EXPERIMENTAL INVESTIGATIONS ON VIBRATIONS AND ACOUSTIC NOISE OF AN INDUCTION MOTOR

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By

Wen Wen Li

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ABSTRACT

Electric motors are important machines as they are widely used in industry. Unfortunately, they produce annoying noise which is a big concern. In order to obtain better understanding of vibrations and noise produced by induction motors, extensive investigations have been conducted on a specially designed test motor. It is well known that electromagnetic forces cause vibrations of the motor, producing radiated acoustic noise. The physical interpretations drawn from the experimental results reported in this thesis are beneficial to correlate the vibrations and the radiated noise.

ISO and IEEE standards stipulate the procedures for conducting acoustic measurements so that reliable, reproducible results with specified level of accuracy can be obtained. ISO and IEEE standards describe suitable methods and measuring systems in order to arrange all the investigations in such a way that a systematic analysis can be performed. Relevant discussions with reference to these standards are presented in the thesis.

After discussing the noise problems of induction motors encountered in industry and the workplace, the basic definitions and terms used for sound measurements are provided. Brief descriptions of various instruments used for vibration and noise measurements are also given.

Before proceeding with the actual experimental investigations, it is essential to summarize the theoretical analyses of electromagnetic fields and electromagnetic forces produced in an induction motor. Harmonic analysis of the stator current, spectral analysis of the induced voltage in stator search-coils, and noise measurements using a sound-level-meter form the preliminary investigations which bridge theoretical analyses and detailed experimental investigations.

Vibration measurements are fundamental in providing information on spectral distributions of noise. Mode-shape measurements show the stator deformations under electromagnetic forces, which are created by the three-phase currents. The effects of impressed voltage and the change of load on vibration levels are also investigated.

Noise measurements are conducted in both an ordinary laboratory and an anechoic chamber. The ordinary laboratory is similar to the practical workplace, which is neither a free-field nor a reverberant-room. The measurement results obtained in the laboratory are of practical importance. The anechoic chamber provides the free-field condition, where measurements corresponding to various standards are required. The results obtained in both ordinary laboratory and anechoic chamber are compared to produce useful practical information about the noise level change caused by sound fields. Also, the directional characteristics are carefully studied in the anechoic chamber. The results obtained are very helpful in understanding the nature of the noise radiation patterns of the motor.

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LIST OF PRINCIPAL SYMBOLS

$A_0, A_1, ..., A_n$	Fourier coefficient
$B_1, B_2, ..., B_n$	Fourier coefficient
$B(\theta,t)$	Air-gap flux-density, T
BW	Band-width, Hz
F, $F(\theta,t)$	Force, N
I	Sound intensity, Wm^{-2}
K_{cS}, K_{cR}	Carter's coefficients
L_P	Sound pressure-level, dB
L_{pi}	Band pressure-level resulting from i^{th} measurement, dB
$L_{P(M)}$	Average sound pressure-level, dB
L_w	Sound power-level, dB
$M(\theta,t)$	Magnetomotive force (MMF), A (ampere-turns)
N	Number of sampling points
P_1, P_2, P_n	Measuring locations
S	Number of stator slots
S(t)	Function of a signal
T	Period, s
ΔT	Time interval, s
W	Average sound power, W
W_{ref}	Reference sound power, 1×10^{-12} W (1 pW)
X, X_1, X_2	Amplitude
X	Coordinate axis
Y, Z	Coordinate axis
Z	Number of rotor slots

a,b,c	Some important values, m
c	Velocity of sound in the medium, ms^{-1}
f	Frequency, Hz
f_c	Center frequency, Hz
f_1	Lower cut-off frequency, Hz
f_2	Upper cut-off frequency, Hz
Δf	Frequency spacing, Hz
f_{max}	Maximum frequency component, Hz
g_1	Integer
k	Integer
m	Mass, kg
n	Integer
n	Circumferential mode
p	Sound pressure, Pa (Nm^{-2})
p	Pairs of poles
p_{ref}	Reference pressure, 2×10^{-5} Pa (Nm^{-2})
p_{rms}	Root-mean-square sound pressure, Pa (Nm^{-2})
r_d	Reference radius, m
r_s	Equivalent radius, m
s	Stiffness or spring constant, N/m
s	Slip
s_0	1.0 m^2
t	Time, s
u	Particle velocity, m/s
v	Velocity, m/s
x	Displacement, m
$x(t)$	A pure sinusoidal signal
α	Arbitrary constant
ϕ	Initial phase angle
θ	Location around the circumference, mechanical radians
ω	Angular frequency, rad/s

$\lambda(\theta,t)$	Permeance, Wb/A
λ_0	Average air-gap permeance, Wb/A
ρ	Constant equilibrium density of the medium, kg m^{-3}
η	Integer
μ_0	Permeability of free space, $4\pi\times10^{-7}$ H/m
δ	Air-gap length, m

Subscripts

k,n,η	Refers to the corresponding harmonic orders
p	Refers to the fundamental air-gap field
R	Refers to rotor
S	Refers to stator
sa	Saturation

1. INTRODUCTION

Electric motors provide power for a large and increasing part of modern industry. Noise is often a problem not only in the working environment, caused by production machinery in the factory to business machines in the office, but also in homes from the hair-dryer to the lawn mower.

A quiet product has distinct marketing advantages over its noisy competitor no matter what it is designed for. But achieving a worthwhile reduction in the noise output of a product can be an extremely costly, difficult and time-consuming process. For example, considering a 100 W hair-dryer, which is a low power domestic appliance, if only a fraction of this available power is converted into noise, the sound pressure-level at a distance of 30 cm could be of the order of 80 dB [1]. It is, therefore, easy to envisage the difficulties involved in reducing the noise of electrical machines, ranging from a small motor to a large 500 MW generator in a power plant.

Since the acoustical energy loss is insignificant, this explains why design engineers do not worry about the acoustical energy loss, and noticeable noise problems. On the other hand, owing to increasing economic pressures, modern electrical machines are designed to use higher currents and flux-densities, which often result in noise problems.

Increasing applications of electrical machines have resulted in growing awareness of the noise problems produced by them. Also, more and more people are concerned about environmental noise and occupational noise exposure. Noise, by virtue of its diverse effects ranging from mere nuisance or annoyance to actual demonstrable physiological harm, presents a special problem requiring far more expertise and interdisciplinary efforts than perhaps any other traditional environmental problems [2]. Legislation requiring assessment, control and abatement of noise has been enacted at all governmental levels [3]. Hence, noise control is of interest to machine designers, work engineers and safety officers, and others.

No matter what initially stimulates the concern about a possible noise problem, the first action should be to ascertain if a noise problem exists, i.e., to determine the value of the noise. It is universally accepted that the sound power-level is a very important index, though sound pressure-level is a useful parameter to describe sound waves quantitatively.

Due to many concerns, it is required to reduce machinery noise. Many manufacturers, now, attempt to reduce the noise of their products at the design stage. Noise occurs as a by-product of mechanical or aerodynamic motion which may be necessary to, or produced by, the normal operation of the machine and can be readily associated with its various moving parts. Rubbing and rolling contact, impact of moving parts, panel resonance induced by imbalance, meshing of gears, turbulent flow, and fan tones, all have characteristic spectra from which the source of the noise can be identified [1].

When electrical and mechanical mechanisms operate within a machine, the dynamic forces produce structural vibrations in the machine. These vibrations are transmitted through the machine and produce exterior surface vibrations and related sound. Noise from machinery is usually complex and it is a combination of many sinusoidal components. It is always important to understand the origin of the noise and magnitude of the noise before any noise-control methods are performed. The analysis of the sound from a machine provides very important information on the design and performance of the machine. Also, it provides useful information for future improvements.

Most of the work done, so far, was concerned with the identification and explanation of the more prominent components of noise and vibration, in order to provide information about the rules to produce quieter machines and the prediction of noise at the design stage. In this connection, the important aspect is the measurement of vibrations and noise produced by electrical machines.

1.1 Annoyance and Damage Caused by Noise

Sound ordinarily refers to audible pressure fluctuations in air. When a body moves through a medium or vibrates, some energy is transmitted to the surrounding medium in the form of sound waves. Sound is also produced by turbulence in air and other fluids, and also by fluids moving past stationary bodies. In general, sound may be transmitted by solids, liquids and gases. As is well known, sound travels much faster in solids than in air.

Sound is produced within a large frequency range. The audible sound for young persons is between about 20 Hz and 20,000 Hz. Sound may consist of a single pure tone, but in general, it is made up of several tones of different loudness. Noise is defined as unwanted sound. Noise and sound are produced by an aircraft, punch press, stereo speaker system, etc. Sound is the result of a source setting a medium into vibrations. Usually, the medium is air and the receptor is the ear. Based on the characteristic of sound, the sensory conclusion drawn by the brain may be noise or sound, i.e., unwanted or wanted sound. What is pleasing to one individual may be disturbing noise to others. Thus, the distinction between noise and sound can be subjective [4, 5].

Noise draws emotional responses with respect to conscious and subconscious levels. It annoys, awakens, angers, distracts, frustrates and creates stresses, which results in physiological and psychological problems. Noise is invisible, yet its effects are profound.

Annoyance is a more complex phenomenon than loudness; it is influenced by a variety of acoustic and non-acoustic factors. The acoustic factors include the absolute level, duration, and spectral distribution of sound energy, as well as fluctuations in them. Non-acoustic factors include adaptation (habituation or sensitization), degree of involvement in ongoing activities at the time of noise exposure, attitudes toward noise sources and their operators, and the body condition.

Excessive noise levels are generally acknowledged to have adverse effects on health and well-being. Studies indicate that excessive noise can cause fatigue in exposed individuals, lower efficiency and productivity, impaired speech communication, hearing loss, and can create physical and psychological stress. Excessive noise is almost everywhere today, e.g., offices, schools, hospitals and other institutional facilities, in all classes of public buildings and factories [4, 6, 7].

High noise levels in factories can make speech communication difficult and at times impossible. The problem of hearing loss due to excessive noise exposure is of particular concern to industry, and to the governments. An estimated 14 million workers in the U.S. are exposed to hazardous noise [6]. With impaired hearing, it is very difficult to lead a normal life either on or off the job. Noise may tire out the inner ear, causing temporary hearing loss. After a period of time off, hearing is restored. With continuous noise exposure, the ear will lose its ability to recover from temporary hearing loss, and the damage will become permanent. Permanent hearing loss results from the destruction of cells in the inner ear, cells which can never be replaced or repaired. Such damage can be caused by long-term exposure to loud noise or, in some cases, by brief exposure to very loud noise. Workers who have been exposed to significant level of noise over a work life of 40 years or so show consistent patterns of hearing loss. Impairment of speech communication among workers is deterrent to efficiency and productivity as well as detrimental to the occupant's comfort and sense of well-being.

Excessive noise levels are often experienced by individuals beyond plant boundaries. Nearby residents, office personnel, and visitors to noisy plants are often similarly exposed to excessive noise and are likewise subject to the adverse effects of such noise on health and well-being.

Excessive noise can destroy the ability to hear and it may also put stress on other parts of the body, including the heart. Although research on the effects of noise is not quite complete, it appears that noise can cause quickened pulse rate, increased blood pressure and narrowing of the blood vessels. Exposure over a long period of time may cause an added burden on the heart. Noise may also put stress on other parts of the body by causing abnormal secretion of hormones and tension on muscles. Workers exposed to excessive noise complain of nervousness, sleeplessness and fatigue. Noise exposure can also reduce job performance and may cause increase rates of absenteeism [6].

For most effects of noise, there is no cure. So, prevention of excessive noise exposure is the only way to avoid ill-effects to health. The damage done by noise depends mainly on how loud it is and on the exposure period. The frequency (or pitch) can also have some effects since high-pitched sounds are more damaging than low-pitch ones. Pure tones are more disturbing than a broad-band sound. For frequencies in the range of 3000 to 6000 Hz, hearing losses increase rapidly over the first 10 to 15 years of exposure, and then they remain constant as the same exposure continues for a period of 40 to 50 years. At lower frequencies, 500 to 2000 Hz range, the hearing loss does not increase as rapidly but it continues to increase throughout the period of exposure [8].

1.2 Noise from Rotating Electrical Machines

The electric motors and drives provide the mechanical power for a large and increasing part of modern industrial economy. Owing to the increasing economic pressures modern electrical machines are designed to use higher currents and flux-densities, which often result in noise problems. The increasing applications of electrical machines have resulted in a growing awareness of the noise problem produced by them.

Stricter regulations for noise-control are now being enforced in order to protect people from the hazards of a noisy environment. The reduction of noise has become an important consideration in designing electrical machines.

Generally, there are three basic types of noise sources associated with electrical machines:

(i) Windage (aerodynamic origin),

(ii) Mechanical (mechanical motion and parts), and

(iii)Magnetic (electromagnetic fields).

The flow of air through an electrical machine can cause noise problems. The flow of air is obstructed by the rotating parts of the machine producing the windage-noise. The siren tones are produced by the chopping action of the rotor bars and blades on the ventilation air that passes through the machine and is being exhausted from the stator.

The mechanical noise is caused by bearings, brushes, imbalance of rotating parts, etc. Rotor imbalance as a noise-producing element has been practically eliminated by modern balancing equipment and techniques. Sleeve-journal type bearings are really not a noise contributor, but ball and roller bearings do produce substantial noise. The condition of the bearing parts and the clearances between them are very important considerations. Brush noise is another source of mechanical noise determined by the condition and quality of the brushes, their holders, and the rotating contact surface.

The electromagnetic noise is produced by the forces created by the magnetic-field of machine. Forces acting across the air-gap of a machine produce cyclic deformations giving rise to vibrations of the stator-core. These forces can be particularly troublesome if they are coincident with resonant frequencies of the stator-core or other parts of the machine. At every point on the air-gap surface, there is a varying force proportional to the square of the flux-density. The sum of the tangential components of this force is proportional to the total torque which produces the useful work of the motor. Pulsations of the tangential force produce a torsional vibration of the stator which, in turn, may cause the frame of the stator to rock on its mountings, leading to structure-borne vibrations. The radial components of the magnetic forces do not contribute towards useful work, but produce noise. The magnetic forces are determined by the mechanical and electromagnetic arrangements of the stator-rotor assembly.

The radial magnetic forces depend on [8]:

- The number of stator and rotor slots and the difference between these two numbers.
- The nature of the magnetic-field produced by the machine.
- Permeance variations in the air-gap caused by stator and rotor slots, saturation, and air-gap eccentricities.
- The radial length of the air-gap.

1.3 Measures and Regulations for Noise Control

The international concern for the wide-spread adverse effects of environmental noise has created a demand for the development of community noise control programs. At the present time, however, there is no universal criterion for defining excessive sound for its properties are unlike those of any other pollutant; a sound leaves no residue and becomes noise only when it is "undesired" and causes unpleasant psychological or physiological reactions [9].

Noise is a problem of great economic importance in modern society. As mentioned earlier, when the noise level in business or educational institutions is high enough to interfere with speech communication, economic losses are sustained. Compensation cases involving claims for many millions of dollars towards permanent hearing damage have been filed in the courts [8]. Another aspect of the economic importance of noise is shown by the effects of noise on property values. For example, the noise from the operation of an airfield or from a factory does influence the value of the land in the surrounding area. Considerable efforts are being made by industry to develop products that are quiet, and by the business world to achieve quiet conditions in offices and factories for economic reasons. While it is not always possible to state explicit relationships between noise and its effects on humans, it is of utmost significance that business and industry are spending considerable amounts of money and effort to achieve quiet conditions. It has been estimated that the total annual dollar sales of acoustical materials have increased tenfold during 80's in the United States [8].

Because of the growing awareness of noise problems, strict regulations for noise control are now being enforced in order to protect people from the hazards of noisy environment. For example, in the United States, regulatory measures and program tools for noise-control are exercised by national, state, and local governments. In addition, control measures by consumers, industry, and standards organizations are also exercised. The following are examples of regulatory controls and proposed controls in the United States [4]:

- Federal Government:
  - (i) Environment Protection Agency.
  - (ii) Department of Transportation, including Federal Highway Administration (FHWA), Federal Aviation Administration (FAA), and other agencies.
  - (iii) Department of Labor, Occupational Safety and Health Administration (OSHA).
  - (iv) Department of Interior.
  - (v) Housing and Urban Development (HUD).
  - (vi) Department of Health, Education, and Welfare (HEW), National Institute for Occupational Safety and Health (NIOSH).
  - (vii) Other Federal Agencies.
- State and Local Regulatory Measures.
- Consumers.
- Industry.
- Standards Agencies.

Also, similar regulations are enforced in many industrialized countries.

1.4 Standards and Institutes Concerning Noise Problems

Development agencies are increasingly recognizing that a standardization infrastructure is a basic condition for the success of economic policies aimed at achieving sustainable development. No industry in today's world can truly claim itself to be completely independent in many aspects. Today's free-market economies increasingly encourage diverse sources of supply and provide opportunities for expanding markets. On the technology side, fair competition needs to be based on identifiable, clearly defined common references that are recognized from one country to the next, and from one region to the other.

Standards are documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions of characteristics to ensure that materials, products, processes and services are fit and proper. Industry-wide standardization is a condition existing within a particular industrial sector when the large majority of products or services conform to the same standards. It results from consensus agreements reached between all economic players in that industrial sector; suppliers, users, and often governments. They agree on specifications and criteria to be applied consistently in the choice and classification of materials, the manufacture of products, and the provision of services [8].

There are many non-governmental organizations responsible for the development and documentation of noise standards. As international organizations, there are International Organization for Standardization (ISO) and International Electrical Commission (IEC). USA organizations include American National Standards Institute (ANSI), Institute of Electrical and Electronic Engineers (IEEE), Acoustical Society of America (ASA), Institute of Noise Control Engineering (INCE), and 36 other organizations. There are also more than 30 non-USA national organizations around the world, such as Standards Council of Canada, British Standards Institution, China State Bureau of Technical Supervision, etc.

1.5 The Noise Problem of Induction Motors

Electric motors are the most important type of electrical machines. They are widely used in numerous applications. The range of sizes and types of electric motors is extensive, and the number and diversity of their applications continue to expand. In 1993, electric motors account for the single largest use of electricity in the US economy; roughly 53% of all electricity consumed [10]. Three-phase induction motors are the most widely used motors in industry because they are more economical to produce, robust and require less maintenance than other types of motors. They constitute about 80% of the total number of motors used in an average plant [11]. The vast majority of the induction motors used in industry are squirrel-cage induction motors because of their low cost, high reliability and fairly high efficiency.

Polyphase induction motors span over a range of ratings from ½ hp to as large as 45,000 hp, depending on the capability of the local electrical power system. Most motors convert at least 80% of their electrical input energy into useful mechanical output. For large machines, the efficiencies are often higher than 90%. Table 1.1 shows the population of induction motors in the United States according to the power rating [12].

Table 1.1: Estimated population of polyphase induction motors in the United States.

Horsepower Rating	Population
5-20	10,000,000
21-50	3,300,000
51-125	1,700,000
126 and larger	400,000

Due to the special role that induction motors play in modern industry, the vibration and noise problems caused by them have been studied by several researchers. In one of the earlier papers, Erdelyi [13] gave the general mathematical description of the amplitudes of electromagnetic force-waves, the dynamic response of the motor therefore required. The sound pressure-levels were measured in octave-bands whose center frequencies are 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz by using A- and C- weightings, respectively. Also, the overall A-weighting and C-weighting values were obtained. In order to isolate the noise emitted from the loading machines, a sound barrier was used between the motor and the coupling-load. The four motors used were 600 hp, 700 hp, 1000 hp and 1500 hp, respectively. The measured results from three measuring positions reported in this paper, just cover the noise characteristics of the motors partially.

The maximum allowable noise levels associated with the operation of electrical machines of different sizes and speeds are stipulated in the various standards, e.g., Ref [17]. Although these noise levels present the upper limit, they do not necessarily reflect upon the achievable levels with the present state of the art for the design of electrical machines. The researchers have made progress with respect to vibration and noise problems of induction motors. However, much more understanding of the procedures and instrumentation for the measurements, and the necessary improvements, are still required on the study and the correlation between vibrations and noise.

1.6 Objectives

As discussed earlier, the noise problem of induction motors is a big concern due to their importance in industry. Although many researchers have published extensive information on the vibration and noise studies of induction motors, there is a need to analyze the electromagnetic forces, vibrations and the resulting noise of induction motors systematically.

The spectral investigations on electromagnetic forces, vibrations and noise definitely provide useful information in depth in achieving a good sonic design. The various electromagnetic forces acting on the stator and rotor of a motor may produce excessive vibrations and noise, especially when the frequencies of the exciting forces are equal to or near the resonant frequencies of the machine structure. Balan [18, 19] developed excitation systems to study in detail the vibration response of the machine stator-structures over a very wide audible frequency range, using a 10 hp squirrel-cage and a 120 hp wound-rotor induction motor. It is clear that there are circumferential deformations of the stator under exciting forces, as well as longitudinal deformations. Varying the frequency of the exciting-force creates different deformation patterns. The air-gap field of an induction motor contains a variety of harmonic components. Balan has performed the theoretical analyses on air-gap harmonic-fields and electromagnetic forces systematically, taking into account the variation of air-gap permeance, saturation, and multiple armature reaction. He focuses on the vibration aspects of research of induction motors. Extensive investigations on the audible-noise aspects are required to pursue this research further.

In this thesis, based on the theoretical analyses of electromagnetic forces and the previous investigations on motor vibrations, investigations are carried out on a 10 hp squirrel-cage induction motor to achieve the following objectives:

- To acquire a physical understanding of the vibration and acoustical characteristics of medium size induction motors.
- To obtain relevant qualitative and quantitative information about the magnetic-fields in the air-gap of a squirrel-cage induction motor.
- To analyze the mechanical response of the stator under complex electromagnetic forces.
- To examine the sound emission and radiation patterns of the motor under different operating conditions.
- To compare the measured acoustic parameters in different sound fields.

1.7 A Brief Description of the Thesis Contents

Experimental studies on vibrations and noise are presented in this thesis. The investigations are conducted with a view to obtain physical understanding about the electromagnetic forces and the correlation between vibrations and the radiated noise.

Necessary basic definitions of vibrations and noise along with the description of signals are introduced in Chapter 2. General description and discussions on the currently available instruments, in the laboratory, for the measurements of vibrations and noise are provided in Chapter 3. To make a noise reading meaningful, it is required that standard procedures are followed. Hence, discussions concerning noise-standards and noise-measurements are described in Chapter 4. Also, theoretical analyses of magnetic-fields and electromagnetic forces are summarized in Chapter 4 as a general preparation for the experimental investigations.

Descriptions of the specially designed test motor and the loading device are presented in Chapter 5. Before proceeding with detailed experimental investigations related to vibrations and noise produced by the induction motor, necessary preliminary investigations are done and they are reported in Chapter 5. Important information on vibration measurements, including mode-shapes and the changes in vibration levels with load is presented in Chapter 6. In Chapters 7 and 8, noise investigations in both an ordinary laboratory and an anechoic chamber are reported, and they are compared. The conclusions of the thesis are provided in Chapter 9.

2. VIBRATION AND NOISE SIGNALS AND DEFINITIONS

Sound ordinarily refers to audible pressure fluctuations in air. Sound may be produced by mechanical vibrations, motion of a body through air or other fluid, motion of a fluid past a stationary body, and fluid turbulence. Most noise sources commonly encountered are associated with vibrating surfaces. Noise and vibrations are interrelated; they relate to the transfer of molecular motion energy in a medium. The nature of the vibrations associated with acoustics varies, a tuning fork produces a simple sinusoidal vibration, whereas the vibrations generated by a bowed violin string are very complex. In the case of an explosion, the vibrations and noise are non-periodic. Both vibrations and noise deal with the oscillatory behavior of bodies.

Considering electrical machines, forces of magnetic and mechanical origins produce vibrations directly in the machine structure. The forces of aerodynamic origin cause pressure fluctuation in the surrounding air. It is well known that polyphase induction motors of all sizes produce unpleasant noise. The noise produced by electromagnetic forces is particularly troublesome. The magnitude of vibrations, and hence the sound produced at any position is primarily dependent on the original forces, the mechanical response of the machine structure and its mountings, and the sound radiation characteristics of the motor.

An accelerometer is used to measure vibrations, and a microphone is used to measure sound and noise. Both the transducers provide signals which are of complex sinusoidal nature. A pure tone gives a signal consisting of a single sinusoidal function; a complex signal will consist of many frequency components. The study of single frequency signals forms the basis from which more complex signals can be analyzed and synthesized. Linearity is usually assumed when describing typical vibration and body that is being measured. These three quantities are inter-related by differentiation. The choice of the parameter is very important when making a vibration measurement, particularly when it includes a wide frequency-band.

The nature of most mechanical systems is such that large displacements only occur at low frequencies, therefore, measurement of displacement will give emphasis to the low frequency components. Usually the displacement measurement is performed where amplitude of displacement is particularly important, e.g., where displacement beyond a given value will result in equipment damage; or relative motion between rotating bodies and structure of a machine needs to be measured.

Velocity measurements are used at intermediate frequencies, where transducer outputs of displacement measurements may be too small to be measured conveniently. They are used extensively in measurements on machinery where the velocity spectrum is usually more uniform than either displacement or acceleration spectra.

Acceleration measurements are used where forces, loads and stresses must be analyzed. It should be mentioned that accelerometers are smaller than velocity and displacement transducers; also they have a wide frequency range from very low to very high values. Since integration is preferred over differentiation in electronic circuitry, displacement and velocity can be obtained by simple integration of acceleration. In general, accelerometers are preferred over displacement and velocity transducers.

The accelerometers are preferred over displacement and velocity transducers for the following reasons [20]:

- They have a wide frequency range from very low to very high values, as mentioned earlier.
- The acceleration parameter is more frequently needed since destructive forces are often related to acceleration rather than to velocity or displacement.
- Measurement of transients and shocks can be easily made, considerably easier than displacement or velocity sensing.

- Displacement and velocity parameters can be obtained by simple integration of acceleration.

2.3 Sound Parameters and Definitions

In order to conduct investigations related to sound and noise, one needs good understanding of the basic parameters and familiarity with definitions associated with sound. A brief review of important parameters and definitions is provided below.

2.3.1 Sound Pressure-Level

Sound is a pressure-wave that propagates through an elastic medium, having inertia and elasticity, at some characteristic speed. It is the molecular transfer of motion energy, therefore sound cannot pass through a vacuum. The pressure fluctuations in air are due to molecules of air vibrating back and forth about their original position, thereby passing on some of their energy of movement. These pressure fluctuations are of a vibratory nature, causing the neighboring air pressure to change but no actual movement of the air takes place.

Sound can be measured by displacement, velocity, or acceleration of particle and sound pressure. As the ear is a pressure sensitive mechanism, it is most convenient to use pressure as the measure of magnitude of sound. The amplitude of sound pressure affecting the ear varies from 2×10^{-5} Pa (20 μPa) at the threshold to 200 Pa in the region of ear damage. It is customary to report sound measurements in decibels because of the wide range of sound pressure of interest. The sound pressure-level is defined as:

$$L_P = 10\log_{10}(\frac{p_{rms}^2}{p_{ref}^2}) = 20\log_{10}(\frac{p_{rms}}{p_{ref}}), \quad (2.3)$$

where, p_{rms} = root-mean-square sound pressure,

p_{ref} = reference pressure.

For convenience, p_{ref} is taken as the pressure at the average threshold of hearing at 1000 Hz frequency, which is 2×10^{-5} Pa (20 μPa) corresponding to 2×10^{-5} Nm^{-2}.

2.3.2 Sound Power-Level

The passage of sound waves is accompanied by the flow of acoustic energy. Sound power is defined as the rate per unit time at which sound energy is radiated in a given frequency-band. For ease of comparison, the sound power radiated by a source is expressed as the sound power-level in dB defined by:

$$L_w = 10\log_{10}(\frac{W}{W_{ref}}), \qquad (2.4)$$

where, W is the average sound power emitted by an object in watts;

W_{ref} is the reference sound power in watts, 1×10^{-12} W (1 pW).

The main advantage of using sound power-level is because of simplicity. L_w is a "single figure number" which depends only on the sound source, and not on other factors such as distance from the point of measurement, or details of the acoustic environment [21]. In contrast, the sound pressure-level produced by a machine varies both with the distance between the machine and the point of measurement, and with the environment in which the sound source is placed. But, the measurement of sound power-level requires specific test-rooms [8].

The L_w value itself has no significance subjectively, unlike the sound pressure-level, which can be related to what is actually heard. Also, the sound power-levels are not measured directly, but are calculated from the mean-square sound pressures at a number of microphone locations spatially arranged, and averaged over an appropriate surface enclosing the source in a free-field, or averaged over the volume of a reverberant-room in which measurements are made.

Further, sound power-level can be specified independently of the measurement surface and environmental conditions, which avoids the complications associated with sound pressure-levels that require additional specified data. Since sound power-level provides a measure of radiated energy, which is advantageous in acoustic analysis and design, it is also the index required by international standards [17, 22].

2.3.3 Sound Intensity

In a specified direction, the sound intensity at a given point in a sound field is defined as the average sound power passing through a unit area perpendicular to the specified direction at that point. The sound intensity is given by:

$$I = p \times u, \qquad (2.5)$$

where, p is the sound pressure at that point,

and u is the particle velocity in that direction.

For plane and spherical sound waves (whose sound pressure and other acoustic variables are functions of one spatial coordinate, x-coordinate and radial distance from the source, respectively) propagating in a free-field, i.e., a field free from reflections, the sound intensity along the direction of wave propagation is:

$$I = \frac{p^2}{\rho c}\ (\mathrm{Wm^{-2}}), \qquad (2.6)$$

where, p=sound pressure (rms) in Nm^{-2},

ρ=constant equilibrium density of the medium in kgm^{-3},

and c=velocity of sound in the medium in ms^{-1}.

The product of ρ and c is defined as the characteristic impedance of the medium. At 20 °C and standard atmospheric pressure, the characteristic impedance of air is:

$$(\rho c)_{air} = (1.21\ \mathrm{kgm^{-3}}) \times (343\ \mathrm{ms^{-1}}) = 415\ \mathrm{kg\ m^{-2}\ s^{-1}}.$$

Since intensity describes the rate of energy flow, it is a quantity having a direction. To determine sound intensity, it is necessary to measure both the sound pressure p and the particle velocity u simultaneously, at the same point. Due to the fact that it is impossible to place two transducers at the same point in space, all intensity measurements involve certain compromises and limitations.

2.3.4 Loudness

The ear acts as a pressure transducer, converting airborne sound signals to nerve impulses that are transmitted to the brain for decoding. Unfortunately, no simple relationship exists between the measured physical sound pressure-level and the human perception of the same sound. The loudness of a sound is a subjective effect, which is a function of the ear and the brain as well as amplitude and frequency of the signal [1, 8].

The human perception of loudness of pure tones and other noise types has been exhaustively investigated. Based on many tests of people with normal hearing in the age group of 18 to 25 years, a set of normal equal loudness contours has been established, as shown as Figure 2.1. These contours show that the sensitivity of the ear varies with frequency and pressure-level. For example, a sound of 70 dB at 80 Hz is as loud as the sound of 60 dB at 1000 Hz, as evident from Figure 2.1; the ear is less sensitive to low frequencies than to high frequencies. As sound pressure-levels increase, the ear becomes more uniformly sensitive to all frequencies. The equal loudness level expressed in Phons is the same numerical value as the sound pressure-level at 1 kHz.

2.3.5 Frequency Weighting

As human perception of loudness varies with the frequency of a sound, noise with most of its energy concentrated in the middle frequencies (near 1 kHz) is perceived as louder than noise of equal energy concentrated either at lower frequencies (say 100Hz) or higher frequencies (around 20 kHz). The effect of frequency is more prominent with soft sounds than it is with loud sounds.

Frequency weighting takes typical human response into account when all of the audible frequency components of a noise sample are to be described by a single number. Instead of reporting the sound level in each frequency band, the weighted sound level may be used. In order to simulate roughly the variation of the ear sensitivity with frequency, frequency weightings called A-weighting, B-weighting, and C-weighting are standardized by the IEC 651 [23].

The frequency response of A-weighting takes a frequency of 1kHz as the reference and gives predetermined positive or negative adjustments to all other frequencies. For example, it gives approximately 19 dB attenuation at 100 Hz since the

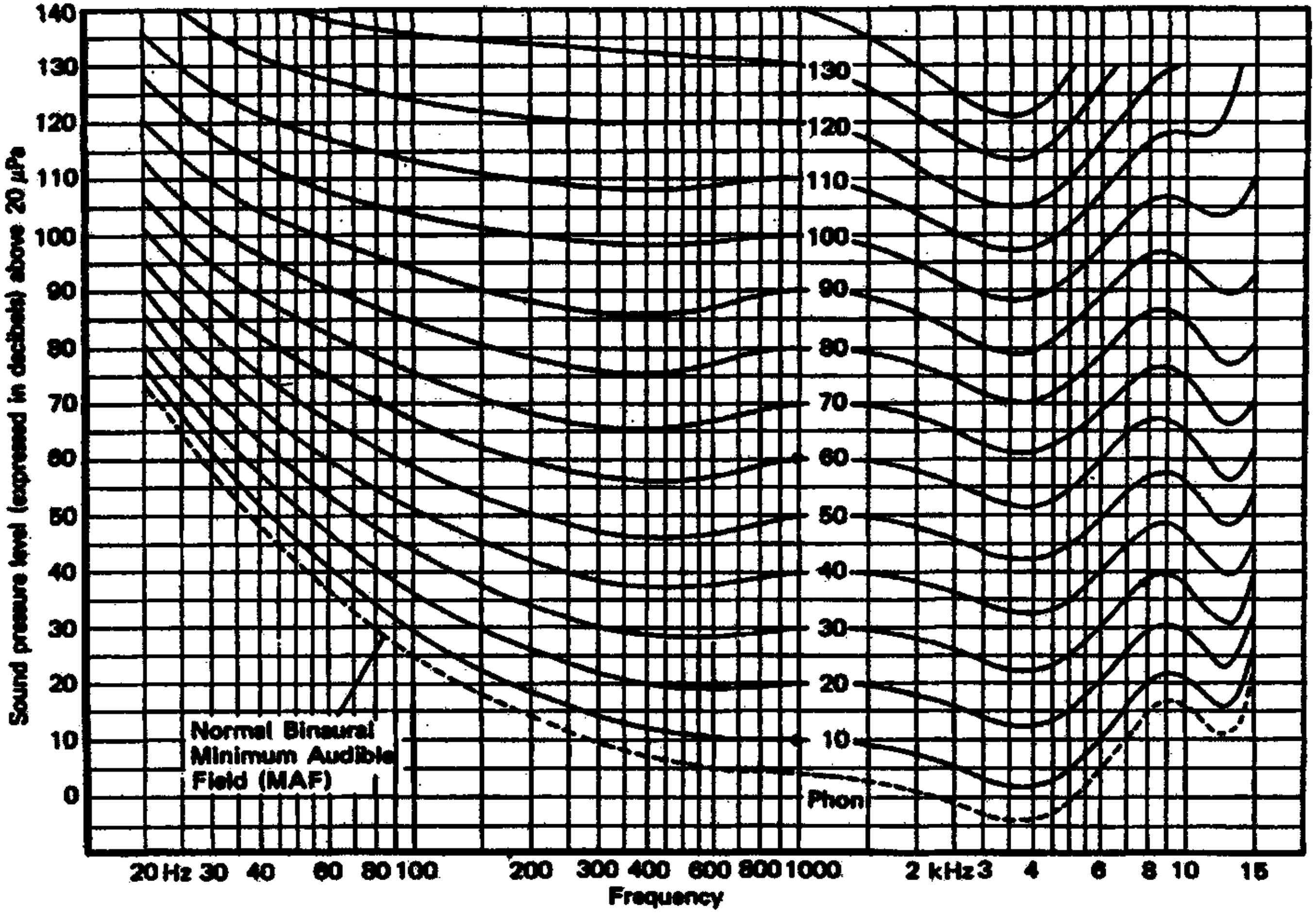


Figure 2.1 : Normal equal loudness contours for pure tones [1].

human ear regards a 100 Hz pure tone having a sound pressure-level of 29 dB as equally loud as a 1000 Hz pure tone having a sound pressure-level of 10 dB. So A-weighted sound level represents the combined total sound pressure-level in the entire audible frequency range of 20 Hz to 20 kHz with A-weighting adjustment. Also B-, and C-weightings are generally used for louder sounds. A-weighting values are used much more frequently than the others.

A-weighting is beneficial in allowing quick determination of the signal value that represents the noise level. In most cases it is in close correspondence to the subjective human sensation of hearing. It should be mentioned that the A-weighting results may differ from the human ear response at low and high sound pressure-levels, and also the information on the individual noise components and their frequencies cannot be obtained. A given sound pressure-level in A-weighting does not represent the same perception as that of a pure tone at a well defined frequency.

2.4 Sound Fields

The basic elements of a noise problem include the source, the path and the receiver. Airborne sound may be influenced by reflection, diffraction and absorption. The sound level in a room is affected by reflection and absorption at the walls. So sound field characteristics are very important for the noise-measurement.

2.4.1 Free-Field

A free-field is defined by ISO Standards [24] and [25] as " A sound field in a homogeneous and isotropic medium free from boundaries. In practice, it is a field in which the effects of the boundaries are negligible over the frequency range of interest". It can be a laboratory room which provides a free-field over a reflecting plane (floor, base plane), a flat outdoor area that meets the standards, or a room in which there are sufficient sound absorbing materials on the walls and ceilings.

In a free-field, a suspended non-directional sound source emits sound uniformly in all directions. As the spherical wave front progresses farther from the source, the spherical surface area increases with the square of the distance, the sound intensity decreases as the square of the distance from the source although the sound power remains constant. If the distance is doubled, the sound energy spreads over four times the area, and the intensity is one-forth its original value, this follows the "inverse-square-law". There is, therefore, a drop of 6 dB in the measured sound pressure-level from the source when the distance is doubled.

Real noise sources such as machines with vibrating surfaces differ from the simple point source. The machine has a definite size which is certainly not a point; it may radiate different amounts of sound energy in different directions. Each portion of a vibrating machine surface radiates sound. Sound pressure-level in the vicinity of the practical sound source often shows an appreciable variation with position, even when the source is in a free-field. Near to the machine, the contributions of the various portions combine in a complex way and it is difficult to predict local variations in sound pressure. This region close to the machine is called the "near-field" in which the sound pressure-level does not decrease by 6 dB each time the distance from the source is doubled. Further away, the noise contributions from the various parts of the machine correlate smoothly and the machine radiates as a whole. This region is called the "far-field" in which the sound pressure distribution varies smoothly with distance according to the inverse-square-law.

The extent of the near-field region depends on the dimensions of the machine and the wavelengths of sound being radiated. In order to ensure far-field conditions, measurement of machine noise should ideally be taken at distances of not less than several wavelengths or several machine dimensions from the sound source, whichever is greater. The practical consequences are that the far-field measurements may be used as the basis for predicting noise levels, whereas near-field measurement will give unreliable results if used for the same purpose. However, there will be many occasions when near-field measurements have to be taken. For example, far-field measurements may be impossible to do for large machines in small rooms. Under such circumstances, the near-field measurements are the most appropriate to conduct.

The sound measurements performed in a free-field may be used to rate apparatus according to its sound power output, in order to predict the sound pressure-levels produced by an apparatus or machine in a given enclosure or environment.

2.4.2 Reverberant-Field

Sound from a source in a room with hard walls, floor and ceiling is reflected back and forth many times. At any particular location in the room, the sound is the sum of two portions. The one is the direct sound which arrives from source to receiver without having been reflected from any of the room surfaces. The other is the reverberant sound which is reflected by surfaces from many different directions. According to ISO standards' definition, [26, 27 and 28], a reverberant sound field is "That portion of the sound field in the test room over which the influence of sound received directly from the source is negligible". In a reverberant-field, the sound pressure-level does not decrease according to the inverse-square-law, but it is uniform throughout the room.

If the sound source in a reverberant room ceases suddenly, the sound will persist for some time. This persistence is called reverberation. Measurements obtained in a reverberant-field are used to rate apparatus according to its sound power output, to establish sound control measures, and to predict the sound pressure-levels produced by an apparatus or machine in a given enclosure or environment.

2.4.3 Semi-Reverberant-Field

In order to determine whether the noise produced by a machine is in compliance with safety and health regulations, it is necessary to know the sound pressure-levels around the machine. Users and purchasers want to know how much noise the machine would make when it is installed in the plant, rather than the levels measured on a test stand or in a free-field. In this case, often the sound measurements must be made under actual operating conditions that are neither free-field nor reverberant-field. That is, the floor, walls and ceilings are neither completely absorbent nor completely reflecting. Most industrial sound measurements are made in these semi-reverberant locations.

The characteristics of a semi-reverberant room are between free-field and reverberant-field. It is obvious that sound pressure-levels in a semi-reverberant-field do not decrease with distance according to the inverse-square-law as they do in a free-field. At the given distance from the source they are somewhat higher in a semi-reverberant-field than they would be in a free-field.

2.5 Comments

In this chapter, basic parameters and important definitions associated with vibrations and sound have been presented. They form the necessary information to proceed with investigations on vibrations and noise problems of electrical machines.

Before conducting any experimental investigations, one has to decide what instruments and measuring systems are suitable to obtain meaningful data and results pertaining to vibrations and noise. General description and discussions on the currently available instruments for the measurements of vibrations and noise are provided in the next chapter.

3. INSTRUMENTATION FOR VIBRATION AND NOISE MEASUREMENTS

Reliable measurements depend on the correct choice of the most suitable instruments for the particular measurement situation and the correct use of the instruments. Generally, there are three parts for a measurement system: transducer sensing part, signal-processing part and displaying part. The sensing part consists of transducers which convert the physical changes to be measured into electrical signals. In the second part, this electrical signal is then subjected to a variety of processes which condition the signal in the required manner. The processed signal is then displayed by the displaying part so that it is read and recorded.

3.1 Instrumentation for Vibration-Measurement

As mentioned before, vibrations can be measured and described in terms of any of or all the three quantities: displacement, velocity and acceleration. There are different transducers available for the measurement of mechanical vibrations. Among various kinds of transducers, displacement gauges work on a capacitive principle, and the electrodynamic type gauges (coil and magnetic-field principle) give a direct measurement of vibration velocity. As discussed in Chapter 2, acceleration is preferred over displacement and velocity. The most commonly used device for vibration measurements in the audio-frequency range is the piezo-electric accelerometer. It provides an electrical signal which is proportional to the vibration acceleration. Also, accelerometers are convenient and compatible with the same instruments that receive a microphone signal.

A vibration measuring system essentially consists of an accelerometer, a preamplifier, signal conditioning devices, and displaying units.

3.1.1 Accelerometer

A piezo-electric material produces an electric charge proportional to the stress applied to it within its linear elastic range. Its electrical resistance depends on the applied force. The most widely used accelerometers are fabricated using piezo-electric materials, loaded with a small weight and designed to have a very high natural resonance frequency. Since piezo-electric accelerometers have comparatively low mechanical impedance, their effects on the motion of most structures are negligible. The output of an accelerometer is proportional to the acceleration. Piezo-electric accelerometers are widely used for general-purpose acceleration, shock and vibration measurements. They are rugged and comparatively small, suitable even for high frequency applications [20,8].

Piezo-electric accelerometers are available in a wide range of specifications and are offered by a large number of manufacturers. For example, a shock accelerometer may have a natural frequency of up to 250 kHz, and one for low-level seismic measurements might have natural frequency of only 7 kHz. They are manufactured as small as 3×3 mm in dimensions with about 0.5g in mass. They have excellent temperature ranges, and some of them are designed to survive the intensive radiation environment of nuclear reactors [20].

The mounting of an accelerometer on a vibrating structure is very important to obtain reliable results, otherwise large errors may occur. There are five common ways of accelerometer mounting via:

(1) a connecting threaded stud,

(2) a cementing stud,

(3) a thin layer of wax,

(4) a magnet, and

(5) a hand held probe.

The type of mounting affects the resonant frequency and hence the useful measurement frequency of the transducer. Methods (1) to (3) produce very good frequency responses; method (4) limits the frequency response but it provides good electromagnetic isolation; method (5) limits the frequency response to about 1000 Hz but is very convenient for quick measurements.

3.1.2 Preamplifier

The accelerometer has a very high electrical output impedance; that means the output signal is of very low power. This output signal may be reduced significantly by the electrical loading effect of the cables and amplifiers following the accelerometer. To amplify the weak signals from the accelerometer is the basic purpose of the preamplifier. More importantly, the preamplifier modifies the signal to a lower and more suitable impedance which is less prone to the influence of external interferences.

There are three types of preamplifiers: the voltage preamplifier, the charge amplifier and the line-drive preamplifier. The essential difference between the voltage preamplifier and the other two is the loading effect of the accelerometer cable. With a voltage amplifier, the sensitivity of an accelerometer together with cable is highly dependent on the cable length. So the voltage preamplifiers are seldom used. The output voltage of a charge amplifier is proportional to the charge applied at the input. The line-drive amplifier has been made possible by the development of miniaturized thick-film circuits so that it can be attached to or even included internally in the transducer. But line-drive preamplifiers typically have some restriction of dynamic range and frequency range in comparison with a high-quality general-purpose charge amplifier [8].

3.1.3 Signal Conditioning Devices and Displaying Units

Sometimes the output signals from the preamplifier may not be strong enough for further signal-processing; under these conditions, further amplifier stages are necessary. Such amplifiers increase the relatively weak signal to a value sufficient to drive the indicating meter, or other recording equipment to display the signal. Also, in order to limit the measurement errors caused by spurious signals or by signals outside the working range of the accelerometer, low-pass and high-pass filters are required.

Although an accelerometer is the best transducer to use, in general, it is often preferable to evaluate vibration in terms of velocity or displacement. Most criteria for evaluating machine housing vibrations are effectively constant-velocity based, however, some vibration criteria (e.g. for aircraft engines) are expressed in terms of displacement. Acceleration signals can be integrated electronically to obtain velocity and displacement signals as already discussed. Integrating circuits may consist of a simple RC circuit, active amplifier or digital integrator. Indications of RMS, peak or peak-to-peak values of signals are usually provided.

The display units may be an analog device which is a meter with pointer, or of a digital kind. All the parameters are displayed with their units. Also, there are output facilities to allow the signals to be connected to an oscilloscope, a tape recorder, a printer, etc.

3.2 Instrumentation for Noise-Measurement

3.2.1 Microphone, Microphone Extensions and Windscreens

A microphone converts the variations in pressure of sound waves into time-varying electrical signals. Ideally, the electrical signals generated should be an exact analog of the sound wave, and there should be a linear relationship between the output signal of the microphone and the sound pressure at the microphone for all the frequencies within the useful range of the microphone. The presence of a microphone should not disturb the sound field when it is installed. The microphone should have stable sensitivity not influenced by time or ambient conditions.

A microphone that is designed and constructed so as to comply with standardized specifications for certain critical electroacoustical performance characteristics is called the "measurement microphones". There are three principal types of measurement microphones: condenser (capacitor) microphone, prepolarized microphone, and piezo-electric microphone.

Condenser microphones have good voltage sensitivity and frequency response. They are the basis of international standards for laboratory-standard microphones. They have superior electrical and acoustical characteristics, and their good mechanical design can provide reliable reproducibility of these characteristics. They generally give accurate and consistent results. For general applications, condenser microphones with a nominal diameter of 13 mm (1/2") offer a good compromise between sensitivity and frequency range. But they are more expensive to construct than the other two types. Prepolarized microphones are suitable for class 1 or class 0 accuracy requirements; piezo-electric microphones are suitable for class 2 accuracy.

In order to avoid exterior influences as much as possible, or to comply with the most critical frequency response requirements, microphone extensions and cables are provided by the manufacturers to isolate the microphone from the interfering effects of the instrument case and the observer. Wind-noise is produced when air flows past a microphone. This may seriously affect the sound level measurement values outdoors. Windscreens are specially designed acoustically to provide a good protection against wind-noise [29].

3.2.2 Sound-Level-Meter

The most common and convenient instrument for measuring the sound pressure-level of a sound field is a sound-level-meter. This is a portable instrument for the measurement of frequency-weighted and time-averaged sound pressure-level. Most of the sound-level-meters are small, light and battery-powered. A block diagram showing the principal components of a sound-level-meter is given in Figure 3.1.

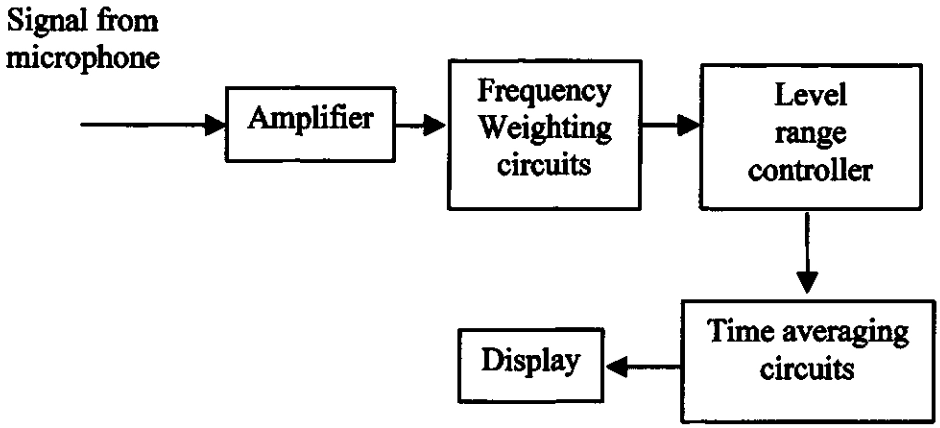


Figure 3.1 : Block diagram of a sound-level-meter.

The amplifier amplifies the signal from the microphone sufficiently over a wide frequency range to permit the measurement of low sound pressure-levels. Frequency weighting circuits alter the frequency-response characteristics according to international standards, giving greater importance to sounds in some frequency ranges over the other frequency ranges in order to determine the overall reading of the meter. A-weighted sound levels provide an adequate correlation with a variety of human responses to many types of noise sources. This is the most widely used frequency weighting. A noise-measurement standard or code stipulates the frequency weighting to be used.

The pressure-level range controller adjusts the range of sound levels that can be measured for a given setting of the controls. Time averaging circuits provide the time-average values of a squared sound pressure signal. There are two standardized exponential-time-weightings in wide use; fast and slow. A fast sound level is always more strongly influenced by recent sounds, and less influenced by sounds occurring in the distance past than the corresponding slow sound level. The standard fast and slow time constants are 0.125 second and 1 second, respectively.

The display device may provide an analog, quasi-analog, or digital display. An analog display often is a pointer moving across a graduated scale. A quasi-analog indicator like liquid crystal display may also be used. A digital display usually gives a numeric readout.

Four types of sound-level-meters are designated by International Standard IEC 651 [23]: type 0, 1, 2 and 3. Type 0 is the most accurate, which is the laboratory reference standard intended entirely for calibration of other sound-level-meters. Type 1 is the precision sound-level-meter intended for laboratory use or for field use where the acoustical environment can be closely controlled. Type 2 is the general-purpose sound-level-meter, which is intended for general field use and for recording noise level data for later frequency analysis. Type 3 is the survey level meter for preliminary investigations.

3.2.3 Analyzers

The aim of acoustic measurement is to provide objective physical measurements of noise which can be compared with predetermined criteria in order to judge its acceptability. Frequency analysis is an attempt to describe sound or vibration in terms of contributions at various frequencies. The sound pressure-level of noise can be measured in a series of frequency intervals called "frequency-bands". Octave and fractional (percent) octave-bands are most commonly used in noise measurement, though constant band-widths are sometimes adopted. One reason for this choice is that a one-octave change in frequency anywhere within the audible range has about the same auditory significance. The same could be said of the perception of an one-third octave change in frequency. For example, if the frequency of a sound changed from 40 to 50 Hz, the change could be detected by the human ear virtually as easily as a change from 4000 to 5000 Hz, whereas a frequency from 4000 to 4010 Hz would probably be imperceptible.

Frequency analysis allows us to look at the sound levels in each frequency-band. This information is particularly useful when trying to locate the cause of a noise problem. For example, the gear clash frequency for a simple gear system may be calculated by:

$$f = \frac{RPM \times NUM}{60}, \tag{3.1}$$

where, f = frequency, Hz; RPM = shaft speed; NUM = number of gear teeth.

If a frequency spectrum shows a significant peak at a frequency equal to the gear clash frequency, then noise-control effort could be directed at the gear. Similarly, the noise contributions of other components can also be identified by frequency analysis.

When it is desirable to have a detailed frequency description of a noise (i.e., the sound pressure distribution with frequency), spectrum-analysis which is the process to determine this distribution is required. Spectrum or frequency-analyzers are used to fulfill this function. The frequency-analyzer contains filters which reject signals at all frequencies except the selected frequencies or the frequency ranges. Thus, the reading of the instrument indicates the magnitude of the sound pressure at those frequencies passed by the filters only. Most commonly used analyzers for acoustical analysis have a nominal band-width that is proportional to the center frequency of the filter. The octave-band analyzer has a nominal band-width of one octave, whereas other constant percentage analyzers have certain percentage band-width.

3.2.3.1 Octave-Band Analyzer

The octave-band analyzer is the most common used analyzer for industrial noise measurements. It separates the complex noise into frequency-bands one octave in width, whose upper cut-off frequency is twice the lower cut-off frequency. It measures the pressure-level in each of the bands. As shown in Figure 3.2, the cut-off frequencies (f_1, f_2) are the frequencies at which the filter output is attenuated by 3 dB. The center frequency f_c of the band-pass filter is the geometric mean of the upper and lower cut-off frequencies. The band-width (BW) is the difference between the lower cut-off frequency and the upper cut-off frequency, BW=($f_2 - f_1$) [30]. For an octave filter, $f_2 = 2f_1$. The center frequency f_c for an octave filter is the geometric mean of the lower and upper cut-off frequencies:

$$f_c = \sqrt{f_1 f_2}\,.$$

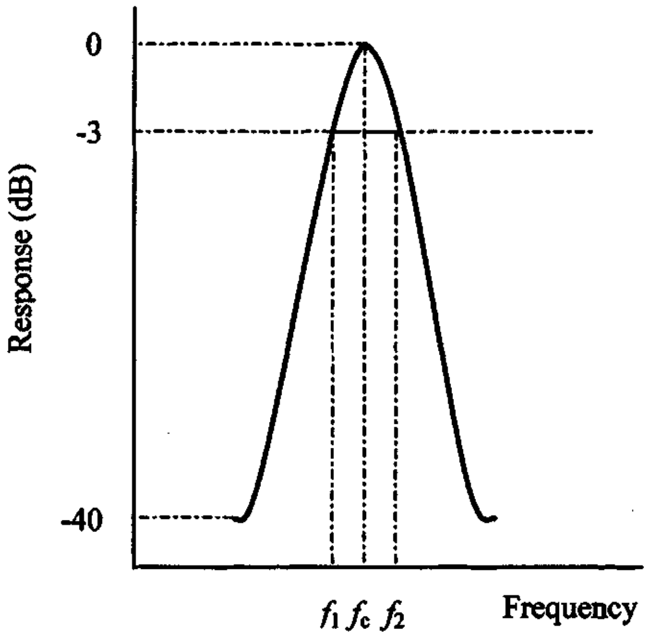


Figure 3.2 : Octave-band analyzer.

Ideally, the analyzer would pass all frequencies within the octave, and attenuate totally all frequencies outside the band. Octave filters are specified by their center frequencies. Numerical values of the exact center frequencies and the band limits for octave filters are laid down in the international standard IEC 225 [31] as shown in Table 3.1.

An octave-band analyzer can separate components whose frequency differences are large, e.g., a component at 60 Hz from another one at 120Hz. For a much finer and detailed frequency analysis, narrow-band analyzers are used.

Table 3.1 : Center frequencies and band limits for octave filters.

Nominal center frequency f_c(Hz)	Approximate lower band limit f_1 (Hz)	Approximate upper band limit f_2 (Hz)
16	11.3	22.6
31.5	22.3	44.5
63	44.5	89.1
125	88.4	176.8
250	176.8	353.6
500	353.6	707.1
1000	707.1	1414.2
2000	1414.2	2828.4
4000	2828.4	5656.8
8000	5656.8	11313.6
16000	11313.6	22627.2

3.2.3.2 Narrow-Band Analyzer

A narrow-band analyzer may be either a constant band-width or a constant-percentage band-width type. A constant band-width analyzer has filter band-widths that are independent of the frequency at which the filter is tuned. For example, if the band-width of the filter is 30 Hz, the analyzer has a bandwidth of 30 Hz whether the center frequency of the analyzer is set at 100, 1000, or 10000 Hz. In acoustical analysis the most commonly used analyzers are constant-percentage band-width type.

The use of constant-percentage band-width analysis is based on the observed response of the human ear to bands of noise. As the center frequency of the band increases, the band of frequencies increases in proportion. Thus, a family of constant-percentage filter response characteristics is identical when plotted on a log-frequency scale, as shown in Figure 3.3 [7].

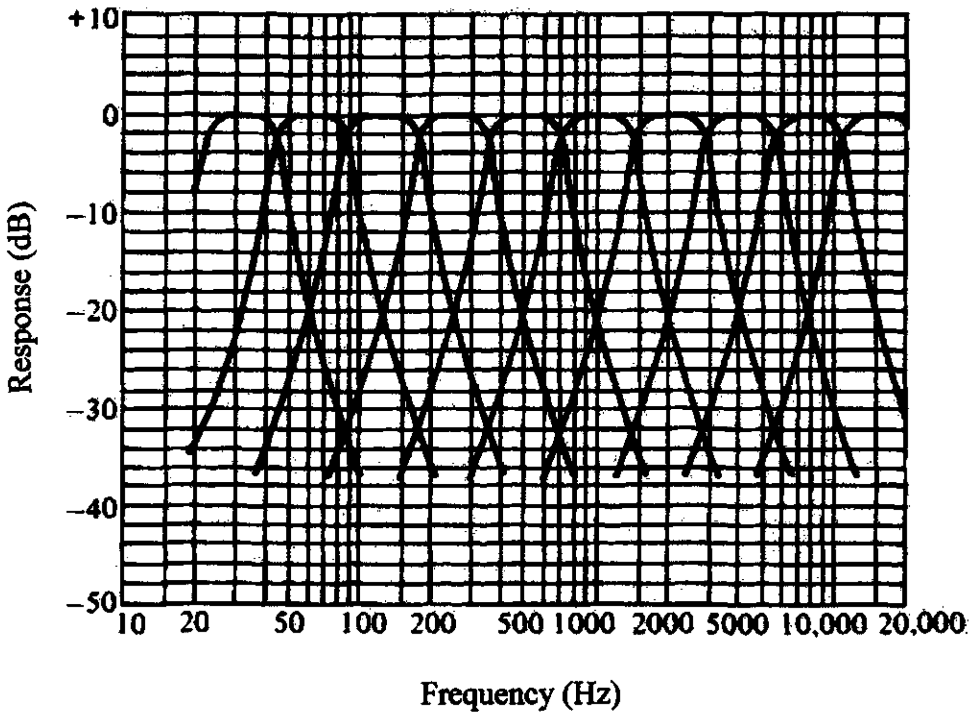


Figure 3.3 : Narrow-band analyzer.

As discussed previously, the center frequency (f_c) is defined as the geometric mean of the upper (f_2) and lower (f_1) cut-off frequencies: $f_c = \sqrt{f_1 f_2}$. For sound measuring equipment, the general relationship between the upper cut-off frequency f_2 and the lower cut-off frequency f_1 is:

$$f_2 = 2^{\alpha} f_1,$$

where, α is an arbitrary constant, giving,

$$f_2 = 2^{\alpha/2} \cdot f_c, \qquad f_1 = \frac{f_c}{2^{\alpha/2}},$$

then the band-width BW is:

$$BW = (f_2 - f_1) = \left(2^{\alpha/2} - \frac{1}{2^{\alpha/2}}\right) f_c, \tag{3.2}$$

which confirms that the band-width is a constant-percentage of the center frequency. The band-width of the individual filter of constant-percentage band-width analyzer increases with the increase in the center frequency.

When $\alpha=1$, it is an octave-band analyzer, whose band-width to center frequency ratio is:

$$\frac{BW}{f_c} = \frac{(f_2 - f_1)}{\sqrt{f_1 f_2}} = \frac{(2f_1 - f_1)}{\sqrt{f_1 \cdot 2f_1}} = \frac{1}{\sqrt{2}} = 0.707. \quad (3.3)$$

The octave-band analyzer is a constant-percentage analyzer at 70.7%. When $\alpha=1/3$, it is a one-third octave-band analyzer of 23.2% band-width. Also, the center frequencies and cut-off frequencies for one-third octave-band filters are described by ISO Standard 225 [31].

In the case of studies involving wide-band noise, i.e., where appreciable sound pressure and power exists over a large portion of the audible frequency range, octave- and one-third octave band-width analyses are usually sufficiently discriminatory as to give reasonable and meaningful data.

Other band-widths, such as 1/10-octave (7% of the center frequency) and even narrower band analyzers, have been used in special cases where finer and more detailed frequency analyses are required. They are used to measure accurately the frequency of a sharp peak in the spectrum, and thus provide information about its cause.

The constant-percentage filters with continuously variable center frequency, where any center frequency within the range of the analyzer can be selected, provide a more accurate picture of the frequencies and magnitudes of dominant components. The spectrum drawn by a constant-percentage analyzer with continuously variable center frequency is a continuous curve.

Virtually all one-octave frequency analyzers are "stepped", i.e., the analyzer can be tuned only to the center frequencies prescribed. Almost all constant-percentage analyzers narrower than 1/3-octave are continuously tunable.

3.2.3.3 FFT-Analyzer

According to Fourier's theorem, any complex periodic signal with repetition time T(s) can be broken into a series of harmonic-components whose frequencies are multiples of the fundamental frequency (1/T). Conversely, complex harmonic signals may be built up from the combinations of harmonically related single frequencies. In Figure 3.4, a periodic signal is represented by a line-spectrum of frequencies according to Fourier's theorem. The frequency spacing between the lines is 1/T. If T increases, then 1/T decreases and the line spacing decreases accordingly [App. A].

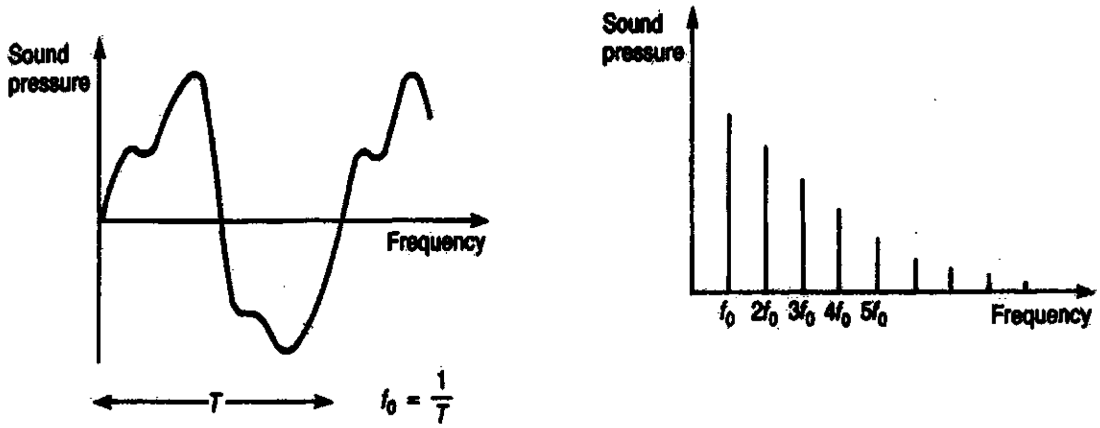


Figure 3.4 : Line-spectrum of frequencies.

The Fourier-transform is the extension of Fourier's theorem to non-repetitive signals. The period T is extended to infinity, and then the evaluation of an integral over this time is performed. Fourier-transform of some simple signals may be evaluated exactly by using mathematical techniques. For most complex signals, the use of numerical methods of integration requires a very large number of calculations. Fast Fourier Transform (FFT) analysis was derived for vastly reducing the calculation time of Fourier-transform.

FFT-analyzers use digital signal-processing techniques to produce very rapid narrow-band frequency analysis of acoustic signals. In an FFT-analyzer, a sample of the signal is digitized, the FFT calculations are performed on the digitized sample in order to produce a line-spectrum. When T is the total duration of the sample in seconds, the fundamental frequency in this spectrum is 1/T, and the frequency spacing between the lines is $\Delta f = 1/T$. A FFT performed on a sample of N points produces a spectrum of N/2 frequency lines. The time interval between each digital sample is $\Delta T = T/N$, so the sampling rate is N/T. The maximum frequency component in the line spectrum is $f_{max} = \frac{N}{2} \times \frac{1}{T}$, as shown in Figure 3.5. The value of N is usually fixed for a particular type of FFT-analyzer. Further, FFT-analyzers operate on discrete blocks of data. Each sample block is captured and then analyzed to produce a line-spectrum while the next block is being captured, and so on.

The main use of FFT-analysis is for very rapid frequency analysis of signals having prominent tonal and harmonic characteristics. Machines producing vibrations like pumps and fans, etc., produce a vibration spectrum which contains components at the rotation speed and its harmonics. The levels of these components give a good indication of wear and onset of faulty operation. Hence FFT-analysis is widely used in condition-monitoring of machinery [21,32].

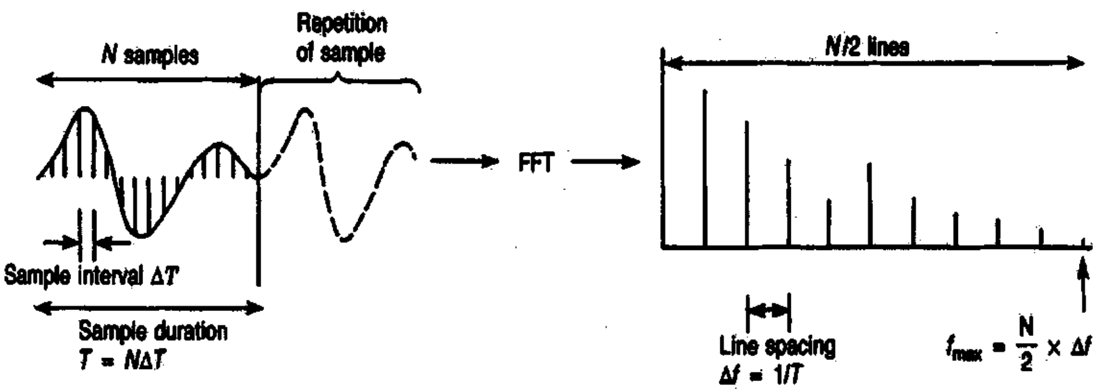


Figure 3.5 : Line-spectrum of FFT-analyzer.

3.3 Comments

The instruments used for vibration and noise measurements and their characteristics are discussed in this chapter. A good understanding of the advantages and disadvantages of various instruments is very helpful to perform successful experimentation.

Discussions on the standards and codes related to noise measurement are presented in the next chapter. As a part of preparation, some theoretical investigations are summarized in the next chapter.

4. NOISE-STANDARDS AND THEORETICAL INVESTIGATIONS

Measurement quantities like acceleration, sound pressure-level, sound power-level, etc., are the basic quantities to describe vibrations and noise. These quantities can be obtained by various instruments. To make these quantities meaningful and useful, the measurement standards and test-codes are needed.

Vibrations of the motor structure and the emitted noise are inter-related. Theoretical analyses provide the guidelines for experimental investigations, while experimental results can trace the causes, and help to improve the performance. It should be emphasized that preparations of experimental procedures, and theory related to magnetic-fields and electromagnetic forces are necessary before actual experimental investigations are conducted.

4.1 Quantities and Considerations for Noise-Measurements

Quantities commonly used to describe the noise emission of a source include either the sound pressure-level at specified distances from the source, or the sound power-level of the source, or both.

Sound pressure-level is a meaningful descriptor of the noise emission of a source only if the location of the point of the observation and a description of the acoustic environment are given. A value of sound pressure-level in itself is not sufficient.

Sound power-level is a meaningful descriptor of the total noise emission of the source. It does not require additional information about the distance from the source and the nature of the acoustic environment. Only a few sources are omni-directional, i.e., they radiate essentially the same amount of sound energy in all directions. Many sources are highly directional, radiating more sound energy in some directions as compared to others. Therefore, directional characteristic, or directivity, is an important descriptor of a sound source. When the source radiates into a free-field, attention is focused on both its sound power-level and directivity. If the same source is in a room in which there are many reflections from boundary surfaces, the directivity becomes of lesser importance; this is because reflections from the boundaries tend to make the sound field more uniform. In this case, sound power-level information is a sufficient descriptor for the sound source [7, 8, 33].

Sound power-level and directivity data are useful for:

- Calculating the approximate sound pressure-level at a given distance from a machine operating in a specified environment.
- Comparing the noise radiated by machines of the same type and size.
- Comparing the noise radiated by machines of different types and sizes.
- Determining whether a machine complies with a specified upper limit of sound emission.
- Planning in order to determine the amount of noise-control required under certain circumstances.
- Engineering work required to assist in developing quiet machinery and equipment.

Before an acoustical measurement program is performed, the objective and the problems should be clearly defined. The following considerations are required prior to doing the measurements:

- The purpose for measurements. For example, to ensure that a piece of equipment or machinery complies with specifications. Or, to provide technical information for use in noise-control evaluation and in a noise-reduction program.

- The physical dimensions of the sound source, the directional characteristics of the sound source, and the normal temporal pattern of the noise (e.g., impulsive or steady).
- The required data and measurements, the measurement accuracy.
- The selection of relevant standards and test-codes for measurements.
- The availability and accessibility of the measurement site.
- The influence from the ambient conditions, such as temperature, humidity, wind, dust, vibration and ambient noise sources other than major noise sources.
- The operating characteristics of the noise sources and the effects of these characteristics on the noise produced.
- The relationship between noise emission of the sound sources and the time of the day.

The more information that is considered and prepared, the better is the possibility of appropriate and reliable measurements.

4.2 Noise-Measurement Standards and Test-Codes

4.2.1 Introduction

Most noise-measurements are taken in order to characterize a particular noise source and/or a particular noise environment. For example, measurements are taken to determine the radiated sound power of a machine, or to determine its directivity, or to determine the spectral composition. Also, measurements are taken in order to determine the sound pressure-level at a residential property near a highway, or to determine the average background noise level inside a conference room.

Noise-standards are important in any noise-control program. A noise-standard establishes a uniform procedure for obtaining sound level data. It assists in making quantitative assessments of the subjective effects of noise on human beings, and prescribes criteria for sound levels under different environmental conditions. The primary reason for using a noise-measurement standard is to let the recipient of the data know that certain aspects of the measurement process have been fully considered in accordance with a particular standard. As a result, the measured data meet specified minimum requirements for accuracy and precision.

A measurement standard is a prescribed procedure for conducting a measurement in such a way as to obtain reliable, reproducible results with a specified level of accuracy. A test-code is primarily a measurement standard that is applicable to a specific class or type of machinery or equipment [8]. The basic difference between a standard and a test-code is that standard provides information on the general procedures for making noise measurements and evaluations. A test-code, using one or more of the basic standards as references, specifies the procedure for noise measurement and evaluation of a specific type of machine or piece of equipment or particular kind of installation. Noise test-codes are prepared by industry associations, engineering societies, industrial organizations, and other groups which have well-organized expertise in the design, manufacture, installation, and operation of a particular type of equipment for which the test-code is applicable.

The noise specification for machinery or equipment places an upper limit on the noise emission of equipment to be purchased. It should describe how measurements are to be made to determine compliance with the noise limit, and it should indicate applicable test-codes and how the acoustical data should be interpreted. When a purchase specification demands that a certain noise emission value be not exceeded, or when a manufacturer states that a product does not exceed a certain noise emission value, it is essential that these values be unambiguous. The standards provide the necessary definitions, guidelines for determining the noise emission values to be declared for both individual machines and batches of machines, and procedures for verifying that the declared values are met.

A test-code states whether the noise emission is to be expressed in terms of the sound power-level of the source, or in terms of sound pressure-levels at specified positions. It should limit the scope of the test-code to one class or type of machine. It also should require laboratory environments for all measurements (the only exceptions should be equipment that is too large for available laboratory spaces or which cannot be moved from its installation, either indoors or outdoors). It must also describe the expected accuracy of the measurements and the operation of the source. The test-code should be keyed to a basic standard, the use of which in conjunction with the test-code is mandatory.

4.2.2 Selection of Standards and Test-Codes for Investigations

There are numerous national and international standards concerning noise measurements; International standards, US standards, British standards, and others.

The British Standards Institution (BSI) was formed in 1901, and it was incorporated under Royal Charter in 1929. BSI is one of the oldest national standards bodies. BSI works with manufacturing and service industries, businesses and governments to facilitate the production of British-goods.

Institute of Electrical and Electronic Engineers (IEEE) is one of the organizations publishing acoustical consensus standards in the USA. IEEE standard 85 [34] defines approved methods for conducting tests and reporting with regard to sound produced by rotating electrical machines with an accuracy of ± 3 dB.

International standardization is well-established for many technologies in such diverse fields as information processing and communications, textiles, packaging, distribution of goods, energy production and utilization, ship-building, banking and financial services. It will continue to grow in importance for all sectors of industrial activities for the foreseeable future. Export minded industries have long sensed the need to agree on world standards to help rationalize the international trading process. This led to the establishment of ISO. Since ISO standards have been widely adopted giving considerable benefits to the industry, trade and consumers, users have more confidence in products and services that conform to International Standards.

The work of ISO with regard to acoustics began in 1947. As of today, about 90 ISO International Standards have been developed. They cover a wide range of test methods and specifications relating to noise sources, acoustical phenomena, their generation, transmission, and reception, etc.

There are seven ISO standards for sound power measurement; ISO 3740 to ISO 3746 [24-28, 35-36]. The first one, ISO 3740, serves as a guide to the other six. This standard describes the selection of appropriate International Standards for determination of sound power-level. The six standards (ISO 3741 to 3746) are classified into three grades: the precision (most accurate), the engineering and the survey (least accurate) method.

The accuracy or uncertainty in the determination of sound power-levels is expressed as a standard deviation in decibels. The main factor affecting the classification is the quality of the test-environment available (either anechoic, semi-anechoic or reverberant). The survey-method is for testing machines in situ, i.e., no special test-environment. It is considered that this method is only suitable for overall, A-weighted sound power-levels with an accuracy of 5 dB(A), whereas the other methods allow for octave or maybe even 1/3-octave band measurements, which provide much greater accuracy.

These seven ISO standards contain many specifications concerning the noise source, the positioning of the microphones during tests, the information to be recorded (detailed information concerning the source, environment, instrumentation, etc), and the information to be reported.

ISO 1680/1 (part-1) and 1680/2 (part-2) are test-codes for the measurement of airborne noise emitted by rotating electrical machinery [37,38]. Part-1 of ISO 1680 is based on ISO 3744 and has been drafted in accordance with ISO 3740. The main purpose of part-1 is to specify a clearly defined measurement method for rotating electrical machines operating under steady-state conditions, the results of which can be expressed in sound power-levels so that all machines tested using this code can be directly compared. Other methods, such as the precision methods of ISO 3741,3742 and 3745, may also be used to determine sound power-levels if the installation and operating conditions of this part of ISO 1680 are used. Part-1 of ISO 1680 specifies, in accordance with ISO 2204 [39], an engineering-method (grade 2) for measuring the sound pressure-levels on a rectangular parallelepiped surface enveloping the machine for the calculation of the sound power-level produced by the machine.

Part-2 of ISO 1680 is based on ISO 3746 and has been drafted in accordance with ISO 3740. The main purpose of this part of ISO 1680 is to specify a survey-method requiring less effort for the measurements than laid down in the engineering-method (ISO 1680/1) and which, in general, results in a lower grade of accuracy. It may also be applied in those cases where one or several conditions (such as operating conditions, number or positioning of microphones) or an otherwise engineering type of measurement cannot be conducted.

ISO 1680 outlines the procedures which may be used to evaluate the test-environment and specifies the characteristics of suitable measuring instruments. ISO 1680 applies to the measurement of airborne noise from rotating electrical machines, such as motors and generators (d.c. and a.c. machines) without any limitation on the output or voltage, when fitted with their normal auxiliaries. It applies to rotating electrical machines with any linear dimension (length, width or height) not exceeding 15 m.

The data obtained according to these international standards are used for:

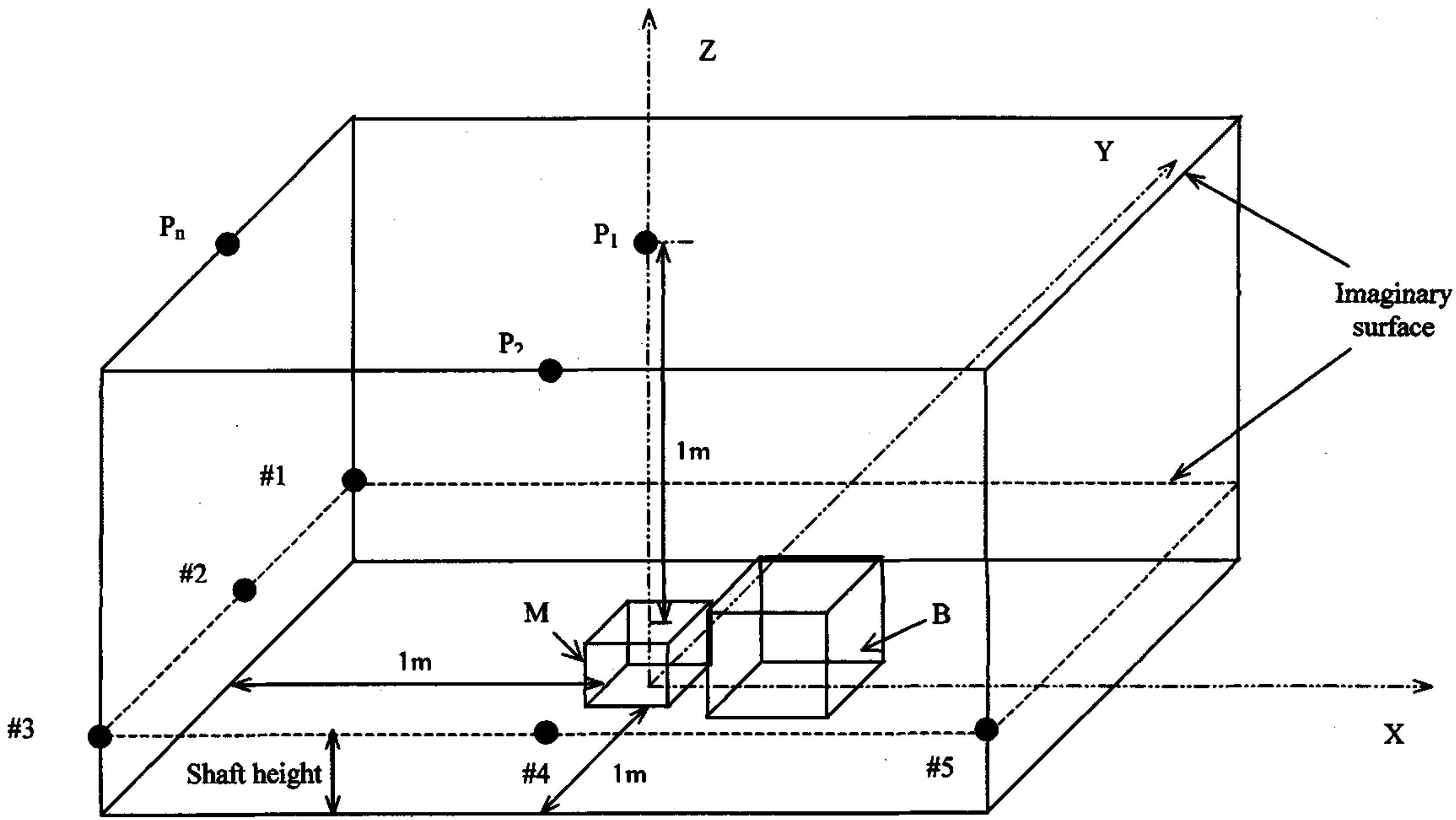
- Rating apparatus according to its sound power output.
- Establishing sound-control measurements.
- Predicting the sound pressure-levels produced by a device or machine in a given enclosure or environment.
- Comparison of machines which are similar in size and kind or different in size and kind.

4.2.3 Measuring Surfaces and Location Points of Microphone

There are three imaginary measuring surfaces recommended by ISO 3744 [24]; hemispherical measurement surface, rectangular parallelepiped surface and conformal surface. The hemispherical measurement surface is the most preferred one for sound power measurements. But in practical situations, machines are placed in the rooms in which the microphone positions on a hemispherical surface or on a conformal surface cannot be easily located. Hence, the rectangular parallelepiped surface is chosen because it is simple, also it is recommended by IEEE Std 85 [34].

When measuring noise from rotating machinery, locations are recommended on the axis-plane level, the plane through the shaft axis of the motor under investigation. Imaginary measuring surface-planes are also considered on top of the machine, and on all the four sides of the machine. The planes on the four sides of the machine are vertical, and 1 meter distant from each of the surfaces of the machine. The top horizontal plane is 1 meter above the top surface of the motor. Figure 4.1 illustrates the layout of the measuring surfaces, where M is the motor under investigation and B is the loading device. Salient measuring locations are shown as #1, #2, ..., P_1, P_2, P_n, etc. For large equipment, like turbine generators, some additional measurements may be needed near the couplings, burners, steam leaks, etc. The measurement locations will vary with the sources and their environment. Published standards (ISO standards, IEEE standards, etc.) serve as a guide to determine the number of key measuring positions around the test motor.

Considering the limitations encountered in a laboratory, and with reference to ISO 3744 and IEEE Std 85, the measuring locations have been shown in Figure 4.1. All the measuring points are located on the vertical planes which are 1 meter away from the vertical surfaces of the motor. This distance ensures that measurements are made in the far-field. Location points #1 to #5 are on the same horizontal axis-plane which is parallel to the base of the motor under investigation. The base of the motor is used as the reference plane whose height is zero (Z=0). Points P1, P_2, P_n are on the horizontal plane in parallel to the base having the height of 1 meter above the top of the motor.



M: motor. B: eddy-current brake or loading device.

Figure 4.1 : Layout of measuring points on imaginary surfaces in an ordinary laboratory.

4.3 Theoretical Analyses of Magnetic-Fields and Electromagnetic Forces Produced in Electrical Machines

All electrical motors and generators, ranging in size from the fraction horsepower units found in home appliances to the giants used in industries, depend upon the electromagnetic field as the coupling permitting interchange of energy between an electrical system and a mechanical system, and vice versa.

Considering the case of an induction machine, the electromagnetic forces that act on the stator and rotor surfaces are mainly produced by the rotating magnetic-fields that are present in the air-gap. The magnetic forces acting on the stator teeth have both a tangential and a radial component. The tangential component is responsible for the motor torque, and it is only a minor source of motor noise. The radial component produces larger deformations of the stator-core, and it is the principal source of magnetic noise.

Detailed analyses were performed by Balan [18] for vibrations and noise produced by induction motors. Since the theoretical analyses of the machine vibrations and the resultant noise form the bases for practical investigations, it is sufficient to summarize the analyses and briefly describe the procedures.

For a symmetrical, three-phase integral-slot-winding with p pairs of poles in a motor, the magnetomotive force (MMF) produced contains fundamental component and harmonic-components. The general form of MMF is:

$$M(\theta,t)=\sum_{n=-\infty}^{\infty} M_{n,p}\cos(np\theta-\omega t), \qquad (4.1)$$

where, θ is the location around the circumference in mechanical radians, ω is the angular velocity of the supply, $n=(1+6g_1)$, $g_1=0, \pm1, \pm2, \ldots$.

The air-gap of an induction motor of small to medium size is usually around a fraction of a millimeter. The slotting of the stator and rotor, in which the current carrying conductors are placed, introduce appreciable variation in the length of the air-gap around the circumference. The effects of magnetic saturation are ignored while calculating the permeance variation due to slotting. After considering the slotting of both stator and rotor, the resultant air-gap permeance can be expressed in a general form as:

$$\lambda(\theta,t)=\lambda_0\{1+\sum_{k=1}^{\infty}\lambda_{Sk}\cos(kS\theta)\}\times\{1+\sum_{n=1}^{\infty}\lambda_{Rn}\cos[nZ\theta-\frac{nZ}{p}(1-s)\omega t]\}, \quad (4.2)$$

where, S is the number of stator slots, Z is the number of rotor slots, s is the slip.

Considering the saturation effects, the revised air-gap permeance due to slotting and saturation is given in a general form as:

$$\lambda(\theta,t)=\lambda_0\{1+\sum_{k=1}^{\infty}\lambda_{Sk}\cos(kS\theta)\}\times\{1+\sum_{n=1}^{\infty}\lambda_{Rn}\cos[nZ\theta-\frac{nZ}{p}(1-s)\omega t]\}$$

$$\times[\sum_{\eta=0}^{\infty}\lambda_{sa\eta}\cos[2\eta(p\theta-\omega t)], \quad (4.3)$$

where, $\lambda_0=\dfrac{\mu_0}{\frac{1}{2}[K_{cS}K_{cR}+K_{cS}+K_{cR}-1]\delta}$,

μ_0 is the permeability of free space (H/m),

δ is the air-gap length (m),

K_{cS}, K_{cR} are Carter's coefficients given in reference [18].

The product of the MMF and the permeance gives the air-gap flux-density, which has the following expression:

$$B(\theta,t)=\sum_{k=-\infty}^{\infty}B_K\cos[p_K\theta-\omega_K t+\theta_K], \quad (4.4)$$

where, p_k is the number of pole-pairs of the kth harmonic flux-density with a maximum amplitude of B_k, ω_k is the corresponding angular velocity and θ_k is its phase angle.

Hence, the radial force acting per unit area on the stator and rotor surface at a given location is:

$$F(\theta,t)=\frac{1}{2\mu_0}B^2(\theta,t)=\frac{1}{2\mu_0}\{\sum_{k=-\infty}^{\infty}B_k\cos[p_k\theta-\omega_k t+\theta_k]\}^2 . \qquad (4.5)$$

Considering just the first order terms in the permeance expression, and also only the fundamental component in the MMF, the resulting flux-density is:

$$B(\theta,t)=M_p\lambda_0\cos(p\theta-\omega t)+\frac{M_p\lambda_0\lambda_{S1}\lambda_{R1}}{4}\cos\{(Z-S+p)\theta-[\frac{Z}{p}(1-s)+1]\omega t\}$$

$$+\frac{M_p\lambda_0\lambda_{S1}\lambda_{R1}}{4}\cos\{(Z-S-p)\theta-[\frac{Z}{p}(1-s)-1]\omega t\}$$

$$=B_p\cos(p\theta-\omega t)+B_{S1}\cos\{(Z-S+p)\theta-[\frac{Z}{p}(1-s)+1]\omega t\}$$

$$+B_{S1}\cos\{(Z-S-p)\theta-[\frac{Z}{p}(1-s)-1]\omega t\}. \qquad (4.6)$$

Finally, the force produced by this flux-density is:

$$F(\theta,t)=\frac{B_p^2}{2}\cos(2p\theta-2\omega t)+\frac{B_pB_{S1}}{2}\{\cos[(Z-S+2p)\theta-\left(2\frac{Z}{p}(1-s)+2\right)\omega t]$$

$$+\cos[(Z-S)\theta-\frac{Z}{p}(1-s)\omega t]\}+\frac{B_pB_{S1}}{2}\{\cos[(Z-S)\theta-\frac{Z}{p}(1-s)\omega t]$$

$$+\cos[(Z-S-2p)\theta-\left(\frac{Z}{p}(1-s)-2\right)\omega t]\}$$

$$=F_p\cos(2p\theta-2\omega t)+F_{S1}\{\cos[(Z-S+2p)\theta-\left(2\frac{Z}{p}(1-s)+2\right)\omega t]$$

$$+\cos[(Z-S)\theta-\frac{Z}{p}(1-s)\omega t]+\cos[(Z-S-2p)\theta-\left(\frac{Z}{p}(1-s)-2\right)\omega t]\}$$

$$(4.7)$$

This equation reveals that the interaction of the fundamental air-gap field with the slot harmonic-fields produces three distinct components in the radial-forces. These slot-harmonic forces act on the stator at frequencies as:

$$[\frac{Z}{p}(1-s)-2]f, \qquad [\frac{Z}{p}(1-s)]f, \qquad \text{and } [\frac{Z}{p}(1-s)+2]f.$$

When the higher order harmonic-components are included in the permeance wave, the slot-harmonic forces will act on the stator surface at frequencies as:

$$[n\frac{Z}{p}(1-s)-2]f, \quad [n\frac{Z}{p}(1-s)]f, \quad \text{and } [n\frac{Z}{p}(1-s)+2]f,$$

where n=0, 1, 2, 3, … .

In no-load condition, the important slot and saturation harmonics of the 10 hp induction motor under investigation are: 120Hz, 240Hz, 360Hz, 480Hz, 720Hz, 930Hz, 1170Hz, 1290Hz, 1410Hz, 1980Hz, 2010Hz, 3300Hz, 5280Hz, 6330Hz, 6450Hz, 6570Hz, and 7740Hz.

4.4 Comments

Before proceeding with the actual experimental investigations, discussions of important quantities and procedures for the experiments are presented in this chapter. Standards and test-codes for the measurement of noise which provide the guidelines for the procedures are described. Following the standards, the measuring surfaces and location points of microphones are then described. Also, theoretical analyses of magnetic-fields and electromagnetic forces are summarized as a general preparation for the experimental investigations.

The results of the experimental investigations performed on the test motor, and the related information will be presented in the following chapters.

5. DESCRIPTION OF TEST MOTOR AND PRELIMINARY INVESTIGATIONS

5.1 Description of Test Motor and Loading Device

Before proceeding with the preliminary and other experimental investigations, it is beneficial to provide the description of the test motor and the loading device.

In order to acquire physical understanding about the magnetic-fields and electromagnetic forces, extensive experimental investigations have been carried out on a specially designed 10 hp, 4-pole, three-phase squirrel-cage induction motor. The motor has 36 stator slots which contain a double-layer winding connected in star. Throughout the investigations reported in this thesis, the stator phase-belts have been connected in parallel. The rotor cage-winding is placed in 43 semi-closed rotor slots. Further details of this test motor are given in Appendix B.

Several search-coils having a span equal to the tooth-width were used to obtain the signals that provide information about the magnetic-fields.

Since the machine vibrations can cause vibrations of the base, floor or surrounding structure in the frequency range to be measured, the test machine should be vibration-isolated from the base using resilient mounts. This 10 hp test motor is placed on rubber blocks having a diameter of 50 mm and thickness of 25 mm. This elastic mounting arrangement ensures that there is virtually no vibration interference from the substructure. Also, a flexible coupling is used to isolate the shaft from the loading device. Further, the end-shields of the motor are removed, and the rotor is supported by pedestals on both sides of the stator. This ensures some elimination of rotor effects that may influence the measurements made on the stator [40].

An electric eddy-current brake was used as loading device, which consists of a brake-rotor and a brake-stator. The brake-rotor is composed of two thin metal discs bolted on two ends of the shaft, and the stator is composed of magnetizing coils fixed between these two discs. When the direct current is supplied to the coils, ring-shaped magnetic-flux is formed around the coils through the brake-stator and rotor. The electric eddy-current is induced when the rotating discs cut the magnetic-flux and the energy absorbed by the brake is converted into heat by the induced eddy-currents. Eddy-current brake is very quiet under operation. The power it consumes can be controlled easily by adjusting its excitation current. Hence, it was used as the loading device for the induction motor. Also, the eddy-current brake is supported by rubber blocks in order to isolate the vibration from the substructure.

To provide a better understanding of the whole assembly, Figure 5.1 gives the pictorial view of the test motor and the eddy-current brake.

5.2 Preliminary Investigations

According to the analyses summarized in Chapter 4, the magnetic-field in the air-gap of an induction machine is not a pure sinusoid. Harmonic-fields are always present in addition to the fundamental field. The slot-harmonics are generated due to the distribution of the windings and the variations in the length of the air-gap caused by the slotting of the stator and rotor surfaces. The magnetic saturation of the teeth and cores of both stator and rotor tends to distort the field distribution in the air-gap. Modern economical factors usually result in operation of the machine with appreciable magnetic saturation, which acts as an additional source of air-gap field harmonics.

In order to acquire physical understanding about the magnetic-field of the machine, some preliminary investigations are performed in this chapter on a 10 hp, squirrel-cage induction motor. The preliminary investigations include; the harmonic analysis of the stator current, spectral analysis of the induced voltage in stator search-coils, and octave sound measurement by using sound-level-meter.

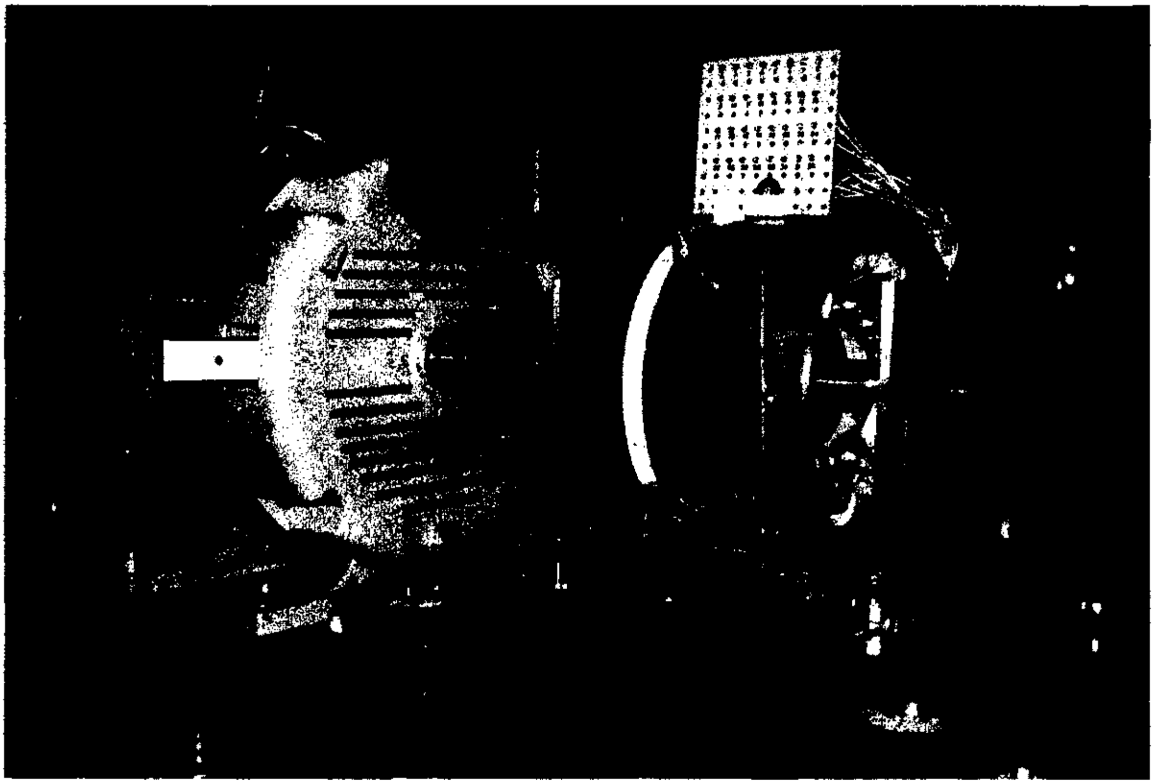


Figure 5.1 : The assembly of test motor and eddy-current brake.

5.2.1 Harmonic Analysis of the Stator Current

An ideal sinusoidal distribution of MMF is possible only if the machine has an infinitely large number of slots, and the turns of a winding are sinusoidally distributed in the slots. This is not possible to attain in practice. In a practical machine, the winding is distributed in a finite number of slots and all the coils are, generally, identical. As a result, when current flows through a winding the MMF distribution in space has a stepped wave-form which contains a fundamental component and a family of space-harmonics.

A practical way to obtain useful information on MMF is to analyze the current in the stator windings. In order to perform the harmonic analysis of the current, a signal proportional to the stator current is used. This signal is derived by measuring the voltage drop across a standard ammeter shunt which is connected in series with the phase-winding. The shunt produces a voltage drop of 50 mV when 5 A current flows through it. The signal across the shunt is fed to Hewlett Packard 3580A Spectrum Analyzer directly.

Table 5.1 and Table 5.2 show the measured spectra of the current in a stator phase-winding at no-load. The motor is rated for 230V (Line to Line) in star connection while the stator-belts are connected in parallel. Table 5.1 shows the measured spectrum of the current when the motor is operated at 50% of the rated voltage, and Table 5.2 shows the spectrum at 100% of the rated voltage.

Table 5.1 : Measured spectrum of the current in a stator phase-winding when motor is running at 50% V_{rated} at no-load.

Frequency (Hz)	Voltage (rms) (mV)	Current (A)
60	41.0	4.1
120	0.35	0.035
180	0.69	0.069
300	1.22	0.122
420	0.6	0.06
660	0.12	0.012
780	0.06	0.006
1140	0.045	0.0045

Table 5.2 : Measured spectrum of the current in a stator phase-winding when motor is running at 100% V_{rated} at no-load.

Frequency (Hz)	Voltage (rms) (mV)	Current (A)
60	105.0	10.5
120	0.75	0.075
180	2.25	0.225
300	2.55	0.255
420	2.35	0.235
540	0.07	0.007
660	0.18	0.018
780	0.2	0.02
900	0.044	0.0044
1020	0.17	0.017
1140	0.16	0.016
1380	0.085	0.0085
1460	0.047	0.0047

From the above two tables, it is clear that the MMF produced by the stator contains harmonic-components besides the fundamental for both applied voltages. As the applied voltage is increased from 50% to 100% rated value, the saturation effects introduce additional harmonic-components in MMF.

5.2.2 Spectral Analysis of the Induced Voltage in Stator Search-coils

The magnetic forces that produce vibrations which lead to acoustic noise radiated by the machine, are created by the pulsations of the magnetic-fluxes through the iron. Hence, information on magnetic-fields is very useful for the analysis of the magnetic forces. Search-coils are used to obtain the signals for the analysis of magnetic-fields.

A search-coil usually consists of a loop of single turn of copper conductor. It is placed at the top of a stator slot under the tooth lip. The radial magnetic forces that act on the stator are caused by the flux-pulsations through the stator teeth. It is appropriate to use search-coils having a span equal to the tooth-width to sense the flux-pulsations through a tooth [18].

Figure 5.2 shows the block diagram of the measuring system. Different kinds of search-coils were implanted inside the stator for various investigations by Balan [18,19]. Signals from two search-coils (#1 and #2) which have a span equal to the tooth-width are fed to the Hewlett Packard 3580A Spectrum Analyzer for spectral analysis. Also HP54601 Digital Storage Oscilloscope and HP Thinkjet printer are used to record the wave-form of the signals obtained.

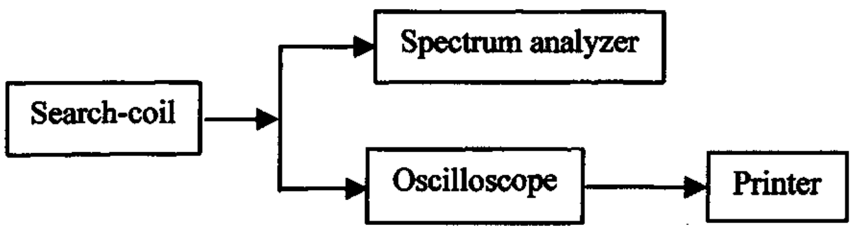


Figure 5.2 : Block diagram of the measuring system for signals from the search-coils.

The signals from these two search-coils (#1 and #2) are obtained when the motor runs at no-load under two operating conditions; applied voltages across the stator windings are 50% and 100% of the rated value, respectively. Figure 5.3 and Figure 5.4 show the oscillograms of the induced voltage in #1 search-coil, whereas Figure 5.5 and Figure 5.6 show the oscillograms of #2 search-coil. The ripples in all these oscillograms clearly show that there are many harmonic-components in the air-gap field.

The oscillograms just give the overall wave-forms of each signal, but they do not provide the information about the frequency components. In order to obtain the spectral distribution of harmonic-components, the induced voltage from each search-coil is fed to the spectrum analyzer. The values for each frequency component from the spectrum analyzer are recorded in Table 5.3 to Table 5.4.

It is clear that there are many harmonic-components accompanying the fundamental component in the magnetic-fields. When the impressed voltage is increased to 100% of rated value, additional saturation components are introduced. The results reported here are very similar to those obtained in Ref [18].

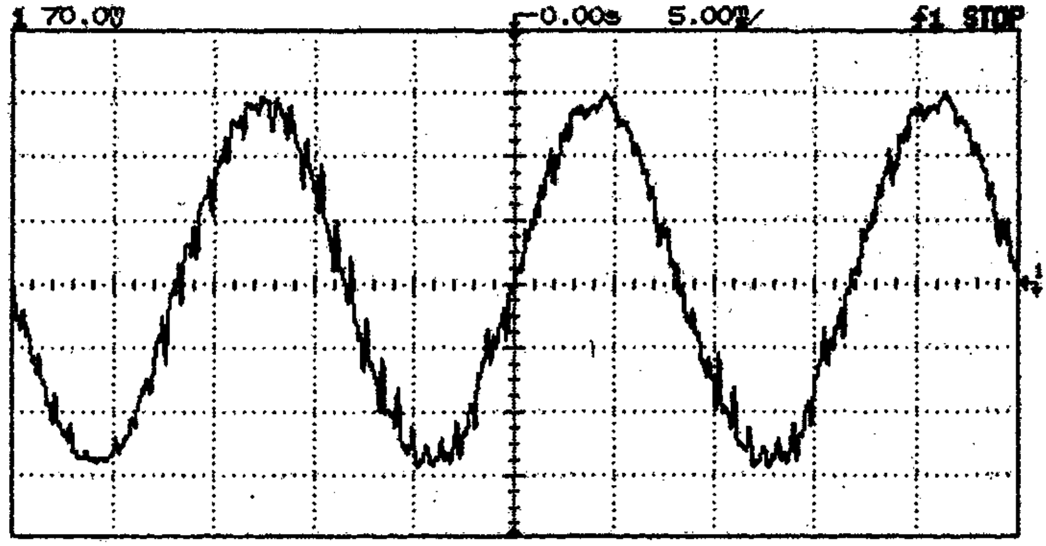


Figure 5.3 : Oscillogram of induced voltage from #1 search-coil (one tooth-width) when the impressed voltage across the stator winding is 50% of V_{rated}.

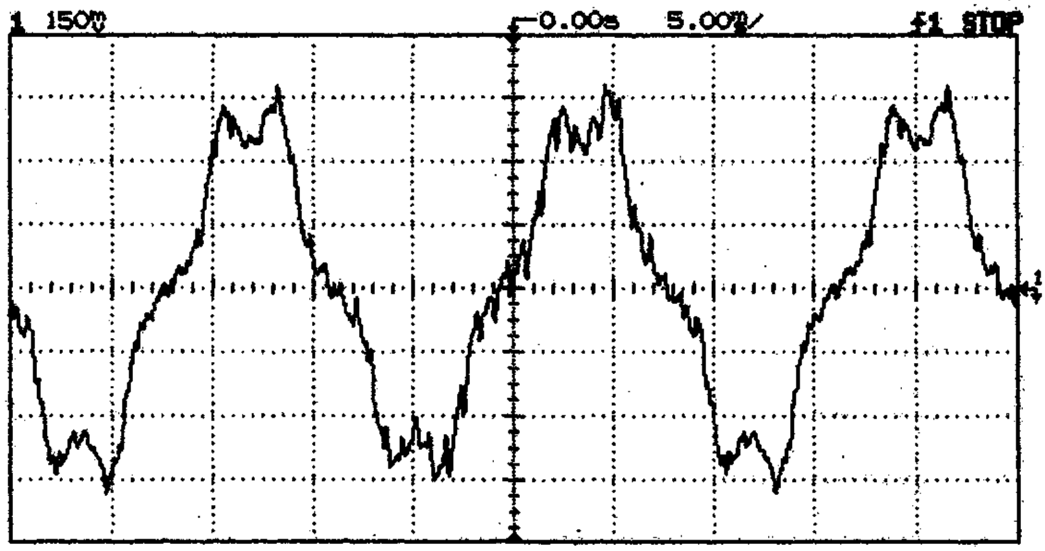


Figure 5.4 : Oscillogram of induced voltage from #1 search-coil (one tooth-width) when the impressed voltage across the stator winding is 100% of V_{rated}.

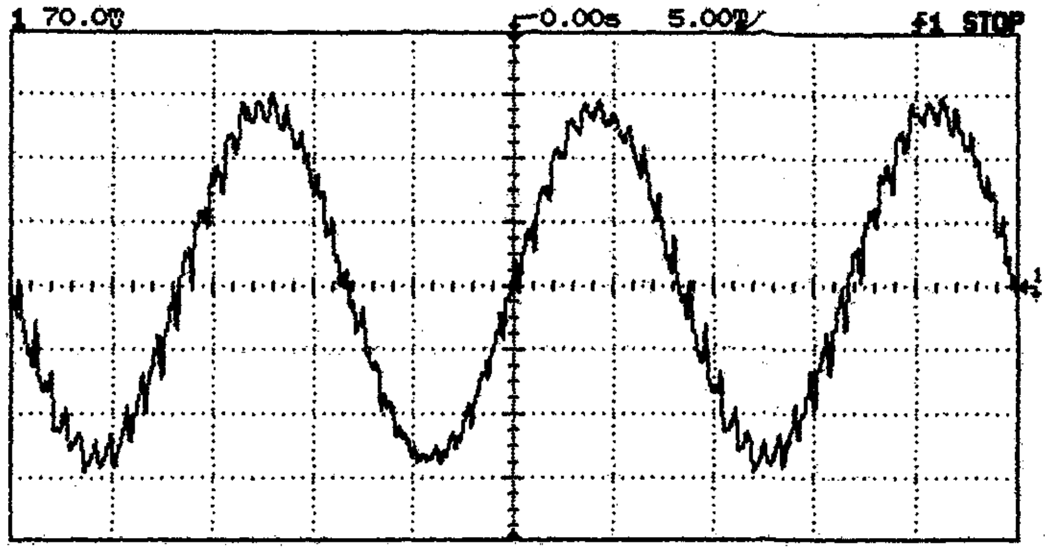


Figure 5.5 : Oscillogram of induced voltage from #2 search-coil (one tooth-width) when the impressed voltage across the stator winding is 50% of V_{rated}.

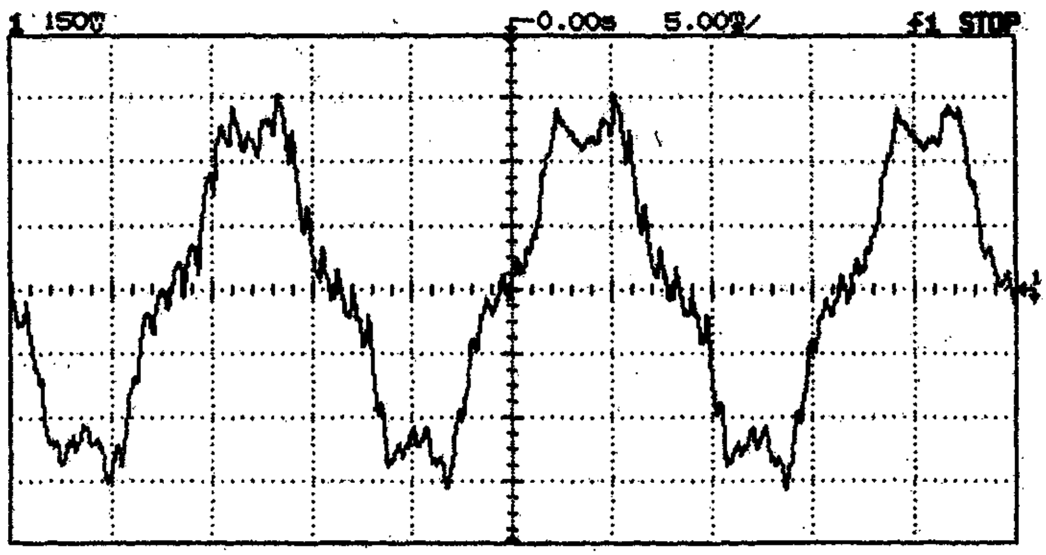


Figure 5.6 : Oscillograms of induced voltage from #2 search-coil (one tooth-width) when the impressed voltage across the stator winding is 100% of V_{rated}.

Table 5.3 : Measured spectra of the induced voltage in #1 stator search-coil (one tooth-width) for 50%, and 100% rated voltage.

Frequency (Hz)	50% V_{rated}	100% V_{rated}
	Measured value (mV)	Measured value (mV)
60	141.0	280.0
120	1.0	*
180	2.1	30.0
300	1.2	46.5
420	1.85	23.0
720	1.18	2.0
1230	2.45	6.25
1350	5.25	12.0
1380	2.0	3.5
1410	1.4	2.25
1470	1.75	5.5
1500	1.2	2.0
1590	1.15	4.25
1710	1.1	2.5
1800	1.08	2.0
2520	3.5	3.0
2550	1.9	1.75
2640	4.65	4.75
2670	3.2	4.0
3810	3.65	4.5
3930	3.2	4.25
4050	*	1.8
5100	*	1.1

* : Values cannot be measured as they are below the threshold of the instrument.

Table 5.4 : Measured spectrum of the induced voltage in #2 stator search-coil (one tooth-width) for 50%, and 100% rated voltage.

Frequency (Hz)	50% V_{rated}	100% V_{rated}
	Measured value (mV)	Measured value (mV)
60	136.0	270.0
120	0.88	*
180	1.24	26.5
300	1.55	44.5
420	*	19.0
720	1.06	1.9
1230	1.06	5.2
1350	8.2	18.5
1380	2.35	4.0
1410	*	2.25
1470	1.55	5.5
1500	*	2.0
1560	1.15	*
1590	*	4.25
1710	*	3.25
1800	*	2.0
2520	1.95	2.25
2550	1.3	1.45
2640	3.65	4.75
2670	2.1	3.75
2760	*	1.75
3810	2.6	3.0
3930	2.9	4.0

* : Values cannot be measured as they are below the threshold of the instrument.

5.2.3 Noise Measurements Obtained Using Sound-Level-Meter

As discussed in Chapter 3, the sound-level-meter is a portable instrument which is convenient and suitable for the common measurements of sound levels. The sound pressure-level results obtained by using the sound-level-meter are reported in the following part of this chapter, in order to obtain some information which can describe the noise of the test motor quickly when it is operating in an ordinary laboratory.

Generally, the components of a sound-level-meter include a filter network in addition to a microphone, amplifiers, attenuators and a read-out meter giving sound pressure-level. Most sound-level-meters include A-, B-, and C-weighting networks as well as an all-pass (linear) arrangement without weighting. Sometimes provision is made for external band-pass filter, octave-band or one-third octave-band analysis. Sounds encountered in practice are seldom ever steady in level. Fluctuations in level are almost always encountered, and sometimes the variations in level can be quite large. To accommodate this phenomenon, the sound-level-meter is provided with two measuring responses. "Fast" has a time constant of 125 ms and is designed to approximate the response of the ear. "Slow" has a time constant of 1 s, which does not simulate the response of the ear. It is useful to determine mean levels when the measured sound fluctuates continuously and violently during the course of a measurement.

The B&K Sound Level Meter Type 2203 is an accurate instrument designed for outdoor use as well as for laboratory measurements. B&K Octave Filter Set Type 1613 is used in conjunction with B&K Sound Level Meter Type 2203 to measure the sound levels of the motor. The center frequencies of each octave filter are; 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz.

Since detailed sound and noise measurements will be presented in the following chapters, the results obtained by using sound-level-meter are provided here. Detailed information about the selection of measuring points has been discussed in Chapter 4 (Figure 4.1). The location of measuring positions for the measurements using the sound-level-meter are shown in Figure 5.7.

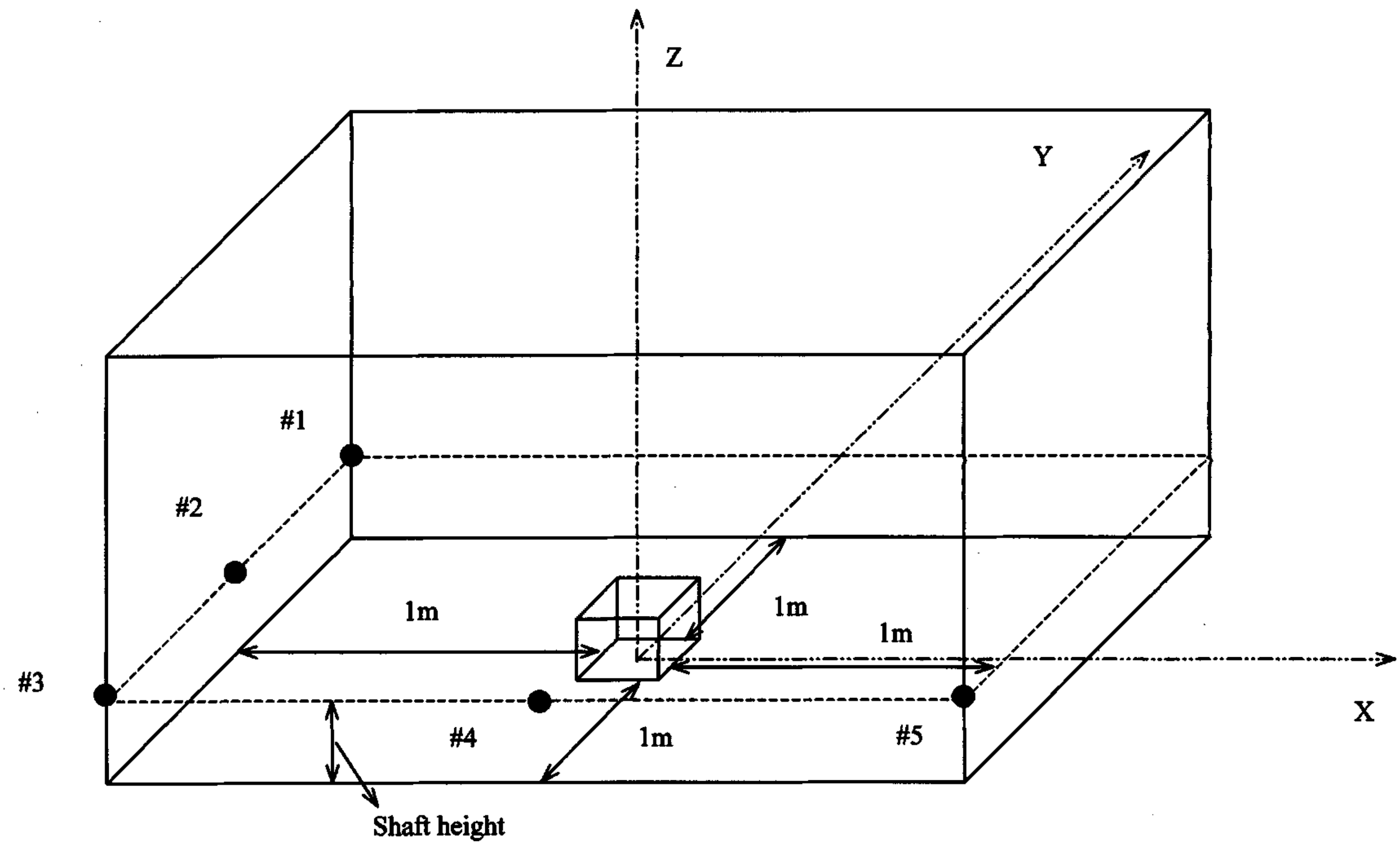


Figure 5.7 : Measuring positions for the noise measurements by using sound-level-meter.

The sound-level-meter is held by a tripod at each of the five measuring positions. These five positions are on the imaginary surface which is through the shaft of the motor and parallel to the base plane. The distance of each point from the motor surface is also indicated in Figure 5.7. The direction of the microphone is fixed in such a way that the direction of the sound waves is aligned with the axis of the microphone.

Table 5.5 and Table 5.6 show the measured results when the motor runs at 50 % and 100% rated voltage during the day-time under no-load condition, respectively. The left column under each measuring position shows the background noise, the right column shows the sound pressure-levels of the motor when it is running. As a comparison, Table 5.7 shows the results measured when the motor is still operating at 100% rated voltage, but in the evening. The fast time-weighting is used since the motor radiates steady noise. From the measured data, it is clear that:

- Background noise is quite high during the day-time. The interferences of background noise are important concerns for sound measurements.
- In the frequency-bands less than 250 Hz, the sound pressure-levels for both background noise and motor noise are not very different. These results do not carry much significance.
- As the applied voltage increases, the sound pressure-levels of some frequency-bands increase.

5.3 Comments

Since extensive experimental investigations have been performed on the specially designed test motor, the descriptions of both test motor and loading device are provided in this chapter. The harmonic analysis of the stator current, spectral analysis of the induced voltage in stator search-coils, and sound measurement by sound-level-meter form the preliminary investigations, which are necessary before one conducts detailed investigations related to vibration and noise problems of the induction motor.

The vibration measurements that provide information on electromagnetic exciting forces are reported in the next chapter.

Table 5.5 : Measured sound pressure-levels of the motor operating on 50% rated voltage at five measuring positions under no-load condition (day-time).

Center Frequency (Hz)	Point #1		Point #2		Point #3		Point #4		Point #5	
	B-G in dB	M in dB	B-G in dB	M in dB	B-G in dB	M in dB	B-G in dB	M in dB	B-G in dB	M in dB
31.5	52	52	51.5	52	53	53.5	53	53.5	54.5	54.5
63	50.5	51	50	50	51	51	49.	49.5	48	48.5
125	48.5	49	47.5	47.5	47.5	48.5	46.5	49	48.5	52.5
250	38.5	47.5	40.5	48.5	42.5	47.5	38.5	48.5	41.5	49.5
500	37.5	52	37	51.5	37.5	51.5	37	52	37.5	50
1000	30.5	52.5	31	50	31	50.5	31.5	51	31.5	49
2000	23.5	44.5	24	45.5	22.5	43.5	25.5	43.5	24	43.5
4000	18.5	44.5	17.5	42.5	18	44.5	19	44	17.5	43.5
8000	14	27	13.5	27.5	13.5	26.5	14	30.5	14	27.5
A–weighting	37.5	55.5	37	53	38	54	37	54.5	38	52.5

B-G: background noise M: measured motor noise

Table 5.6 : Measured sound pressure-levels of the motor operating on 100% rated voltage at five measuring positions under no-load condition (day-time).

Center Frequency (Hz)	Point #1		Point #2		Point #3		Point #4		Point #5	
	B-G in dB	M in dB	B-G in dB	M in dB	B-G in dB	M in dB	B-G in dB	M in dB	B-G in dB	M in dB
31.5	51	52	52	52	53	54.5	54	54	55	56
63	51	52	50	50	52	53	51	51	50	50
125	47	50	48	51	49	51	48	51	50	54
250	39	48	42	51	42	49	41	49	41	51
500	36	52	37.5	54	37.5	51	37.5	52	38	51
1000	30	58	30.5	54	31	54.5	30	53.5	30	55.5
2000	23	46	23	44	22	44	22.5	46	23	44
4000	16.5	43	16	43.5	16.5	42.5	16	44	16	42
8000	14	30	14	32	14.5	31	14	34.5	14	34
A–weighting	37	57.5	38.5	56	39	55.5	38.5	55.5	39	56.5

B-G: background noise M: measured motor noise

Table 5.7 : Measured sound pressure-levels of the motor operating on 100% rated voltage at five measuring positions under no-load condition (evening).

Center Frequency (Hz)	Point #1		Point #2		Point #3		Point #4		Point #5	
	B-G in dB	M in dB	B-G in dB	M in dB	B-G in dB	M in dB	B-G in dB	M in dB	B-G in dB	M in dB
31.5	41.5	42	42	43.5	42.5	43.5	46.5	47.5	48	50
63	40	42	41	42	46	46.5	44.5	46	47	48
125	43.5	48	45.5	49	45.5	48	45	47.5	49.5	53
250	34	47.5	37	51.5	36.5	48	37.5	48	35.5	50
500	35	53	34.5	53	34	52	35	52	37	49
1000	23	62	27.5	56	26	52	24	54	27	51
2000	20	46	20	45	18.5	44	20.5	47	21	43
4000	13	43	13	42	14	44	12.5	44	13	41
8000	13.5	29.5	13.5	32	13.5	32.5	13.5	35	13.5	33
A–weighting	34	62	35.5	56.5	34.5	56	35.5	56	36.5	54

B-G: background noise M: measured motor noise

6. VIBRATION MEASUREMENTS

As discussed previously, electrical machines produce annoying noise. International standards stipulate the maximum noise levels and the methods to rate the noise levels. Sound powers are basically used for the labeling of machinery and equipment [22]. In IEC 34-9 [17, 41], the maximum permissible A-weighted sound power-levels are specified according to the method of cooling and degree of protection for machines. For example, a three-phase cage induction motor whose rated output is within 5.5 kW to 11 kW with 4 poles, the maximum A-weighted sound power-level is 81 dB. A-weighted value is beneficial in allowing quick determination of the noise level, but it does not provide the information on the individual noise components and their frequencies.

Often, information on the frequencies at which the noise levels are prominent is necessary. More importantly, the noise spectrum is useful in improving the techniques for machine design. In such cases, the spectrum or frequency analysis of the noise is required.

Frequency analysis refers to the resolution of a signal into a series of contiguous (adjoining) frequency-bands. Since the air-borne noise of a motor is produced by the vibrations of the stator, which are caused by the magnetic forces of the machine, the spectra of the sound signals can be compared with the spectra of vibrations produced by the machine. Special attention should be paid to a spectral-peak which appears at the same frequency in both sound signal and vibration signal since this is an evidence of a strong contribution by a particular source.

Other than the oscilloscope and the printer, all the instruments used throughout all the investigations reported in this chapter and following chapters are from B&K.

These instruments were purchased especially for the research associated with vibrations and noise.

Before proceeding with the noise measurements, it is appropriate to conduct the vibration measurements first, as this would provide the fundamental information about the frequencies at which the machine would radiate in the noise spectrum. The prediction of vibrations and noise is both complex and also specific to each machine with its system's parameters. Balan [18,19] focused on the theoretical analyses of electromagnetic forces, and experimental investigations on the mechanical response of an induction motor. With the help of these theoretical analyses and methods, investigations on vibrations were conducted, and these are reported in this chapter.

Compared to the noise measurements, vibration measurements are fairly straightforward because the accelerometers are in touch with the vibrating surface directly. In contrast, noise signals can be affected by background noise and test-environment. The investigations on both vibrations and noise are arranged in such a way that their results can be easily compared in order to obtain the correlation.

6.1 Measuring Instrumentation and Experimental Set-up

According to the previous discussions, electromagnetic forces are the main contributors that create the motor vibrations and the radiated noise. Since there is no direct method to measure electromagnetic forces in practice, the measurements of the vibration signals on the motor structure can provide very useful information on the electromagnetic forces.

Since the air-gap lengths vary from about a fraction of a millimeter for small machines to a little over a millimeter for large machines, the vibration measurements are conducted on the outside surface of the machine in practice.

6.1.1 The Measuring Instruments

B&K accelerometer type 4383 is used for vibration measurements and analysis. The active element of this accelerometer consists of piezo-electric discs loaded by seismic masses and held in position by a clamping ring. When the accelerometer is subjected to vibrations, the combined seismic mass exerts a variable force on the piezo-electric element. Due to the piezo-electric effect, this force produces a corresponding electrical signal. The type of accelerometer used in the experimentation is capable of measuring the accelerations in the range of 0.02 to 200 g with an output sensitivity of 200 mV/g ("g" being the acceleration due to earth's gravity) over the audio frequency range. However, the acceleration signal requires amplification and conditioning.

The vibration transducer should load the vibrating body, on which it is mounted, as little as possible. It is important that any additional mass must not change the original motion of the vibrating body, ideally. This additional mass may have inconsequential results when obtaining measurements on heavy machinery parts, but it can cause substantial changes if the vibration transducer is attached to light sheetmetal. Compared with the motor stator, in the present investigations, the mass of the accelerometer is negligible.

The way in which the accelerometer is attached to the vibrating surface is very important. In order to get the greatest accuracy, the method of fixing the accelerometer to the vibrating body should be as direct and steady as possible, since any flexibility between the accelerometer and the surface will cause measuring errors and produce a "mounting resonance" which will reduce the useful frequency range of the transducer. The best method of mounting is to use a steel stud screwed into both the vibrating surface and the base of the accelerometer, because this method provides the highest resonance frequency (up to 100 kHz) of any of the mounting techniques. Also, it permits measurements at very high vibration levels without loosening the transducer. It permits very high operating temperature, and gives accurate and reproducible results since the measurement positions are always fixed.

Since the stator-structure of the motor is smooth, therefore, the stud cannot be screwed in. Hence the beeswax-method, which provides a resonance frequency almost as high as that of the stud-mounting, is used when the motor temperature is less than 40 °C. As the temperature of the motor increases as the load increases, the beeswax melts when the motor is running with load. Under such circumstance, the magnetic-method is used for vibration measurement when the motor is running with load, although its frequency response is not as good as the wax-mounting. As discussed above, the added mass of the magnet is not significant for vibration measurements.

The output of the accelerometer needs to be modified through a preamplifier, as already discussed in Chapter 3. The Vibration Pick-up Preamplifier Type 1606 is designed for this purpose, to be used in vibration measurements and it constitutes an important link between the accelerometer and the appropriate measuring amplifier. The preamplifier mainly consists of a two-stage amplifier whose input impedance is made high to ensure a low cut-off frequency of the accelerometer, and a set of integrating-networks which can convert acceleration dependent signal into a signal proportional to velocity or displacement, and a built-in shaker table for the calibration purposes. Although the acceleration in absolute values of acceleration can be done, it is more convenient to express the acceleration signal in terms of mV.

B&K Frequency Analyzer Type 2107 is an AC operated audio frequency analyzer of the constant percentage band-width type. It has been designed especially as a narrow-band sound and vibration analyzer, but it may be used for any kind of frequency analysis and distortion measurements within the specified frequency range. The typical response curves are shown in Figure 6.1, f_c being the center frequency of the filter, i.e., the frequency to which the analyzer is tuned.

The attenuation in dB of a frequency one-octave away from f_c is shown in Figure 6.1. These selectivity curves correspond to the relative band-widths of the selection filters. The 3 dB band-width for each selectivity curve is given as percentage value in Table 6.1.

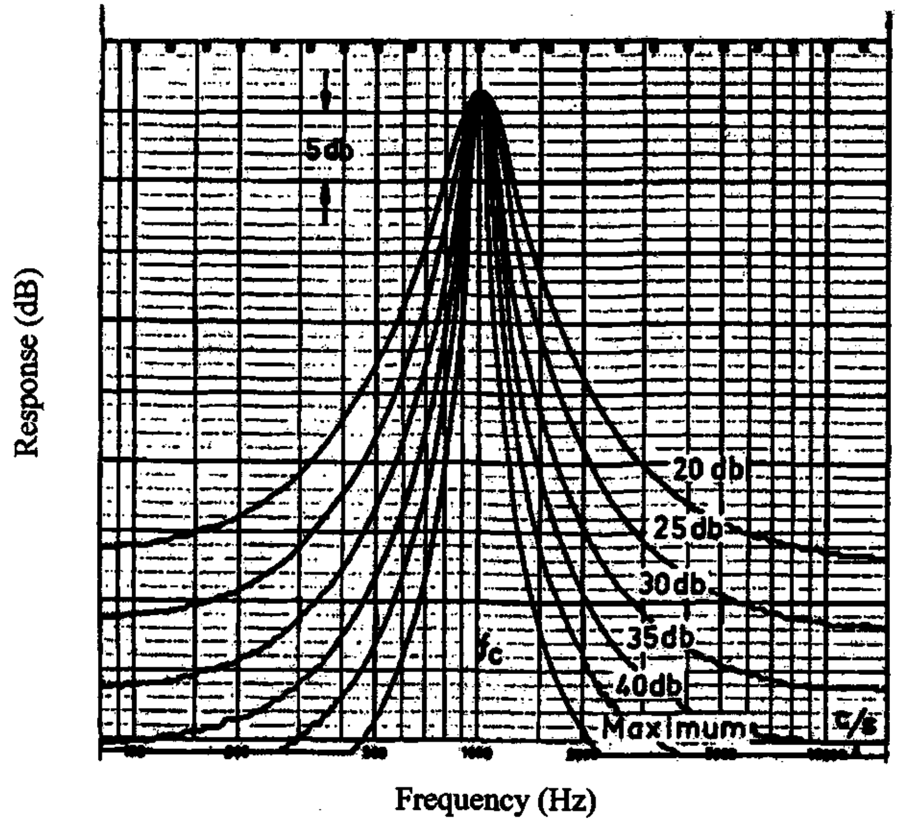


Figure 6.1 : Response curves of B&K Frequency Analyzer Type 2107.

Table 6.1 : Relative band-widths of the filters.

Octave Selectivity in dB	3 dB Band-width in Percent (%)
20	29
25	21
30	16
35	12
40	8.5
Max. approx. 45	6

The Charge Amplifier 2635 is a comprehensively equipped charge conditioning amplifier intended for general vibration measurements with a piezo-electric accelerometer input. The Tunable Band Pass Filter Type 1621 is a variable frequency band-pass filter which gives the ability to perform narrow-band frequency analysis. It consists of a tunable single pole Butterworth-filter with switchable band-width. Five contiguous frequency sub-ranges can be selected from the instrument's overall frequency range between 0.2Hz and 20 kHz, with each sub-range covering one order of magnitude.

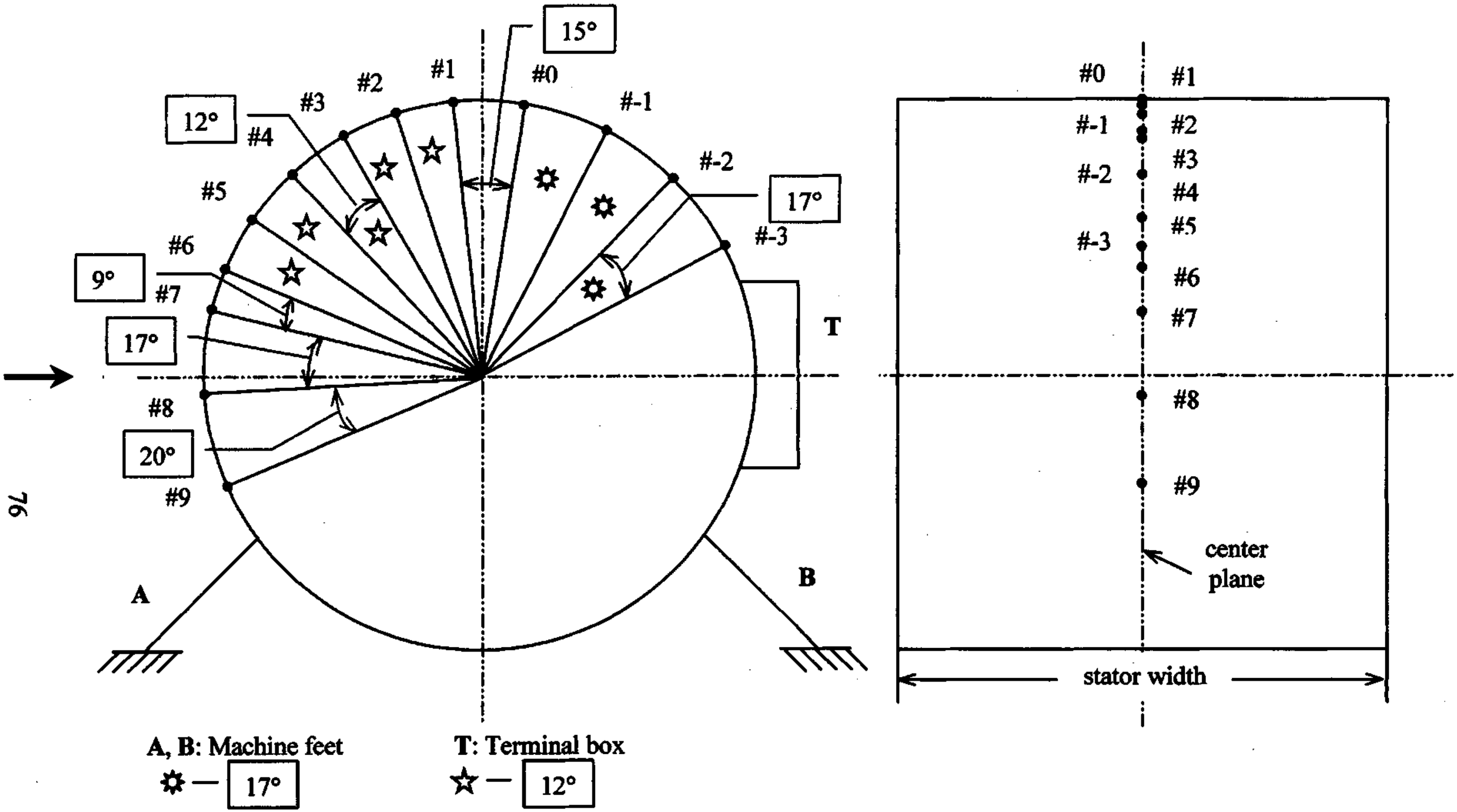
6.1.2 The Measuring Points

Vibration measurements depend on the requirement or objective of the investigations. Sometimes several measuring points may be good enough to complete the task, while in some cases more points are required. In order to explain the correlation between the stator vibrations and the noise-emission from the motor, and also the vibration-modes of the motor, 13 measuring points (see Figure 6.2) are chosen. The measuring points should be as many as possible in order to obtain good vibration-modes. Using too many measuring points would be time consuming, and information obtained may not provide extra useful information compared to the chosen 13 points.

Points #–3 and #0 are two points accessible on the right side of surface of the motor. Points #–3, #–2, #–1 and #0 are equally placed on the right surface. Point #1 is the top point on the left side of surface, #7 is the point near the middle and it is so chosen that good fixing of the accelerometer is ensured in spite of the arc. Point #6 is at the "anti-node" at 720 Hz, which was decided by careful preliminary investigations, and point #8 is the corresponding "node". Points #2 to #5 are equally placed between point #1 and #6. As there are also longitudinal vibration-modes [19], all the above 13 points are on the center-plane perpendicular to the shaft-axis of the motor so that the mode-shape measurements are radial circumferential modes.

6.2 Spectral Distribution of Vibration Signals

According to the theoretical analyses summarized in Chapter 4, important slot and saturation harmonic-components cover a wide frequency range. As the first step, it is important to obtain the experimental information about the spectral distribution of harmonic-components.



(a) measuring point along the stator circumference

(b) left side view (⟶)

Figure 6.2 : Layout of the vibration measuring points on the surface of the stator of motor.

Since no-load is the required condition set by standards, it is appropriate to conduct the spectral investigations in no-load condition. In addition to the running condition under 100% rated voltage, 50% rated voltage was also chosen so that the information about the changes in the vibration levels with applied voltage could be obtained. The block diagram of the measuring system is shown in Figure 6.3. The experimental procedures are:

- The motor is supplied with 3-phase voltage of 50% rated value (115V), and the rotation is close to 1800 rpm. At each of the 13 measuring points, the Frequency Analyzer is tuned in to scan the whole frequency range of interest.
- With applied voltage of 100% rated value (230 V), the motor is running close to 1800 rpm. Also, the whole frequency range of interest is scanned at 13 measuring points.

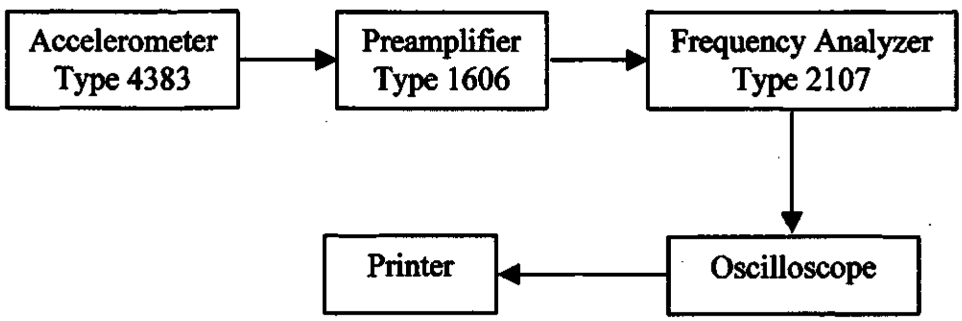


Figure 6.3 : The block diagram of the measuring system for vibration level measurements.

The measured results at point #6 are plotted in Figures 6.4 and 6.5, as an example, to show the measured experimental results. In order to present the measured values clearly and conveniently, the vibration levels are expressed in dB. It is evident that the vibration levels increase as the applied voltage is increased. Also, those harmonic-components predicted by theoretical analyses do appear as expected.

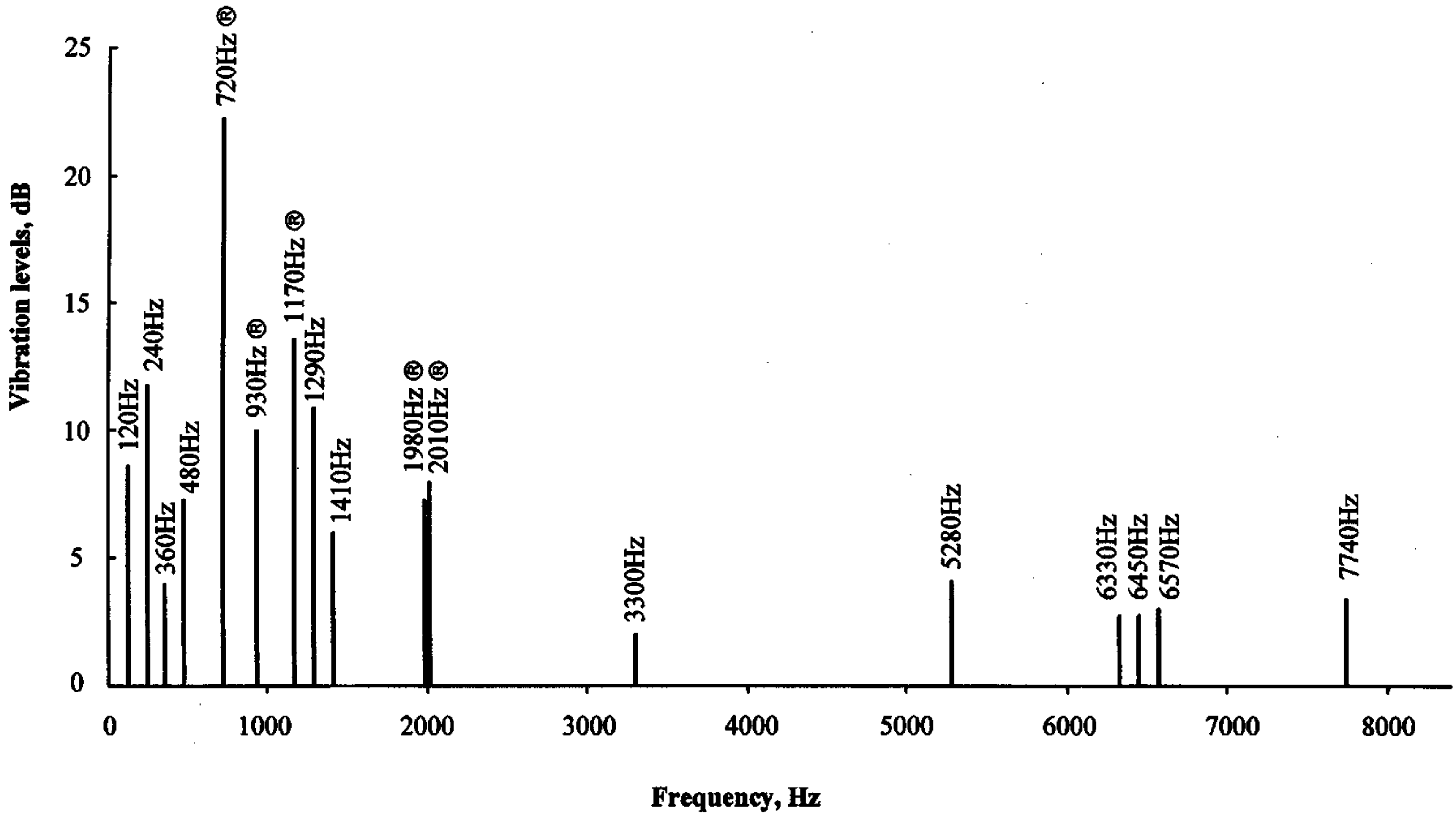


Figure 6.4 : Spectral distribution of vibration signals at point #6 when the motor is applied with 50% of rated voltage without load.

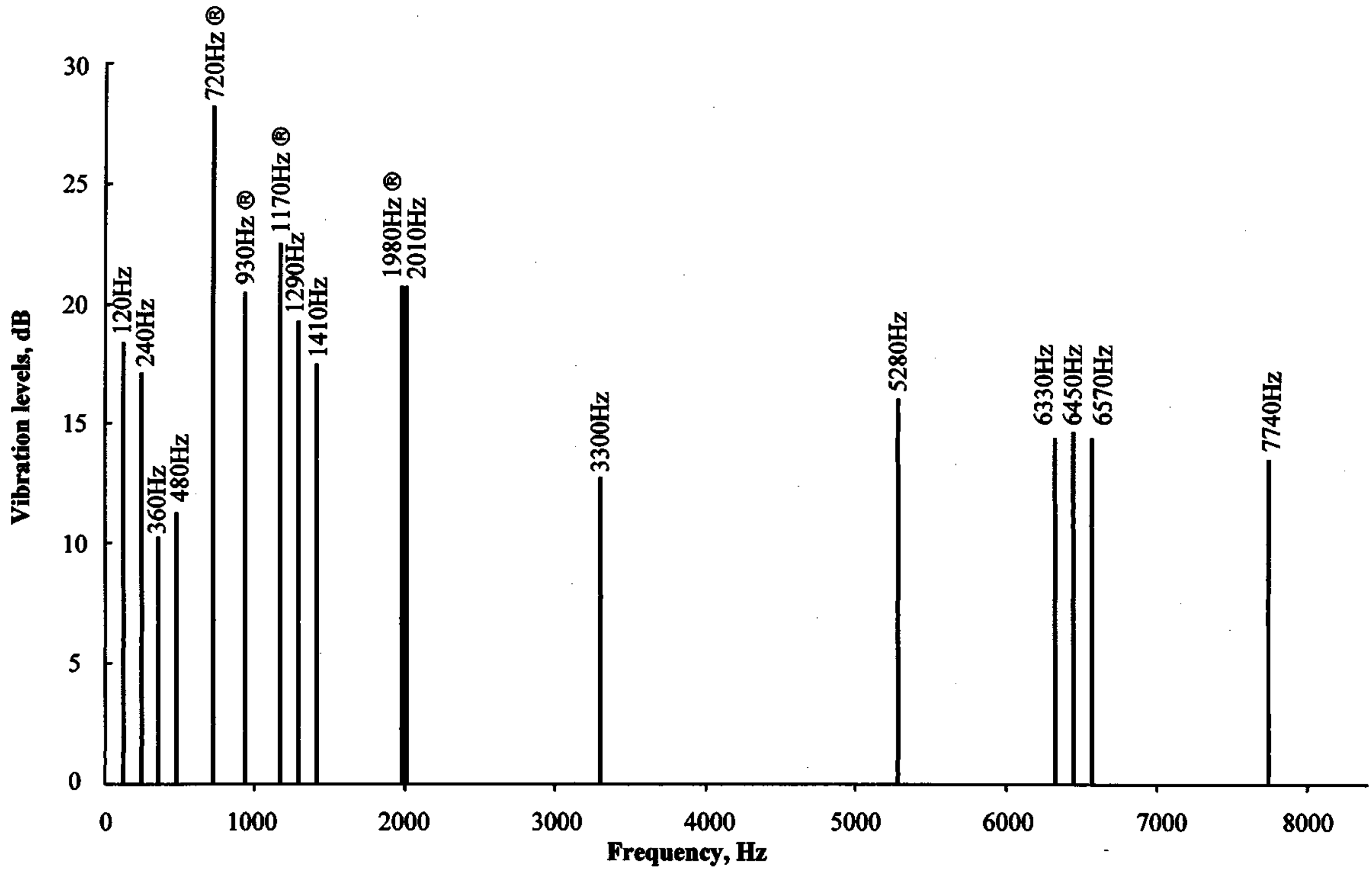


Figure 6.5 : Spectral distribution of vibration signals at point #6 when the motor is applied with 100% of rated voltage without load.

During the investigations, it was observed that the readings at some frequencies were not steady. They were oscillating to some extent. Referred to the oscillograms shown by oscilloscope, it was recognized that it was the result of interference from the neighboring frequencies, which cannot be totally attenuated by the filters of analyzer. Detailed discussions regarding the interference problems and the possible solutions are provided in Appendix C. Due to the fact that it was not possible to completely eliminate the interference of neighboring frequencies in the investigations, the following methods were used to obtain the measured values.

- The oscillogram on the oscilloscope and the reading of Frequency Analyzer are used together to obtain the reliable measured value.
- The frequencies at which interference may exist are theoretically sorted out. When the filter is tuned to one of these frequencies, the oscillogram is referred first to decide if there is interference.
- If there is interference, the "oscillating-range" of vibration level is recorded from the analyzer. Then, the middle value of the oscillating-range is taken as the reading of vibration level. Since the Frequency Analyzer has been used for both vibration and noise investigations, the errors caused by the interference from neighboring frequencies are kept at minimum and they will be same for both vibration signals and noise signals.

After finishing the investigations on spectral distribution of vibration signals at each measuring point, it became clear that the vibration levels of the same frequency at these 13 points are different under the same operating conditions of motor. This is the phenomenon produced by the electromagnetic forces. The mode-shape measurements in the next section provide visual description of this phenomenon.

6.3 Mode-shape Measurements

Electromagnetic forces are distributed around the circumference of the machine. They produce cyclic deformations of the stator and rotor. The circumferential mode of a particular vibration, n, is defined as the number of cycles of associated deformations along the circumference. The various modes of vibrations of stator and rotor of a machine are shown in Figure 6.6.

Balan [18] measured the modes and resonant frequencies of the test motor under magnetic shaker excitation. The resonant frequencies of the stator with windings are presented in Figure 6.7, which were measured by Balan. As a contrast in excitation, modes of the same stator under the standard three-phase power supply were measured. When measuring the mode-shape of vibrations at certain frequency, two accelerometers (B&K 4383) at two different points were used. One accelerometer was treated as the reference. If the vibration wave from the other accelerometer is in phase with the wave from the reference accelerometer, the displacement directions of these two points are in phase, i.e., they are both in the direction inward or outward off the equilibrium position. If these two waves are out of phase, the displacement directions of these two points are opposite, one is inward, and the other is outward, or vice versa.

Due to limitations of the instrument, two different systems were used to process the signals from the two accelerometers. Figure 6.8 shows the block diagram of the measuring system. After processing the vibratory signals through these two systems, they are fed to HP54651B oscilloscope simultaneously so that the phase comparison can be made.

The operating conditions for the mode-shape measurements of the test motor are:

- The motor was running by itself (idling), i.e., without coupling the load device. The supplied voltage was kept at 50% of rated voltage (115V).
- The motor was still running by itself (idling), but the impressed supplied voltage was at 100% of rated voltage.

The measured modes for frequencies of 720 Hz and 3300 Hz are shown in Figure 6.9 to Figure 6.10. As evident, the modes at 720 Hz are well defined. Since 720 Hz is near the most prominent resonant frequency (730 Hz) of the stator (Figure 6.7), even small magnitude of the exciting-force can cause higher level of vibrations. Although it was not possible to get the complete mode-shape, it is very clear from Figure 6.9 that mode-shape at 720 Hz is n = 2. This is in good agreement with the results obtained before [19] for 720 Hz. From the measured results, it is evident that although the mode is same but the vibratory pattern changes to some extent with the voltage applied to the motor is changed. Compared to the modes of 720 Hz, the modes of 3300 Hz were not clearly defined. This can be attributed to the weak resonance at the nearby frequency $f = 3314$ Hz.

6.4 Changes of Vibration Levels with Load

The mode-shape measurements provide the description of the stator deformation under electromagnetic forces, which is the mechanical response of the stator. The changes of vibration levels caused by the changes in operating conditions can give very useful information about the noise level.

The block diagram of measuring system for the vibration level measurements has already been given in Figure 6.3. Also, the experimental procedures used in the investigations are given below:

- Vibration measurement under no-load is a required operating condition for rotating electric machinery. In the present experimentation, the motor is coupled to the eddy-current brake which is without any excitation, i.e., no direct current is supplied to eddy-current brake. The motor is energized at rated voltage 230V and its speed at no-load is near 1800 rpm. The measurements are taken at each measuring point as defined in Figure 6.2. Further, at each point detailed frequency spectra are recorded.
- Vibration measurement when motor is running with 50% of rated load is a very useful condition to obtain good information about vibrations and noise produced by the motor when loaded with different values, although this condition is not a required condition. To load the motor, the eddy-current brake is supplied with

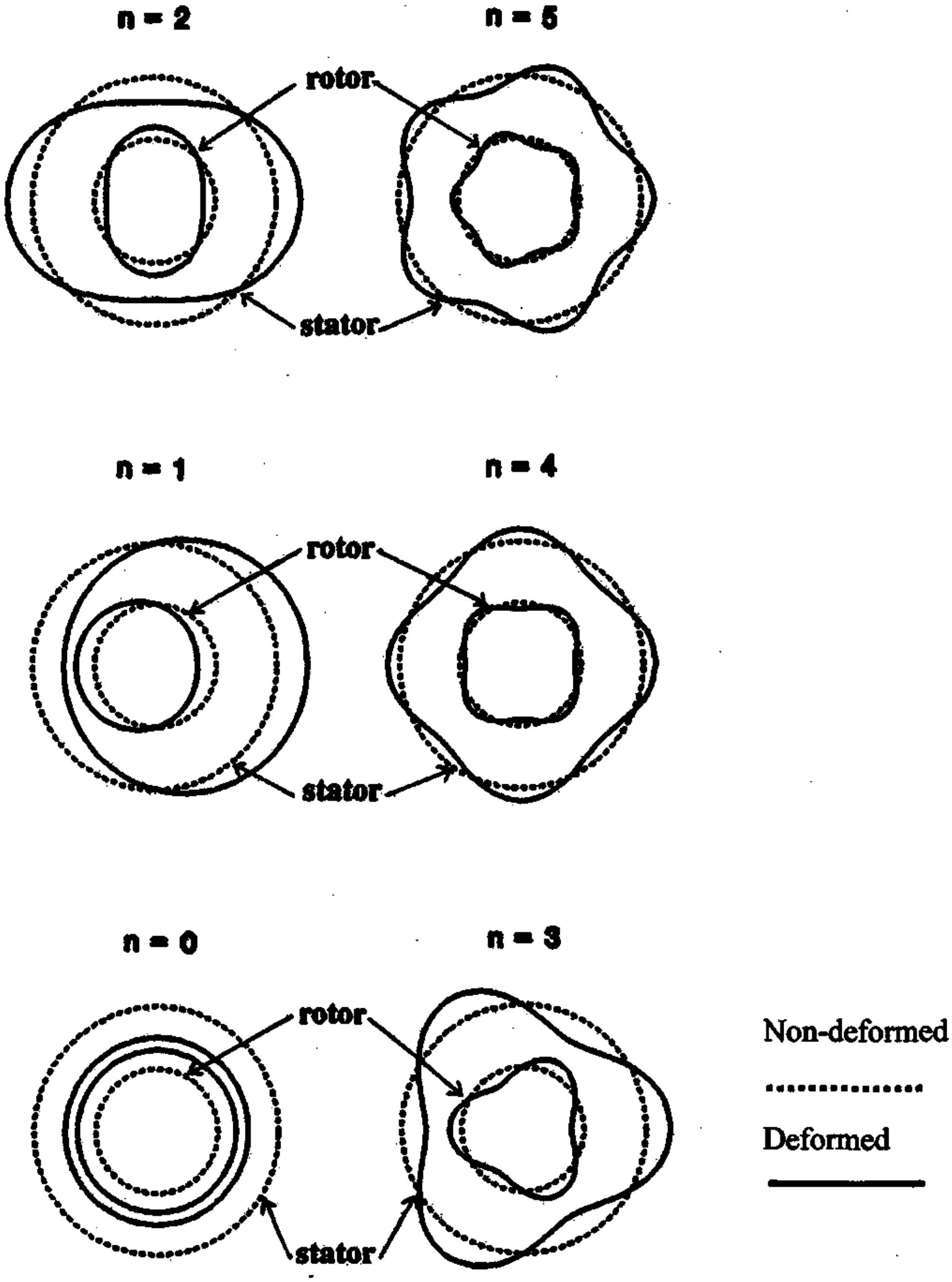


Figure 6.6 : Some important modes of vibrations in an induction machine.

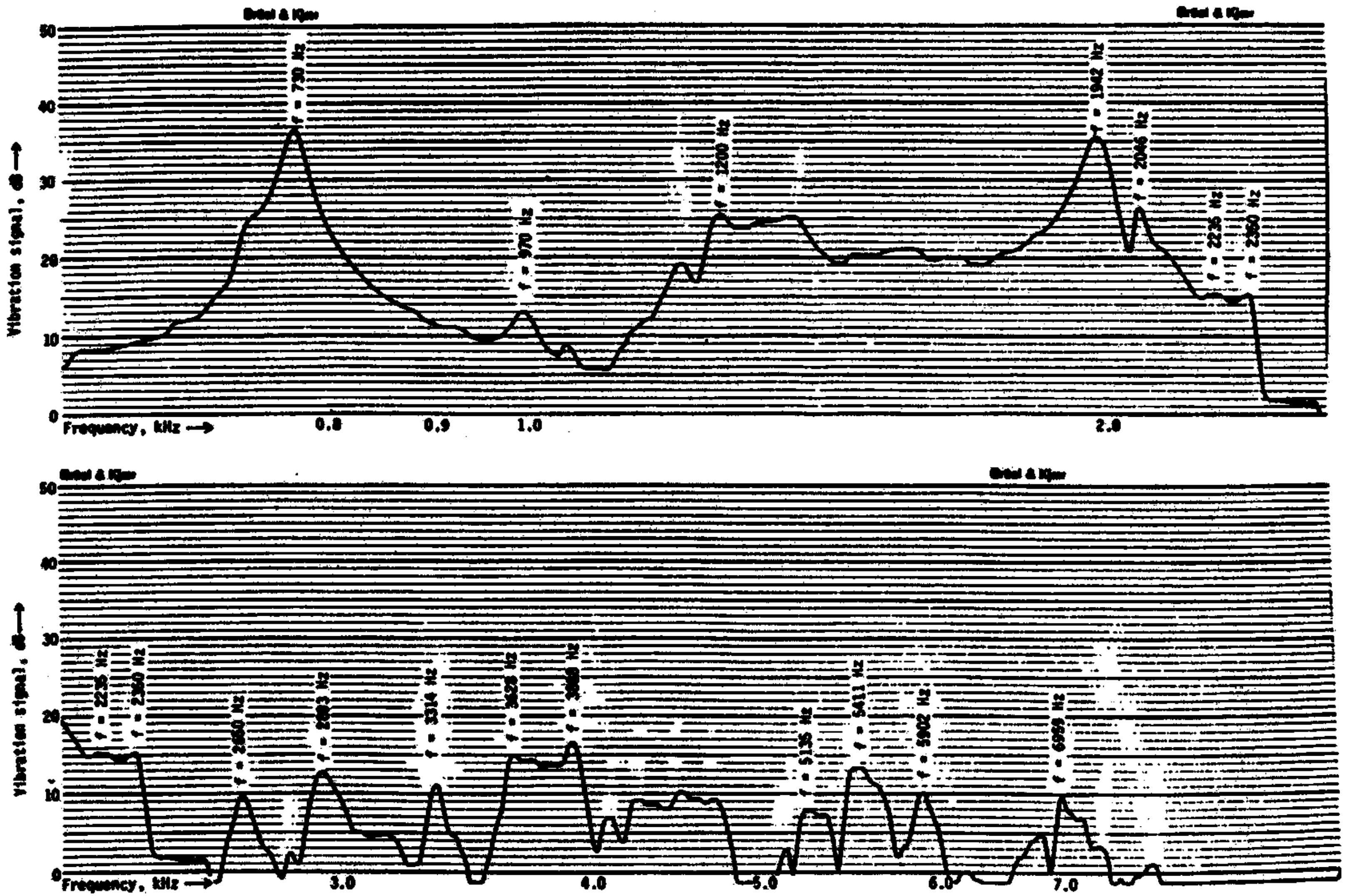


Figure 6.7 : Resonant frequencies of the stator with windings.

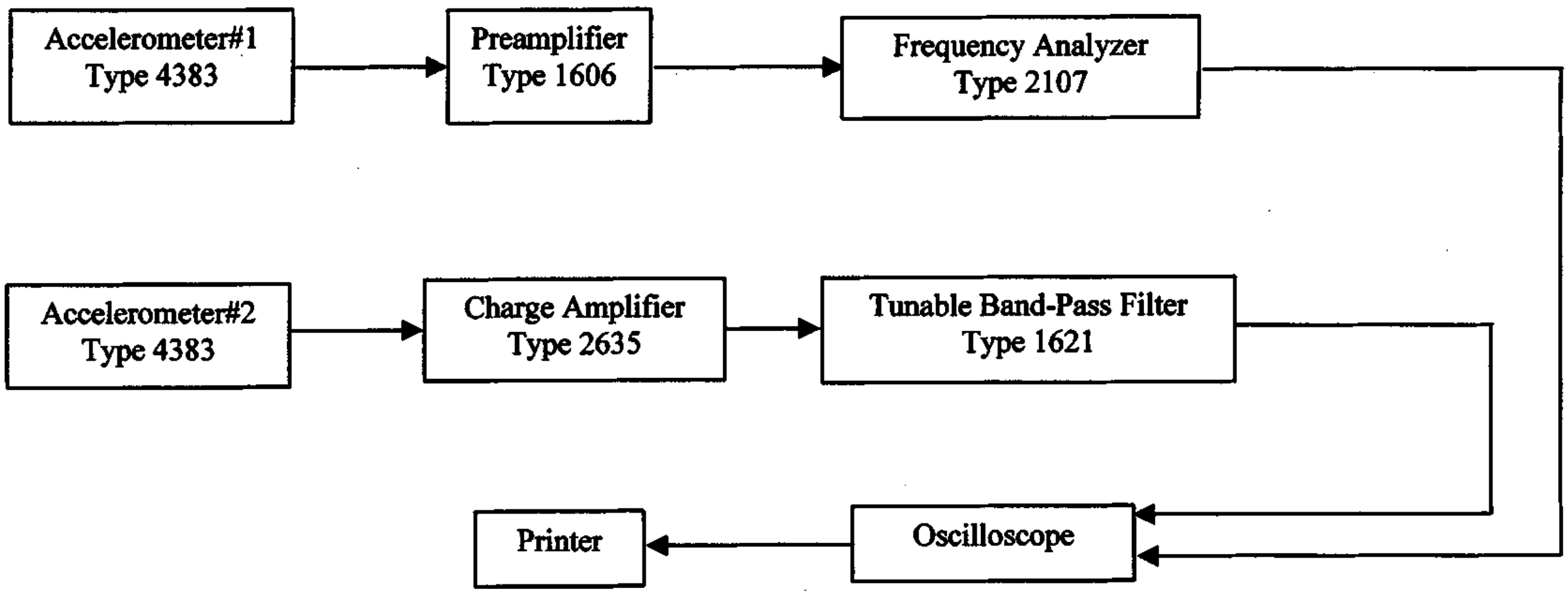
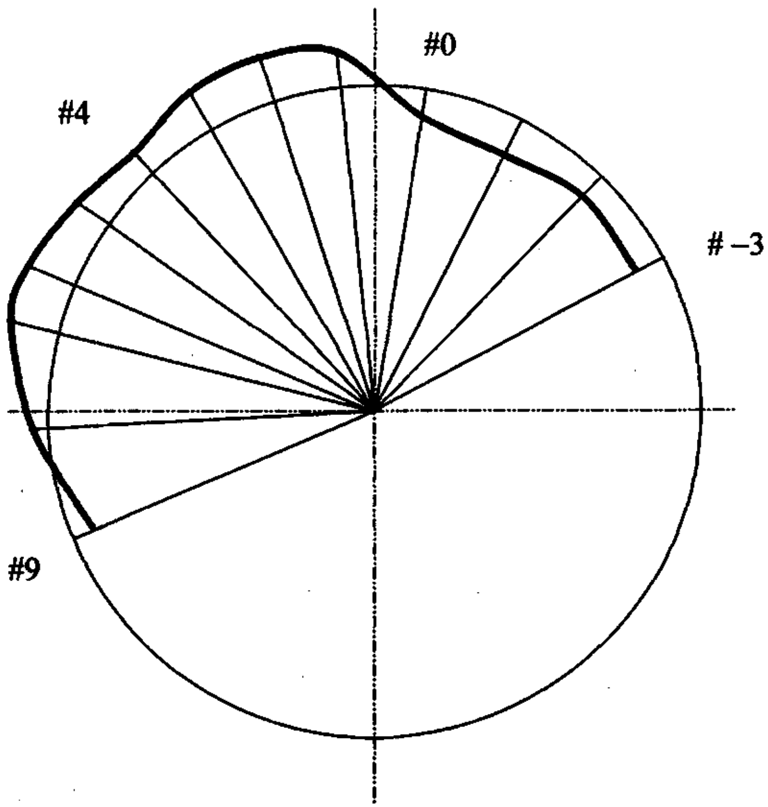
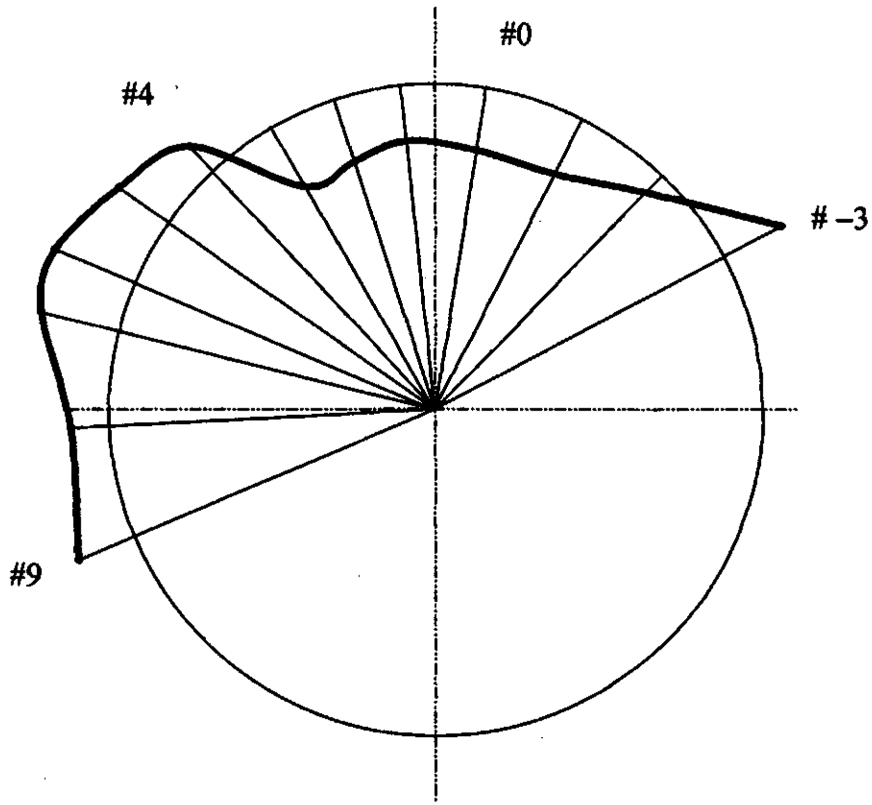


Figure 6.8 : Block diagram of the measuring system for mode-shape analysis.

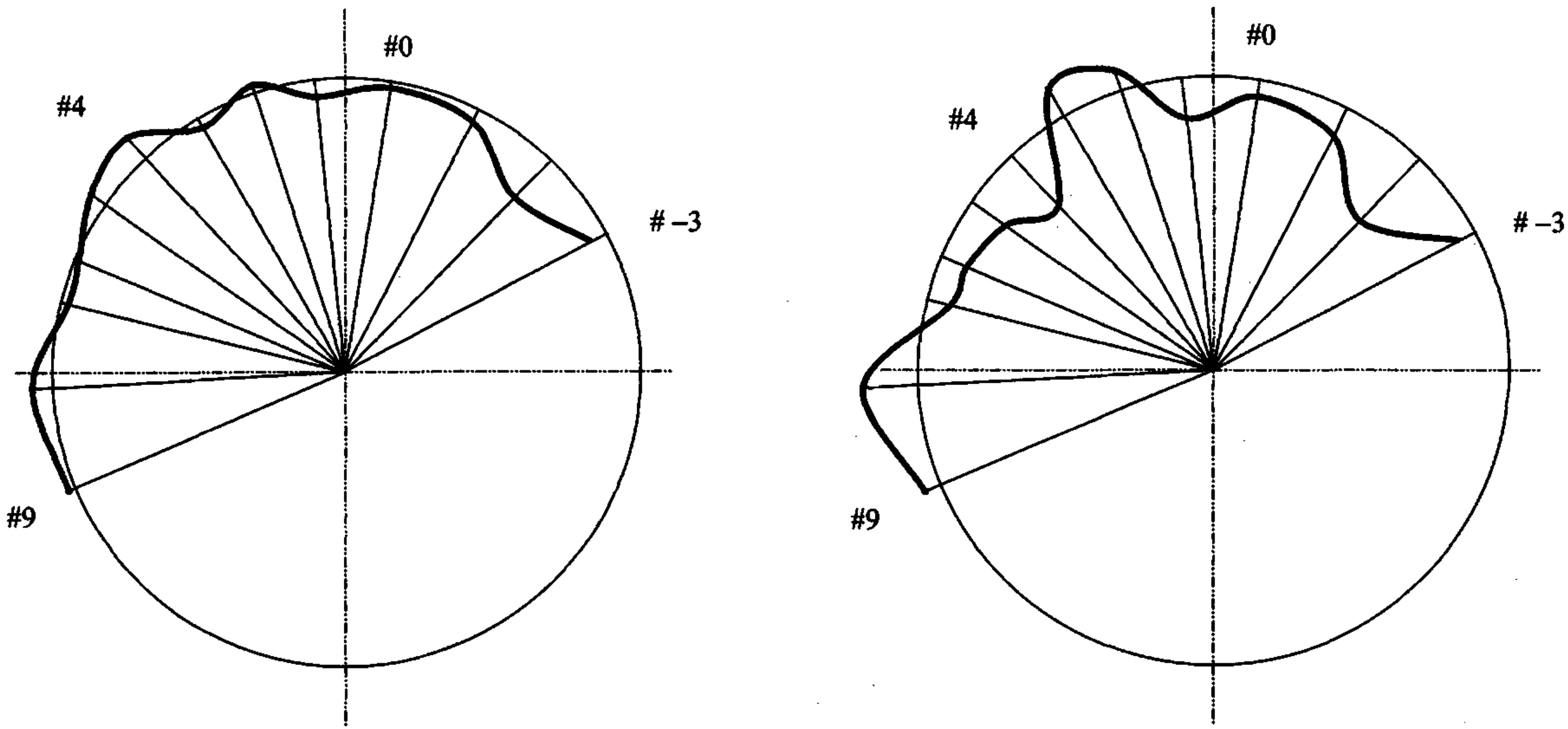


(a) 50% rated voltage



(b) 100% rated voltage

Figure 6.9 : The measured modes of stator at 720Hz when the applied voltages are 50%, and 100% of rated voltage.



(a) 50% rated voltage

(b) 100% rated voltage

Figure 6.10 : The measured modes of stator at 3300Hz when the applied voltages are 50%, and 100% of rated voltage.

suitable direct current to its stator coils, to ensure that the motor is loaded at 3.75 kW. The motor is energized at rated voltage 230V and runs at 1778rpm. Also, the detailed frequency spectra are taken at each measuring point.

- The vibration measurement when motor is running with full load is a required operating condition. To achieve this condition, the eddy-current brake is supplied with suitable excitation current while the motor is energized with rated voltage. Again, detailed frequency spectra at each measuring point are taken.

Two accelerometers of the same type are used for the measurements at each point in order to reduce the error caused by the accelerometer itself. Four sets of measured data were taken and they are averaged to reduce the measurement error.

The circuit diagram of power supplies to the motor used for the measuring system is shown in Figure 6.11. To monitor the motor running conditions (current, voltage and power), three single-phase AC Power Analyzers, Type PA2100, were used.

Among the 13 measuring points, the measurement results at three points, #2, #6 and #9 are selected and they are given here as the examples to do the analyses. As shown in Figure 6.2, these three points cover the top, middle and lower part of the motor stator. Measurement results are provided in Table 6.2, and the plots of the variation in the slot-harmonic components with load for these three points are shown in Figure 6.12 to Figure 6.17. Also, Table 6.3 is provided to bridge the information contained in Table 6.2 and in all the figures from Figure 6.12 to 6.17.

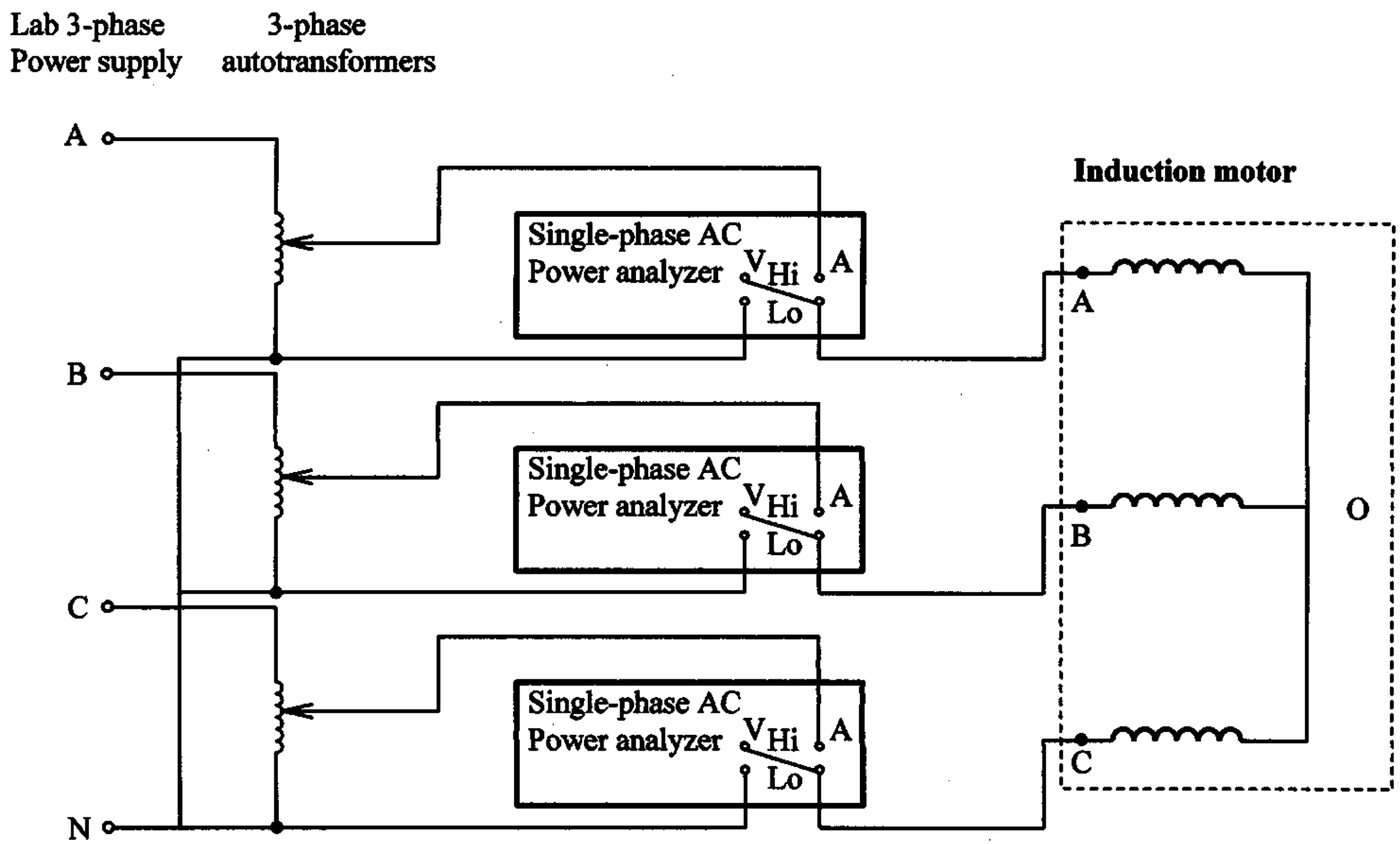


Figure 6.11 : Circuit diagram for power supplies and monitoring of the current, voltage and power of the motor.

Table 6.2 : Measured results of vibration levels with load.

Frequency of harmonic components (Hz)			Vibration levels at point #2 (mV)			Vibration levels at point #6 (mV)			Vibration levels at point #9 (mV)		
No-load	50%load	Full load	No-load	50%load	Full load	No-load	50%load	Full load	No-load	50%load	Full load
720	**720**	***720***	4.15	**3.07**	***2.2***	3.23	**2.15**	***2.09***	2.9	**1.86**	***2.33***
930	**914**	***896***	0.84	**0.98**	***2.03***	0.84	**1.07**	***2.19***	0.96	**1.05**	***2.52***
1170	**1154**	***1136***	3.1	**5.55**	***7.15***	1.62	**4.85**	***7.5***	4.05	**6.5**	***17.25***
1290	**1274**	***1256***	1.08	**1.92**	***2.25***	0.74	**1.58**	***2.31***	1.55	**2.21**	***4.7***
1410	**1394**	***1376***	0.85	**1.02**	***2.18***	0.48	**0.89**	***2.04***	0.95	**1.07**	***2.88***
1980	**1948**	***1913***	1.91	**2.64**	***4.7***	1.88	**3.15**	***5.25***	1.53	**2.51**	***5.25***
2010	**1994**	***1976***	1.83	**2.91**	***5.45***	1.82	**3.15**	***5.8***	1.71	**2.86**	***6.5***
3300	**3268**	***3233***	0.91	**1.26**	***1.55***	0.91	**0.92**	***1.59***	0.87	**0.83**	***1.49***
5280	**5217**	***5145***	2.03	**2.78**	***5.4***	2.07	**2.68**	***3.33***	1.2	**2.31**	***2.01***
6330	**6251**	***6162***	2.93	**3.6**	***6.6***	2.21	**2.85**	***4.3***	2.1	**4.35**	***8.45***
6450	**6371**	***6282***	3.11	**3.9**	***5.3***	2.3	**3.15**	***3.9***	2.19	**4.95**	***5.85***
6570	**6491**	***6402***	3.09	**3.45**	***6.1***	2.15	**2.9**	***4.3***	2.15	**4.4**	***7.65***
7740	**7645**	***7538***	4.5	**8.75**	***17.85***	3.45	**8.2**	***11.85***	2.89	**6.15**	***4.2***

Table 6.3 : Information on harmonic-components and the corresponding frequencies.

Series number	Formulae for calculating frequencies of harmonic-components	Frequency of harmonic-components (Hz)		
		No-load	Half load	Full load
Series 1	Saturation component: $12f$	720	720	720
Series 2	$[\frac{Z}{P}(1-s)-6]f$	930	914	896
Series 3	$[\frac{Z}{P}(1-s)-2]f$	1170	1154	1136
Series 4	$\frac{Z}{P}(1-s)f$	1290	1274	1256
Series 5	$[\frac{Z}{P}(1-s)+2]f$	1410	1394	1376
Series 6	$[2\frac{Z}{P}(1-s)-10]f$	1980	1948	1913
Series 7	$[\frac{Z}{p}(1-s)+12]f$	2010	1994	1976
Series 8	$[2\frac{Z}{P}(1-s)+12]f$	3300	3268	3233
Series 9	$[4\frac{Z}{P}(1-s)+2]f$	5280	5217	5145
Series10	$[5\frac{Z}{P}(1-s)-2]f$	6330	6251	6162
Series11	$5\frac{Z}{P}(1-s)f$	6450	6371	6282
Series12	$[5\frac{Z}{P}(1-s)+2]f$	6570	6491	6402
Series13	$6\frac{Z}{P}(1-s)f$	7740	7645	7538

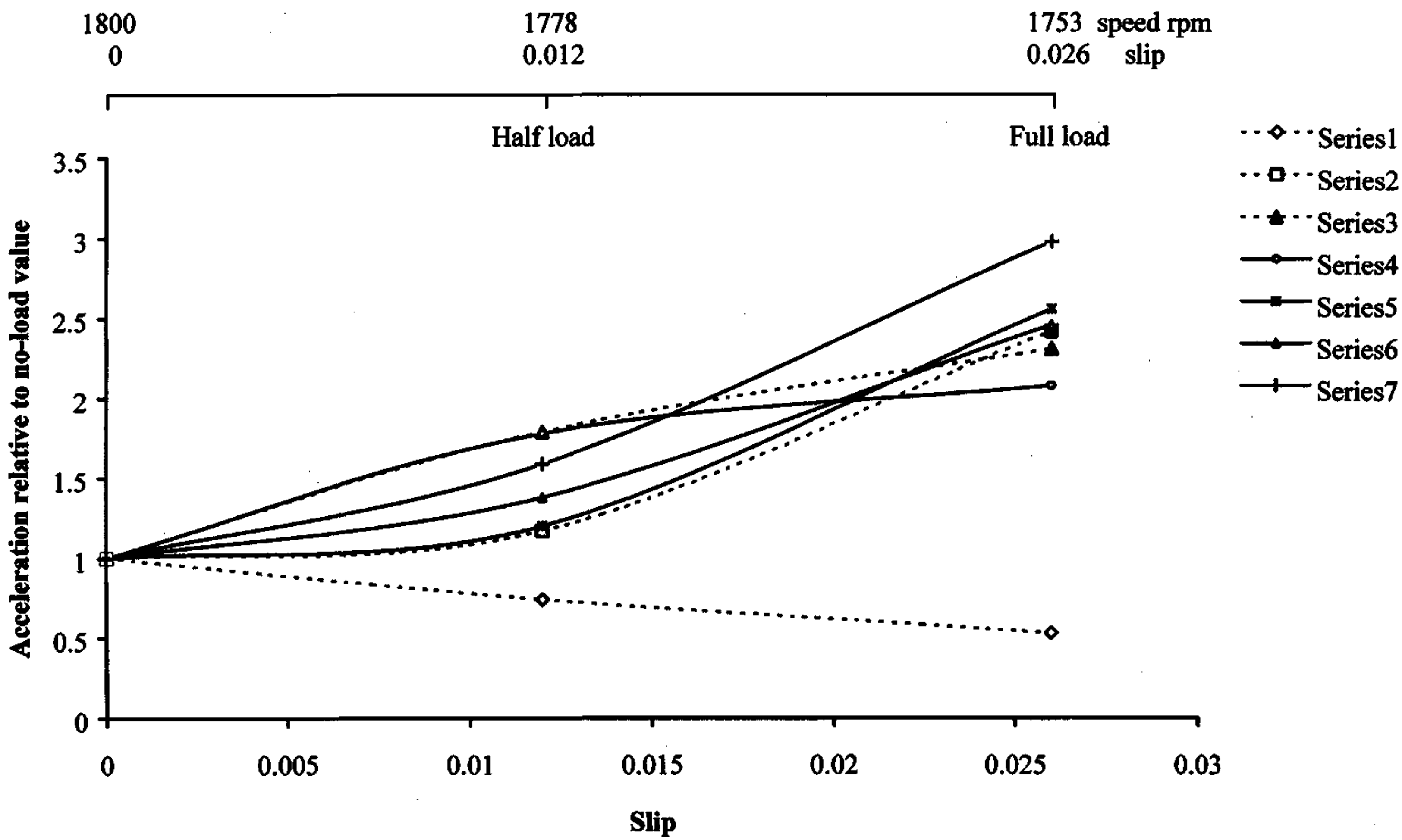


Figure 6.12 : Plot of the variation of the harmonic-components with load at point #2 (Part-I). (The acceleration amplitudes are shown relative to their amplitudes at no-load.)

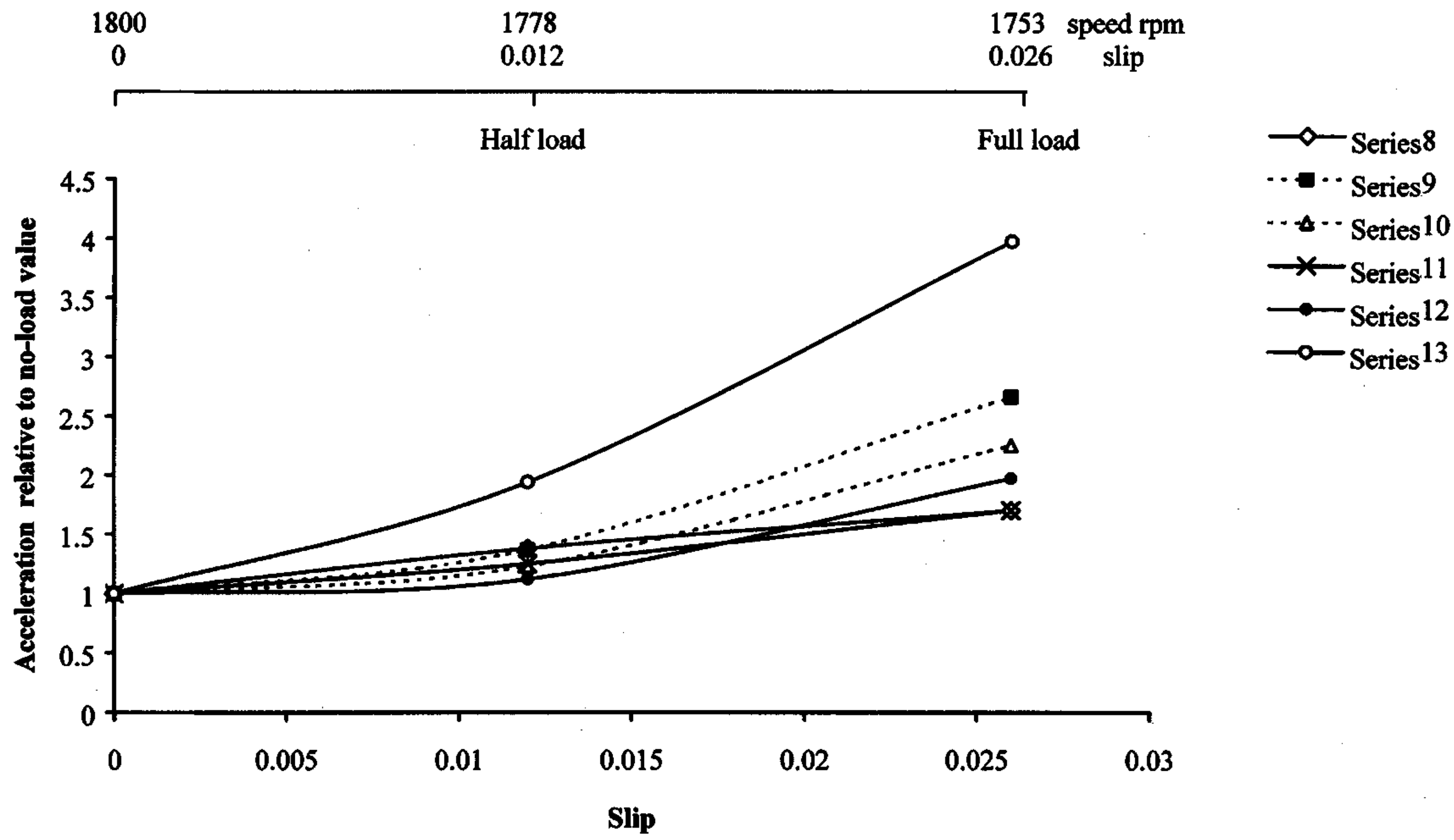


Figure 6.13 : Plot of the variation of the harmonic-components with load at point #2 (Part-II).
(The acceleration amplitudes are shown relative to their amplitudes at no-load.)

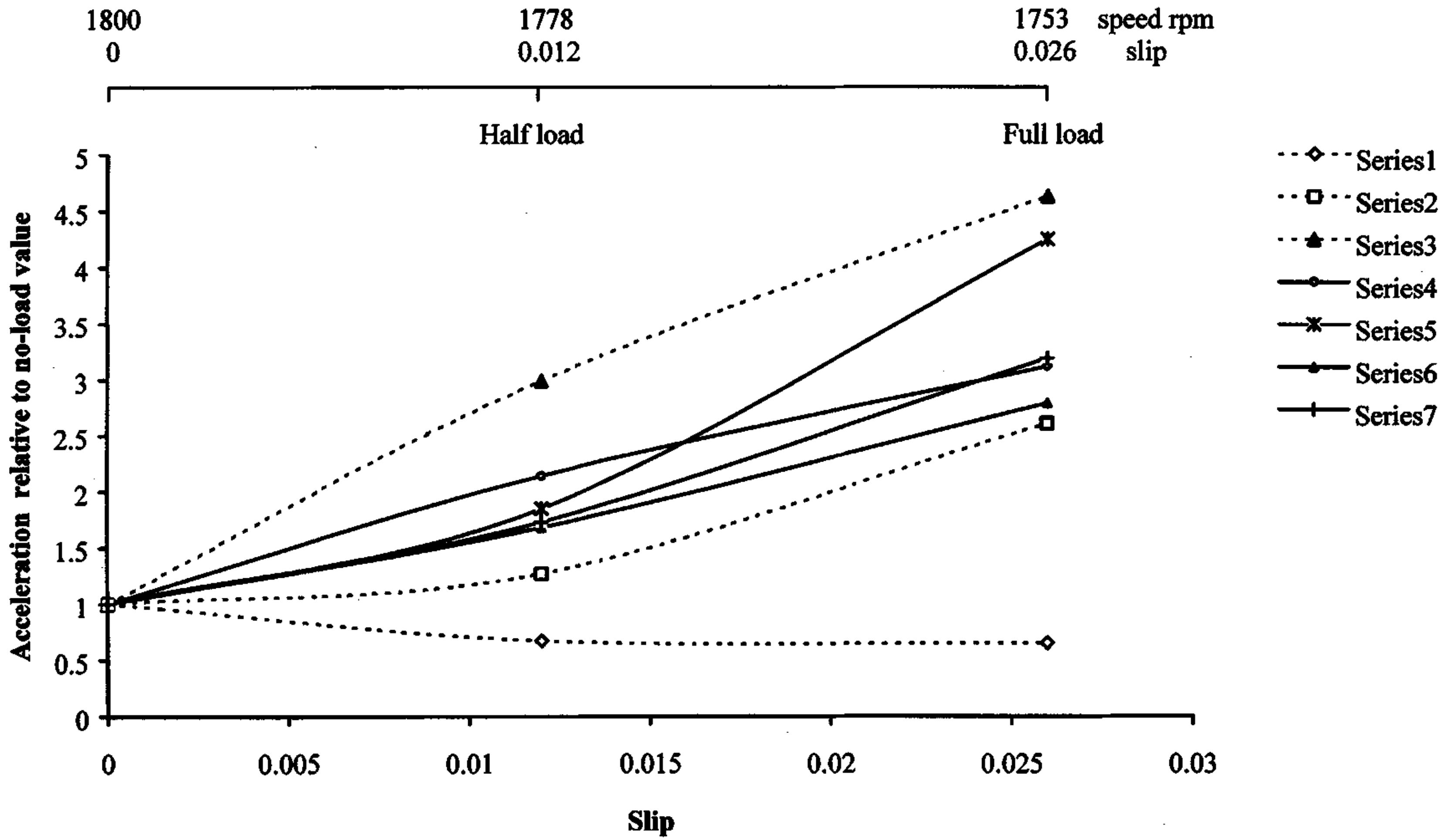


Figure 6.14 : Plot of the variation of the harmonic-components with load at point #6 (Part-I). (The acceleration amplitudes are shown relative to their amplitudes at no-load.)

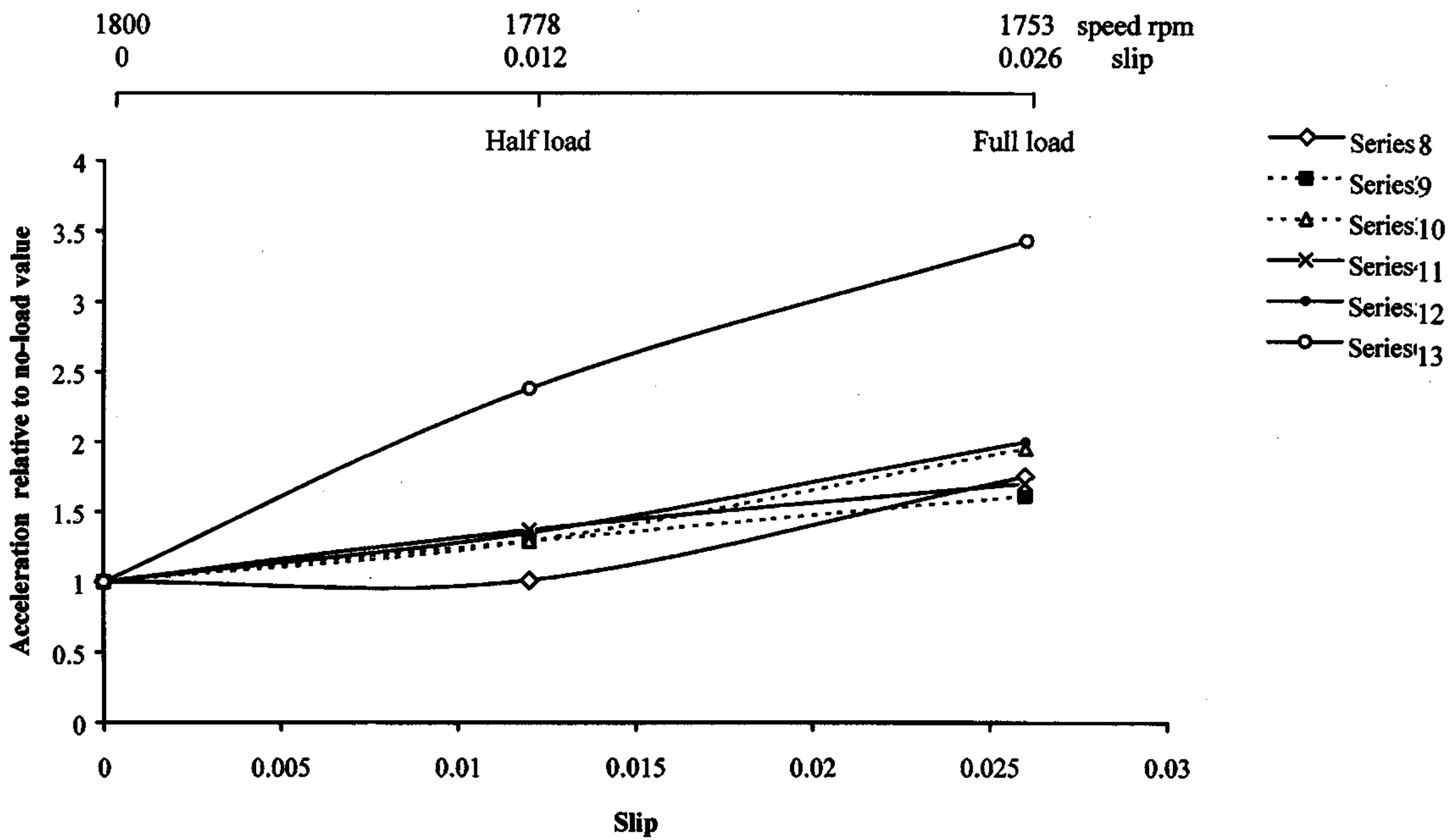


Figure 6.15 : Plot of the variation of the harmonic-components with load at point #6 (Part-II). (The acceleration amplitudes are shown relative to their amplitudes at no-load.)

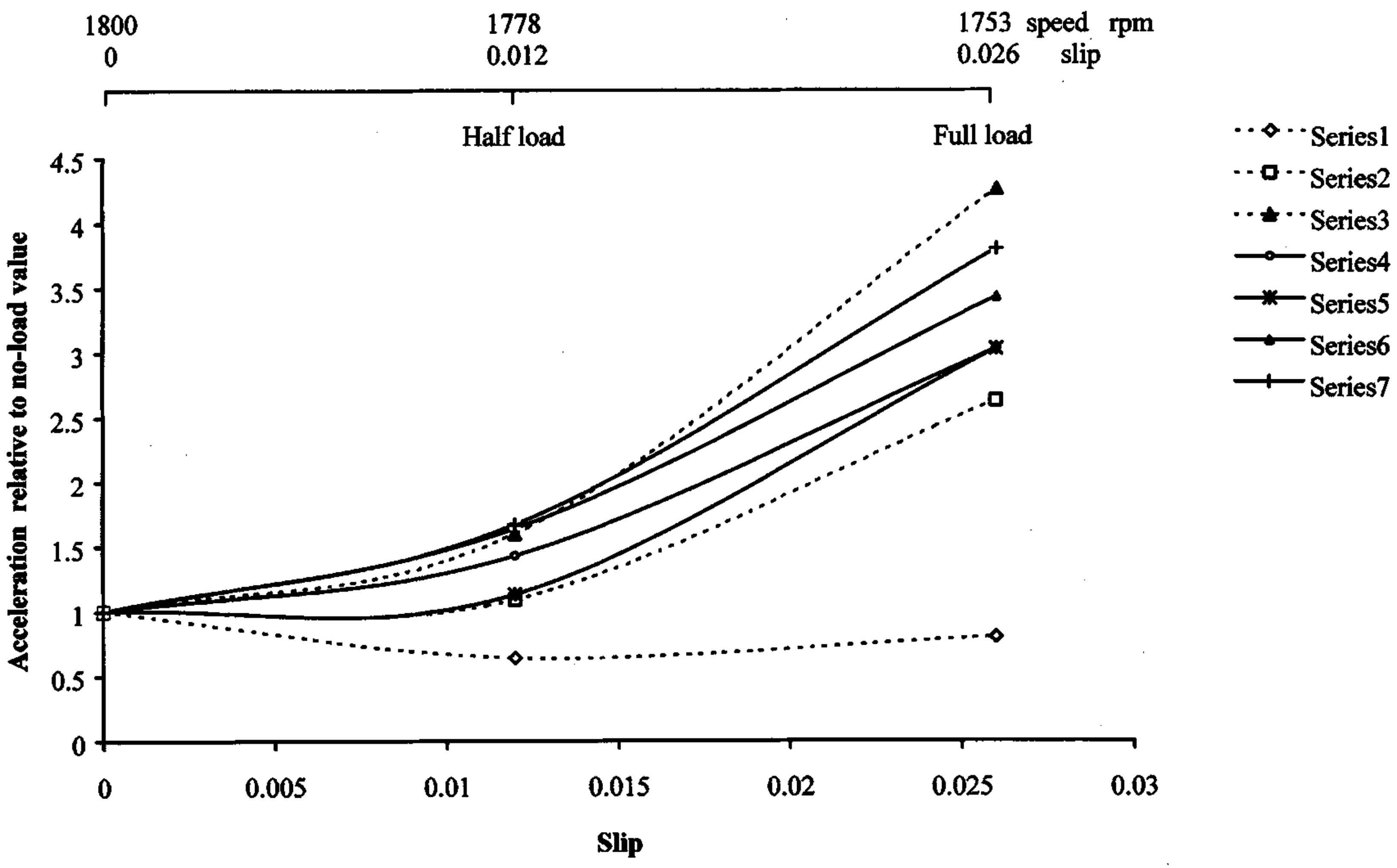


Figure 6.16 : Plot of the variation of the harmonic-components with load at point #9 (Part-I).
(The acceleration amplitudes are shown relative to their amplitudes at no-load.)

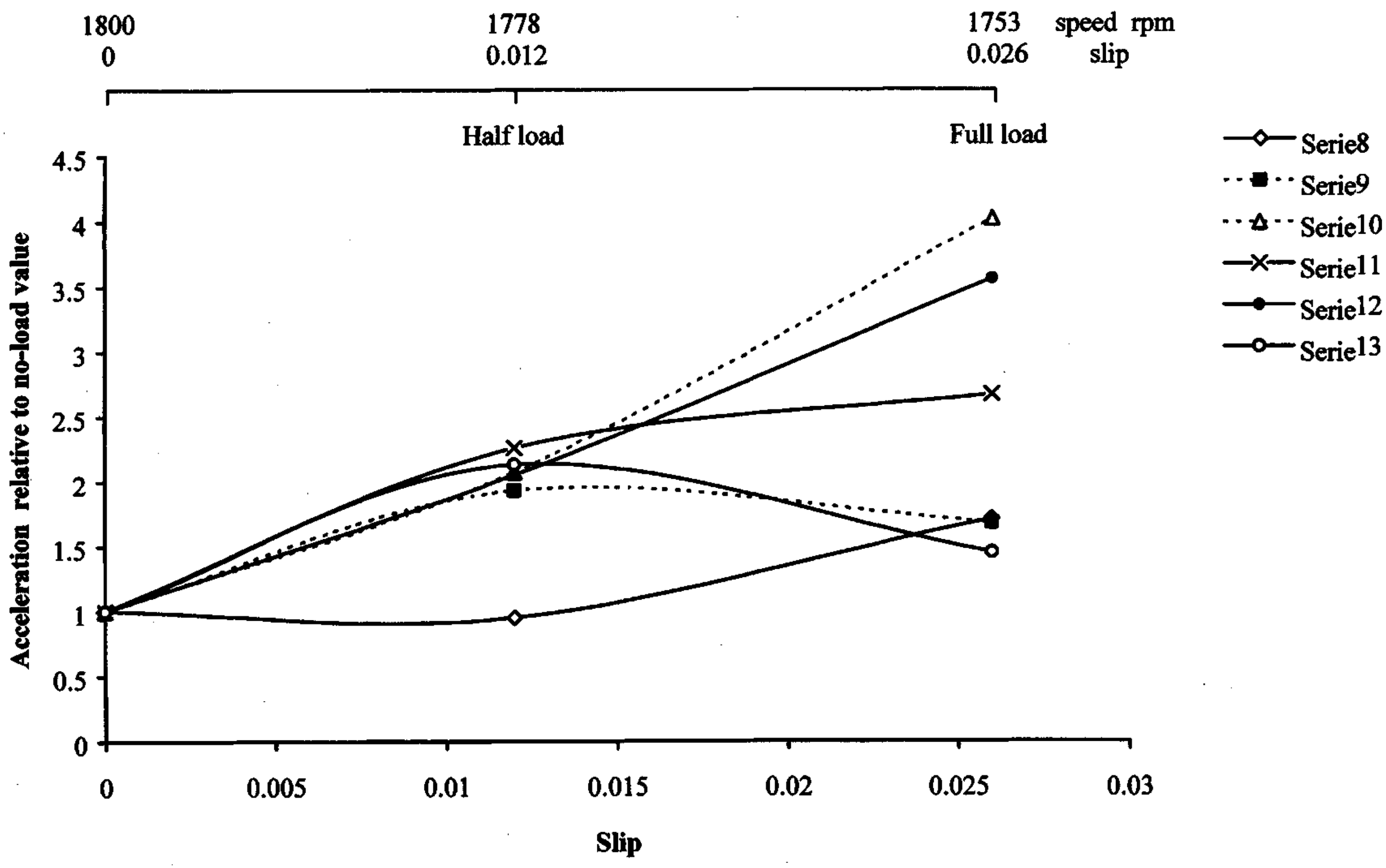


Figure 6.17 : Plot of the variation of the harmonic-components with load at point #9 (Part-II). (The acceleration amplitudes are shown relative to their amplitudes at no-load.)

From the results reported in Table 6.2 and Table 6.3, and Figure 6.12 to Figure 6.17, the following observations are made:

- In general, the vibration levels of the slot-harmonic components increase with the increase in load. The amount of load has a definite effect on the vibration levels of the motor. This leads to the fact that the electromagnetic forces increase as the motor load is increased. But the trend is non-linear, and the level of the increase at each frequency is different.
- The electromagnetic force produced by saturation effects (720 Hz) decreases as the load is increased. Even when motor is operating without any load, the magnetic-field of the motor is highly saturated. The introduction of load brings in certain degree of saturation in the machine, which affects the level of 720 Hz vibrations.

6.5 Comments

In order to obtain sufficient information on various vibrations, 13 measuring points were chosen after careful considerations. Experimental results for spectral distribution of vibration signals are in good agreement with the theoretical analyses. Mode-shape measurements were also conducted, which provide information about the circumferential deformations of the stator under the excitation of the three-phase power supply. From the results reported in this chapter, it is observed that the vibration levels generally increase as the load is increased. However, the trend of increase is non-linear in nature.

Based on the results of vibration investigations, it should be expected that the noise levels would increase as the load on the motor is increased. Having done the vibration investigations, the next phase is to focus on the measurements of noise produced by the test motor. In the following chapter the noise investigations in an ordinary laboratory are dealt with, where the sound wave reflections from the walls are present.

7. NOISE INVESTIGATIONS IN AN ORDINARY LABORATORY

The vibration measurements can provide the information about the electromagnetic forces as well as noise produced by an electrical machine. Spectral measurements of vibrations have been reported in the last chapter, which provide the fundamental information about the expected noise produced by the source. The distribution of the sound power versus frequency is also needed for identifying the noise-generation mechanism.

The human ear basically responds to the sound pressure, but the sensitivity varies with the frequency. Referring to Figure 2.1, the human ear is most sensitive to sound in the frequency range from 1 kHz to 5 kHz, while the sensitivity drops at higher and lower frequencies. It should be mentioned again that noise measurements are more complex compared to vibration measurements. Several factors may influence the noise measurements. Some of the factors are: size of source, source operating conditions, surroundings, measurement position, etc. The influence of these factors can be controlled in different manners according to the goal of the measurements.

In most situations, people are exposed to the noisy environment caused by the running industrial machinery. It is the actual industrial site that can cause health problems to people. Noise levels measured in industrial environment carry more practical meaning, and they are of great importance to the industry. Unfortunately, the real industrial environment is not ideal for sound measurements. The ordinary laboratory environment is similar to the industrial workplace where it is neither a free-field nor a reverberant room. Therefore, it can be used for the noise investigations.

Since the standards and the measuring location points have already been discussed in Chapter 4, the other parts of the noise experimentation are provided in this chapter.

7.1 The Measuring System

B&K condenser microphone 4165 (1/2") is used for general sound measurements and the standardized noise measurements. This microphone has good sensitivity and it is more omni-directional due to its smaller diameter. Microphone-preamplifier 2639 is a high performance preamplifier with very low inherent noise and high input impedance. The low output impedance of preamplifier allows the use of long extension cables. This preamplifier is used with a wide range of B&K condenser microphones, which are used for accurate acoustic measurements. It accepts 1/2" microphone directly. The noise measuring system is shown in Figure 7.1.

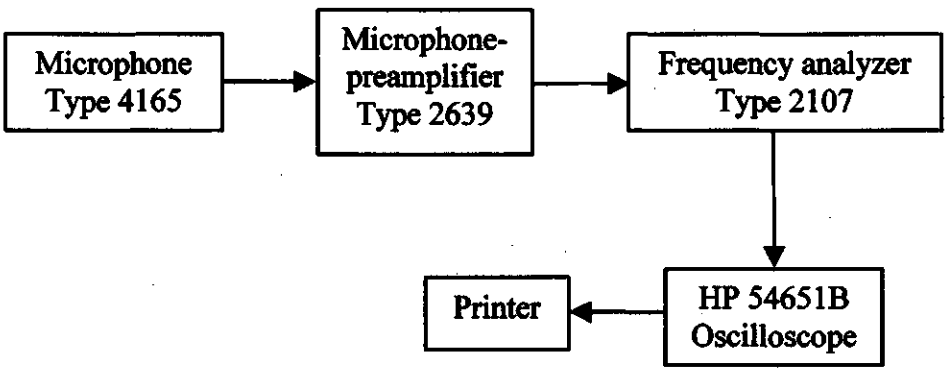


Figure 7.1 : Block diagram of noise measuring system.

7.2 Background Noise

Since a microphone picks up all the sound signals in its sound field, the sound measurements are affected by the environment. Before performing the actual noise measurements, special measurements were made to determine the background noise (noise emitted by the sources other than the test motor) in the laboratory.

The surfaces for measuring noise and location points of microphone to be used for the noise measurements have already been discussed in Chapter 4. The noise investigations conducted in the ordinary laboratory are in accordance with the previous discussions. The measuring location points are those as shown in Figure 4.1.

Table 7.1 shows the measured background noise from 11 p.m. to 6 a.m., during this duration the air ventilation system in the building is shut off, and from 9 a.m. to 5 p.m. during which the ventilation system operates. It is clear that higher values of background noise during the day-time can cause very large errors in the results of noise measurements. To avoid as much as possible the influence from the background noise, all the noise investigations were performed from 11 p.m. to 6 a.m., during which the ventilation system is shut off and also the interference from major personnel activities is minimum.

7.3 Some Practical Considerations

As sound measurements can be affected by many factors, the following considerations are taken into account during the experimental investigations in order to get better measurement results.

- Although the microphones used are omni-directional, the microphones should be oriented with its axis towards the machine.
- To obtain good sound measurement results, the instruments should be used in a manner that they will not alter the sound field being measured. This will include:
  a. The operator and instruments must not be located between the microphone and the noise source. Also, all the instruments should be placed away from the microphone to prevent sound reflections.
  b. The measurement should be performed away from any other object which may block or reflect the sound to be measured.
- At each measuring point, two microphones of the same type are used to measure the noise from the source. This technique eliminates the errors

introduced by the microphone itself. Further, four sets of measured data are averaged to minimize the errors introduced by the readings of the instruments.

Table 7.1 : Measured background noise during different times.

Freq-	Point #1 (dB)		Point #2 (dB)		Point #3 (dB)		Point #4 (dB)		Point #5 (dB)	
uency	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day
720	**24**	32	**22**	31	**25**	32	**22**	34	**22**	34
930	**26**	30	**24**	29	**24**	30	**22**	31	**23**	31
1170	**28**	29	**25**	29	**24**	29	**24**	30	**24**	30
1290	**30**	30	**27**	28	**26**	28	**28**	30	**26**	31
1410	**27**	30	**23**	28	**23**	28	**24**	28	**23**	30
1980	**20**	26	**<20**	23	**<20**	24	**<20**	24	**21**	27
2010	**<20**	23	**<20**	23	**<20**	23	**<20**	25	**<20**	27
3300	**<20**	24	**<20**	23	**<20**	23	**<20**	25	**<20**	27
5280	**<20**	23	**<20**	23	**<20**	22	**<20**	25	**<20**	26
6330	**<20**	23	**<20**	23	**<20**	21	**<20**	25	**<20**	26
6450	**<20**	22	**<20**	23	**<20**	22	**<20**	26	**<20**	27
6570	**<20**	22	**<20**	22	**<20**	21	**<20**	25	**<20**	27
7740	**<20**	22	**<20**	22	**<20**	21	**<20**	27	**<20**	26

Night: noise measured from 11 p.m. to 6 a.m.
Day: noise measured from 9 a.m. to 5 p.m.
<20 dB: values are less than 20 dB, being negligible.

7.4 Changes of Sound Levels with the Applied Voltage

Since the noise limits specified in the standard [17,41] are applicable to machines at no-load, noise measurements under no-load condition are the required measurements. For this no-load condition, the machine shall operate at rated voltage, rated frequency, and rated speed with appropriate field current.

In order to obtain additional information on the noise when the motor is operating without load under some voltage less than the rated value, applied voltage of 50% rated value was chosen so that the changes of sound levels with the applied voltage can be compared.

To conduct the noise measurements, the test procedures are:

- At each measuring position, before running the motor, or after shutting off the motor, background noise is taken at each frequency band of interest.
- Motor noise spectra (sound pressure-level with frequency) are recorded at each measuring position when the motor is running at no-load with 50% of rated voltage.
- Motor noise spectra are recorded at each measuring position when the motor is running at no-load with 100% of rated voltage.

All the readings thus obtained are the sound pressure-levels at each measuring point. However, the sound power-levels are the required quantities. The procedures used to calculate the sound power-levels from sound pressure-levels are described in Appendix D. The sound power-levels of the motor at no-load are listed in Table 7.2. It is clear that even when the applied voltage is 50% of rated value, the noise levels in some frequency-bands are quite high. As expected, sound power-level in each frequency-band is generally higher at 100% rated voltage than 50% rated voltage. It is to be noted that the change in the applied voltage does not change the sound power-levels equally for different frequency-bands. The biggest change is 8 dB for 1980 Hz, but there is virtually no change for 3300 Hz.

Table 7.2 : The sound power-levels of the test motor in various frequency-bands at no-load.

Center frequency (Hz)	Sound power-levels (dB)	
	50% rated voltage	100% rated voltage
720	57	**59**
930	57	**58**
1170	55	**61**
1290	50	**55**
1410	49	**53**
1980	48	**56**
2010	50	**57**
3300	56	**56**
5280	39	**44**
6330	39	**42**
6450	38	**43**
6570	38	**42**
7740	34	**39**

7.5 Changes of Sound Levels with Load

Due to the difficulties in measuring techniques, noise limits for machines on load are not set by the standards. Usually, the load does have influence on the motor noise. It is of great significance if information on the effects of the load on noise levels of the motor can be obtained. The influence of load on vibrations has been presented in

Chapter 6; the effects of the load on noise produced by the motor are presented and discussed in this chapter.

To conduct the noise measurements, the test procedures are:

- Background noise is recorded for each frequency-band of interest at the measuring points.
- Motor noise-spectra are recorded at each measuring position when the motor is running under no-load condition. The motor is coupled with eddy-current brake which is not supplied with DC current excitation. The motor is energized at rated voltage of 230 V, and it is running at a speed very close to 1800 rpm.
- Noise-spectra are measured under half load condition. The eddy-current brake is supplied with suitable DC current which ensures that the motor is loaded with 3.75 kW of power. The motor is energized at 230 V and runs at 1778 rpm.
- Noise-spectra are then measured at full load condition. The eddy-current brake is supplied with the maximum allowable DC current that loads the motor fully.

Figure 7.2 shows the pictorial view of the measuring set-up in the laboratory. The measuring systems used are shown in Figure 6.11 and Figure 7.1. Again, sound power-levels are calculated according to Appendix D. Table 7.3 shows the calculated sound power-levels from the measuring data, which are also plotted in Figures 7.3 to 7.7.

From the experimental results, the following information is obtained:

- At 720 Hz, the magnitude of noise level decreases as the load increases. The measurement results of vibrations and noise at 720 Hz are caused by saturation effects. As rotor currents are larger when the load increases, more load causes higher saturation. Since the radial-force is proportional to the square of the air-gap flux-density, the value of radial-force produced is almost constant once the motor saturates. However, the trend of the noise level with load at 720 Hz is in very good agreement with the results of vibration measurements.

Figure 7.2 : The measuring set-up in the laboratory.

- Generally, the magnitudes of all the slot-harmonic fields increase with load, so the related force components also increase. It is evident from the vibration measurements that the magnitudes of all the force components produced by the slot-harmonics increase by considerable amount when the load is raised from 3.75 kW to full load condition. In contrast to the vibration results where more load causes higher magnitude of vibrations, the values of sound power emitted by the motor for different loads at the following frequencies do not change significantly;

$[\frac{Z}{P}(1-s)-6]f$, $[2\frac{Z}{P}(1-s)-10]f$, $[\frac{Z}{p}(1-s)+12]f$,

$[2\frac{Z}{P}(1-s)+12]f$, $[4\frac{Z}{P}(1-s)+2]f$, $[5\frac{Z}{P}(1-s)-2]f$,

$5\frac{Z}{P}(1-s)f$, $[5\frac{Z}{P}(1-s)+2]f$, $6\frac{Z}{P}(1-s)f$.

The values of sound power emitted by the motor at the above frequencies lie within the range of variation ≤ 3dB. Considering the vibration levels of these frequencies, the stator is not a good sound radiator.

- According to Balan [18], the interaction of the fundamental air-gap field with the slot-harmonic fields produces three distinct components in the radial-forces. The frequencies at which the slot-harmonic forces act on the stator are: $[\frac{Z}{P}(1-s)-2]f$, $\frac{Z}{P}(1-s)f$, $[\frac{Z}{P}(1-s)+2]f$.

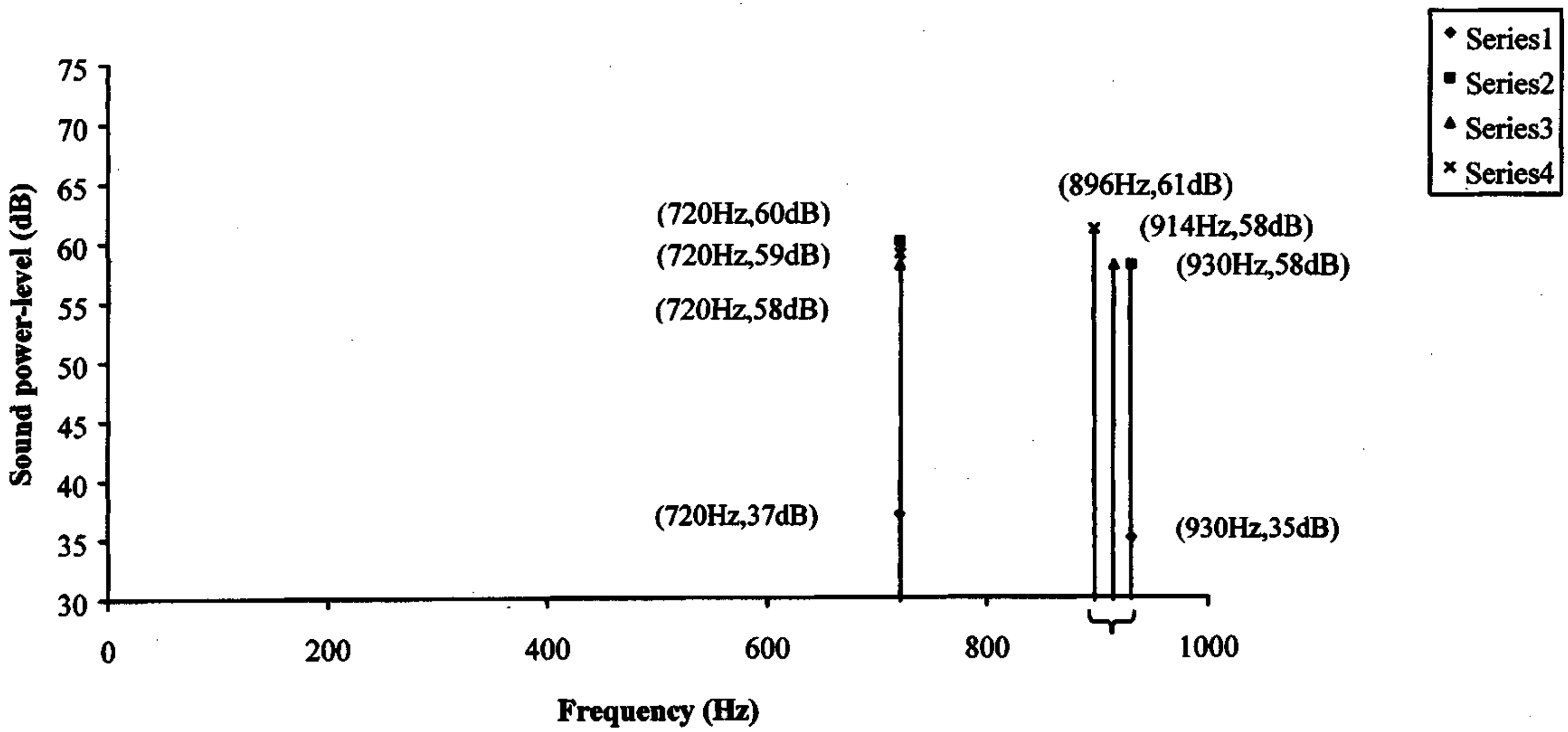
  The values of sound power at these three frequencies increase considerably with load.

- From the results obtained through the investigations, it is evident that the harmonic-force at $[\frac{Z}{P}(1-s)-2]f$ (f = 1136 Hz at full load) is the main contributor of noise.

Table 7.3 : Sound power-levels of the motor under different operating conditions.

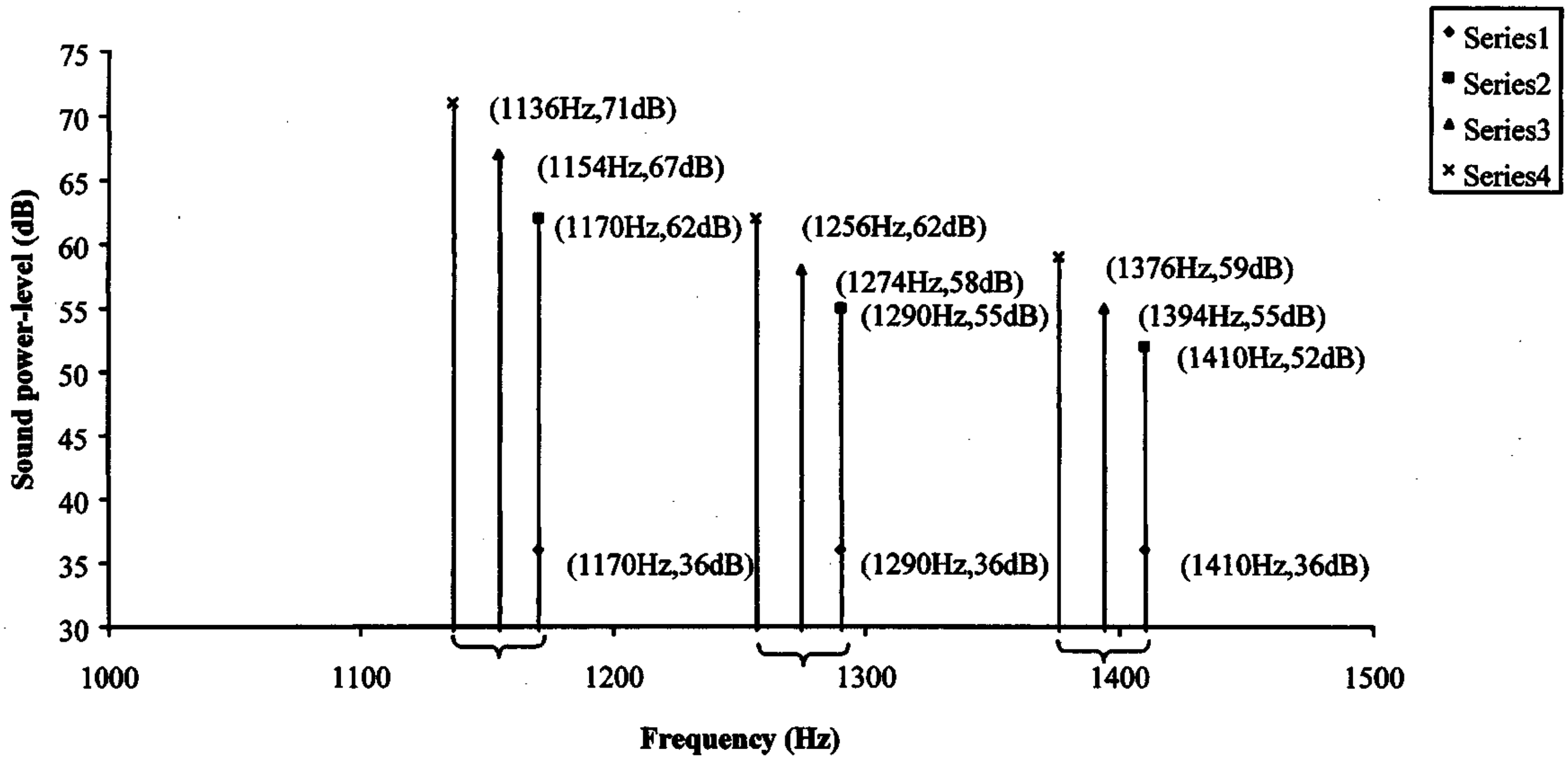
Frequency (Hz)	Sound power-level (dB)		Frequency (Hz)	Sound power-level (dB) 50% load	Frequency (Hz)	Sound power-level (dB) Full load	Difference between full load noise and background noise (dB)
	Background	No-load					
720	**37**	**60**	720	**58**	720	**59**	**22**
930	**35**	**58**	914	**58**	896	**61**	**26**
1170	**36**	**62**	1154	**67**	1136	**71**	**35**
1290	**36**	**55**	1274	**58**	1256	**62**	**26**
1410	**36**	**52**	1394	**55**	1376	**59**	**23**
1980	**35**	**60**	1948	**60**	1913	**62**	**27**
2010	**36**	**61**	1994	**61**	1976	**63**	**27**
3300	**35**	**56**	3268	**56**	3233	**56**	**21**
5280	**34**	**50**	5217	**52**	5145	**52**	**18**
6330	**<34**	**49**	6251	**48**	6162	**52**	**>18**
6450	**<34**	**48**	6371	**49**	6282	**49**	**>15**
6570	**<34**	**48**	6491	**48**	6402	**51**	**>17**
7740	**<34**	**44**	7645	**46**	7538	**45**	**>11**

<34: the sound power-levels calculated from the sound pressure-levels which are less than 20 dB (being negligible).



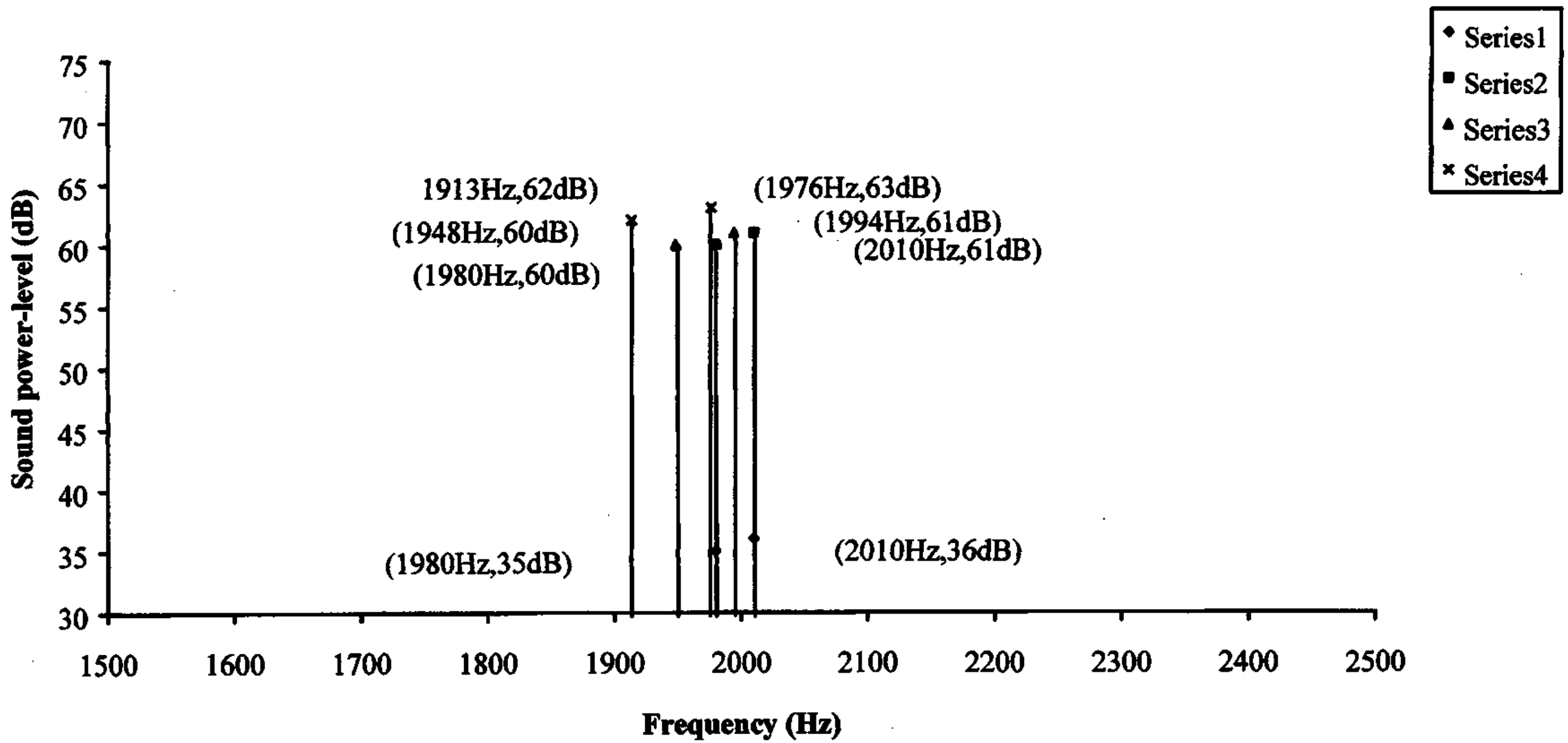
Series 1: background noise.
Series 2: noise of motor without load.
Series 3: 50% load noise.
Series 4: 100% load noise.

Figure 7.3 : Sound power-levels of motor under different operating conditions in ordinary laboratory, frequency range from 0 to 1000 Hz.



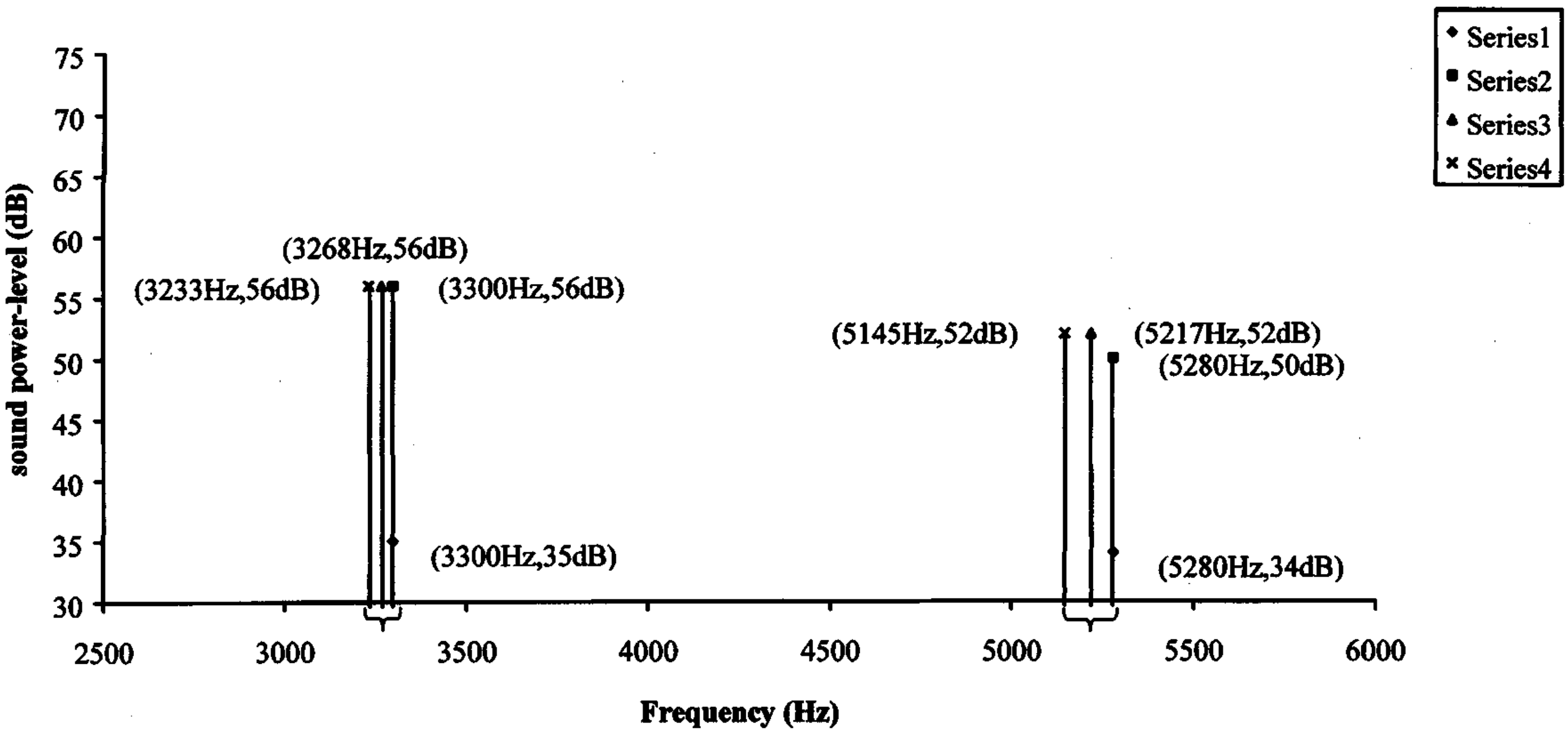
Series 1: background noise.
Series 2: noise of motor without load.
Series 3: 50% load noise.
Series 4: 100% load noise.

Figure 7.4 : Sound power-levels of motor under different operating conditions in ordinary laboratory, frequency range from 1000 to 1500 Hz.



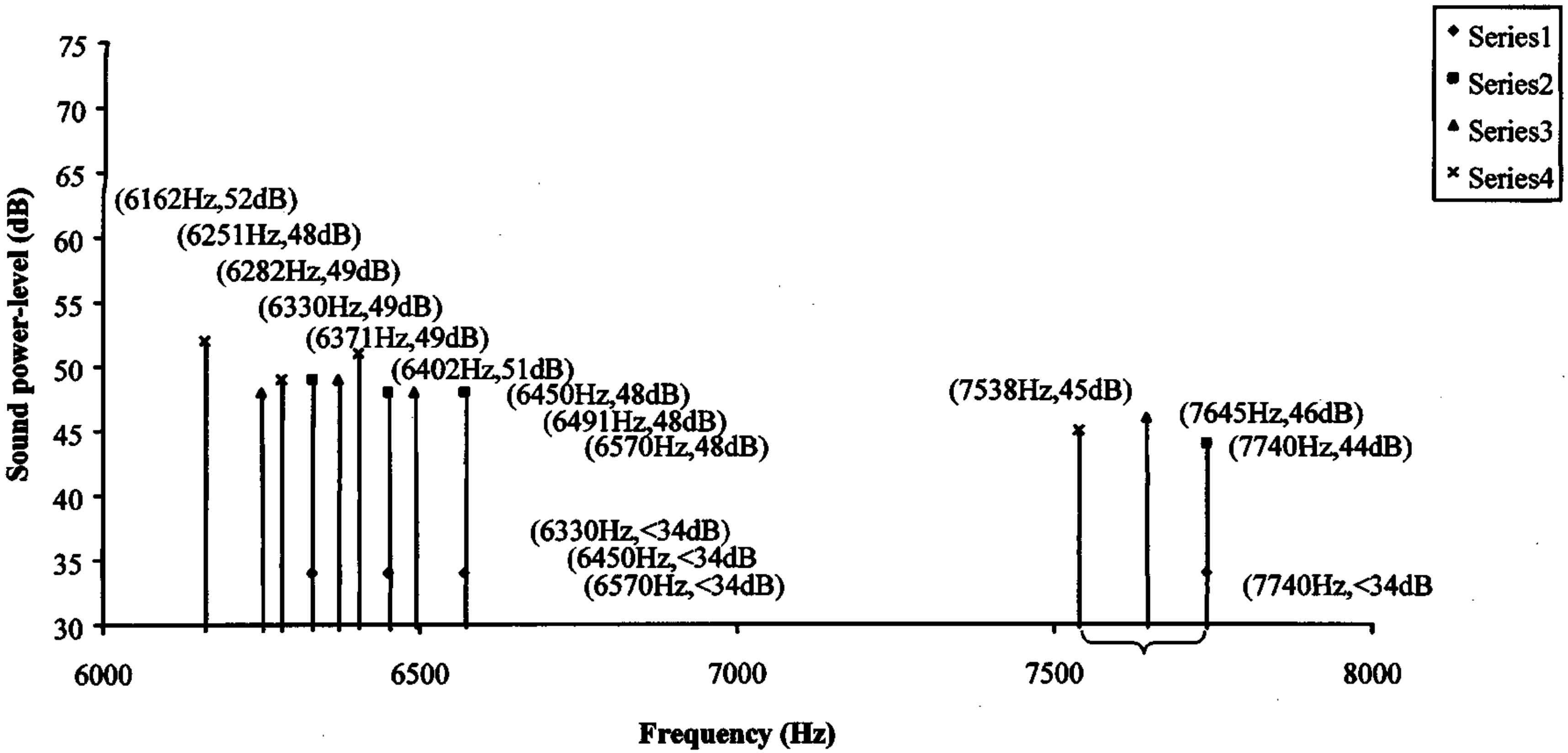
Series 1: background noise.
Series 2: noise of motor without load.
Series 3: 50% load noise.
Series 4: 100% load noise.

Figure 7.5 : Sound power-levels of motor under different operating conditions in ordinary laboratory, frequency range from 1500 to 2500 Hz.



Series 1: background noise.
Series 2: noise of motor without load.
Series 3: 50% load noise.
Series 4: 100% load noise.

Figure 7.6 : Sound power-levels of motor under different operating conditions in ordinary laboratory, frequency range from 2500 to 6000 Hz.



Series 1: background noise.
Series 2: noise of motor without load.
Series 3: 50% load noise.
Series 4: 100% load noise.

Figure 7.7 : Sound power-levels of motor under different operating conditions in ordinary laboratory, frequency range from 6000 to 8000 Hz.

7.6 Comments

Detailed investigations of frequency analyses on noise signals in the ordinary laboratory are presented in this chapter. The frequency analyses of vibration signals provide very important information on electromagnetic forces, which create the vibrations of the stator giving rise to the radiated noise.

Vibrations and noise are inter-related. The noise is the product of motor vibrations, from which people suffer in the workplace. Both vibration and noise analyses provide important information that can be used to improve the motor design, and to implement other noise-control methods.

The noise-measurements in the ordinary laboratory are very important because the laboratory is similar to the work place. Also, noise-measurements in the anechoic chamber have been performed and they are presented in the next chapter.

8. NOISE INVESTIGATIONS IN THE ANECHOIC CHAMBER

In most situations, as already discussed, people are exposed to the noisy environment where industrial machinery is running. It is the real industrial exposure to noise that can cause health problems to people. The actual noise levels measured in the industrial environment convey more practical meaning, and such measurements are of practical importance to industry, although the real industrial environment is not ideal for sound measurements.

The investigations in the ordinary laboratory are of importance as they have practical significance because they provide the information akin to that exists in the real workplace. Due to the fact that noise-measurements can be affected by many factors, the noise levels prescribed by standards are, usually, sound power-levels obtained in special sound fields, free-field or reverberant-room.

An anechoic chamber is a specially constructed chamber in which the walls, floor and ceiling are covered with sound absorbing material in the form of wedges. Since these wedges are effective in eliminating reflected sound, the measurement of sound pressure-level produced by a noise source in this chamber is the direct sound only, which arrives from the source to receiver without having been reflected. The anechoic chamber provides the free-field condition, where accurate noise measurements can be made.

The size of the chamber limits the size of the machine which can be tested. The noise-measurement in the chamber is convenient for the machines which can be easily moved into the chamber, also the noise measurements can be made in the far-field of the machine. Since there exists practical difficulty in installing eddy-current brake in the anechoic chamber, which was used as the loading device of the test motor, only those measurements of sound pressure-level when the machine is running by itself (idling) have been made in the chamber.

8.1 Measuring Surfaces and Points

Since the noise measurements in the anechoic chamber were made in order to be consistent with those performed in the ordinary laboratory, the measuring surfaces and the distances between the measuring surfaces to the motor surfaces are identical both in the laboratory and the chamber. Because the spatial limitations in the chamber are different from those in the laboratory, most of the measuring points in the chamber are the same as used in the laboratory. Figure 8.1 shows the measuring surfaces and points in the chamber.

8.2 Background Noise

Background noise has, evidently, influence on the noise measurements conducted in the ordinary laboratory. In order to make sure that there is no extra background noise in the anechoic chamber that may interfere with the noise investigations of the motor, measurements of background noise at selected measuring points in the chamber were performed for the same time periods as in Chapter 7. These results are listed in Table 8.1.

In Table 8.1, only those frequency-bands in which the sound pressure-levels are higher than 20 dB are listed. Sound pressure-level less than 20 dB is negligible for the noise measurements of the motor. It should be noted that there is no big difference between the background noise measured during the day-time and that measured during the night. Further, the measured noise levels in the frequency-bands of interest in the anechoic chamber are not affected by the background noise, so there are no time constraints on the experimentation.

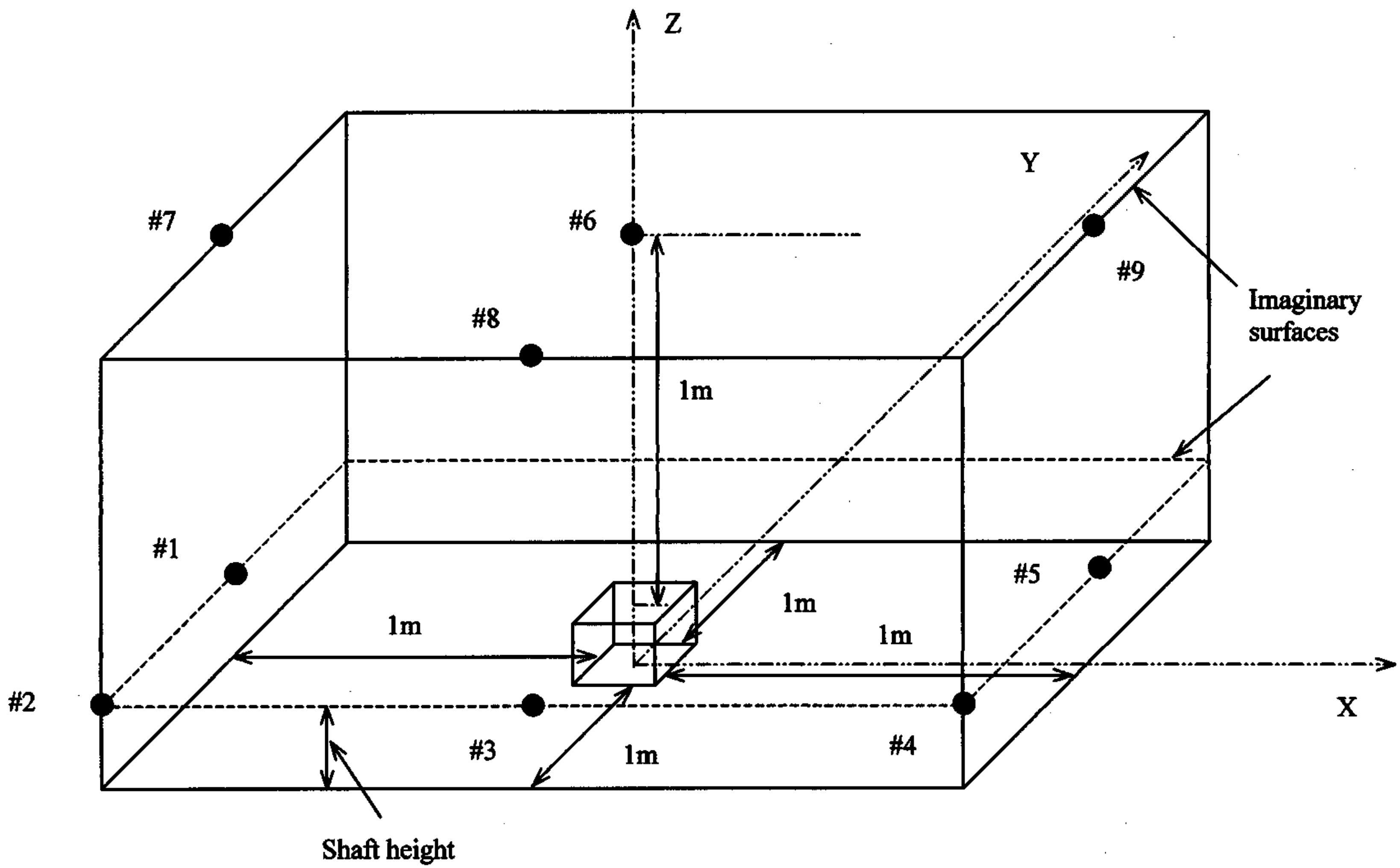


Figure 8.1 : Layout of measuring points on the imaginary surfaces in the anechoic chamber.

Table 8.1 : Measured sound pressure-levels at three measuring points for different time periods in the anechoic chamber.

Frequency (Hz)	Point #3 (dB)		Point #4 (dB)		Point #5 (dB)	
	Day-time	Night	Day-time	Night	Day-time	Night
120	21	22	21	23	21	23
240	21	22	20	22	20	21
360	<20	21	<20	21	<20	21

Day-time: from 9 a.m. to 5 p.m.
Night: from 11 p.m. to 6 a.m.
<20 dB: the value less than 20 dB, being negligible.

8.3 Sound Level Measurements

Because the anechoic chamber provides the free-field condition in which accurate sound power-levels can be obtained, the measured results recorded here can state the noise levels from the test motor. Further, the comparison between the values obtained in the ordinary laboratory and the anechoic chamber can provide very important information on the changes of sound levels caused by the sound fields. This is very useful information for the prediction of the approximated values of the sound levels in a free-field from the data obtained by the manufacturer in the industrial situation.

All the precautions to be followed for the sound measurements in the anechoic chamber are the same as those in the ordinary laboratory, which have been described in Chapter 7.3. Also, the measuring instruments and techniques are same as those in Chapter 7, keeping the system errors to be same. The experimental procedures are:

- Sound pressure-levels are recorded at each of the measuring points in the frequency-bands of interest when the motor is running at 50% of rated voltage without load. Although this operating condition is not required by the standards, it provides information on the changes of noise levels with the applied voltage.

- The sound pressure-levels are measured, when the motor is running at 100% of rated voltage without load. This is the required motor operating condition, under which the sound power-levels are to be calculated according to ISO standards.

The sound pressure-levels are used to calculate the sound power-levels according to the procedures given in Appendix D.

A photographic view of experimental set-up in the anechoic chamber is shown in Figure 8.2. Figure 8.3 and 8.4 show the measured results obtained in the anechoic chamber. Table 8.2 shows the variation in the sound power-level with the impressed voltage to the motor. Also, the measured results under the same operating conditions in both the ordinary laboratory and the anechoic chamber are shown in Figure 8.5 to Figure 8.8. From the above results, the followings are observed:

- The noise emitted from the machine varies with the applied voltage. The sound power-level increases with the increase of the impressed voltage both in the ordinary laboratory and in the anechoic chamber. In each frequency-band, the increase of magnitude in the ordinary laboratory is approximately equal to the increase in magnitude in the anechoic chamber.
- For the same operating conditions, the sound power-levels obtained in the anechoic chamber are lower than their counter-parts in the ordinary laboratory. The sound wave reflections in the laboratory cause the difference.
- The sound power-level differences between the two sound fields at 50% rated voltage are bigger than the differences at 100% rated voltage.
- At 1170 Hz, at which the sound power-level is the highest, the sound power-level is approximately the same for both sound fields at 100% rated voltage.
- For other frequencies, the sound power-level differences between the two fields are 6 dB or less in the case of 100% rated voltage.

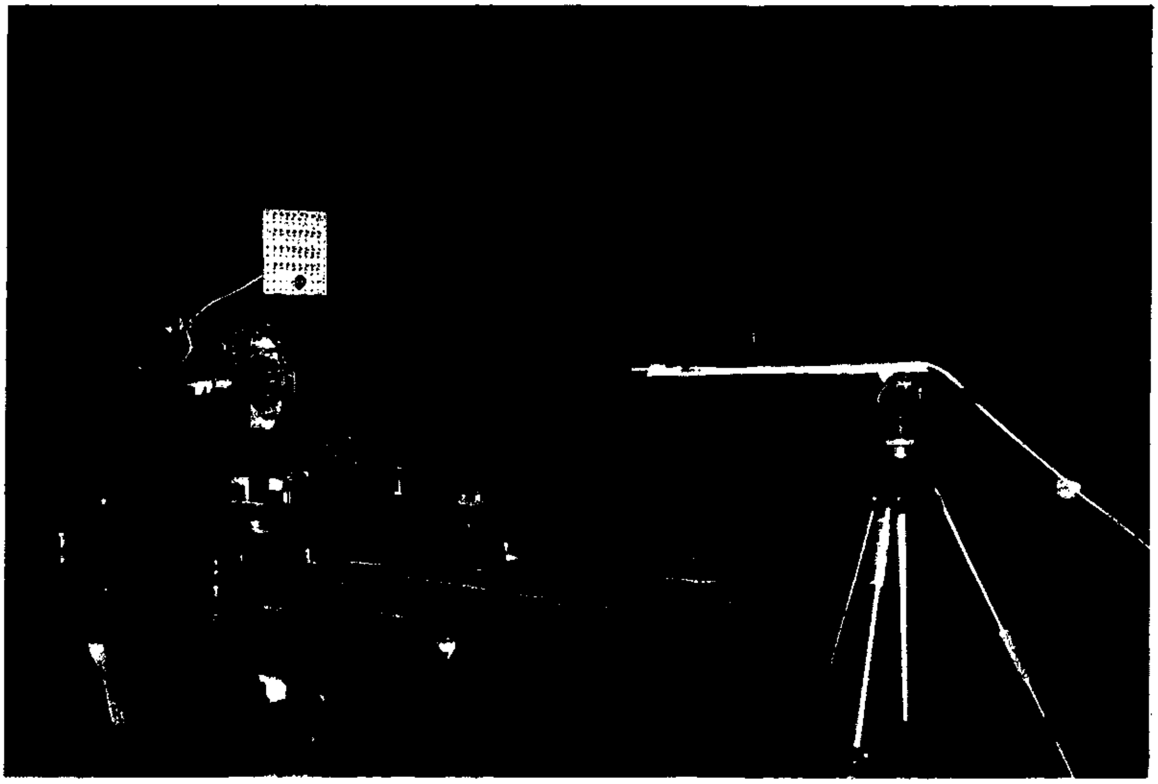
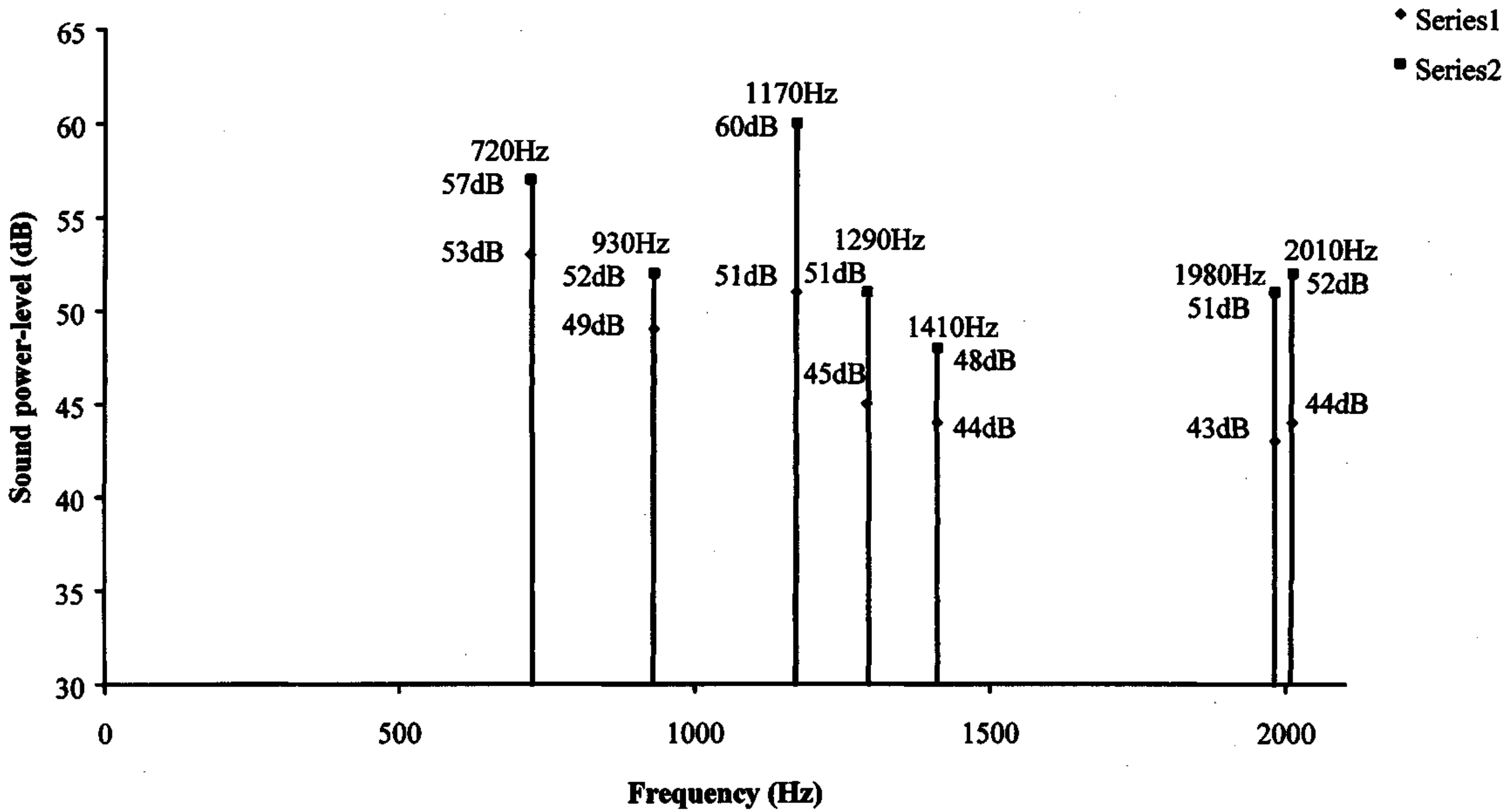


Figure 8.2 : A photographic view of experimental set-up in the anechoic chamber.

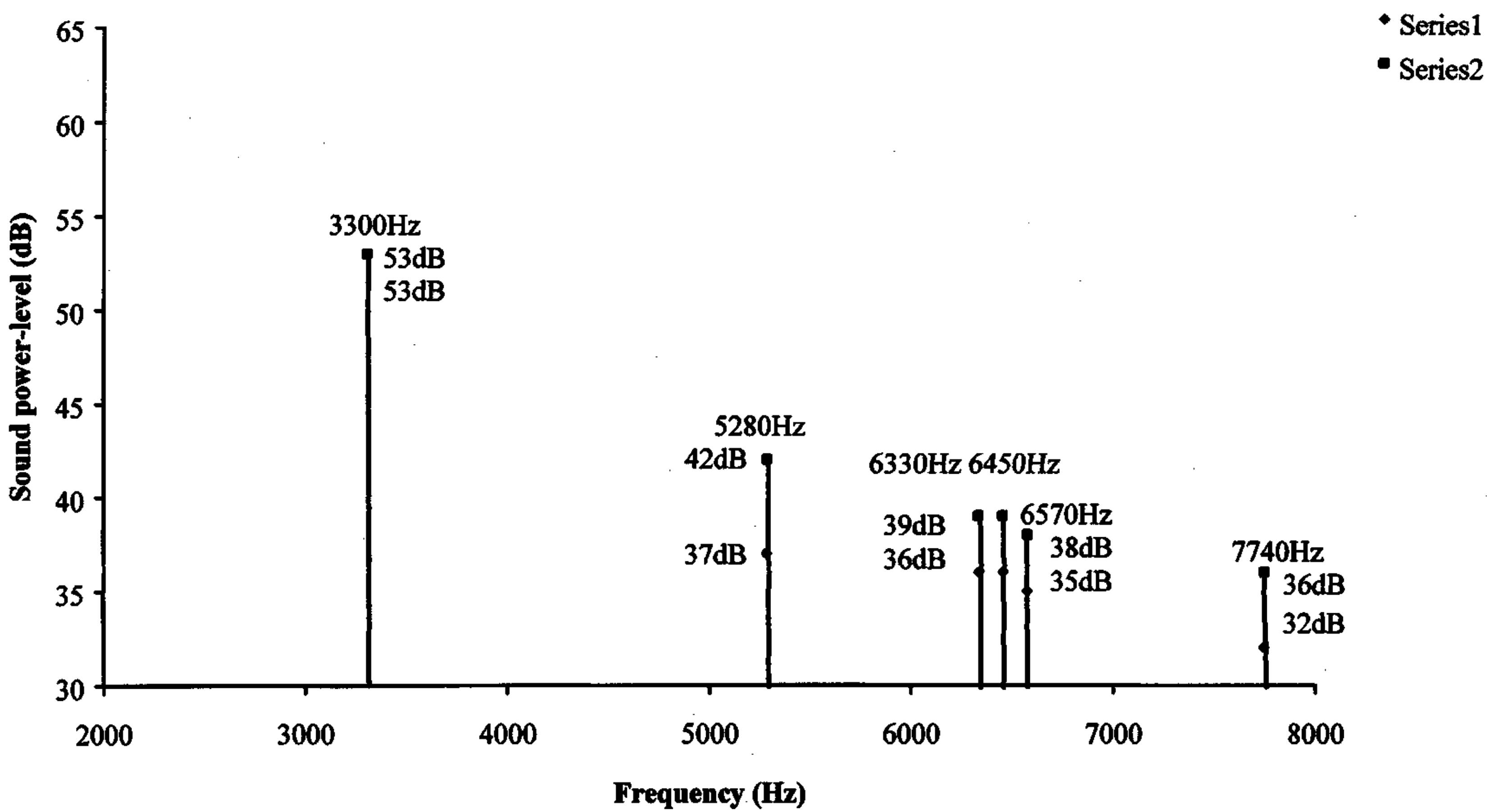
Table 8.2 : Variation in the sound power-levels with impressed voltage to the motor in anechoic chamber.

Frequency (Hz)	Sound power-levels (dB)		
	50% rated voltage	100% rated voltage	Difference in dB
720	53	57	4
930	49	52	3
1170	51	60	9
1290	45	51	6
1410	44	48	4
1980	43	51	8
2010	44	52	8
3300	53	53	0
5280	37	42	5
6330	36	39	3
6450	36	39	3
6570	35	38	3
7740	32	36	4



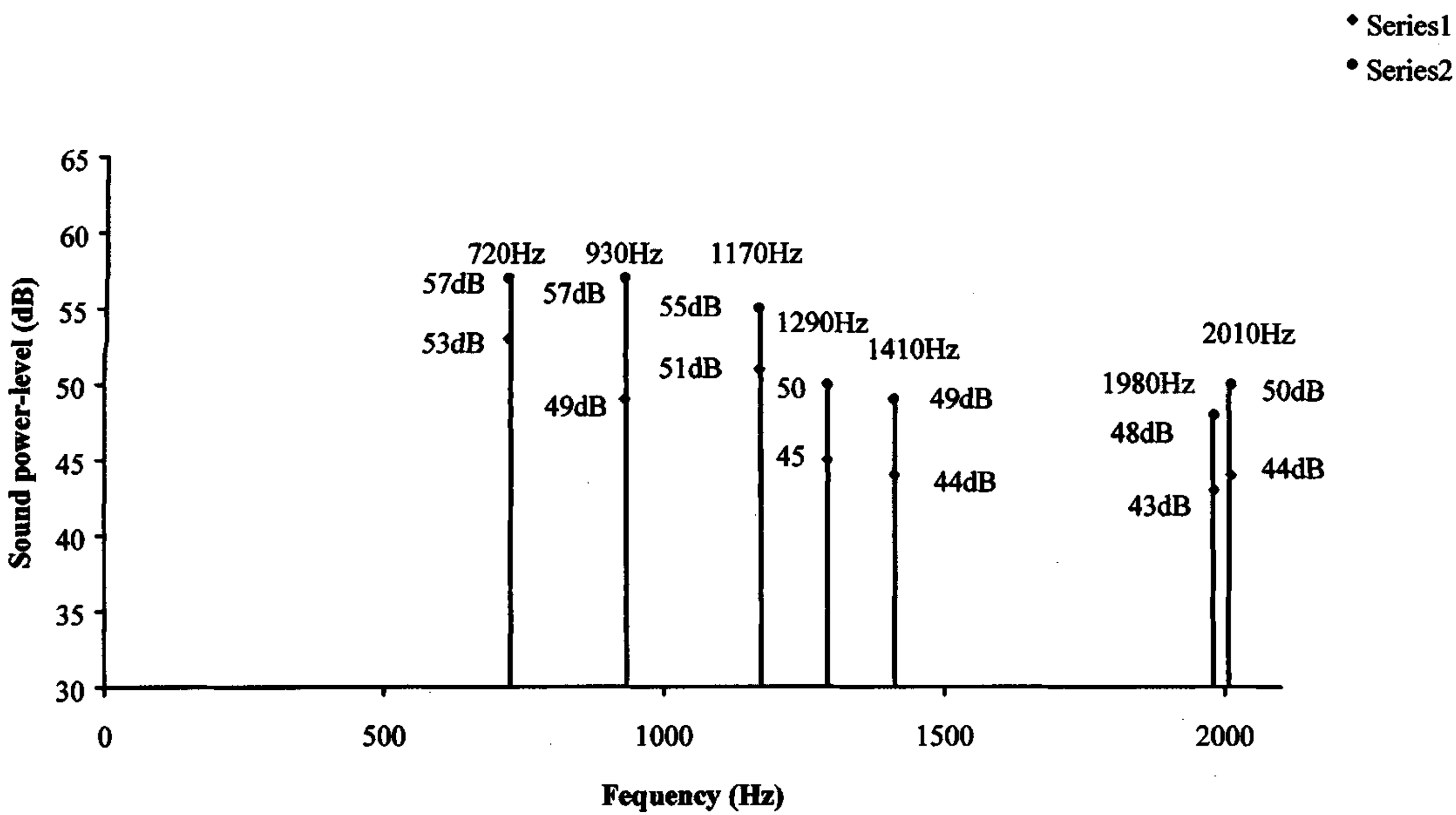
Series 1: motor running by itself @ 50% rated voltage.
Series 2: motor running by itself @ 100% rated voltage.

Figure 8.3 : Measured results of sound power-levels in the anechoic chamber.



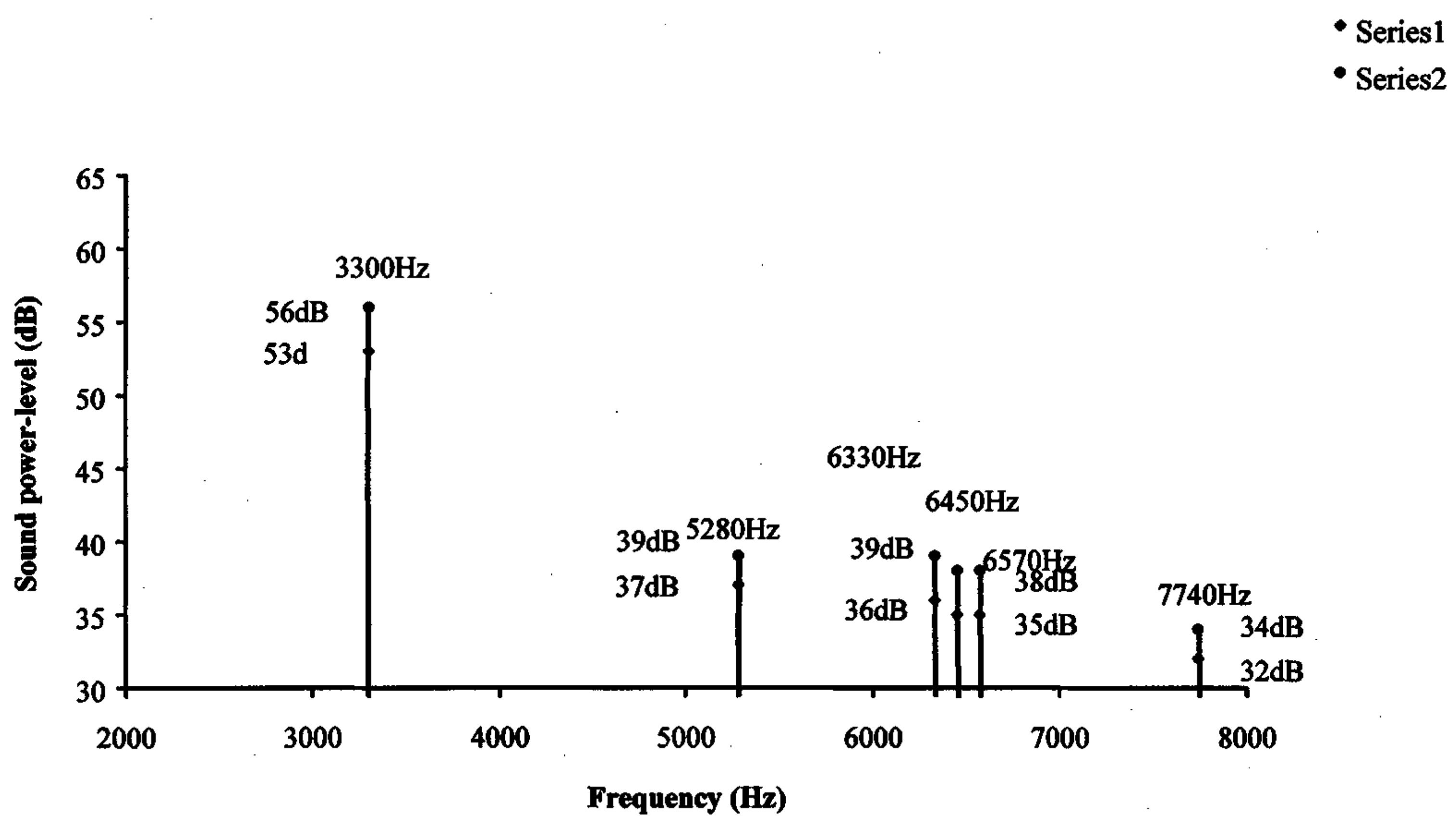
Series 1: motor running by itself @ 50% rated voltage.
Series 2: motor running by itself @ 100% rated voltage.

Figure 8.4 : Measured results of sound power-levels in the anechoic chamber.



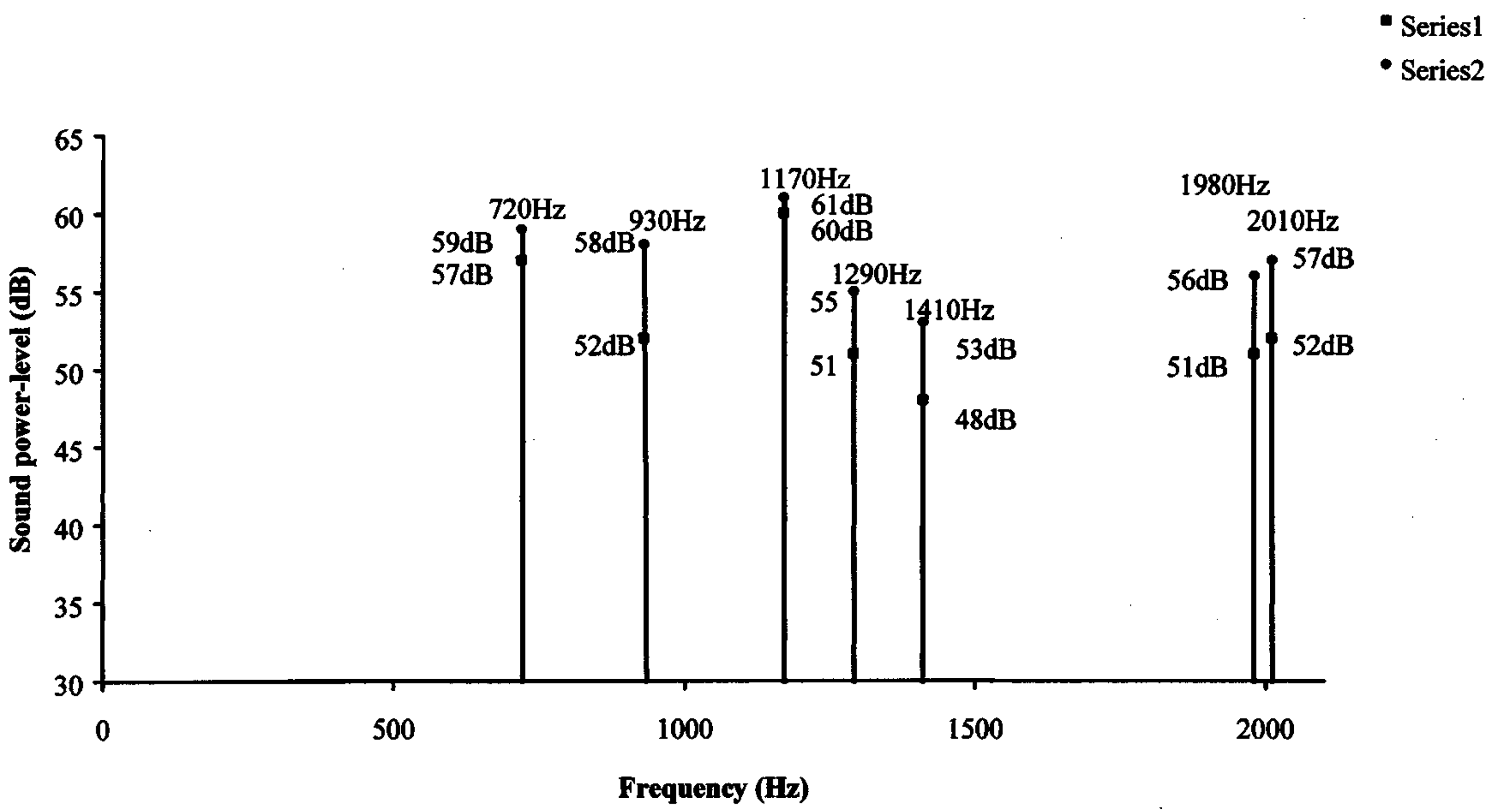
Series 1: sound power-level in the anechoic chamber.
Series 2: sound power-level in the laboratory.

Figure 8.5 : Comparison of sound power-levels when the motor was operating at 50% rated voltage.



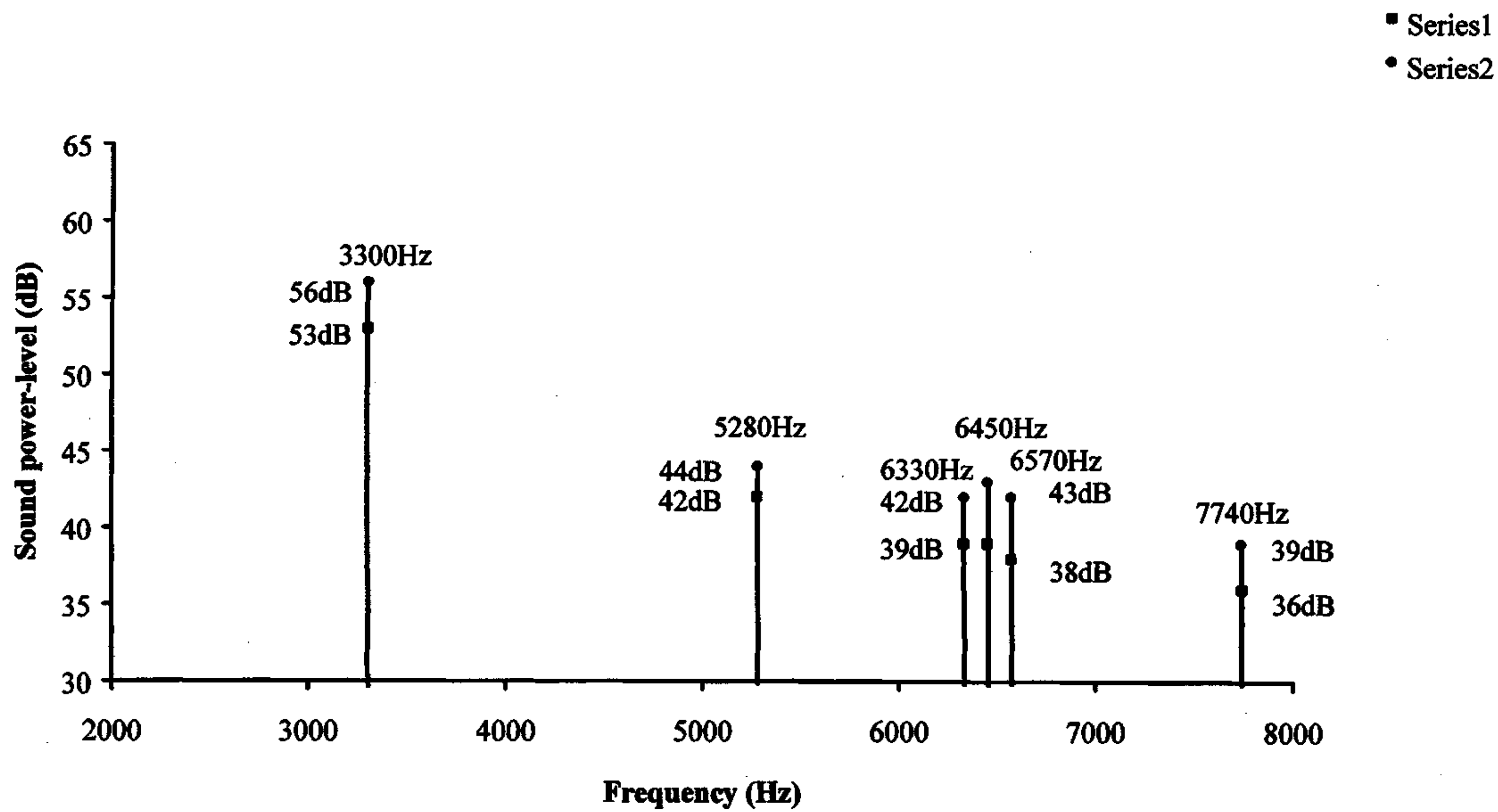
Series 1: sound power-level in the anechoic chamber.
Series 2: sound power-level in the laboratory.

Figure 8.6 : Comparison of sound power-levels when the motor was operating at 50% rated voltage.



Series 1: sound power-level in the anechoic chamber.
Series 2: sound power-level in the laboratory.

Figure 8.7 : Comparison of sound power-levels when the motor was operating at 100% rated voltage.



Series 1: sound power-level in the anechoic chamber.
Series 2: sound power-level in the laboratory.

Figure 8.8 : Comparison of sound power-levels when the motor was operating at 100% rated voltage.

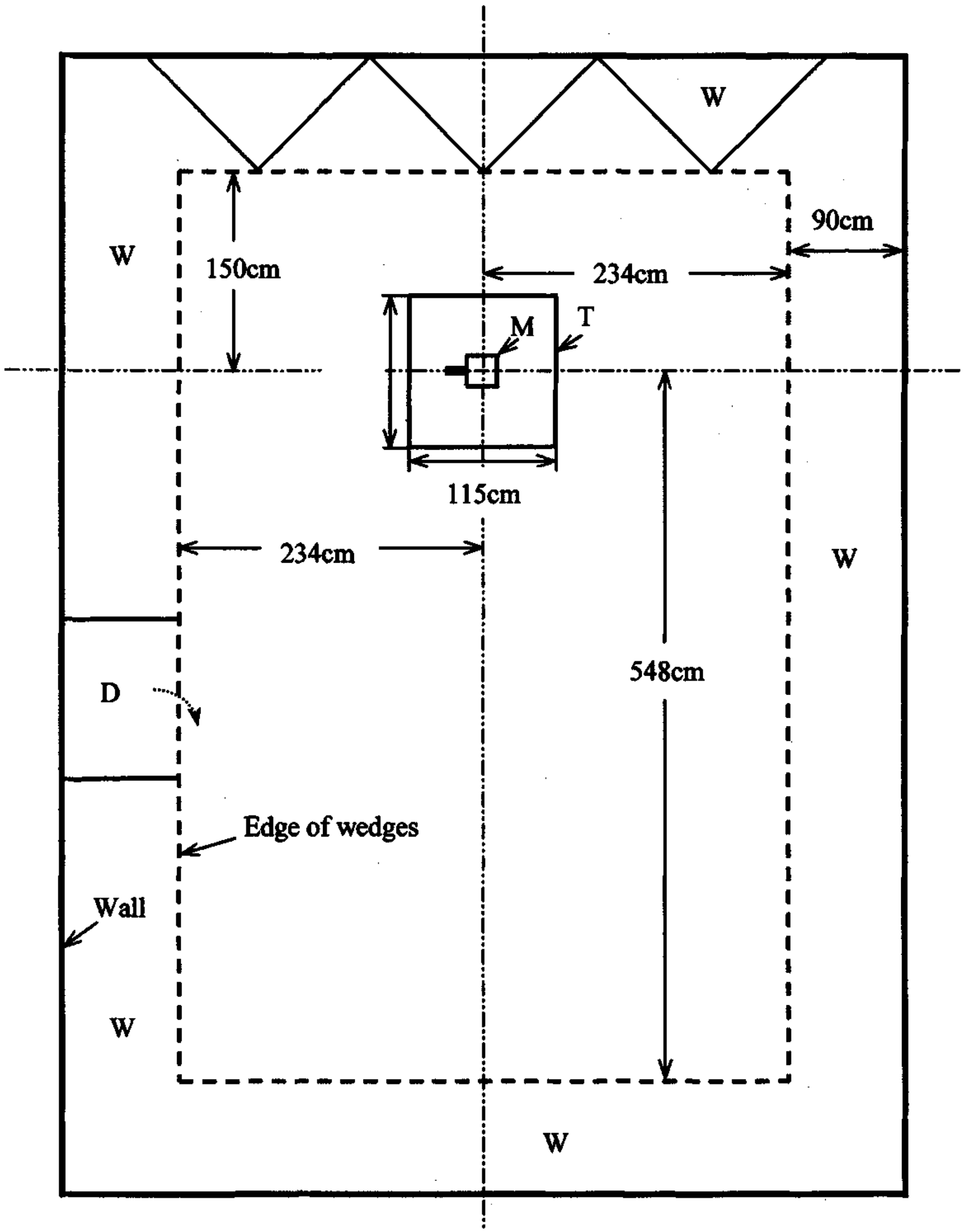
8.4 Directivity Measurements

The free-field conditions exist in the room because the walls of an anechoic chamber are covered by absorption materials. Thus, it is possible to determine the directional properties of the motor in an anechoic room by taking a number of sound level measurements surrounding the source.

In general, except for the ideal point source, the sound field of any extended source will display directional patterns. Depending on the characteristic of the sound field, a 0 to 6 dB decrease in sound pressure-level is expected with doubling of distance from the source. Any compact source will appear as a point source if the measuring distance is far enough from it. It is expected that a 6 dB drop would occur per doubling of the distance, at sufficient distances from the source in a free-field. Because of the vibration-modes of the stator, not all parts of the stator vibrate in phase with each other. However, the sound pressure-level in the vicinity of the motor does not decrease by 6 dB each time the distance from the source is doubled.

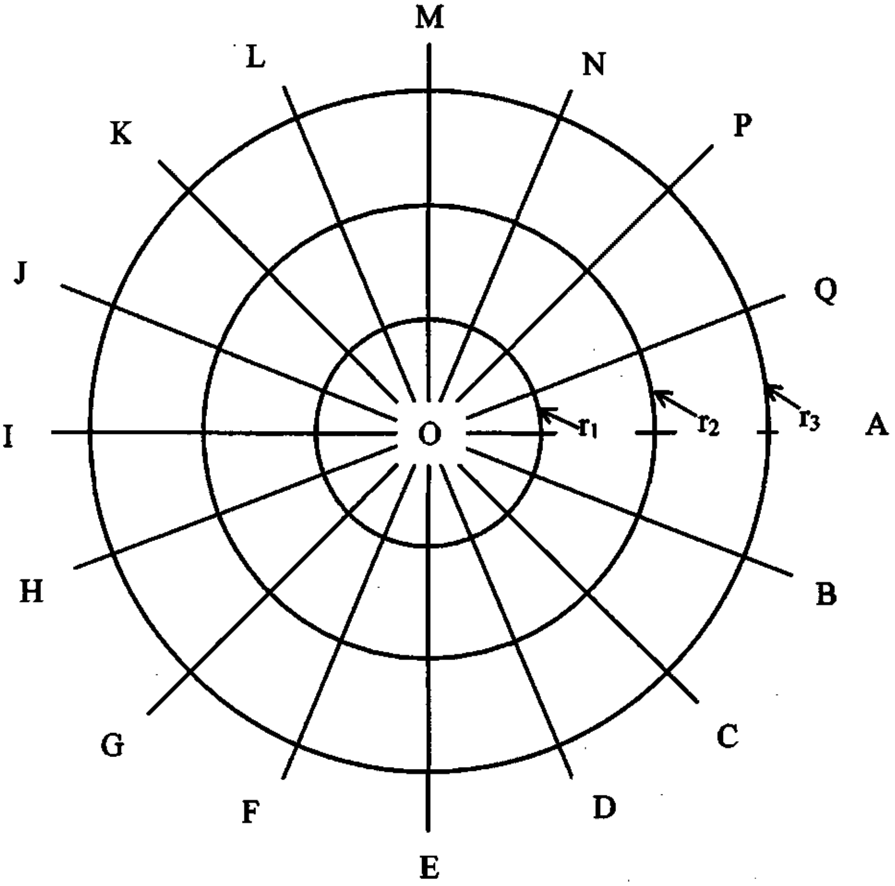
Also, the motor does not radiate noise uniformly in all directions due to the structure and the shape of the motor. At a fixed distance away from the motor, the values of sound pressure-level in any frequency-band are generally different for different directions.

The layout and the dimensions of the anechoic chamber are shown in Figure 8.9. In order to describe the sound field of this 10 hp motor, systematic measurements of sound pressure-levels on a horizontal plane through the shaft were carried out along 16 radii, which equally divide this plane. Along each radius, there are definite measuring points. The distance from the geometrical center of the motor to each measuring point is 50 cm, 100 cm and 150 cm respectively, as shown in Figure 8.10 and Figure 8.11.



D: entrance door. M: motor. T: mounting table. W: wedges.

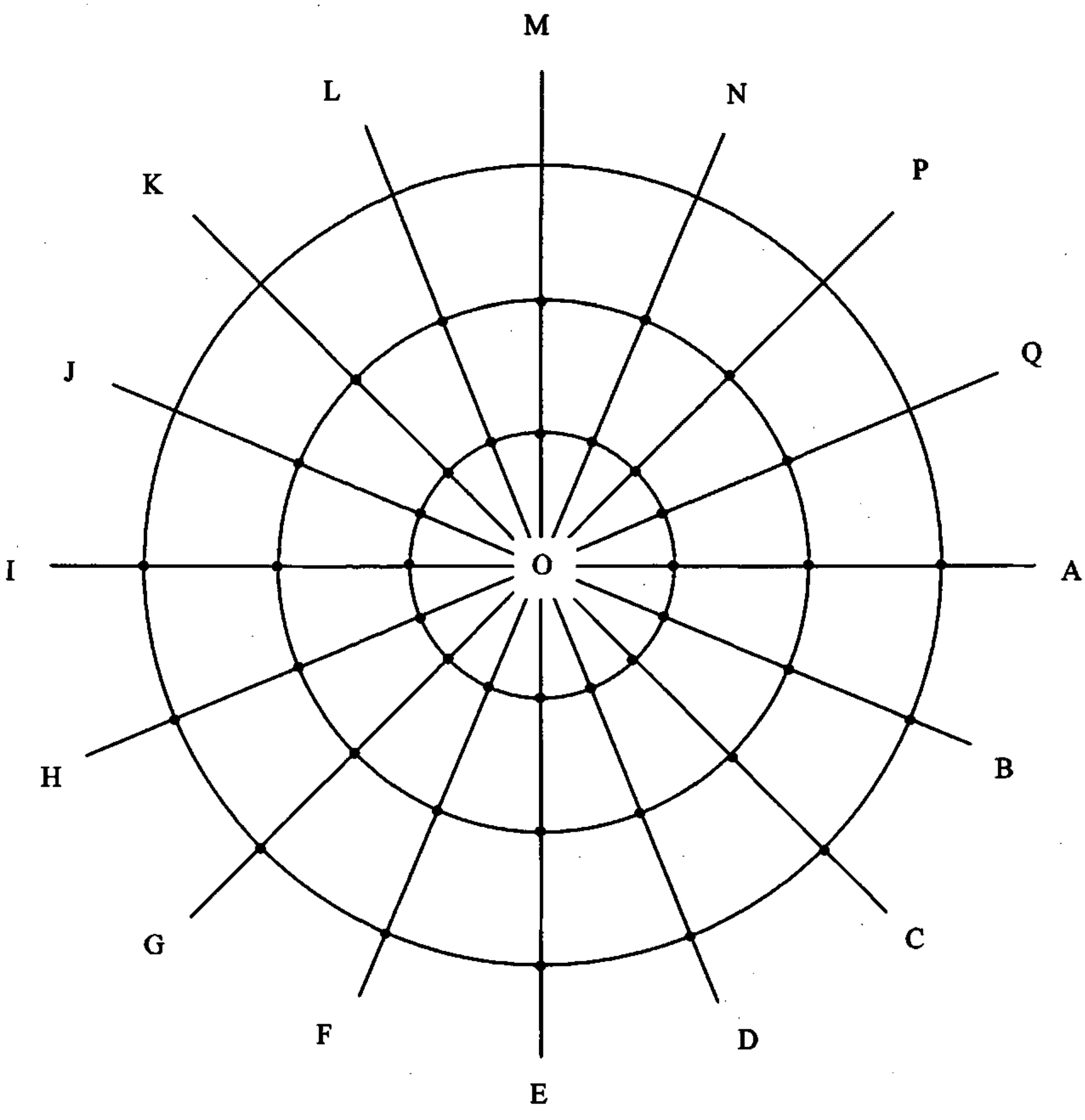
Figure 8.9 : Layout and dimensions of anechoic chamber.



O: centroid.

Location of measuring points along each radius; r_1=50cm, r_2=100cm, and r_3=150cm.

Figure 8.10 : Layout of the radii and measuring points along the radii, OA, OB, ..., OQ.



O : centroid
• : location of measuring points.

Figure 8.11 : Layout of the measuring points for directivity measurements.

The directivity of a given source is a function of the frequency. To get some representative examples, one lower frequency-band and one higher frequency-band were chosen at 1170 Hz and 3300 Hz. Sound pressure-levels in frequency-bands of 1170 Hz and 3300 Hz were measured when the motor was running at 50% of rated voltage and 100% of rated voltage. The values are shown in Table 8.3. At each point, the measured sound pressure-level is labeled in the figures from Figure 8.12 to Figure 8.15. The sound pressure-levels at other locations were estimated by interpolation between the measured levels. Thus, the 50 dB and 55 dB equal loudness contours for $f = 1170$ Hz have been constructed as shown in Figure 8.16 and Figure 8.17. The 45 dB and 50 dB equal loudness contours for $f = 3300$ Hz have been also constructed as shown in Figure 8.18 and Figure 8.19.

From the experimental data, the followings are observed:

- The directional pattern of the sound field of this 10 hp induction motor, either in 1170 Hz frequency-band or in 3300 Hz frequency-band is not symmetrical.
- For 1170 Hz, the peak sound pressure-level is approximately along the direction perpendicular to the shaft. While in 3300 Hz frequency-band, the peak sound pressure-level is along the shaft direction.
- The operating conditions change the directional patterns in the 1170 Hz frequency-band. In this case, it is not possible to deduce the directional pattern at 100% rated voltage from the directional pattern at 50% rated voltage.
- The directional patterns of sound field around the 10 hp induction motor in 3300 Hz frequency-band are fairly similar for different operating conditions. Also, the values of sound pressure-level at each measuring point remain almost same for different operating conditions.

Table 8.3 : The measured sound pressure-levels at different measuring points for 1170 Hz and 3300 Hz when the motor was running at 50% and 100% rated voltage.

Designation of radius	Position	Sound pressure-level of f = 1170 Hz (dB)		Sound pressure-level of f = 3300 Hz (dB)	
		50% V_{rated}	100%V_{rated}	50% V_{rated}	100%V_{rated}
OA	50 cm	49	57	46	47
	100 cm	41	49	39	40
	150 cm	37	45	36	37
OB	50 cm	44	51	45	44
	100 cm	38	48	40	41
	150 cm	36	44	34	37
OC	50 cm	43	48	47	48
	100 cm	39	45	43	44
	150 cm	37	45	40	40
OD	50 cm	49	59	47	46
	100 cm	46	56	43	43
	150 cm	43	53	40	40
OE	50 cm	52	62	50	50
	100 cm	46	57	43	43
	150 cm	44	53	40	40
OF	50 cm	47	56	45	45
	100 cm	43	52	43	43
	150 cm	40	49	41	40
OG	50 cm	45	55	50	50
	100 cm	41	51	42	43
	150 cm	39	48	39	40
OH	50 cm	48	59	56	55
	100 cm	44	54	51	52
	150 cm	40	49	48	48
OI	50 cm	48	57	59	58
	100 cm	42	50	53	52
	150 cm	39	46	50	49

Continued ...

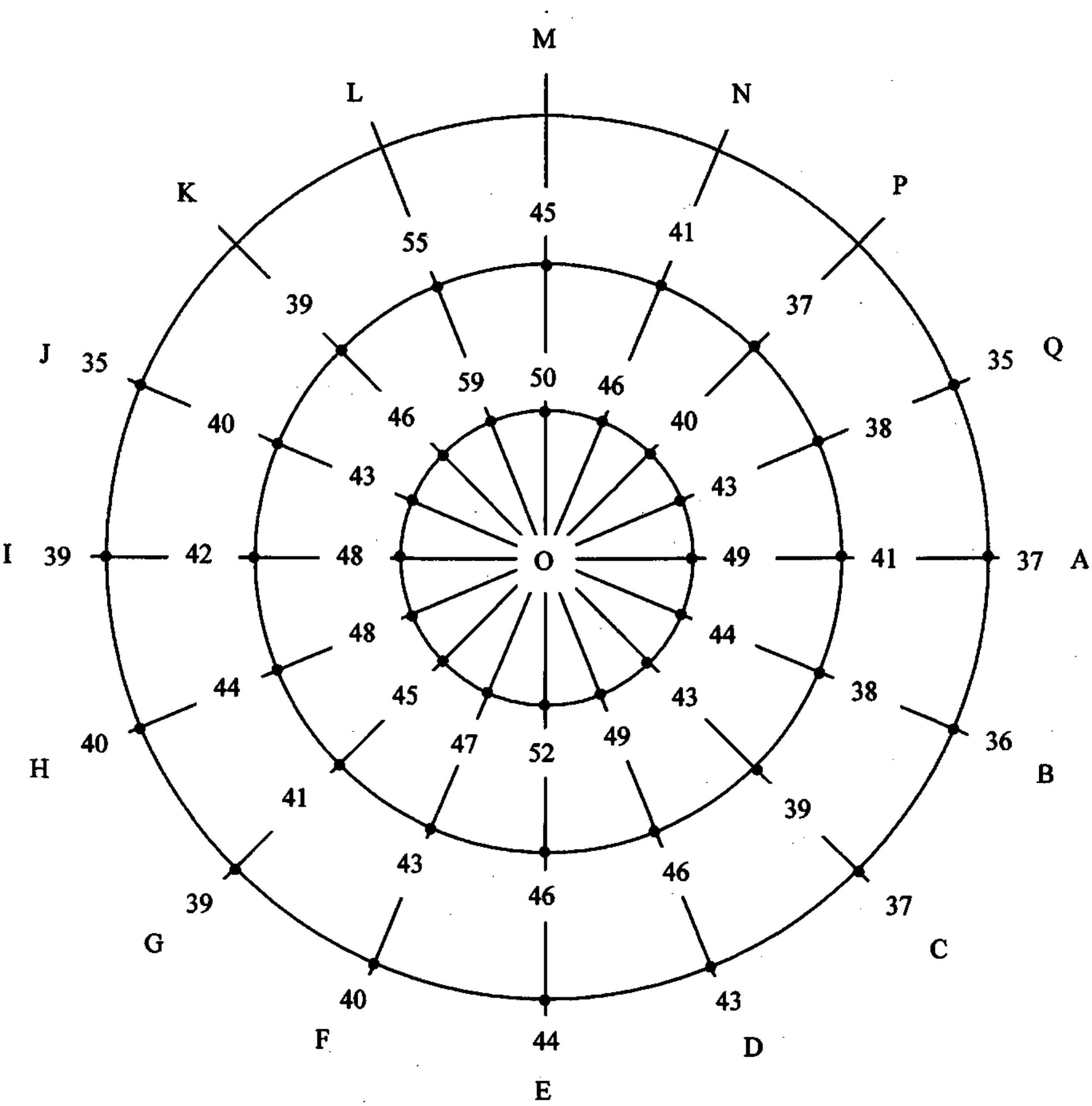
Table 8.3 Continued :

OJ	50 cm	43	51	56	56
	100 cm	40	47	52	51
	150 cm	35	41	48	47
OK	50 cm	46	53	50	50
	100 cm	39	48	46	45
OL	50 cm	59	50	49	48
	100 cm	55	46	44	44
OM	50 cm	50	60	47	47
	100 cm	45	56	42	43
ON	50 cm	46	53	49	48
	100 cm	41	49	41	44
OP	50 cm	40	50	44	44
	100 cm	37	47	41	41
	150 cm	36	44	38	39
OQ	50 cm	43	53	45	44
	100 cm	38	46	41	41
	150 cm	35	42	37	38

8.5 Comments

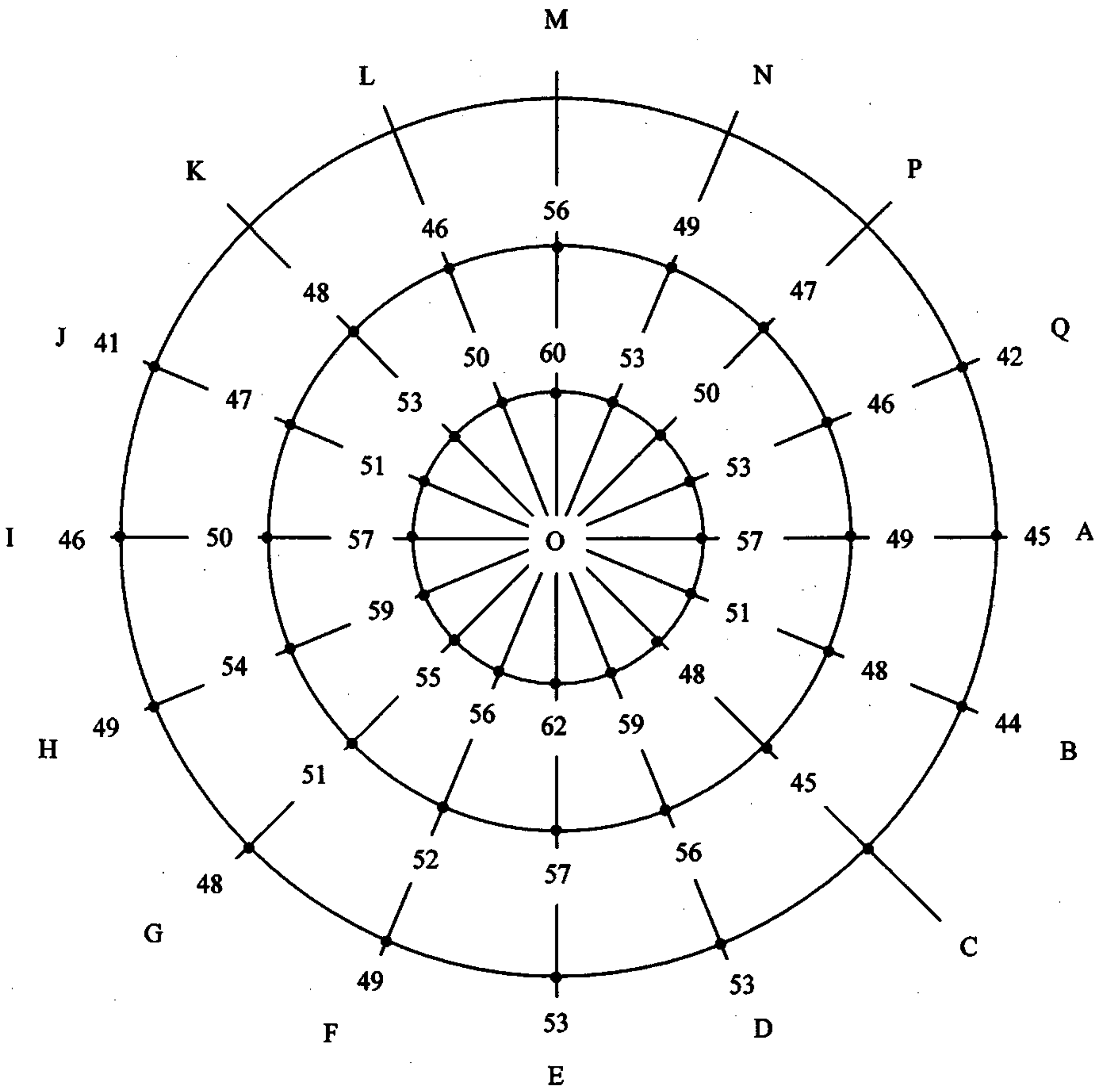
Experimental investigations on the test motor under free-field conditions were carried out in the anechoic chamber. Sound level measurements, when motor operates under no-load in the free-field, provide very useful information about the sound radiated from the test motor. Also, comparisons are presented between the results obtained in a free-field, and also in an ordinary laboratory which is similar to the real workplace.

Equal loudness contours are presented in this chapter for 1170 Hz and 3300 Hz. These contours describe the directional properties of the motor.



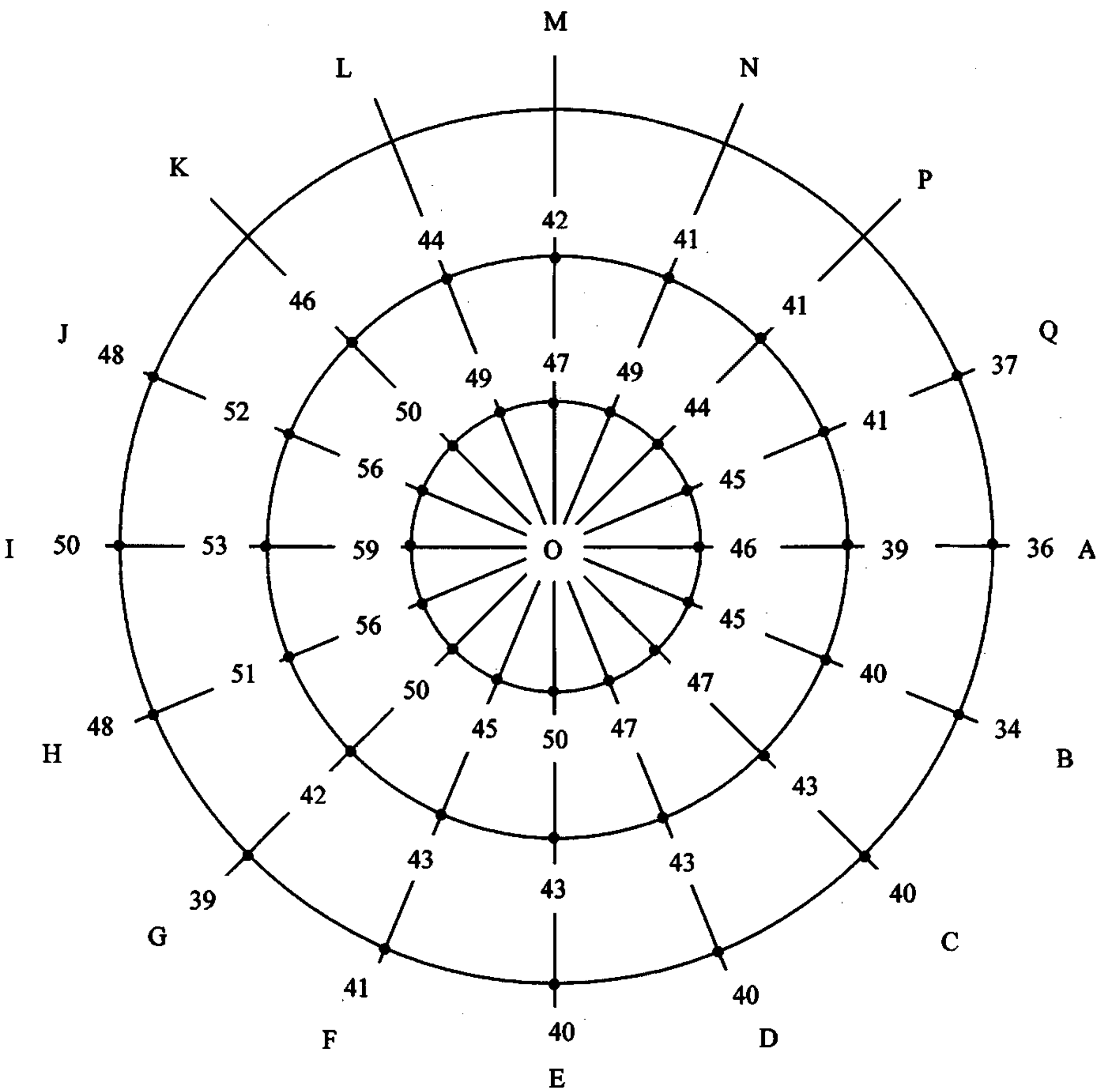
O : centroid.
• : location of measuring point.

Figure 8.12 : The measured values of sound pressure-levels at the measuring points for $f = 1170$ Hz when the motor operates at 50% rated voltage.



O : centroid.
• : location of measuring point.

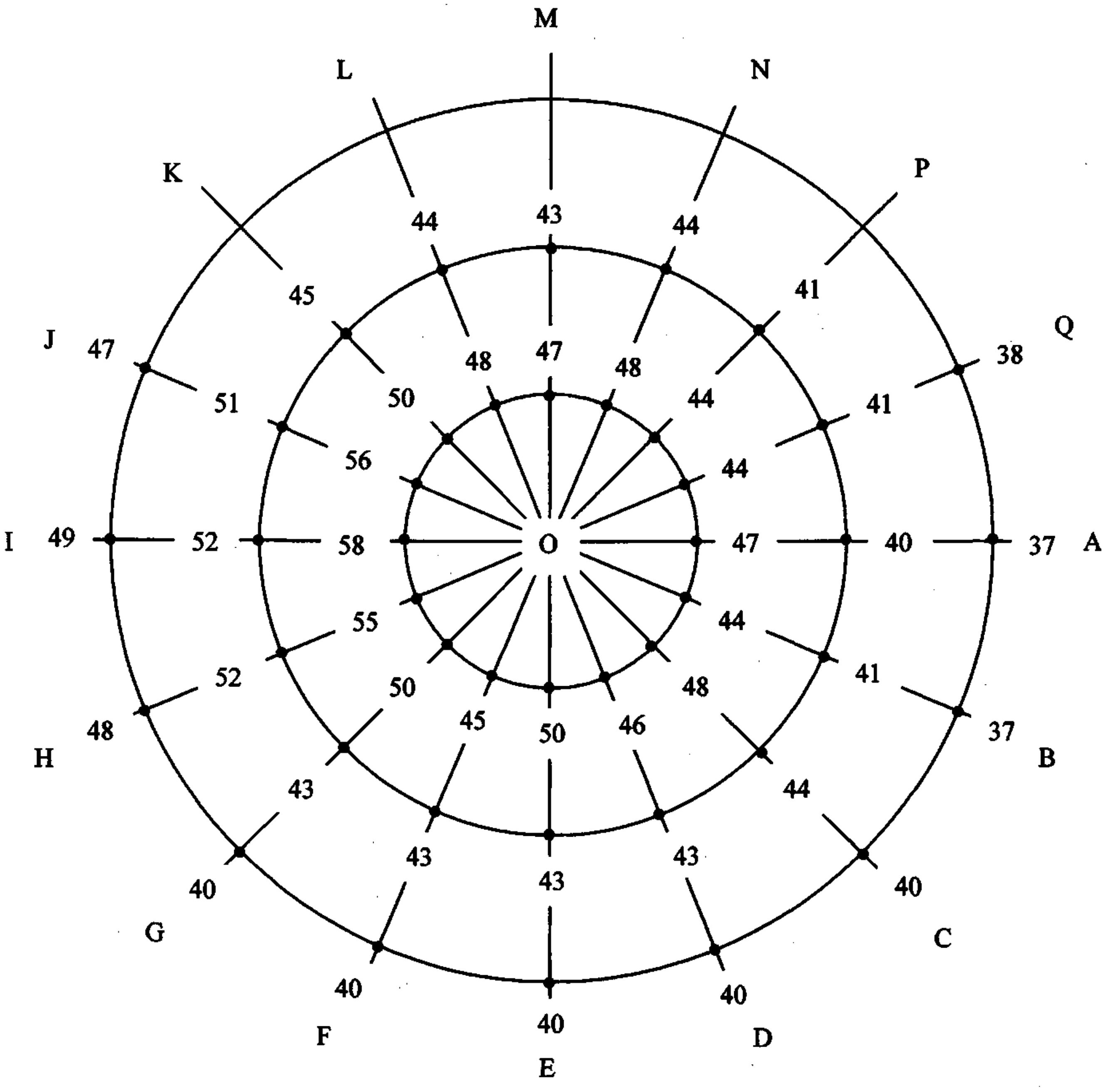
Figure 8.13 : The measured values of sound pressure-levels at the measuring points for $f = 1170$ Hz when the motor operates at 100% rated voltage.



O : centroid.

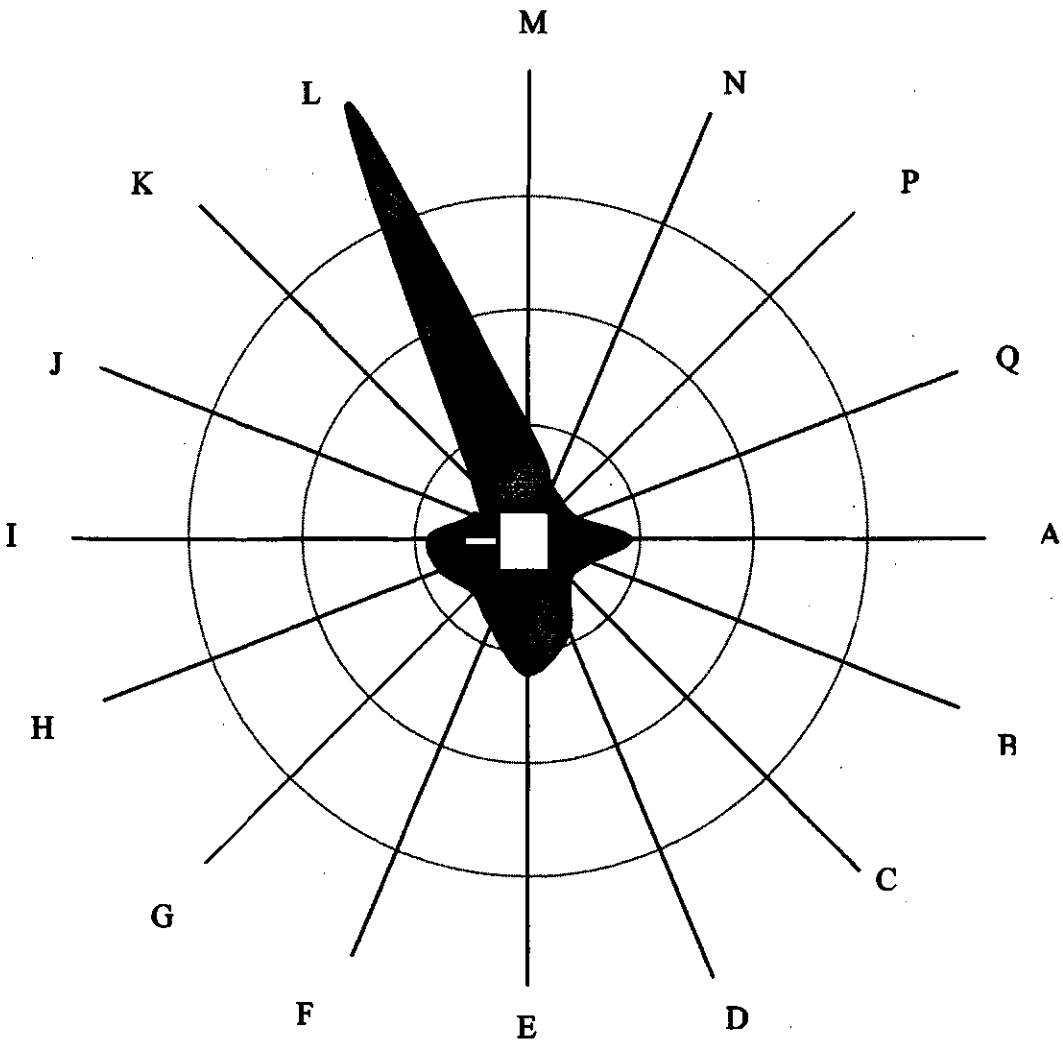
• : location of measuring point.

Figure 8.14 : The measured values of sound pressure-levels at the measuring points for $f = 3300$ Hz when the motor operates at 50% rated voltage.



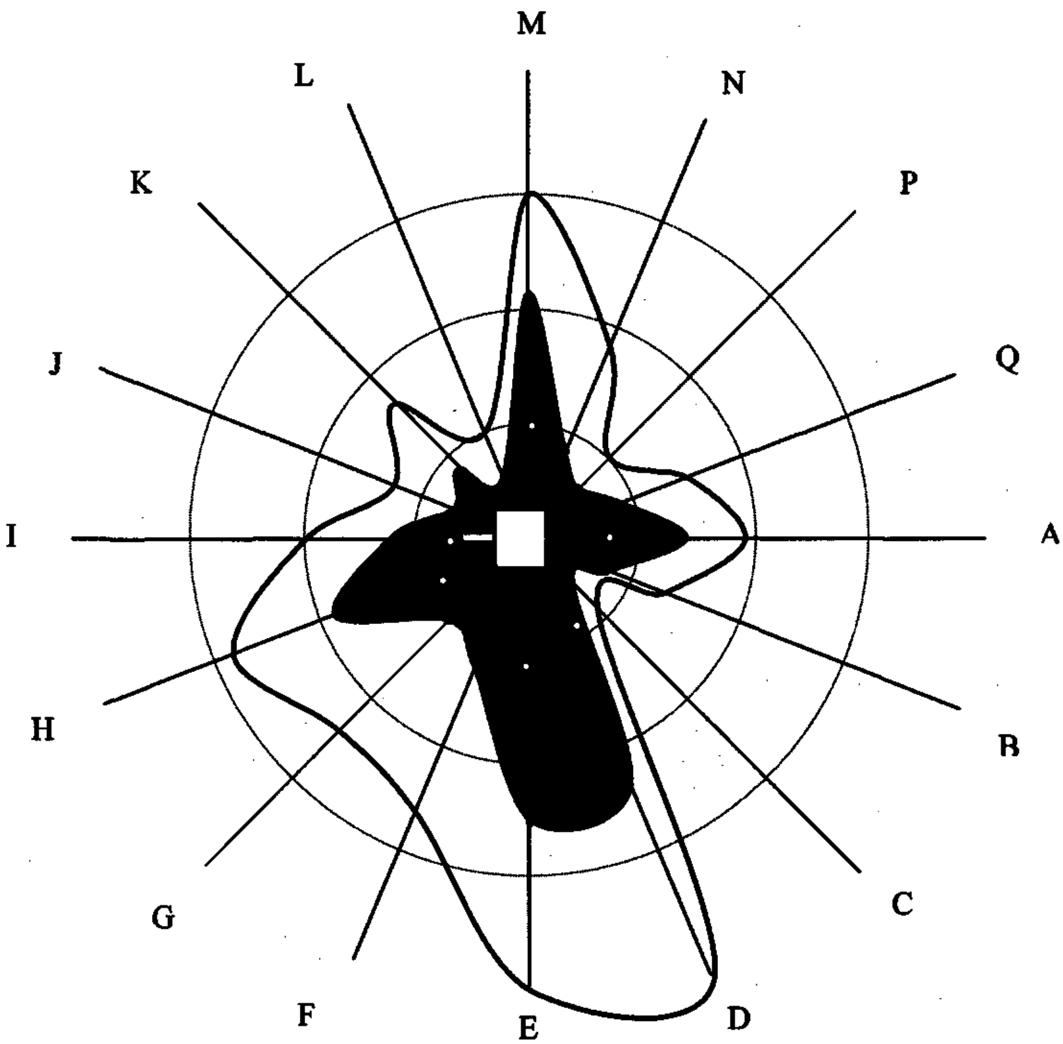
O : centroid.
• : location of measuring point.

Figure 8.15 : The measured values of sound pressure-levels at the measuring points for f = 3300 Hz when the motor operates at 100% rated voltage.



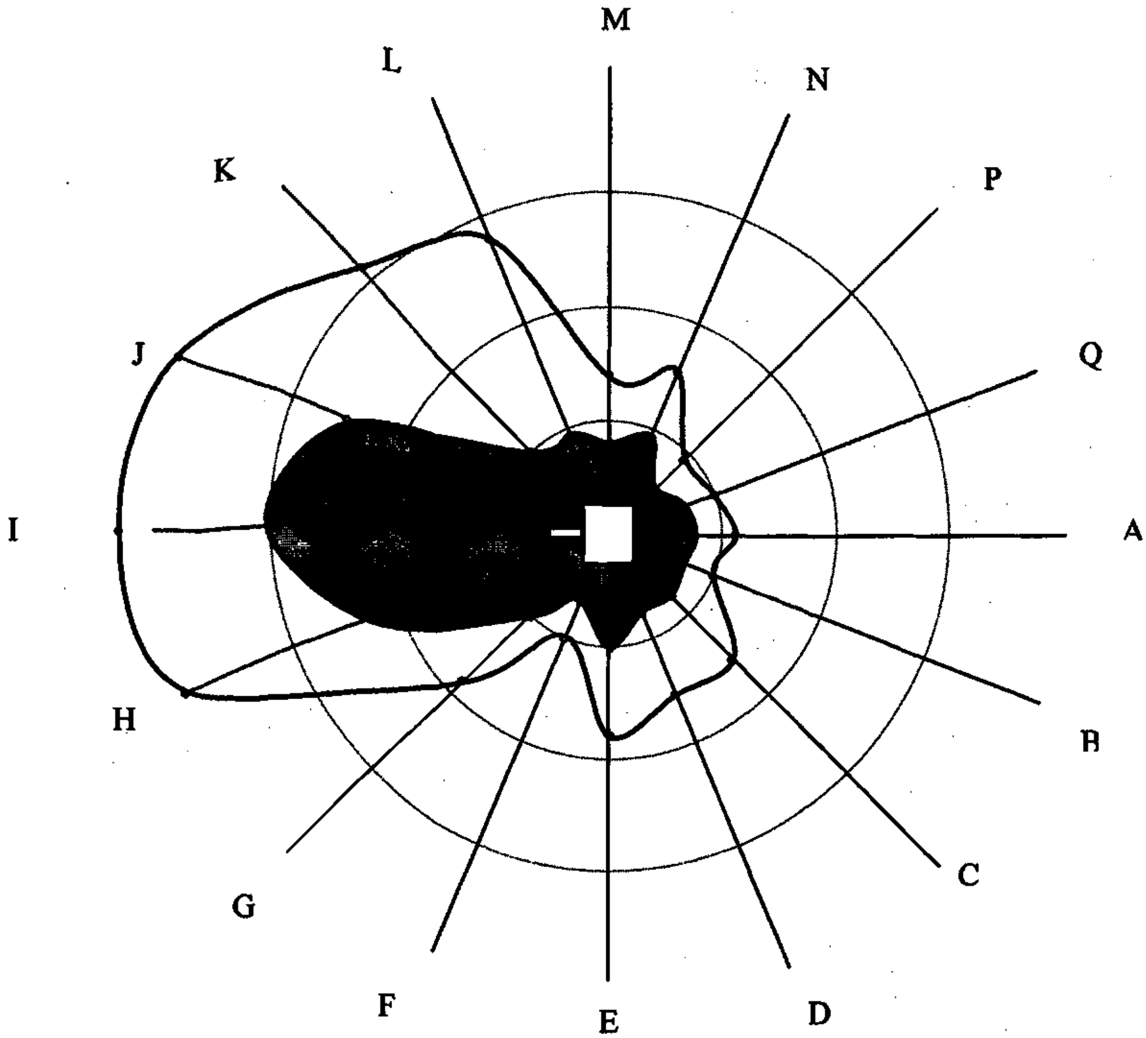
▬ : sound pressure-level contour of 50 dB.
■ : zone > 50 dB.

Figure 8.16 : Directional characteristic of the motor for $f = 1170$ Hz when the motor operates at 50% rated voltage.



▬ : sound pressure-level contour of 50 dB.
▬ : sound pressure-level contour of 55 dB.
■ : zone > 50 dB.
o : location where the sound pressure-level is 60 dB.

Figure 8.17 : Directional characteristic of the motor for *f* =1170 Hz when the motor operates at 100% rated voltage.



– : sound pressure-level contour of 45 dB.
– : sound pressure-level contour of 50 dB.
■ : zone > 50 dB.

Figure 8.18 : Directional characteristic of the motor for $f = 3300$ Hz when the motor operates at 50% rated voltage.

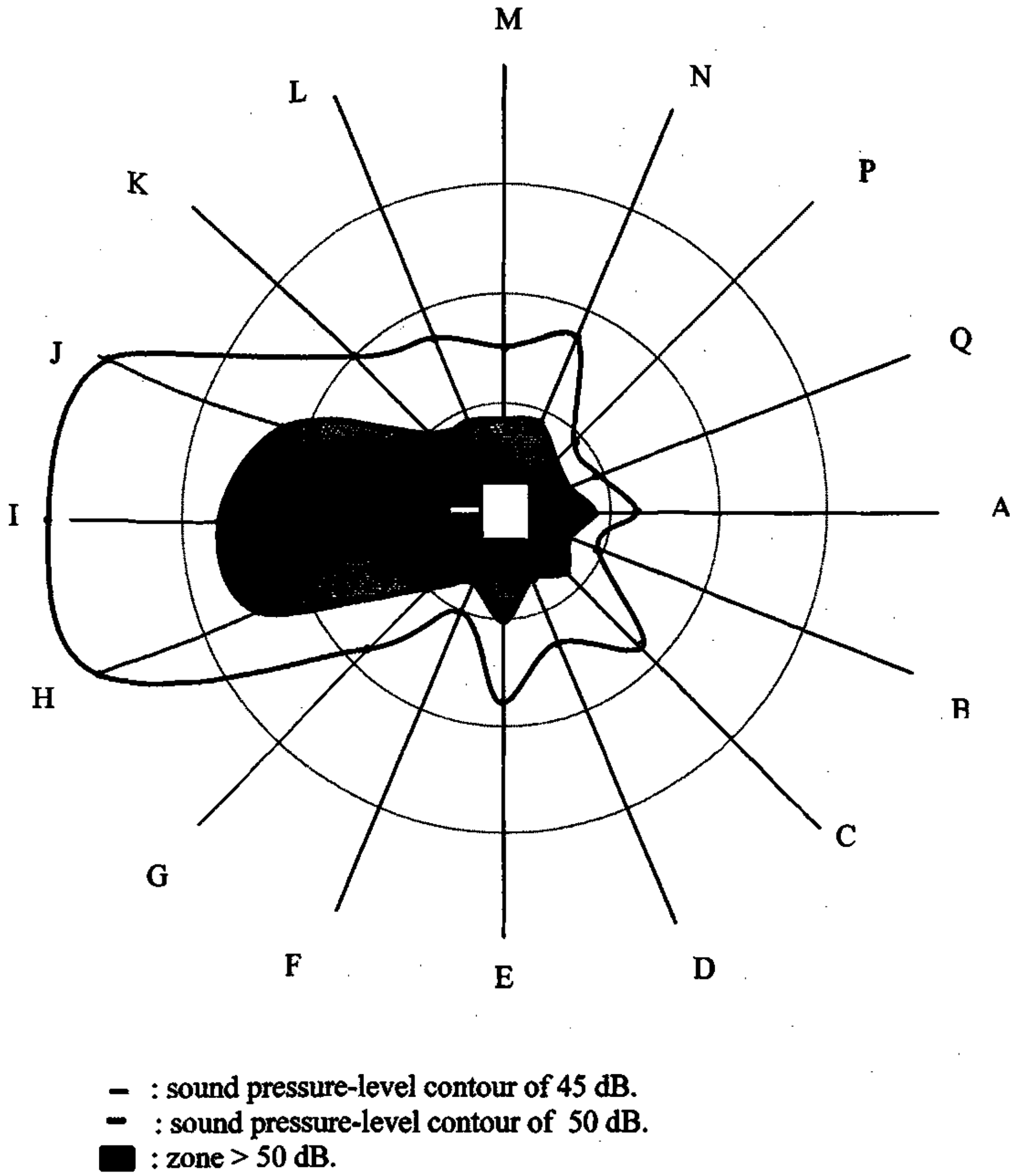


Figure 8.19 : Directional characteristic of the motor for f = 3300 Hz when the motor operates at 100% rated voltage.

9. CONCLUSIONS

Induction motors produce annoying noise. Electromagnetic forces produce vibrations in the motor and the radiated noise. Standards stipulate the maximum noise levels for different kinds of machines. It is important that manufacturers and consumers pay attention to the vibration and noise problems of induction motors.

Theoretical prediction and analyses of the vibrations and noise of an electrical motor are complex. In order to pursue systematic investigations on the vibrations and noise of induction motors, extensive experimental investigations have been conducted on a specially designed test motor in conjunction with the previous theoretical analyses. The investigations have been conducted with a view to acquire more physical understanding and practical information related to the vibration and noise problems. The following conclusions are drawn based on the experimental results.

9.1 Preliminary Investigations

In order to get the fundamental understanding and basic information about the magnetic-fields and electromagnetic forces before conducting detailed experimental investigations, preliminary investigations including harmonic analysis of the stator current, spectral analysis of the induced voltage in stator search-coils, and noise measurements using sound-level-meter were performed first.

- An ideal sinusoidal distribution of MMF (magnetomotive force) is very difficult to obtain in practice. The measured spectrum of the current in a phase of stator winding clearly shows that in addition to the fundamental component, there are harmonic components in the lower frequency range. Saturation effects introduce additional harmonic-components in MMF.

- The search-coils having a span equal to the stator tooth-width provide information on the flux-pulsations through a tooth. The measured oscillogram and spectrum of the induced voltage in the search-coils prove that harmonic-components cover quite a wide frequency range.
- The preliminary noise measurements by using sound-level-meter are necessary. They provide very important information on background noise levels. It is clear from these measurements that choosing a suitable time period in a day is very crucial in order to get correct noise results in an ordinary laboratory. Also, these preliminary measurements show that the highest sound level is in the frequency range around 1 kHz. Close attention should be paid to this frequency range.

9.2 Vibration Measurements

Frequency analysis of vibrations provides the information on frequencies at which the machine would radiate the noise. These measurements are helpful to improve the design and achieve quiet operation of electrical machines. Since electromagnetic forces produce the vibrations of the stator and the radiated noise, spectrum-analysis of vibration signals is more fundamental compared to the noise measurements.

- Mode-shape measurement results provide direct information about the stator deformation under standard three-phase excitation. The mode varies with the frequency. At 720 Hz, the circumferential mode is n=2, which is in good agreement with the previous measurement results under magnetic shaker excitation. Due to the fact that 720 Hz is near the most prominent resonant frequency of the stator, the mode-shapes are clear and well defined. The mode-shapes at 3300 Hz are not well defined because of weak resonance around this frequency.
- The mode for a particular frequency is the same, but the vibratory pattern may change with the voltage applied to the motor.
- The vibration levels at the slot-harmonic frequencies increase as the load of the motor is increased. Higher load causes higher levels of vibrations, however, the

magnitude of the increase for each frequency is different. The relationship of vibration level and load is not linear.

9.3 Noise Measurements in an Ordinary Laboratory

In practice, induction motors are installed in a room with characteristics which fall in-between free-field and reverberant rooms. Therefore, the noise measurements in an ordinary laboratory hold practical importance. The following conclusions are very important:

- Detailed background noise measurements show that the air ventilation system in the building introduces extra noise that does interfere with the noise measurements in the laboratory. In order to get rid of the interference as much as possible, the best time period to get good noise measurement results is from 11 p.m. to 8 a.m.
- The noise levels are higher when the motor is supplied at rated voltage in comparison to the noise produced at a voltage lower than the rated value. However, even at 50% of the rated voltage, the noise levels at each frequency are substantial. So, in some situations where the necessary supply voltage is not available, the noise levels measured at lower voltage still provide useful information.
- The sound radiation characteristics of the motor are more complex compared to its mechanical response to vibrations. At the frequencies which are produced by the inter-action of the fundamental air-gap field with the slot-harmonic fields, the sound levels are affected considerably by the load of the motor.
- Contrary to expectations, the noise levels at the saturation frequency 720 Hz decrease as the load increases. This trend is in good agreement with that of the vibration measurements.
- The frequency at which the highest noise level occurs is 1170 Hz.

9.4 Noise Measurements in Anechoic Chamber

Compared to the noise investigations performed in the ordinary laboratory, the noise investigations in the anechoic chamber are used to label noise levels and stipulate noise level limits according to the standards. Results obtained in both ordinary laboratory and anechoic chamber are compared so that useful information can be drawn to help in providing information for practical engineering problems.

- By careful measurements at different time periods, the background noise was found to be very low. It does not change much with the time of day in the anechoic chamber. Therefore, the noise measurements in the anechoic chamber are not affected by the background noise.
- The noise levels increase with the increase of the impressed voltage. For each frequency, the increase in magnitude of sound level in both ordinary laboratory and anechoic chamber is similar.
- Under the same operating conditions, due to the reflection in the ordinary laboratory, the sound levels are generally higher. At 1170 Hz, the sound levels are virtually equal for both sound fields.
- The directional patterns of the test motor are not symmetrical at 1170 Hz and 3300 Hz. In a practical situation, therefore, one should not expect a symmetrical directional pattern.

Findings and results of extensive investigations are reported in this thesis in order to obtain good understanding of the vibration and noise problems associated with induction motors. As theoretical analyses for both vibrations and noise of an induction motor are very complex, the interpretations of the results reported in this thesis focus on the physical understanding of the vibrations and radiated noise of an induction motor.

In brief, the following recommendations are made:

(i) It is important that the appropriate standards are followed to conduct the acoustic noise measurements on a machine under investigation.

(ii) Vibrations caused by radial electromagnetic forces are the major source of airborne noise from the electrical machines. A good understanding is required in order to correlate the vibrations and noise.

(iii) The background noise plays an important role, and it should be always considered for acoustic noise measurements.

(iv) Since many factors are associated with vibrations and noise of induction motors, all the frequencies in the audio frequency range should be considered for the noise and directivity characteristics of the machine.

(v) Because of the complexity and the nature of vibrations and noise, each machine has to be considered separately in order to obtain the information on vibration and noise problems. The techniques to reduce the noise have to be then applied.

It is hoped that the procedures and methods for vibration and noise investigations reported in this thesis would prove to be useful for practical problems.

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APPENDIX A: DESCRIPTION OF SIGNALS

The propagation of sound may be visualized by considering a vibrating body as shown as Figure A.1. A mass m is fastened to a spring and constrained to move parallel to the spring. As the body moves forward, it compresses the layer of air in contact with it. This compression travels outward as a sound wave. As the vibrating body moves in the reverse direction, the surrounding air is rarefied. This rarefaction travels outward in a manner similar to the compressions, in sympathy with the vibration motion.

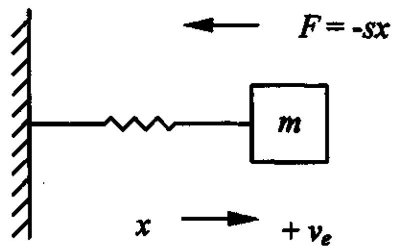

Figure A.1 : Sinusoidal vibration.

When the mass m is displaced slightly from its rest position and released, the mass will vibrate. The measurement shows that the displacement of the mass from its rest position is a sinusoidal function of time. Sinusoidal vibration of this type is called pure sinusoid.

If s is the stiffness or spring constant in N/m, the restoring force F in Newtons (N) with the displacement x (m) of the mass m in kilograms (kg) can be expressed as:

$$F = -sx . \qquad \text{(A.1)}$$

Substituting this expression for force into the general equation of linear motion:

$$F = m\frac{d^2x}{dt^2}, \qquad \text{(A.2)}$$

where $\frac{d^2x}{dt^2}$ is the acceleration of the mass, giving:

$$\frac{d^2x}{dt^2}+\frac{s}{m}x=0. \tag{A.3}$$

If a constant ω_0 is defined as $\omega_0=\sqrt{s/m}$, the above equation takes the form:

$$\frac{d^2x}{dt^2}+\omega_0^2x=0. \tag{A.4}$$

This is an important linear differential equation with the well-known solution, that is expressed as the following. If the initial conditions at t = 0 being initial displacement x_0 and velocity v_0 then:

$$x(t)=X\sin(\omega_0 t+\phi), \tag{A.5}$$

where X is the amplitude of the motion and ϕ is the initial phase angle, which are given by

$$X=\sqrt{x_0^2+\left(\frac{v_0}{\omega_0}\right)^2}, \tag{A.6}$$

$$\phi=\tan^{-1}\left(-\frac{v_0}{\omega_0 x_0}\right). \tag{A.7}$$

Equation (A.5) is the mathematical expression of a pure sinusoidal signal.

In many important situations that arise in acoustics, the motion of the noise source is a linear combination of the vibrations induced by more than two simple sinusoidal signals. Combining the effects of individual vibrations by linear addition is valid for the majority of cases encountered in acoustics.

Assuming that there are two pure sinusoids $x_1(t)$ and $x_2(t)$ given by the following:

$$x_1(t)=X_1\sin\omega_1 t=X_1\sin 2\pi f_1 t, \tag{A.8}$$

$$x_2(t)=X_2\sin\omega_2 t=X_2\sin 2\pi f_2 t. \tag{A.9}$$

The combined signal $x(t)$ is:

$$x(t)=x_1(t)+x_2(t)=X_1\sin\omega_1 t+X_2\sin\omega_2 t. \tag{A.10}$$

If x_1(t) and x_2(t) have identical frequencies, a new simple harmonic vibration of the same frequency is produced. In the case of different frequencies, the resulting vibration is not a simple signal which can be represented by a simple sine or cosine function. When the ratio of the larger to smaller frequency is a rational number, the motion is periodic with angular frequency given by the greatest common divisor of ω_1 and ω_2. Otherwise, the resulting motion is a non-periodic oscillation which does not repeat itself. Examples of signal combinations are shown in Figure A.2.

Figure A.2(a) shows:

$x(t) = x_1(t) + x_2(t) = 2\sin(2\pi\times60)t + 3\sin(2\pi\times60)t.$

Figure A.2 (b) shows:

$x(t) = x_1(t) + x_2(t) = 2\sin(2\pi\times60)t + 3\sin(2\pi\times90)t.$

The linear combination of three or more simple harmonic signals is similar to that of two.

From the above discussions, the linear combination of two or more simple sinusoidal signals leads to a complex signal. Conversely, by means of Fourier's theorem, it is possible to describe any complex signal by a harmonic array of component frequencies.

If a signal of period T is presented by the function S(t), then Fourier's theorem [42] states that S(t) may be represented by the harmonic series:

$$S(t) = \frac{1}{2}A_0 + A_1\cos\omega t + A_2\cos 2\omega t + \cdots + A_n\cos n\omega t + \cdots$$

$$+ B_1\sin\omega t + B_2\sin 2\omega t + \cdots + B_n\sin n\omega t + \cdots, \qquad \text{(A.11)}$$

where, $\omega=2\pi/T$. The A's and B's are called coefficients, and they are constants which can be determined by the following formulae:

$$A_n = \frac{2}{T}\int_{-T/2}^{+T/2} S(t)\cos n\omega t\,dt = \frac{2}{T}\int_{-T/2}^{+T/2} S(t)\cos(n\frac{2\pi}{T}t)dt, \qquad \text{(A.12)}$$

$$B_n = \frac{2}{T}\int_{-T/2}^{+T/2} S(t)\sin n\omega t\, dt = \frac{2}{T}\int_{-T/2}^{+T/2} S(t)\sin(n\frac{2\pi}{T}t)dt. \qquad \text{(A.13)}$$

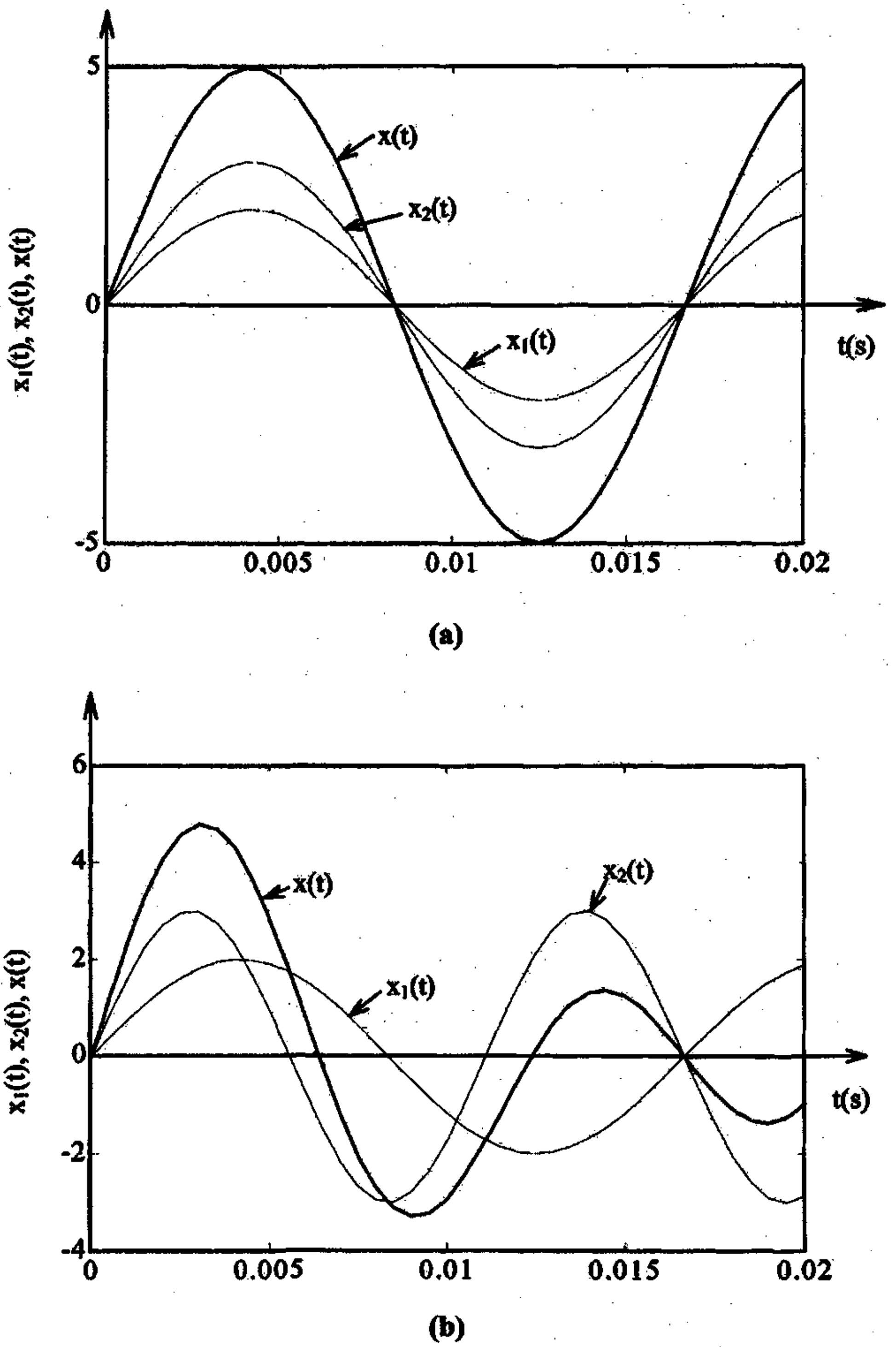

Figure A.2 : Complex signals.

The feasibility of the above integrations depends on the nature and complexity of the function $S(t)$. Fourier analysis is effective because the set of sine/cosine functions is both complete and orthogonal. Completeness guarantees that any periodic $S(t)$ can be represented, orthogonal property guarantees that the Fourier's coefficients are independent of one another.

In theory, the Fourier-series for a harmonic function may be infinite, i.e., it may consist of an infinite number of harmonics. Usually it is strongly convergent, so the amplitude of the higher harmonics reduces rapidly with increasing harmonic number. To achieve a reasonable good equivalence to the original function, few terms need to be computed for smooth functions of time. Also, calculation of Fourier's coefficients is greatly simplified for certain types of functions. If the function $S(t)$ is even, i.e., $S(-t) = S(t)$, then all sine terms will be missing. For an odd function, $S(t) = - S(-t)$, all cosine terms are absent.

APPENDIX B: DATA OF THE EXPERIMENTAL MOTOR

- Name plate details:

  10 hp, 230/460 V, three-phase, 60 Hz, 25/12.5 A, 1740 rpm, class B.

- Design details:

Outer diameter of the stator laminations	304.8 mm
Diameter of the stator bore	152.4 mm
Air-gap length	0.4 mm
Stator-stack length	106 mm
Number of poles	4
Pole-pitch	119.7 mm
Flux per pole	6.1 mWb
Number of stator slots	36
Stator slot opening	2.5 mm
Average stator tooth width	6 mm
Stator back core depth	17 mm
Stator slot pitch	13.3 mm
Number of conductors per slot	26
Total number of conductors in series per phase	312
Conductor size	SWG#19
Type of winding	double layer lap
Coil-pitch	1-8 slots
Number of rotor slots	43
Rotor slot-pitch	11.14 mm
Rotor slot-opening	1 mm
Type of rotor slot	semi-closed

- Calculated data:

	Order of harmonic			
	1	3	5	7
Pitch factor	0.9397	−0.5	0.1737	0.766
Distribution factor	0.956	0.6667	0.2176	−0.177
Winding factor	0.8984	−0.3334	0.038	−0.1359

Carter's coefficient for stator slotting	1.145
Carter's coefficient for rotor slotting	1.127
Corrected air-gap length	0.512 mm

- Equivalent circuit parameters per phase

Stator winding resistance, per phase	0.22 ohms
Stator winding leakage reactance, per phase	0.46 ohms
Magnetizing reactance	21.6 ohms
Rotor resistance referred to stator	0.24 ohms
Rotor reactance referred to stator	0.46 ohms

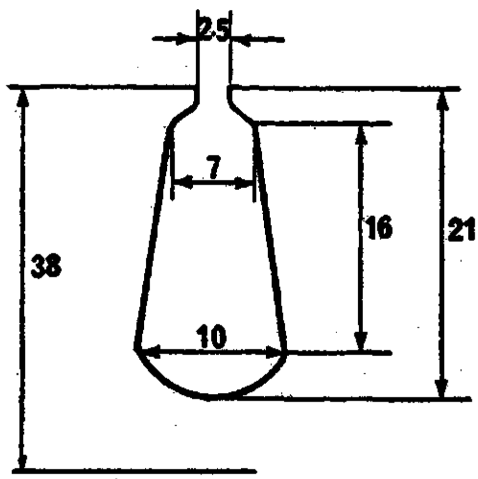

Figure B.1 : Details of stator slot (all dimension are in mm).

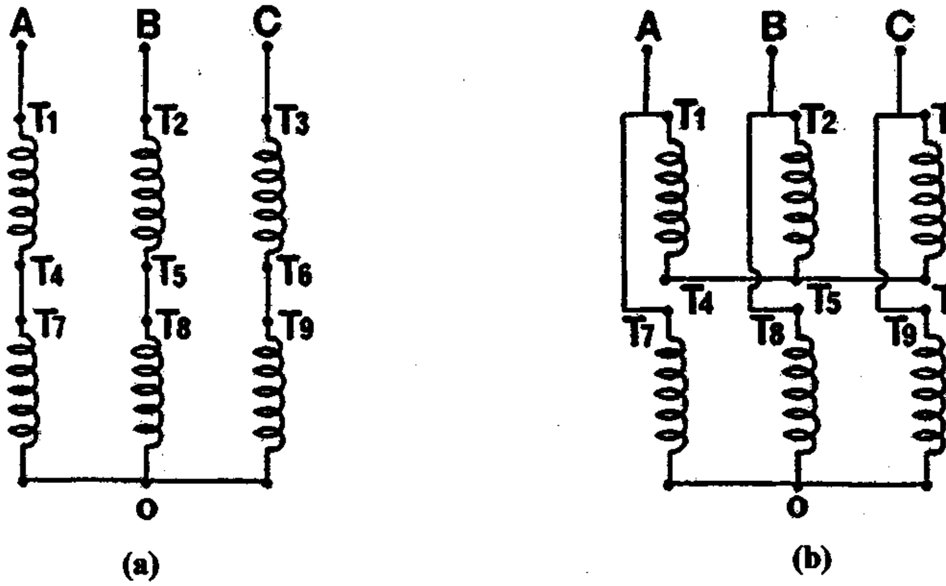

Figure B.2 : Connection diagram for stator windings.
(a) Connection for 460 V.
(b) Connection for 230 V.
A, B, C – Supply terminals.
The star-point O is internally connected.

APPENDIX C: DISCUSSIONS ON SIGNAL INTERFERENCE

C.1 The Interference

If there are two signals of similar but different frequencies, the interaction of two frequencies can occur by an amplitude-modulation process. During this process, the amplitude of one wave is modulated by another wave that has a lower frequency. These two signals will combine as shown in Figure C.1.

(a) Signal of frequency f_1

(b) Signal of frequency f_2

(c) Combined signal

Figure C.1 : The combination of two similar signals, but different frequencies.

The appearance of the spectrum of the combined signal will depend on the band-width of the filter. If the band-width is less than (f_1-f_2), the individual frequencies are distinguishable. Also, assuming that the signals are steady, the peaks of the frequencies will not vary in amplitude with time, Figure C.2 (a). If the band-width is greater than (f_1-f_2), the twin spectral peaks will merge into one peak, whose amplitude will fluctuate at a frequency of (f_1-f_2), Figure C.2 (b). This is evident from Figure C.1(c).

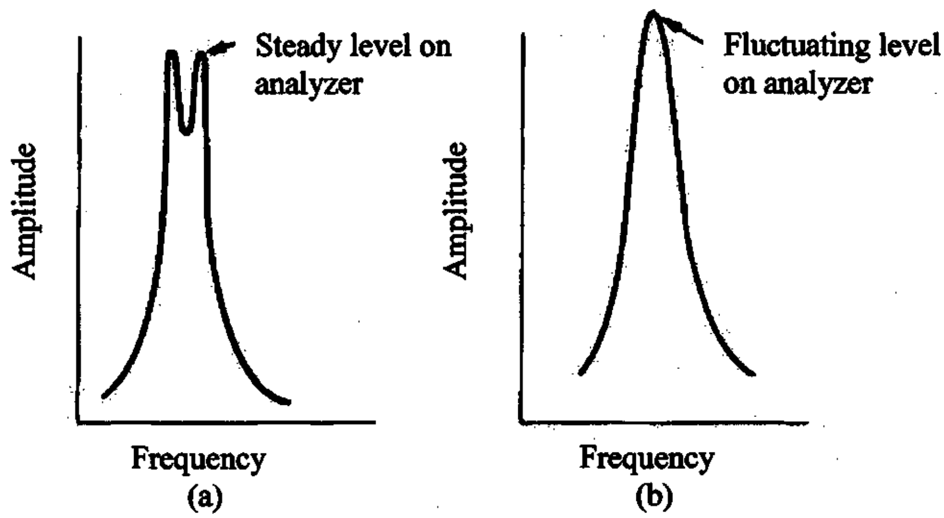

Figure C.2 : The frequency-spectrum of the combined signal.

Table C.1 shows some of the frequency ranges of the filters of Frequency Analyzer Type 2107 used in the experimentation. When the center frequency is tuned to 720 Hz, not only the 720 Hz signal can pass through the filter, but also other signals. In this case, those frequencies less than 1440 Hz and higher than 360 Hz are attenuated to less than 45 dB, when the attenuation characteristic of the filter is chosen at 45 dB (Figure 6.1). So the signals ranging from 360 Hz to 1440 Hz can modulate the 720 Hz signal to some extent. The similar problems would occur when other center frequencies are tuned in. Although these effects are generally not expected, the modulation does have some influence on the signals of interest since the skirt of the filter characteristic extends down past the other frequencies in the range.

Table C.1 : Frequency ranges of some filters.

Center frequency f_c	3 dB band-width		One octave from f_c		Half octave from f_c	
	lower(Hz)	upper(Hz)	lower(Hz)	upper(Hz)	lower(Hz)	upper(Hz)
720 Hz	676.8	763.2	360	1440	540	1080
930 Hz	874.2	985.8	465	1860	697.5	1395
1170Hz	1099.8	1240.2	585	2340	877.5	1755
1290 Hz	1212.6	1367.4	645	2580	967.5	1935
1410 Hz	1325.4	1494.6	705	2820	1057.5	2115
1980 Hz	1861.2	2098.8	990	3960	1485	2970
2010 Hz	1889.4	2130.6	1005	4020	1507.5	3015
3300 Hz	3102	3498	1650	6600	2475	4950
5280 Hz	4963.2	5596.8	2640	10560	3960	7920
6330 Hz	5950.2	6709.8	3165	12660	4747.5	9495
6450 Hz	6063	6837	3225	12900	4837.5	9675
6570 Hz	6175.8	6964.2	3285	13140	4927.5	9855
7740 Hz	7275.5	8204.4	3870	15480	5805	11610

C.2 The Expected Band-pass Filters

To eliminate the modulation problem, interacting with the signals of interest, the expected filters should have narrower band-width and very steep characteristic. The required cut-off frequencies at 45 dB attenuation, and expected band-widths (from 6% f_c to 1% f_c) are listed in Table C.2. In accordance to Table C.2, the orders of expected filters are shown in Table C.3 and Table C.4 if active filters are used. Also Table C.5 and Table C.6 list the expected digital filters designed with the help of MATLAB Signal Processing Toolbox [43]. Since some of the cut-off frequencies at 45 dB (35 dB) attenuation fall into 3dB band-width range, that would mean that it is not possible to design such a filter, the symbol "×" in tables indicates those filters that cannot be designed.

Table C.2 : The expected cut-off frequencies, and 6% f_c to 1% f_c 3dB band-width frequencies.

Center frequency f_c (Hz)	Cut-off frequencies (Hz)		6% f_c band-width (Hz)		5% f_c band-width (Hz)		4% f_c band-width (Hz)		3% f_c band-width (Hz)		2% f_c band-width (Hz)		1% f_c band-width (Hz)	
	Lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower	upper
720	510	930	698	742	702	738	706	734	709	731	713	727	716	724
930	720	1140	902	958	907	953	911	949	916	944	921	939	925	935
1170	1050	1290	1135	1205	1141	1199	1147	1193	1152	1188	1158	1182	1164	1176
1290	1170	1410	1251	1329	1258	1322	1264	1316	1271	1309	1277	1303	1284	1296
1410	1290	1530	1368	1452	1375	1445	1382	1438	1389	1431	1396	1424	1403	1417
1980	1950	2010	1921	2039	1931	2030	1940	2020	1950	2010	1960	2000	1970	1990
2010	1980	2040	1950	2070	1960	2060	1970	2050	1980	2040	1990	2030	2000	2020
3300	2010	4590	3201	3399	3218	3383	3234	3366	3251	3350	3267	3333	3284	3317
5280	4230	6330	5122	5438	5148	5412	5174	5386	5201	5359	5227	5333	5254	5306
6330	6210	6450	6140	6520	6172	6488	6203	6457	6235	6425	6267	6393	6298	6362
6450	6330	6570	6257	6644	6289	6611	6321	6579	6353	6547	6386	6515	6418	6482
6570	6450	6690	6373	6767	6406	6734	6439	6701	6471	6669	6504	6636	6537	6603
7740	6570	8910	7508	7972	7547	7934	7585	7895	7624	7856	7663	7817	7701	7779

From Table C.3, it is noted that the calculated orders of Butterworth-filters are larger than 10 [44]. Even if the band-pass circuit configuration with minimum components is selected, the number of components used to construct a 10^{th}-order band-pass filter is 25. Practical active band-pass filter design shifts the center frequencies of a group of filters to flatten the pass-band and lessen the phase shift. Parameter adjustment depends on component accuracy, and noise accumulates as the number of sections increases. This makes tuning more difficult and aggravates the phase shift problem. The tuning of a 10^{th}-order filter with at least 25 components is not easy, let alone the filters with orders more than 10. As expected, the order of Chebyshev-filter with the same requirements is much less than that of the Butterworth-filter. Still, the maximum number of filters with orders less than 10 is only half of the number of the filters that can be designed according to the last column of Table C.4. Also, the same tuning difficulties exist for Chebyshev-filters whose orders are equal to or larger than 10. Different orders and analog-filter configurations, for both Butterworth-filters and Chebyshev-filters, are required for different center frequencies. 13 band-pass filters with different orders and configurations are needed for filtering if the center frequency of each filter is fixed. Although a filter with higher order can do better filtering than a filter with lower order, making a tunable filter with an order higher than 10 is very difficult (maximum order is 34 in the last column of Table C.4, 34 is the lowest value when compared with other columns). Too many components are needed to construct an analog-filter with high orders. Considering the practical limitations, analog band-pass filter is not suitable for solving the modulation problem [44–47].

From Table C.5, it is seen that the orders (number of coefficients) of equiripple FIR-band-pass filters are very high, FIR-filters require many coefficients to achieve high performance. The FIR-filter is simple, it can be easily designed with linear methods. It alone can achieve linear phase exactly, and it is stable. The implementation or realization in hardware or on a computer is basically the calculation of an inner product which can be accomplished efficiently. But the FIR-filter requires a rather long time period to achieve certain frequency response, and a large number of arithmetic operations per output value and a large number of coefficients have to be stored. The linear-phase characteristic makes the time delay of the filter equal to half its duration, which may be large. Compared to analog-filters, FIR-digital-filters do not show significant advantage over the analog-filters.

The infinite impulse response (IIR) filter is also called a recursive filter since the feedback is necessary in an implementation. In contrast to the FIR-filter with a polynomial transfer function, the IIR-filter has a rational transfer function which has finite poles as well as zeros. This gives considerably more flexibility and capacity with fewer stored coefficients and less arithmetic requirements. The strength of the IIR-filter is its ability to achieve higher-quality (steep-skirt) filtering with a limited order number design. Generally, an IIR-filter satisfies a given magnitude frequency-response design objective with a lower-order filter, which is evident from Table C.6. Unfortunately, IIR-filters do not have linear phase characteristic, the possibility of instability and greater sensitivity to the effects of quantization must be considered [42, 48-49].

When 3dB band-width is reduced to 2% f_c, analog-filters could be designed though the orders are high. On the contrary, neither FIR-filter nor IIR-filter could be designed at some center frequencies even when the 3dB band-width is reduced to 1%. Although the orders of IIR-filter are very low, they cannot be designed at some frequencies of interest. So, digital filters are not always the solution for modulation problems.

According to the above discussions, there are difficulties if the interference from nearby frequencies is to be eliminated completely. At present stage, B&K Frequency Analyzer is adequate and suitable for the investigations, although some precautions need to be exercised through out the investigations.

Table C.3 : The calculated orders of Butterworth-filters for cut-off frequencies at 45dB and 35 dB attenuations.

Center f_c (Hz)	Cut-off frequencies (Hz)		Order (6% f_c)		Order (5% f_c)		Order (4% f_c)		Order (3% f_c)		Order (2% f_c)		Order (1% f_c)	
	lower	upper	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB
720	510	930	23	18	22	17	22	17	21	17	21	16	21	16
930	720	1140	30	23	29	23	28	22	27	21	27	21	26	20
1170	1050	1290	76	59	71	55	66	52	63	49	59	46	56	43
1290	1170	1410	87	68	81	63	75	58	70	54	66	51	62	48
1410	1290	1530	99	77	91	71	84	65	78	60	72	56	68	53
1980	1950	2010	×	×	×	×	×	×	34709	26996	1018	792	515	401
2010	1980	2040	×	×	×	×	×	×	×	×	1065	828	527	410
3300	2010	4590	17	13	17	13	17	13	16	13	16	13	16	12
5280	4230	6330	34	27	33	26	32	25	31	24	30	24	29	23
6330	6210	6450	×	×	×	×	×	×	1334	1038	587	456	376	292
6450	6330	6570	×	×	×	×	×	×	1465	1139	611	475	385	300
6570	6450	6690	×	×	×	×	×	×	1617	1258	636	494	395	307
7740	6570	8910	×	×	×	×	×	×	42	32	40	31	38	30

×: Filters cannot be designed.

Table C.4 : The calculated orders of Chebyshev-filters for cut-off frequencies at 45dB and 35 dB attenuations.

Center f_c (Hz)	Cut-off frequencies (Hz)		Order (6% f_c)		Order (5% f_c)		Order (4% f_c)		Order (3% f_c)		Order (2% f_c)		Order (1% f_c)	
	lower	upper	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB
720	510	930	8	7	8	7	8	7	8	7	8	6	8	6
930	720	1140	10	8	10	8	9	8	9	7	9	7	9	7
1170	1050	1290	16	13	15	12	15	12	14	11	14	11	13	11
1290	1170	1410	17	14	16	13	16	13	15	12	15	12	14	11
1410	1290	1530	18	15	17	14	17	13	16	13	15	12	15	12
1980	1950	2010	×	×	×	×	×	×	340	273	58	47	41	33
2010	1980	2040	×	×	×	×	×	×	×	×	60	48	42	34
3300	2010	4590	7	6	7	6	7	6	7	6	7	6	7	6
5280	4230	6330	10	8	10	8	10	8	10	8	10	8	10	8
6330	6210	6450	×	×	×	×	×	×	67	54	44	35	35	28
6450	6330	6570	×	×	×	×	×	×	70	56	45	36	36	29
6570	6450	6690	×	×	×	×	×	×	73	59	46	37	36	29
7740	6570	8910	12	10	12	10	12	9	11	9	11	9	11	9

×: Filters cannot be designed.

Table C.5 : The calculated orders of equiripple FIR-filters for cut-off frequencies at 45dB and 35 dB attenuations.

Center f_c (Hz)	Cut-off frequencies (Hz)		Order (6% f_c)		Order (5% f_c)		Order (4% f_c)		Order (3% f_c)		Order (2% f_c)		Order (1% f_c)	
	lower	upper	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB
720	510	930	64	52	63	51	62	50	62	50	61	49	59	48
930	720	1140	65	51	64	51	62	50	62	50	60	49	60	48
1170	1050	1290	125	100	121	95	118	94	114	91	109	88	106	85
1290	1170	1410	128	102	123	99	119	95	116	93	111	89	106	86
1410	1290	1530	130	103	124	100	120	97	116	92	112	90	107	86
1980	1950	2010	×	×	×	×	×	×	×	×	×	×	507	401
2010	1980	2040	×	×	×	×	×	×	×	×	×	×	507	401
3300	2010	4590	248	204	245	201	246	199	243	196	244	193	241	191
5280	4230	6330	326	261	322	259	313	252	305	250	302	244	299	243
6330	6210	6450	×	×	×	×	×	×	×	×	×	×	×	×
6450	6330	6570	×	×	×	×	×	×	×	×	×	×	×	×
6570	6450	6690	×	×	×	×	×	×	×	×	×	×	×	×
7740	6570	8910	304	242	298	233	286	229	281	226	276	223	271	215

×: Filters cannot be designed.

Table C.6 : The calculated orders of Chebyshev IIR-filters for cut-off frequencies at 45dB and 35 dB attenuations.

Center f_c (Hz)	Cut-off frequencies (Hz)		Order (6% f_c)		Order (5% f_c)		Order (4% f_c)		Order (3% f_c)		Order (2% f_c)		Order (1% f_c)	
	lower	upper	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB	45dB	35dB
720	510	930	3	2	2	2	2	2	2	2	2	2	2	2
930	720	1140	3	2	3	2	2	2	2	2	2	2	2	2
1170	1050	1290	4	3	3	3	3	3	3	2	2	2	2	2
1290	1170	1410	4	3	3	3	3	3	3	2	3	2	2	2
1410	1290	1530	4	3	4	3	3	3	3	2	3	2	2	2
1980	1950	2010	×	×	×	×	×	×	×	×	×	×	4	3
2010	1980	2040	×	×	×	×	×	×	×	×	×	×	×	×
3300	2010	4590	2	2	2	2	2	2	2	2	2	2	2	1
5280	4230	6330	3	2	3	2	3	2	2	2	2	2	2	2
6330	6210	6450	×	×	×	×	×	×	×	×	×	×	×	×
6450	6330	6570	×	×	×	×	×	×	×	×	×	×	×	×
6570	6450	6690	×	×	×	×	×	×	×	×	×	×	×	×
7740	6570	8910	3	3	3	2	3	2	2	2	2	2	2	2

×: Filters cannot be designed.

APPENDIX D: CALCULATION PROCEDURES FOR SOUND POWER-LEVELS

The sound power-level of the test motor is calculated from the measured sound pressure-levels at each of measuring points according to the following procedures:

- **The measurement correction.**

  Calculate the difference between the background and the measured sound pressure-level at each measuring point for every frequency-band. The sound pressure-level due to the test machine alone may be approximated by applying the corrections as following [34]:

Difference in decibel level	Decibels to be subtracted from measured level
3	3
4 through 5	2
6 through 9	1

- **Calculation of some important values.**

  According to the size of the motor and the measuring locations, the following important values which are used for sound power-level calculation can be calculated:

(i) $a = \frac{1}{2} \times (\text{ length of machine}) + 1m = \frac{1}{2} \times 23cm + 1m = 1.115\,m,$

$b = \frac{1}{2} \times (\text{ width of machine}) + 1m = \frac{1}{2} \times 26cm + 1m = 1.13\,m,$

$c = (\text{ height of machine}) + 1m = 26cm + 1m = 1.26m.$

(ii) equivalent radius:

$$r_s = [a\frac{(b+c)}{2}]^{1/2} = \sqrt{1.115 \times \frac{2.39}{2}} = 1.154\,m.$$

reference radius:

$$r_d = 1m + \frac{1}{2} \times 26cm = 1.13\,m.$$

- Calculation of the average sound pressure-level, averaged over the measurement surface in frequency-bands:

$$L_{P(M)} = 10\log_{10}\left[\frac{1}{N}\sum_{i=1}^{N}10^{0.1L_{pi}}\right],$$

where, $L_{P(M)}$ = sound pressure-level averaged over the measurement surface (dB),

L_{pi} = band pressure-level resulting from the ith measurement (dB),

N = total number of measurements.

- Calculation of sound power-level in frequency-bands:

$$L_W = L_{P(M)} + 10\log_{10}\frac{2\pi r_s^2}{s_0} = L_{P(M)} + 9.224,$$

where, r_s = equivalent radius,

s_0 = 1.0 m^2,

$L_{P(M)}$ = mean sound pressure-level in frequency-bands(dB).