				
0.5	0.75	67	67		65	64	
0.75	1.0	69	69		65	64	
1.1	1.5	69	69		67	67	
1.5	2.0	70	72		67	67	
2.2	3.0	70	72		72	71	
3.0	5.0	73	76		72	71	
5.5	7.5	73	76		76	75	
7.5	10	76	80		76	75	
11	15	76	80		81	80	
15	20	79	83		81	80	
17	25	79	83		83	83	
22	30	81	86		83	83	
30	40	81	86		86	86	
40	50	84	89		86	86	
45	60	84	89		88	90	
55	75	87	93		88	90	
75	100	87	93		91	94	
100	125	93	96	92	91	94	
110	150	95	97	92	96	98	
150	200	95	97	92	99	100	97
185	250	95	97	92	99	100	97
220	300	98	100	96	99	100	97
260	350	98	100	96	99	100	97
300	400	98	100	96	102	103	99
350	450	99	102	98	102	103	99
370	500	99	102	98	102	103	99
450	600	99	102	98	102	103	99
520	700	99	102	98	102	103	99
600	800	101	105	100	105	106	101
670	900	101	105	100	105	106	101
750	1000	101	105	100	105	106	101
930	1250	101	105	100	105	106	101
1,100	1500	103	107	102	107	109	103
1,300	1750	103	107	102	107	109	103
1,500	2000	103	107	102	107	109	103

Table 1.3 Maximum A-weighted sound power levels L_{wA} in dB(A) at no load for motors with rated speeds 1201 to 3600 rpm according to NEMA [162].

Rated power		1201 to 1800 rpm			1801 to 3600 rpm		
kW	hp	ODP	TEFC	WPII	ODP	TEFC	WPII
0.75	1.0	70	70				
1.1	1.5	70	70		76	85	
1.5	2.0	70	70		76	85	
2.2	3.0	72	74		76	88	
4.0	5.0	73	74		80	88	
5.5	7.5	76	79		80	91	
7.5	10	76	79		82	91	
11	15	80	84		82	94	
15	20	80	84		84	94	
17	25	80	88		84	94	
22	30	80	88		86	94	
30	40	84	89		86	100	
40	50	84	89		89	100	
45	60	86	95		89	101	
55	75	86	95		94	101	
75	100	89	98		94	102	
100	125	89	100		98	104	
110	150	93	100		98	104	
150	200	93	103		101	107	
185	250	103	105	99	101	107	
220	300	103	105	99	107	110	102
260	350	103	105	99	107	110	102
300	400	103	105	99	107	110	102
335	450	106	108	102	107	110	102
370	500	106	108	102	110	113	105
450	600	106	108	102	110	113	105
520	700	106	108	102	110	113	105
600	800	108	111	104	110	113	105
670	900	108	111	104	111	116	106
750	1000	108	111	104	111	116	106
930	1250	108	111	104	111	116	106
1,100	1500	109	113	105	111	116	106
1,300	1750	109	113	105	112	118	107
1,500	2000	109	113	105	112	118	107
1,700	2250	109	113	105	112	118	107
1,850	2500	110	115	106	112	118	107
2,250	3000	110	115	106	114	120	109

Table 1.4 Expected Incremental increase over no-load condition in A-weighted sound power levels ΔL_{wA}, dB(A) for rated load condition for single-speed, three-phase, cage induction motors according to NEMA [162] and IEC 60034-9 Standards [93].

Rated power		Number of poles			
kW	hp	$2p = 2$	$2p = 4$	$2p = 6$	$2p = 8$
1 to 11	1.0 to 15	2	5	7	8
1 to 37	15 to 50	2	4	6	7
37 to 110	50 to 150	2	3	5	6
110 to 400	150 to 500	2	3	4	5

the internal ventilating passages leading directly to the electric parts of the machine itself. The sound power level at rated load should be adjusted according to Table 1.4. The increase in the sound power level under load is mostly due to the change in the air gap magnetic flux density harmonic amplitudes. This effect can be expressed by the following equation [137]

$$\Delta L_W = 10 \log_{10} \left(\frac{B_{load}}{B_{noload}} \right)^2 \tag{1.7}$$

Table 1.5 shows maximum sound pressure level at 1 m from the machine surface according to IEC 60034-9 Standards [93]. Table 1.6 shows maximum sound power level according to IEC 60034-9 Standards [93].

The *sound pressure level spectrum* is the distribution of effective sound pressures measured as a function of frequency in specified frequency bands. It can also be defined as the resolution of a signal into components, each of different frequency and different amplitude (Figure 1.6). If the sound pressure level spectrum is given in a form of the Fourier series

$$p = \sum_{k=1}^{k_{max}} P_{mk} \sin(\omega_k t + \phi_k) \tag{1.8}$$

where P_{mk} is the amplitude of the kth harmonic, $\omega_k = 2\pi k f$ is the angular fequency of the kth harmonic, and ϕ_k is the phase angle for the kth harmonic, the overall sound pressure, level is calculated as a sum of amplitudes squared, i.e.,

$$P = \sum_{k=1}^{k_{max}} P_{mk}^{z} \quad \text{W.} \tag{1.9}$$

The sound pressure level in dB is then calculated according to Equation A.25.

The *broad-band noise* is the noise in which the acoustic energy is distributed over a relatively wide range of frequencies. The spectrum is generally smooth and continuous.

The *narrow-band noise* is the noise in which the acoustic energy is concentrated in a relatively narrow range of frequencies. The spectrum will generally

Table 1.5 IEC 60034-9 limits for sound pressure level at 1 m from machine surface, dB(A) [93].

Rated power	$n < 960$ rpm		$960 < n < 1320$		$1320 < n < 1900$	
kW	ODP	TEFC	ODP	TEFC	ODP	TEFC
$P_{out} < 1.1$		67		70		71
$1.1 < P_{out} < 2.2$		69		70		73
$2.2 < P_{out} < 5.5$		72		74		77
$5.5 < P_{out} < 11$	72	75	75	78	81	81
$11 < P_{out} < 22$	75	78	78	82	81.5	85.5
$22 < P_{out} < 37$	77.5	79.5	80.5	83.5	83	86
$37 < P_{out} < 55$	78.5	80.5	82.5	85.5	86	88
$55 < P_{out} < 110$	82	94	85	89	88.5	91.5
$110 < P_{out} < 220$	85	87	87	91	90.5	93.5
$220 < P_{out} < 400$	86	88	89	92	92.5	95.5
Rated power	$1900 < n < 2360$		$2360 < n < 3150$		$3150 < n < 3750$	
kW	ODP	TEFC	ODP	TEFC	ODP	TEFC
$P_{out} < 1.1$		74		75		77
$1.1 < P_{out} < 2.2$		78		80		82
$2.2 < P_{out} < 5.5$		82		83		85
$5.5 < P_{out} < 11$	81	86	84	87	87	90
$11 < P_{out} < 22$	83.5	87.5	86.5	90.5	90	93
$22 < P_{out} < 37$	85.5	89.5	88.5	92.5	92	95
$37 < P_{out} < 55$	88	94	93	96	95.5	98.5
$55 < P_{out} < 110$	90.5	93.5	92.5	93.5	95	98
$110 < P_{out} < 220$	93	96	95	98	96	100
$220 < P_{out} < 400$	94	98	95	99	98	102

show a localized "hump" or peak in amplitude. Narrow-band sound may be superimposed on broad-band sound.

1.6 Deterministic and statistical methods of noise prediction

In the efforts to predict the noise emitted from an electric machine, there are two approaches: deterministic and statistical methods . In the deterministic method, shown in Figure 1.7a, the electromagnetic forces acting on a motor structure have to be calculated from the input currents and voltages using an electromagnetic analytical model [254] or the FEM model [226]. The vibration characteristics are then determined using a structural model normally based on the FEM [223, 230]. By using the vibration velocities on the motor structure predicted from the structural model, the radiated sound power level can then be calculated on the basis of an acoustic model. The acoustic model may be formulated using either the FEM or boundary-element method (BEM). Generally, for calculating

Table 1.6 IEC 60034-9 limits for sound power level, dB(A) [93].

Rated power	$n < 960$ rpm		$960 < n < 1320$		$1320 < n < 1900$	
kW	ODP	TEFC	ODP	TEFC	ODP	TEFC
$P_{out} < 1.1$		76		79		80
$1.1 < P_{out} < 2.2$		79		80		83
$2.2 < P_{out} < 5.5$		82		84		87
$5.5 < P_{out} < 11$	82	85	85	88	88	91
$11 < P_{out} < 22$	86	89	89	93	92	96
$22 < P_{out} < 37$	89	91	92	95	94	97
$37 < P_{out} < 55$	90	92	94	97	97	99
$55 < P_{out} < 110$	94	96	97	101	99	103
$110 < P_{out} < 220$	98	100	100	104	103	106
$220 < P_{out} < 400$	100	102	103	106	106	109
Rated power	$1900 < n < 2360$		$2360 < n < 3150$		$3150 < n < 3750$	
kW	ODP	TEFC	ODP	TEFC	ODP	TEFC
$P_{out} < 1.1$		83		84		86
$1.1 < P_{out} < 2.2$		87		89		91
$2.2 < P_{out} < 5.5$		92		93		95
$5.5 < P_{out} < 11$	91	96	94	97	97	100
$11 < P_{out} < 22$	94	98	97	101	100	103
$22 < P_{out} < 37$	96	100	99	103	102	105
$37 < P_{out} < 55$	99	103	101	105	104	107
$55 < P_{out} < 110$	102	105	104	107	106	109
$110 < P_{out} < 220$	105	108	107	110	108	112
$220 < P_{out} < 400$	107	111	108	112	110	114

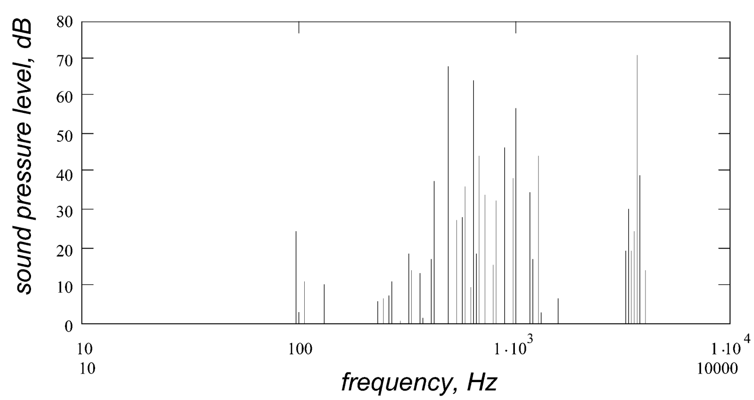

Figure 1.6 Sound pressure level spectrum.

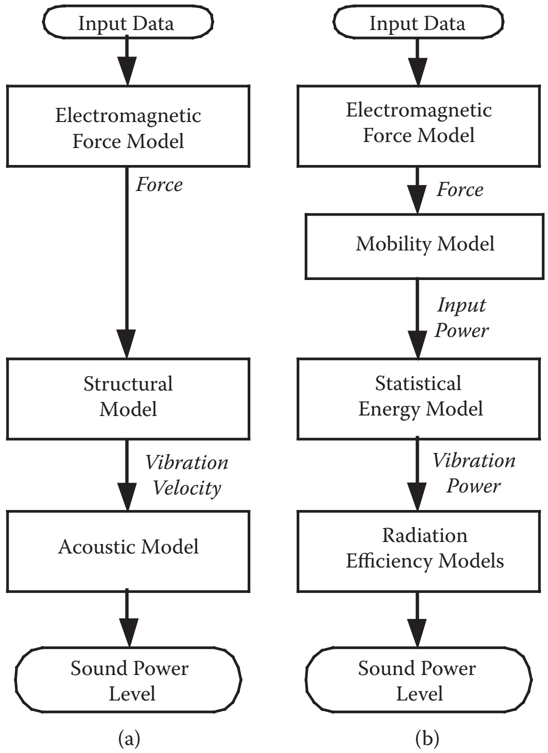

Figure 1.7 Flowcharts for noise prediction: (a) deterministic method; (b) statistical method.

the noise radiated into a space, the BEM is preferred because only the surface of the motor needs to be discretized and the space does not have to be discretized.

Although, the analytical and FEM/BEM numerical approaches seem to work well, there are quite a number of limitations for it to be applied in practice (Section 1.8).

In deterministic approach, sometimes, simplified models can be utilized and analytical calculations can be implemented by writing a *Mathcad*[1] or *Mathematica*[2] computer program for fast prediction of the sound power level spectrum generated by magnetic forces. The accuracy due to physical errors may not be high, but the time of computation is very short and it is very easy to introduce and manage the input data set.

The main program consists of the input data file, electromagnetic module, structural module (natural frequencies of the stator system), and acoustic module. The following effects can be included: phase current unbalance, higher space

[1] industry standard technical calculation tool for professionals, educators, and college students

[2] fully integrated technical computing environment used by scientists, engineers, analysts, educators, and college students

harmonics, higher time harmonics, slot openings, slot skew, rotor static eccentricity, rotor dynamic eccentricity, armature reaction, magnetic saturation. An auxiliary program calculates the torque ripple, converts the tangential magnetic forces into equivalent radial forces, and transfers radial forces due to the torque ripple to the main program.

The input data file contains the dimensions of the machine and its stator and rotor magnetic circuit, currents (including unbalanced system and higher time harmonics), winding parameters, material parameters (specific mass, Young modulus, Poisson's ratio), speed, static and dynamic eccentricity, skew, damping factor as a function of frequency, correction factors, e.g., for the stator systems natural frequencies, maximum force order taken into consideration, minimum magnetic flux density to exclude all magnetic flux density harmonics below the selected margin. The rotor magnetic flux density waveforms are calculated on the basis of MMF waveforms and permeances of the air gap. Magnetic forces are calcualated on the basis of Maxwell stress tensor. The natural frequencies of the stator system are calculated with the aid of equations given in Chapter 5. Those values can be corrected with the aid of correction factors obtained, e.g., from the FEM structural package. Then, using the damping coeffcient as a function of frequency, amplitudes of radial velocities are calculated. The damping factor affects significantly the accuracy of computation. Detailed research has shown that the damping factor is a nonlinear function of natural frequencies. The radiation efficiency factor (Chapter 6), acoustic impedance of the air and amplitudes of radial velocities give the sound power level spectrum (narrow band noise). The overall noise can be found on the basis of Equation 1.9. The overall sound power level calculated in such a way is lower than that obtained from measurements because computations include only the noise of magnetic origin (mechanical noise caused by bearings, shaft misalignment, and fan is not taken into account) and usually, the calculation is done for low number of harmonics of magnetic flux density waves.

The FEMs/BEMs, by their nature, are limited to low frequencies. This is because the number of elements required for the model increases by a factor of 8 when the upper frequency of interest is doubled and the number of vibration modes increases significantly with frequency [230]. If the FEMs/BEMs are applied to a large motor for frequencies up to 10,000 Hz, the number of elements and the computing time required will become prohibitive, as discussed in [223].

A method that is particularly suitable for calculations of noise and vibration at high frequencies is the so-called *statistical energy analysis* (SEA) (Chapter 10), which has been applied with success to a number of mechanical systems such as ship, car, and aircraft structures [140]. This method, however, was applied for the first time to electrical motors in 1999 [43, 223, 230]. The method basically involves dividing a structure (such as a motor) into a number of subsystems and writing the energy balance equations for each subsystem, thus allowing the statistical distribution of energies over various frequency bands to be determined. This method is normally valid for high frequencies where the modal overlap is high [140]. An outline of the calculation procedure using the statistical method is given in Figure 1.7b. The main advantage of the statistical approach is that it does not require all the details to be modeled. The accurate distribution of the electromagnetic force might not be so important; only the total force in a frequency band is required. Thus, the electromagnetic force needs not be calculated using a FEM model and an approach such as that adopted by Cho and Kim [31] might be suitable. By considering the motor as a simple cylindrical shell, the input power due to this electromagnetic force can be formulated using an analytical ”mobility” model. By invoking a statistical energy model, this input power can then be distributed as vibrational power to different subsystems which make up the motor. If the sound radiation efficiencies of these subsystems are known, then the sound power due to each subsystem can be calculated. Since a motor structure can be decomposed into simple structural elements such as cylindrical shells, plates, and beams, the radiation efficiencies of these simple structural elements can be determined analytically, as depicted in the radiation efficiencies model in Figure 1.7b.

1.7 Economical aspects

Figure 1.8 shows the distribution of the magnetic flux density in the magnetic circuit of a 4-pole permanent magnet (PM) brushless machine. The magnetic flux density in the stator return path (yoke) is proportional to the magnetic flux density in the air gap and can be a measure of both the noise of electromagnetic origin and machine

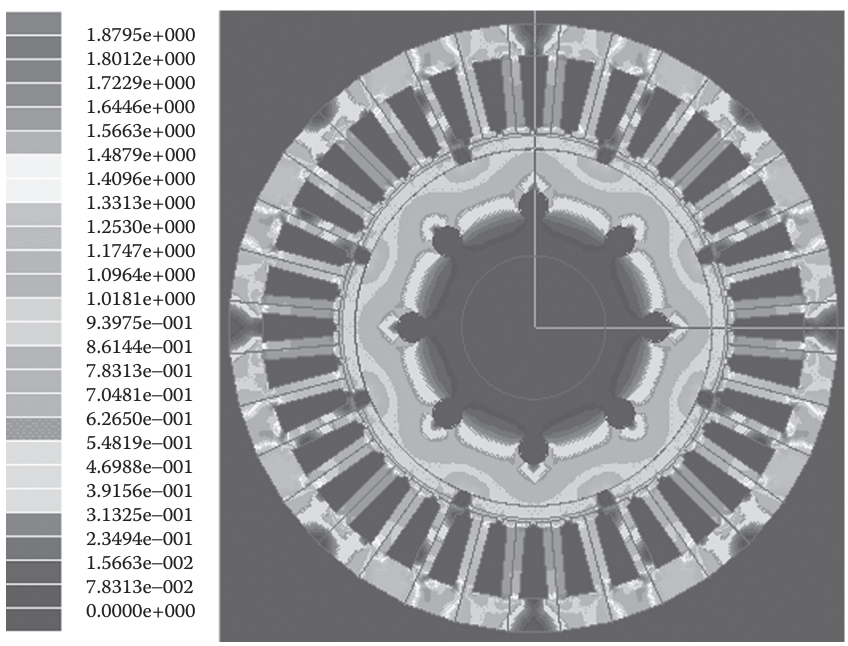

Figure 1.8 Distribution of the magnetic flux density in the cross section of a 4-pole brushless machine with surface PMs, as obtained from the 2D FEM.

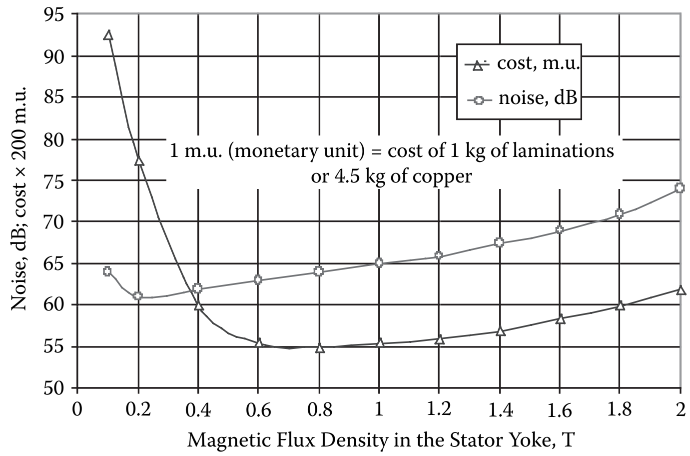

Figure 1.9 Noise level and cost plotted against magnetic flux density (MFD) in the stator yoke for a 200 kW induction motor [2].

cost. Figure 1.9 shows the noise and total cost of an induction machine rated at 200 kW, 50 Hz, 380 V, 1480 rpm [2]. To keep the cost independent of inflation, an arbitrary monetary unit (m.u.) has been used that is equal to the price of 1 kg of steel sheets. Using this unit, the copper wire costs 4.5 m.u./kg and aluminum costs 3 m.u./kg [2]. The minimum of cost is different than the minimum of noise. Therefore, low magnetic flux density (MFD) means low level of noise and, vice versa, increased utilization of the magnetic circuit results in increased noise. The minimum of cost is for the MFD in the stator yoke in the range from 0.6 to 1.0 T. The minimum of noise is for lower MFDs; however, due to increase in dimensions and mass of active materials the cost increases sharply at low MFDs in the stator yoke.

1.8 Accuracy of noise prediction

The results of both analytical and numerical noise prediction may significantly differ from measurements. Forces that generate vibration and noise are only small fraction of the main force produced by the interaction of the fundamental current and the fundamental normal component of the magnetic flux density. The power converted into acoustic noise is only approximately 10^{-6} to 10^{-4} of the electrical input power.

The accuracy of the predicted, say, sound power level spectrum depends not only on how accurate the model is, but also how accurate are the input data, e.g., level of current unbalance, angle between the stator current and q-axis (in PM brushless machines), influence of magnetic saturation on the equivalent slot opening, damping factor, elasticity modulus of the slot content (conductors, insulation, encapsulation), higher time harmonics of the input current (inverter-fed motor), etc.

All the above input data are difficult to predict with sufficient accuracy. Listed below are the common problems encountered in the analytical and numerical noise prediction [213, 220]:

1. The most difficult task in analytical calculation of sound power level radiated by electrical machines is the accurate prediction of the natural frequencies of the stator structure. At present, the best method to calculate the natural frequencies of the stator is to use the FEM. This is the only technique that can take into account with reasonable accuracy the end bells, mountings (feets or flanges) and asymmetries due to, e.g., terminal boxes.
2. The calculation of matrices of the mass $[M]$ and stiffness $[K]$ seems to be obvious in the FEM. However, the physical properties of the materials used in electrical machines design are not known. The anisotropy of laminations, internal stresses caused by manufacturing, and change in stiffness matrix $[K]$ due to temperature variation (differential thermal expansion of the laminations and housing) are mostly not taken into account.
3. The damping matrix $[C]$ in the FEM is difficult to predict. There are no adequate models available for describing damping in laminated materials and structures composed of different types of materials, e.g. copper, insulation, epoxy, laminations. Practice shows that good values for the damping are absolutely essential for predicting accurate vibrational amplitudes.
4. The force vector $\{F(t)\}$ has to be found in all points on the inner stator surface. Even the most accurate FEM programs introduce a lot of errors in force calculations [213]. Forces are usually calculated analytically in the preprocessor module on the basis of magnetic flux density harmonics or using a 2D FEM.
5. Because neither the analytical approach nor the FEM/BEM computations guarantee accurate results, the laboratory tests are always very important.
6. The main advantage of the SEA is that it does not require all details to be modeled.
7. The vibration and acoustic noise can be calculated on the basis of *modal analysis* which is free of calculating the electromagnetic forces [213]. Only flux linkages have to be calculated (Section 9.2.2).
8. The calculated noise level is rather lower than the measured noise level. The calculation is mostly done for low harmonic numbers of the air gap permeance. The measurement gives the total noise level due to all harmonics [220].