Chapter 1

Introduction

Reliability has always been an important aspect in the assessment of industrial products and/or equipment's. Good product design is of course essential for products with high reliability. However, no matter how good the product design is, products deteriorate over time since they are operating under different stress or load in the real environment, often involving randomness. Maintenance has, thus, been introduced as an efficient way to assure a satisfactory level of reliability during the useful life of a physical asset. The earliest maintenance technique is basically breakdown maintenance (also called unplanned maintenance, or run-to-failure maintenance), which takes place only at breakdowns. A later maintenance technique is time-based preventive maintenance (also called planned maintenance), which sets a periodic interval to perform preventive maintenance regardless of the health status of a physical asset. With the rapid development of modern technology, products have become more and more complex while better quality and higher reliability are required. This makes the cost of preventive maintenance higher and higher. Eventually, preventive maintenance has become a major expense of many industrial companies. Therefore, more efficient maintenance approaches such as condition-based maintenance (CBM) are being implemented to handle the situation.

CBM is a maintenance program that recommends maintenance actions based on the information collected through condition monitoring. CBM attempts to avoid unnecessary maintenance tasks by taking maintenance actions only when there is evidence of abnormal behaviors of a physical asset. A CBM program, if properly established and effectively implemented, can significantly reduce maintenance cost by reducing the number of unnecessary scheduled preventive maintenance operations.

A CBM program consists of three key steps

1. Data acquisition step (information collecting), to obtain data relevant to system health.
2. Data processing step (information handling), to handle and analyze the data or signals collected in step 1 for better understanding and interpretation of the data.
3. Maintenance decision-making step (decision-making), to recommend efficient maintenance policies.

Diagnostics and prognostics are two important aspects in a CBM program. Diagnostics deals with fault detection, isolation and identification when it occurs. Fault detection is a task to indicate whether something is going wrong in the monitored system; fault isolation is a task to locate the component that is faulty; and fault identification is a task to determine the nature of the fault when it is detected. Prognostics deals with fault prediction before it occurs. Prognostic is a task to determine whether a fault is impending and estimate how soon and how likely a fault will occur. Diagnostics is posterior event analysis and prognostics is prior event analysis. Prognostics is much more efficient than diagnostics to achieve zero-downtime performance. Diagnostics, however, is required when fault prediction of prognostics fails and a fault occurs. A CBM program can be used to do diagnostics or prognostics, or both.

During the implementation of CBM program upon any rotary machineries, the major concern of any maintenance engineer is about monitoring the health state of bearings. In many cases, the decision about entire health state of rotating machinery depends upon the condition of bearings. It is considered that fault diagnosis of rolling element bearing is very important, since their degradation has detrimental effects on machine reliability.

Hence in this chapter of introduction, a systematic and comprehensive information is presented about the causes of deterioration of bearings and its condition monitoring.

Machine Vibration or noise levels, whether excessive or not, are affected by bearings in three ways: as a structural element defining in part a machine's stiffness; as a generator of vibration by virtue of way load distribution within the bearing varies cyclically; as a vibration generator because of geometrical imperfections from manufacturing, installation or wear and damage after continued use.

Detection of progressive bearing deterioration in operating machinery with the help of certain monitoring techniques has become very important in recent years.

1.1 Need for Monitoring Rolling Bearings

In any manufacturing or processing plant where rotating equipment is used, the majority of the maintenance capital expenditure is spent on bearings. Every time an overhaul is performed and salesman from the major bearing manufacturer make it their business to ensure that the bearings are replaced. Whatever the reason caused the machine to breakdown, the bearings are often replaced, in the vain hope that they might last longer the next time. Bearings are indeed very often blamed for the machine breakdown. However, the failure of the bearing is a result of a number of different problems: a machine running unbalanced, misaligned at a critical speed; a bearing fitted incorrectly; the wrong grease being used; or may be no grease being used at all. A bearing rarely deteriorates from internal causes. Very often bearings are replaced without the origin of the failure being addressed. It is well documented that the majority of machinery vibration problems are caused by unbalance or misalignment, often resulting in bearing failure.

1.2 The Role of bearings in machine vibration

1.2.1 Bearings effects on machine vibration

Rolling Bearings have three effects with respect to machine vibration. The first effect is a structural element that acts as a spring and also adds mass to a system. As such, bearings define, in part, the vibration response of the system to external time-varying forces. The second and third effects occur because bearings act as excitation sources, producing time-varying forces that cause system vibration. In one case this excitation in inherent in the design of rolling bearings and cannot be avoided. In the other case these forces result from imperfections, which usually are avoidable.

1.2.2 Structural Element

With sufficient load, the bearing is a stiff structural member of a machine. It is a spring whose deflection varies non-linearly with force, in contrast to the usual linear spring characteristics assumed in dynamic models, such as the single-degree-of-freedom spring-mass-damper model. As a first approximation, it may be adequate to estimate machine vibration response by considering the bearing as a linear spring. In this case a bearing spring constant is determined by taking the slope of the force-deflection curve of the bearing at the normal operating load. Bearing stiffness increases with increasing load, a characteristic referred to as a "hardening'' spring. Larger nominal operating load or built in preload would result in smaller variations in dynamic bearing deflection when subjected to a particular dynamic load variation. Similarly, increased bearing stiffness raises the value of a resonant frequency associated with this spring, since a resonant frequency is inversely proportional to the square root of stiffness. Moreover, radial stiffness decreases with increasing contact angle, whereas the reverse is true for axial stiffness. Therefore, response to dynamic load variation will depend strongly on the direction of such loads relative to that of the normal load that governs contact angle.

Since the bearing "spring" is non-linear, it is evident that sinusoidal deviations from the nominal load will not cause sinusoidal bearing deflection. When the load is maximum, the increase to nominal bearing deflection will be less than nominal bearing deflection when the load is at its lowest value.

1.2.3 Variable Elastic Compliance

The second effect of bearings on machine vibration occurs because bearings carry load with discrete elements whose angular position, with respect to the line of action of the load, continually changes with time. This mere change of position causes the inner and outer raceways to undergo periodic relative motion even if the bearing is geometrically perfect.

1.2.4 Geometrical Imperfections

The first effect that bearings have on machine vibration arises from geometrical imperfections. These imperfections are always present to varying degrees in manufactured components. Controlling component waviness and other types of errors from manufacturing, distortion, or damage occurring while the bearing is assembled to the machine, is a high priority. The effects of such form errors on machine vibration or noise can be significant.

1.3 Rolling Bearing Damage

The service life of a rolling bearings rotating under load is terminated by material fatigue, unless it is fail-safe by wear at the running surfaces of rings and rolling elements; or by lubrication failure.

Rolling bearing damage is generally detected by unusual operational behavior of the bearing arrangement. Uneven running and uncommon running noise usually indicate flaked running surfaces due to material fatigue or an alteration of the radial clearance due to wear. High friction, i.e resistance to smooth running, can indicate detrimental preload, poor lubrication or damaged rolling contact surfaces. Higher than normal temperatures are a sign of an increase in friction. At first, signs of premature bearing damage, the causes and effects should be analyzed so that steps to avoid further damage can be taken.

It is not always easy to diagnose the primary cause; the original failure may often be obscured by consequential damage. In a severely damaged bearing, for example, it may only be possible to ascertain that overheating and seizure took place. In less seriously damaged bearings, certain conclusions may be drawn, perhaps through examining the ball or roller path. But recommendation to avoid problems in future can only be given based upon the information of operating conditions (load and speed), condition of lubrication and overall design (bearing arrangement, fits etc). Information should also be obtained on damage symptoms in evidence and on relevant secondary phenomena. There are many applications where there is no need for much detailed observations. Neither will one go to lengthy investigations with low cost bearings or small bearings, where systematic investigations are uneconomic. But in custom-built, special purpose and heavy machinery, where seemingly inexplicable damage occurs, systematic investigation and monitoring is very important.

1.3.1 Causes of rolling bearing damage.

To list all known types and causes of rolling bearing damage would go beyond the scope of this chapter, and therefore only most important and considered causes for thesis are discussed. A distinction is made between damage due to fatigue, wear or plastic deformation, and damage originating from the operating conditions, mounting or maintenance. But clear boundaries cannot always be drawn. A bearing subjected to nominal loading fails due to material fatigue after a certain running time. A detrimentally preloaded and overstressed bearing will also fail due to material fatigue, but after a shorter running time.

1.3.1.1 Fatigue

Every rolling bearing rotating under load above the endurance strength limit has a definite fatigue life depending on number of rolling cycles and load. The bearing approaches end of its life when the rolling surfaces of its ring and rolling elements are damaged by material fatigue. A crack is created and it often originates from a predamaged spot on raceway surface, perhaps a particle indentation. The characteristics of individual types of fatigue are as such.

1.3.1.1 a Classical Fatigue

Classical fatigue damage begins with the formation of minute cracks below the surface. As loading continues, crack progress to surface (Figure 1.1) where they cause material to break loose, forming so-called pitting in the contact areas (Figure 1.2). This development of damage is based on a lubricant film which separates the surfaces in rolling contact. If full separation of the surfaces by the lubricant film is not ensured, the sliding contact will cause the cracks to form nearer the surface.

Figure 1.1 First fatigue cracks in inner raceway of a deep groove ball bearing.

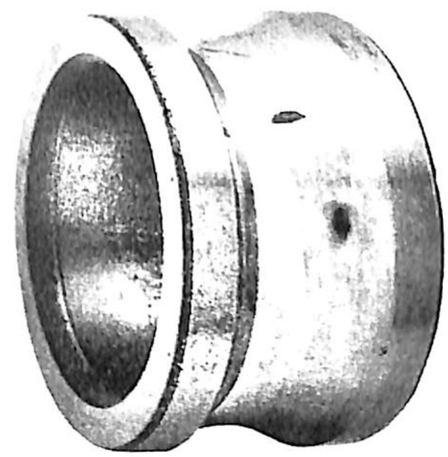

Figure 1.2 Pitting in inner raceway of deep groove ball bearing

1.3.1.1 b Fatigue caused by foreign particle cycling.

Comprehensive investigations into fatigue behavior of bearings under laboratory conditions and practical experience have shown that good cleanliness of the lubricant is an essential precondition for a long bearing life. The life is considerably reduced if foreign particles in the lubricant are cycled. The life-reducing effect of various particle types is illustrated in Figure 1.3. According to Figure 1.3, the hard sand-type particles are particularly harmful. Figure 1.4 shows typical V-shaped pitting that was generated directly behind the indentation of a dirt particle. Such mechanism is frequently responsible for fatigue damage.

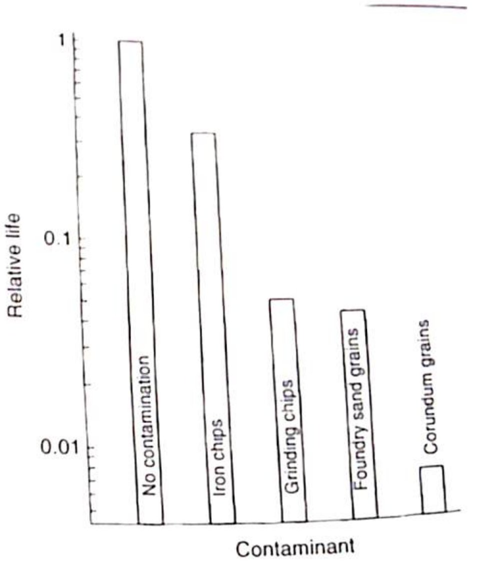

Figure 1.3 Reduction in life due to contaminant

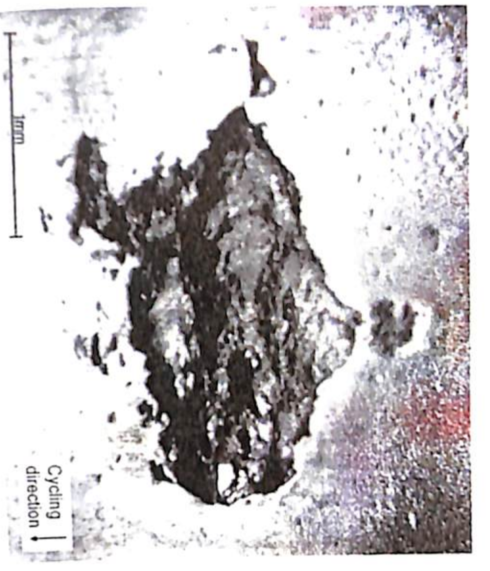

Figure 1.4 Fatigue damage caused by foreign particle indentations: damage forming V Shape.

1.3.1.1 c Fatigue caused by wear

Distributed contact conditions resulting from wear of the raceways is particularly common in bearings with contact. The raceway carries load mainly at unknown areas, which leads to heavy rise on stressing and eventually to material fatigue (Figure 1.5).

1.3.1.1 d Fatigue Caused by poor lubrication

A special type of fatigue occurs when the surfaces in rolling contact are not separated by the formation of an adequate lubricating film. The causes may be lack of lubricant, the absence of suitable EP additives or inadequate lubricant film. In this condition of fatigue, tangential stresses develop in the raceway displaces the maximum stressing towards the surface. At high tangential stresses near the surface, the fatigue damage starts at the surface. At particularly heavy surface stressing, so-called micro pits are frequently generated.

Figure 1.5 Micropitting in raceway of cylindrical roller bearing due to heavy surface stressing.

1.3.1.2 Wear

Wear is a common cause of bearing failure. Wear occurs mainly due to dirt, foreign particles, water or cooling agent entering the bearing through inadequate sealing. And wear damage is often due to contaminated lubricant. Severe wear considerably increases the bearing clearance. Figure 1.6 shows the inner ring of a spherical roller bearing with badly worn raceways, and Figure 1.7 shows a section of the outer ring with worn rolling tracks.

Figure1.6 Worn inner raceway of bearing.

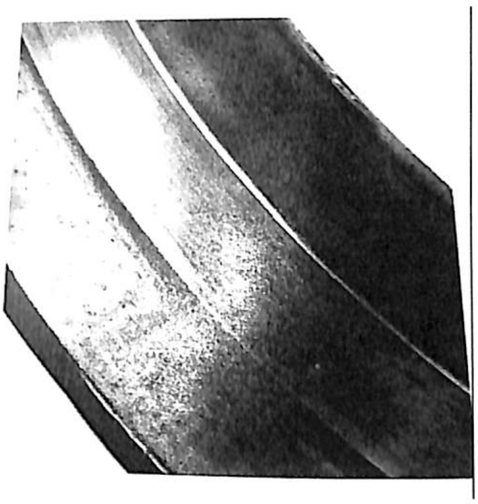

Figure 1.7 Worn outer raceway of bearing

1.3.1.3 Corrosion Damage

The reason for corrosion damage is the formation of rust not only from water, acids etc but also from acidic lubricants. Another cause of corrosion is condensation. It forms in bearings if, in very humid air, the bearing temperature is below the ambient temperature, perhaps during downtimes. Corrosion may damage bearings before installation. The corrosion marks in the outer-ring raceway of a self-aligning ball bearing is shown in Figure 1.8.

Figure 1.8 Corrosion marks in the outer ring of a self-aligning ball bearing.

1.3.1.4 Local Indentations in the raceway.

The raceway of correctly hardened rolling bearings occasionally shows indentations regularly distributed over their entire circumference and having approximately the same shape as the Hertzian contact area. As a consequence, the bearing becomes noisy and uneven in operation. This damage is known as false brinelling.

1.3.1.4 Faulty Mounting

In radial bearings, point load is generally indicated by a track shorter than half the raceway circumference. Excessive preloading or internal deformation can be recognized by track formation. A specified radial or axial preload is permissible when it is necessary to satisfy a definite requirement. Unintentional preloading, the commonest mounting fault, may lead to severe damage.

1.3.1.5 Damage caused by poor lubrication

More than 50% of all rolling bearing damage is caused by defective lubrication. And it contributes to much more damage that cannot be tracked back directly to disturbed lubrication. Inadequate lubrication at the contact areas leads to wear, smearing, scoring and scuffing (Figure 1.9)

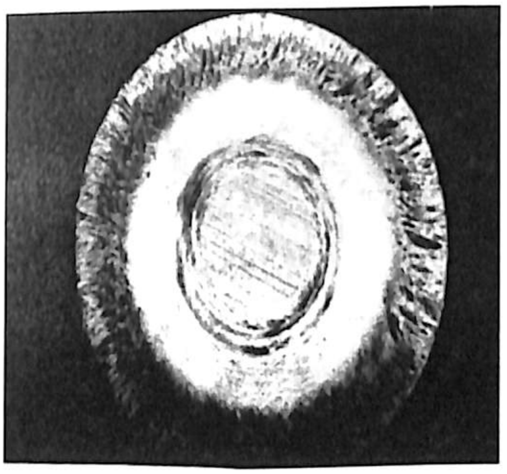

Figure 1.9 Scuffing marks on a tapered roller face.

1.3.1.6 Monitoring Rolling bearings

Rolling bearings are very reliable machine elements, something they have proved a million times over. Their failure rate is low and damage normally develops slowly. Therefore, close condition monitoring is required. In the vast majority of cases the bearing behavior requires no more than subjective supervision by the operating staff. Some useful indicators of bearing damage are high operating temperatures, uneven or rough running, unusual running noises e.g whining or rumbling, and any other continuous alteration of the noise level or reduced working accuracy.

More technical monitoring with instruments may be appropriate in the following cases:

- When bearing damage would be hazardous to human life (e.g. in aviation).
- When bearings are operated at the limits of their capacity, especially at very high speeds.

- When unexpected bearing damage leads to long production downtimes.
- When maintenance costs can be reduced by adequate upkeep.

1.4 Criteria to monitor before failure.

Two types of bearing failure need to be distinguished:

- The bearing condition deteriorates continuously, perhaps due to wear or fatigue.
- The bearing fails spontaneously, perhaps due to hot running or seizure.

Spontaneous failure occurs mainly when the lubricant supply to high-speed bearings is interrupted. According to experience, spontaneous failure is very rare; bearing damage that starts out small usually grows slowly. Slow alterations can be monitored; the three relevant parameters are

- Bearing temperature
- Vibrations and noise
- Wear

Other parameters do not relate directly to the bearing, but they should also be monitored:

- Operating temperature of machine.
- Lubrication plant.
- Bearing Load.

Vibration monitoring of rolling element bearings is probably the most established diagnostic technique for rotating machinery.

1.5 Vibration Measurement

Incipient fatigue damage and cracks are detected by vibration measurements. When damage spots on a bearing are cycled, they generate structure-borne sound and this can be recorded by acceleration pick-ups. Depending on the application, the signals emitted by such defects are in the frequency range between 1 and 100 KHz. Unlike temperature monitoring of rolling bearings, vibration monitoring is used for an early diagnosis of locally restricted damage, particularly from material fatigue. Whereas vibration measuring is not a very reliable method of monitoring the lubrication condition. In order to obtain useful measurements, the following points should be observed:

- Vibration measurements are essentially relative measurements. They are informative either in temporal comparison (trend analysis) or in comparison with identical bearing locations.
- The vibration transducers must be firmly attached.
- The measuring location should be in the load zone of the bearing, if possible.
- The sound expected to be emitted by a damage bearing must be clearly above the overall noise of the machine in the analyzed frequency range.

Out of the variety of vibration measuring instruments, two principal types tend to be used:

- Shock pulse meters
  - Spike energy
  - Shock Pulse meters
  - Bearcon measuring instruments
- Signal analysis instruments.

These instruments may be used for single measurements at certain intervals as well as in stationary monitoring plants.

1.5.1 Signal analyzers

Signal analyzers, e.g. FFT analyzers using fast Fourier transform, process the picked-up signals more thoroughly and comprehensively than shock pulse meters. A frequently employed method is the search for discrete cycling frequencies of cycled damage at the inner ring, the outer ring or the rolling elements. As a rule, the unprocessed vibration signal in the time domain or the frequency domain does not give reliable information on bearing damage. Only after processing does it reveal the extent and location of the damage, and one of the processing methods is envelope detection. An intact rolling bearing generates a vibration signal with a nearly constant amplitude. When an area of the rolling contact surfaces is damaged, an impulse is generated by cycling this area, which suddenly raises the amplitude of the vibration signal. The amplitude decreases until the next cycling of the damaged area. By envelope formation and frequency analysis, the impulse frequency can be assessed from the picked-up signal. By comparing the impulse frequency with the cycling frequencies, which can be calculated from the bearing geometry, it is possible to draw conclusions about the bearing damage. With this method there is a good chance that the interference noise can be removed. Portable and reliable signal analyzers are generally used in industries.

1.5.2 Vibration transducers

We are often faced with the task of measuring the vibration level in a machine to decide if it is within allowable limits. For this we need to use a vibration transducer. Vibration transducers are generally selected based upon the parameter to be measured (Displacement, velocity, acceleration) and the frequency of interest in machinery. In general, displacements are large at low frequencies and displacement sensors, or vibrometers as they are called, are preferred for these frequencies. Acceleration values are large at high frequencies and for such applications accelerometers are preferred. Velocity measurements are useful at intermediate frequencies where the displacements are likely to be small, or where the frequency range of measurements is not known beforehand. The displacement pickup has a maximum frequency range from 0 to about 1000 Hz, the velocity pickup from 10 to about 2500 Hz and the accelerometer from 20 Hz to well above 50 KHz.

Due to the development of higher amplitudes by defective bearings, accelerometers proved to be reliable vibration transducers for bearing monitoring. One of such commonly used vibration transducer is piezoelectric accelerometer.

1.5.3 Piezoelectric Accelerometer.

Piezoelectric transducers are the most widely used in the world of shock and vibration, the reason being their very wide frequency response to amplitude and phase. These pickups involve a class of materials which, when mechanically deformed, produce an electric charge. Unlike other sensors, piezoelectric transducers have a reversible effect, deflecting mechanically when subjected to an applied voltage. The piezoelectric transducer uses Barium Titanate or Lead Zirconate Titanate or Lead Niobate or Lithium Niobate or other suitable piezoelectric crystals as the basic element. This crystal is placed inside a casing with a hard spring pressed against it via a block of mass (Figure 1.10). This stiff spring-light mass combination has a high natural frequency, around 20,000 Hz and is used as an accelerometer. When the whole assembly is subjected to vibration, the mass exerts a variable force on the piezoelectric crystal and the latter in turn develops a voltage or charge proportional to the acceleration to which the transducer is subjected. As the transducer has high impedance, a charge amplifier would be essential to use it to its full capability. The piezo pickup is a contact type of absolute measuring device. It is generally fixed by stud mounting or with a magnetic base. The smaller devices are fixed using bee's wax. The sensitivity of the crystal accelerometer is given either in terms of charge (pC) per g or in terms of voltage per g (mV/g). Typical sensitivity of a crystal accelerometer is 20 pC/g, with a crystal capacitance of 500 pF. Today we have commercially available 'ICP' accelerometers where ICP, is PCB's registered trademark standing for 'Integrated Circuit-Piezoelectric'. This class of transducers has built-in, signal conditioning electronics which converts the high-impedance charge signal produced by the piezoelectric crystal into a usable low-impedance voltage signal. Such as signal can be easily transmitted over ordinary two-wire or coaxial cables over long distances, to any voltage measuring or recording device. Since these ICP sensors are simple to use, have high accuracy, wide frequency range, and low cost, they are very popular in many shock and vibration applications.

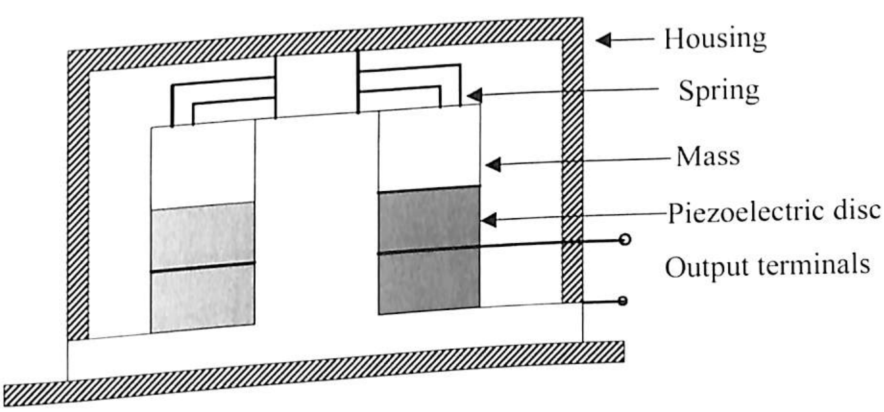

Figure 1.10 Schematic representation of piezoelectric accelerometer.

Another of way of reliable approach of monitoring the rolling element bearing is acoustic emission (AE). Acoustic emission technology has emerged as a promising diagnostic approach.

1.6 Acoustic Emission (AE) Measurement.

Acoustic emission (AE) is the phenomenon of transient elastic wave generation due to a rapid release of strain energy caused by a structural alteration in a solid material under mechanical or thermal stresses. Generation and propagation of cracks, growth of twins, etc. associated with plastic deformation are among the primary sources of AE. Hence it is an important tool for condition monitoring through non-destructive testing. AE instrumentation consists of a transducer, mostly of the piezoelectric type, a preamplifier and a signal-processing unit. The transducers, which have very high natural frequency, have a resonant-type response. The bandwidth of the AE signal can also be controlled by using a suitable filter in the preamplifier. The most commonly measured AE parameters are ringdown counts, events and peak amplitude of the signal. These are demonstrated on a typical AE signal. Ringdown counts involve counting the number of times the amplitude exceeds a preset voltage level (threshold level) in a given time and gives a simple number characteristic of the signal. An event consists of a group of ringdown counts and signifies a transient wave. The advantage of acoustic emission monitoring over vibration monitoring is that the former can detect the growth of subsurface cracks, whereas the latter can detect defects only when they appear on the surface. It is also important to note that the energy released by neighboring components in the vibrational frequency range (up to 50 kHz), which often masks the vibrational energy released from a defective rolling element bearing, do not affect the AE signal released in the very high frequency range.

1.6.1 Acoustic Emission (AE) Transducers.

At the front end of all acoustic measurement systems is a transducer called the microphone, which converts sound pressure variations into electrical signals. Microphone may sense the pressure, the pressure gradient or the particle velocity, which is then converted to an

electrical signal. All precision measurement microphones are mostly pressure sensing condenser microphones for the reason that they detect what the human ear detects, namely pressure. They use a constant electrical charge for conversion of the diaphragm displacement into an analogue electrical signal. If particle velocity or sound intensity is the parameter to be determined, pressure sensing microphones can be used. The measuring microphones influence the sound field, especially at higher frequencies, where the wavelength and microphone dimensions are of the same order of magnitude. However, the influence depends on the type of sound field (pressure-field, free-field or diffuse-field).
In this research work piezoelectric microphone is used for monitoring the health condition of rolling element bearing. Thus, the detailed construction and specification of piezoelectric microphone is presented here.

1.6.2 Piezoelectric Microphone

Piezoelectric microphones employ crystals that can become electrically polarized and produce voltages proportional to the strain. Since the piezoelectric effect is reversible, a piezoelectric microphone will function as a source when an alternating voltage is applied to its terminals. The description of the piezoelectric effect is made complicated by the many directional quantities and the crystal symmetries that enter. Rochelle salt is one of the first materials to be used in acoustic transducers. Single crystals of Rochelle salt have been employed widely in microphones. Unfortunately, the crystals deteriorate in the presence of moisture and get permanently damaged if the internal temperature exceeds 46^0 C. Historically, quartz crystals have been of great significance as transducers. They are impervious to water as well as most corrosive materials, can be subjected to extreme temperatures and are easily manufactured. They can generate longitudinal waves, shear waves or combinations. Other useful materials are sintered ceramics including barium titanate, lead zirconate, lead titanate and mixtures of these and associated compounds. If a microphone is described as 'crystal', it usually contains Ammonium dihydrogen phosphate (ADP); if it is called 'ceramic', barium titanate is the active element.
Piezoelectric microphones are often constructed in a manner shown in Figure 1.11. Here, the sound waves act on a light diaphragm whose center is linked to an end or corner of the piezoelectric element by means of driving pin. Although a single element could be used,

two elements are usually sandwiched together to form a bimorph. Stresses in the crystals, produced by a sound field, generate an output proportional to the acoustic pressure. The voltage output of a bimorph element is proportional to its strain. Many designs incorporate a built-in pre-amplifier next to the crystal. This arrangement reduces the electrical noise and output impedance.

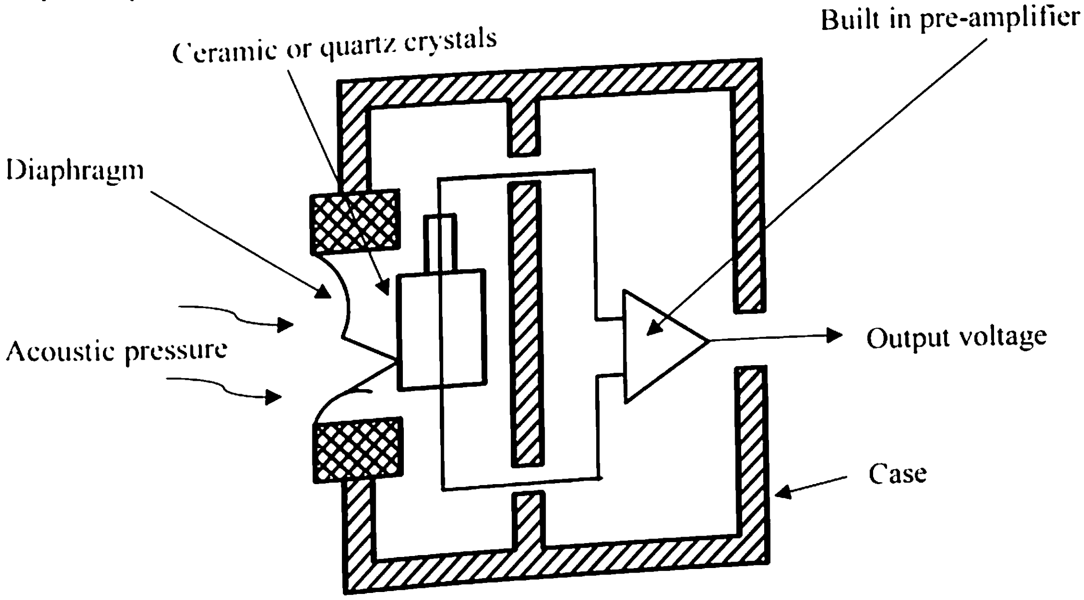

Figure 1.11 Schematic representation of Piezoelectric microphone.

1.7 Organization of Thesis

To address the issue of fault diagnosis of rolling element bearing, this thesis is therefore divided into six chapters which are as follows

1] Literature Review

This chapter provides the deep insights about the various techniques investigated and developed by number of researchers for fault diagnosis of rolling element bearing.

2] Mathematical Modelling.

This chapter deals with the developed non-linear mathematical model for assessing the fault severity of rolling element bearing.

3] Response Surface Methodology.

This chapter provides the insights about the application of response surface methodology for understanding the relationship between different variables.

4] Artificial Neural Network.

A machine learning approach for automated fault diagnosis of rolling element bearing is presented with the help of this chapter.

5] Vibro-Acoustic.

A sensor fusion technology is used in this chapter, to classify the faults according to the predicting capability of two different sensors.

6] Conclusions and future scope

This chapter provides overall conclusion of thesis in the form of fault diagnosis scheme of rolling element bearing. Novelty of the work and future scope in this area of research is also described in this chapter.