CHAPTER 1

INTRODUCTION

1.1 IMPORTANCE OF BEARING VIBRATION MEASUREMENT

Rotary machines are recognized as crucial equipment in power stations, processing industries and automotive industry that require precise and efficient performance. Bearings are the most widely used mechanical parts in rotational equipment and are primary cause of breakdowns in machines. These breakdowns can lead to costly shutdowns, lapses in production, and even human casualties. To minimize machine downtimes, a sensitive diagnosis and robust monitoring system is needed to detect faults in their early stages and to provide warnings of possible malfunctions. Such a monitoring system can reduce maintenance costs, avoid catastrophic failures and increase machine availability.

To develop an effective diagnostic and prognostic system, a comprehensive understanding of the bearing behavior is required. Typically, a rolling element bearing consists of two rings with a set of elements running in the tracks between the rings. The standard shapes of a rolling element include ball, cylindrical roller, tapered roller, needle, and barrel roller, encased in a cage that provides equal spacing and prevents internal strikes.

Even a normally loaded, properly lubricated, and correctly assembled bearing fails due to material fatigue after certain running time. This is referred as fatigue life of a bearing, and it is calculated by equation (1.1).

\[
L = \left( \frac{C}{P} \right)^n
\]  

(1.1)
For a point contact such as a ball, n = 3, and for roller bearings, n = 10/3. P denotes the equivalent dynamic load, depending on the geometry, the radial and thrust load components of the bearing. C denotes dynamic load capacity corresponding to the constant load, where 90% of the identical test bearings reach a fatigue life of one million revolutions. The typical fatigue life of a bearing can be significantly shortened due to manufacturing defects, improper handling and installation, or lack of lubrication. The result is either a localized or a distributed defect in the components of the bearings. The principle of bearing faults and their causes are briefly discussed here.

1.2 TYPES OF BEARING DEFECTS

The defect in the bearing may arise due to improper mounting, improper operation, and overloading. The defects may be classified into distributed and localized defects. Surface roughness, waviness, and misaligned races are included into the class of distributed defects. The localized defects include cracks, pits, and spall caused by fracture on the rolling surface. Some of the reasons for the cause of the defect are discussed below.

(i) **Bearing wear:** The most common source of bearing failure is wear. It can occur as a result of material fatigue in the bearing’s components. Wear can also happen because of foreign particles such as dust, sand, or metal shavings entering due to improper sealing or contaminated lubricant. In the early stages, wear is usually a localized fault that is easily distributed throughout a bearing’s components.

(ii) **Plastic Deformation:** A bearing, subjected to excessive load, high amplitude impact, or shock while stationary, can be damaged by plastic deformation at the contact surface. This type of fault is usually localized.
(iii) **Corrosion:** Water entering due to sealing failure and a corrosive environment are two reasons for bearing corrosion damage. In a corroded bearing, the rust particles, worn off by the rolling elements, have an abrasive effect and generate wear. This type of damage commonly occurs as a distributed fault.

(iv) **Brinelling:** Brinell indentation marks appear in the bearing raceways from different sources. Indentation can result from plastic deformation, created by excessive loads. Machine vibration, hammering during installation, and accidental falls can also cause brinell indentation. The other cause of brinell marks is the passage of electric current due to motor leakage. Premature brinelling damage is a localized defect, but it can affect all the components.

(v) **Improper Mounting:** The most frequent mounting problem is excessive preloading due to improper tolerances which are recognized by track formation in raceways. Misaligned seats and excessive thrust loads can cause localized flaking. The improper use of a hammer or puller in mounting and dismounting a bearing can instigate lip fracture or permanent indentation in raceways.

(vi) **Design and Manufacturing Problems:** Inadequate support, a loose fit, an excessive load applied by a set screw, improper load distribution, wavy raceways and unequal rolling element size, all can result in localized wear.

(vii) **Improper lubrication:** A lubrication problem can cause small and large welding areas or deep scratches in the lip and roller face area. Also colour changes in the bearing components are a sign of lubrication problem.
1.3  DEFECTS IN BEARING SYSTEM

Apart from specific bearing defects discussed in Section 1.2 rub, misalignment and unbalance are the common defects in a bearing system.

(i) **Rub:** Rubbing is an undesired contact between the rotating and stationary part and usually occurs as a secondary effect of some machine malfunctions such as unbalance, misalignment, thermal expansion and fluid-induced self-excited vibration. Generated by some perturbation of normal operating conditions that cause an increase of rotor vibration level, and/or an increase of the rotor centreline eccentricity, the rub can maintain itself. It gradually becomes more severe. Rotor-Stator rubbing may be broadly classified as either partial or full. The former type describes brief intermittent contacts and the latter describes more sustained contact between rotor and stator. Partial rubbing can often occur at a constant shaft location due to the combined effects of modal vibration and the orbital motion of the rotor. Such periodic rub events at a constant location on the shaft can induce a differential temperature gradient. It can lead to a local thermal expansion that causes the shaft to bow. The full annular rub which occurs when the rotor maintains contact with a stator (e.g., a seal) during complete revolution. The most common method of diagnosing rubbing is vibration monitoring of the bearing pedestals via accelerometers and velocity transducers. Generally, a certain level of knowledge of rotor dynamics is required for accurate diagnosis of rubbing.

(ii) **Misalignment:** Misalignment in rotating machinery is one of the most common faults causing other faults and machine
failure. It causes over 70% of rotating machinery vibration problems. A misaligned rotor generates bearing forces and excessive vibrations making diagnostic process more difficult. A perfect alignment can never be achieved practically since misalignment is always present. Also, many factors such as thermal growth, uneven applied loads, inappropriate foundations, etc., can disturb the alignment. For same time, vibration spectrum analysis has been a common tool for misalignment detections. Hence an in-depth study of dynamic forces and vibrations is helpful for understanding and diagnosing of misalignments.

(iii) **Mass Unbalance:** Mass unbalance is the most common cause of vibration problems. It occurs when the rotor mass centreline does not line up with the axis of rotation. The term mass centreline refers to the line that joins the centres of a mass of imaginary thin slices into which the rotor may be divided. In reality, the mass centreline looks like a snake wrapped closely around the axis of rotation. The rotating unbalanced centrifugal force, produced by a given mass unbalance, increases rapidly with rotational speed. This makes high-speed machines, such as screw compressors, gas turbines or some pumps, extremely sensitive to even a small increase in mass unbalance. Mass unbalance of new or repaired rotors is caused by limited accuracy of machining and assembling of parts. The unbalance is minimized by balancing the rotor, which is achieved by placing some corrective weights on the light side of the rotor. This is done also by removing some material from the heavy side. If balancing is done properly, the residual unbalance will be so small that it causes no vibration problem at all.
1.4 BEARING CONDITION MONITORING TECHNIQUES

Typically, most bearing defects arise during its operation. Therefore, the detection of these defects at an early stage without machine disassembly is important for condition monitoring, quality inspection, and predictive maintenance. Various methods are used for the diagnosis of bearing defects. The methods are broadly classified as acoustic measurements, current and temperature monitoring, wear debris detection, and vibration analysis.

1.4.1 Acoustic Measurement

Acoustic emission is the most effective acoustic-based bearing health monitoring method. It is a transient impulse generated by the rapid release of strain energy in solid material under mechanical or thermal stress. The detection of cracks is the prime application of acoustic emission. So, this technique can be used as a tool for condition monitoring of bearing faults and shaft cracks. The measurement of a machine’s sound can also be employed for detecting defects in bearings. Typically, the accuracy of these methods depends on sound pressure and sound intensity data.

1.4.2 Temperature Monitoring

Bearing distributed defects generate excessive heat in the rotating components. Monitoring the temperature of a bearing housing or lubricant is the simplest method for fault detection in rotary machines.

1.4.3 Electrical Motor Current Monitoring

The operating conditions of a machine can be monitored by analyzing the spectrum of the motor current. The changes in the electric background noise are associated with the changes in the mechanical components of the machine.
Therefore, fault signatures can be detected by motor current signal processing techniques.

1.4.4 Wear Debris Analysis

In this method, the presence of metallic particles in the lubricant is detected by sensitive sensors. Furthermore, the spectrographic analysis of the different metallic elements in the lubricant can facilitate the location of the fault.

1.4.5 Vibration Measurement

Since the abnormal vibration of rotary machines is the first sensory effect of component failure, vibration analysis is widely employed in the industry. The fault vibration signal, generated by the interaction between a damaged area and a rolling surface, occurs regardless of the defect type. Consequently, a vibration analysis can be employed for the diagnosis of all these types of faults, either localized or distributed. Furthermore, low-cost sensors, accurate results, simple set ups, specific information on the damage location and comparable rates of damage are the other benefits of the vibration measurement method.

Very often the damage in bearings occurs typically on the rolling element, inner race or outer race. The difficulty of fault detection in bearings lies in the fact that the signature of a defective bearing is spread across a wide frequency band and it can be masked by noise. There are various techniques that can be used for bearing fault detection and these techniques can be classified into three domains, namely frequency domain analysis, time frequency domain analysis and time domain analysis. The frequency domain methods often involve frequency analysis of the vibration signals and they consider the periodicity of high frequency transients. In those processes, the frequency domain methods search for a train of ringing occurring at any of the
characteristic defect frequencies. This procedure becomes complicated considering the fact that the periodicity may be suppressed. These frequency domain techniques include the frequency averaging technique, adaptive noise cancellation and the high frequency resonance technique (HFRT), to name a few.

The HFRT is the most popular technique for bearing fault detection and diagnosis but the disadvantage of the HFRT technique is that it requires several impact tests to determine the bearing resonance frequency. Hence, it becomes computationally expensive. Another commonly used frequency technique for detection and diagnosis of bearing faults is the envelope analysis as presented by McFadden and Smith (1984). The main disadvantage of the frequency domain analysis is that it tends to average out transient vibrations and therefore becomes more sensitive to background noise. To overcome this problem, the time-frequency domain analysis, which shows how the frequency contents of the signal change with time, is used.

1.4.6 Artificial Neural Networks

The pattern classification theory has been a key factor in fault diagnosis. Some classification methods for process monitoring use the relationship between a set of patterns and fault types without modelling the internal processes or structure of an explicit way. Nowadays, Artificial Neural Network (ANN) constitute the most popular method. The ANN is an information processing paradigm inspired by biological nervous systems. The human learning process may be partially automated with ANN’s. It can be configured for a specific application, such as pattern recognition or data classification, through a learning process.

An artificial neuron is composed of some connections, which receive and transfer information. Also there is a net function designed for collecting all
the information (weights x inputs + bias). Then it is sent to the transfer function, which processes it and produces an output.

There are two main phases in ANN’s application: the learning or training phase and the testing phase. The learning phase is critical because it determines the type of future tasks. Once the training phase gets over, the testing phase is followed, in which the representative features of the inputs are processed. After calculating the weights of the network, the values of the last layer neurons are compared with the desired output to verify the suitability of the design.

1.5 MOTIVATION AND OBJECTIVES

In the years previous, vibration-based condition monitoring of rotating machinery has been mostly studied from a signal processing point of view. But very little attention has been paid to the effect of the fault on the bearing’s vibration behaviour. Therefore, the first step in successfully implementing bearing health monitoring is to establish the base-line behaviour of a healthy bearing. Furthermore, although a number of rotary machines operate under variable speeds and load conditions, very few researchers have proposed robust techniques for the fault diagnosis and prognosis of such systems. In the present thesis, rub related vibrations are initially studied. Then a comprehensive analytical and experimental study is conducted to investigate the newly designed pin type coupling with misalignment. Next the results of the analytical studies are validated by using numerical simulations and experiments.

In the next step, a case study of balancing of CNC machine spindle using vibration signature is investigated. This study describes the step by step procedure of balancing to calculate the amount of unbalanced mass required and its exact location to minimize the vibration amplitude. From this study, the vibration levels before and after balancing are investigated. A multi-rotor
unbalanced mass addition and mass subtraction system is investigated for power consumption.

Next, a decision-making scheme, consisting of a neural network is suggested to map the monitoring indices into the bearing’s health under variable speed conditions. The output of the neural system identifies the severity of bearing’s damage. The performance of the diagnostic and prognosis schemes is studied under variable testing conditions. Lastly, the behaviour of the solid contaminants present in the bearing grease lubrication system is investigated using vibration signatures. Lastly, the behaviour of solid particles of different size and different concentration are investigated.

1.6 THESIS OUTLINE

This thesis consists of ten chapters. Chapter 2 presents a brief literature review of studies related to bearing vibration. Studies based on time domain, frequency domain, misalignment and unbalance, vibration due to solid contaminates in lubricant, wavelet methods, vibration distributed defects, and acoustic emission and automatic diagnostic system of monitoring are discussed there. Chapter 3 deals with an experimental study of defect-free and defective bearings to identify the bearing defects of the defective bearing. This is with the help of time and frequency domain signals. Later on, it compares the results of the defect-free bearing signatures. The defect frequencies of the defective bearing are compared with theoretical characteristics frequency values. Time wave form indicates severity of vibrations for defective bearings and the frequency spectrum identifies exact nature of the defects in bearings. In Chapter 4, the behavior of rub-induced bearing vibration signature on shaft is focused. It emphasizes how full annular rub on rotating shaft is simulated. Some interesting results on structural resonance are observed using the time and frequency spectrum.
A newly designed pin type of coupling is introduced to study the fault diagnosis of rotating system with shaft misalignment in Chapter 5. In this regard finite element technique is used to simulate the shaft misalignment and the results are compared with the experimental results. Chapter 6 demonstrates fault diagnosis of unbalanced CNC machine spindle using vibration signatures (a case study on turning centre on condition monitoring). Chapter 7 highlights the fault diagnosis of unbalanced multi-rotor system. In this chapter, the power consumed due to unbalance is estimated for both mass addition and mass subtraction.

Chapter 8 illustrates the fault identification and classification of bearings condition, unbalance and misalignment using Artificial Neural Networks (ANN). It also informs how the most popular networks, namely Back propagation Neural Network, Radial Basis Function Network (RBFN) and Probabilistic Neural Network (PNN) are used for classification and fault identification. How these PNNs are created, trained and tested using MATLAB. Chapter-9 describes condition monitoring of ball bearing subjected to solid contaminants in the lubricant. Then it throws light on how the fine particle of silica is used as solid contaminant. After that, it proceeds to a discussion of the use of particles of different size and concentration to study the behavior of the bearing. Lastly, Chapter 10 summarizes and contains the concluding remarks and recommendations for future research.