CHAPTER 1

INTRODUCTION

This chapter emphasizes the parameters of basics of vibration, types and sources of vibration in ball bearings, vibration measurement techniques, lubricant additives, synthesis and applications of nano particles.

1.1 BASICS OF VIBRATION

Any motion that repeats itself after a period of time is called vibration. The subject of vibration deals with the oscillatory motion of dynamic systems. All bodies possessing mass and elasticity are capable of vibration. The mass is inherent of the body and the elasticity is due to the relative motion of the parts of the body. The vibrating system may be simple or complicated.

Most of the engineering systems comprise the above said elements. Also the system may vary from single degree to multi degrees of freedom. The primary objective in any design is to either eliminate these vibrations or enhance them when it is useful.

Vibrations induced in engineering systems are undesirable. Objectionable vibrations in a machine may cause the loosening of parts, its malfunctioning, or its eventual failure. In general all engineering systems include human beings in their work environment and it is necessary to eliminate these vibrations induced in the system.
The following characteristics are needed to define the vibration,

a) **Period**

The amount of time required to complete one full cycle of vibration is called period of the vibration.

b) **Frequency**

Vibration frequency is simply a measure of the number of complete cycles that occur in a specified period of time such as ‘Cycles-Per-Second’ (CPS) or ‘cycles-per-minute’ (CPM). Although vibration frequency may be expressed in CPS, the common practice is to use the term Hertz (Hz)

c) **Relation between Frequency, Time and Period**

In other words, the frequency of a vibration is simply the ‘inverse’ of the period of the vibration. Thus, if the period or time required to complete one cycle is 1/60\textsuperscript{th} of a second, then the frequency of the vibration would be 60 cycles-per-second or 60 CPS. The following Figure 1.1 explains the vibration terminologies.

![Figure 1.1 Vibration Terminologies](image-url)
d) Significance of Vibration Frequency

There are literally hundreds of specific mechanical and operational problems which can cause a machine to exhibit excessive vibration. Obviously, when a vibration problem exists, a detailed analysis of the vibration should be performed to identify or pinpoint the specific cause. At this juncture it is of utmost importance to know the frequency of vibration.

The forces that cause vibration are usually generated through the rotating motion of the machine's parts. Because these forces change in direction or amplitude according to the rotational speed (rpm) of the machine components, it is clear that most vibration problems will have frequencies that are directly related to the rotational speeds.

e) Vibration Displacement

The vibration displacement is simply the total distance travelled by the vibrating part from one extreme limit to the other extreme limit of travel. This distance is also called the ‘peak-to-peak displacement’.

In Metric units, the peak-to-peak vibration displacement is expressed in micrometers (sometimes called microns), where one micrometer equals one-thousandth of a millimeter (1 micrometer = 0.001 millimeter).

f) Vibration Velocity

Vibration velocity is the measurement of the speed of movement of a machine or machine component as it undergoes oscillating motion. Since the weight is moving, it must be moving at the some speed determined by the displacement and frequency. However, the speed of the weight is constantly changing. At the upper and lower limits of travel, the velocity is zero (0), since the weight must come to a stop before it goes in the opposite direction.
The velocity is the greatest or at its peak as the object passes through the neutral position. Velocity is definitely a characteristic of the vibration, but since it is constantly changing throughout the cycle, the highest or ‘peak’ velocity is selected for measurement.

**g) Vibration Acceleration**

Vibration acceleration is another important characteristic of vibration which can be used to express the amplitude or magnitude of vibration. Technically, acceleration is simply the rate of change of velocity.

![Figure 1.2 vibration parameters](image)

**h) Phase**

Phase with regards to machinery vibration, is often defined as ‘the position of a vibrating part at a given instant with reference to a fixed point or another vibrating part’. The units of phase are degrees, where one complete cycle of vibration equals 360 degrees.
1.2 INTRODUCTION AND TYPES OF BALL BEARING

A bearing is a device which allows constrained relative motion between two or more parts, typically rotation or linear movement. In the engineering application, a bearings act as supports, providing stability, free and smooth rotation. Bearings are classified broadly according to the motions they allow and according to their principle of operation as well as by the directions of applied loads they can handle.

Bearings can be divided into two subgroups: plain bearings and rolling-contact bearings. Each type has some obvious advantages and disadvantages, but there are slight properties as well which are often ignored. Each type of bearing can be found in a multiplicity of places, and each can be lubricated with either oil or grease. Some bearings are lubricated by water, and some are lubricated by air (as in the case of a dentist's drill).

a) Rolling-Contact Bearings

In rolling-contact bearings, the lubricant film is replaced by several small rolling elements between an inner and outer ring. In most cases the rolling elements are separated from each other by cages. Basic varieties of rolling-contact bearings include ball, roller, and thrust as shown in Figure 1.3.

Figure 1.3 Rolling elements for ball and roller bearings
The following are the advantages of rolling contact bearings,

1. At low speeds, ball and roller bearings produce much less friction than plain bearings.
2. Certain types of rolling-contact bearings can support both radial and thrust loading simultaneously.
3. Rolling bearings can operate with a small amount of lubricant.
4. Rolling-contact bearings are relatively insensitive to lubricant viscosity.
5. Rolling-contact bearings have low wear rates and require little maintenance.

b) Ball Bearings

![Ball Bearing Overview](image)

**Figure 1.4 Ball Bearing overview**

A ball bearing is a type of rolling-element bearing which uses balls to maintain the separation between the moving parts of the bearing. However, there are many applications where a more suitable bearing can improve efficiency, accuracy, service intervals, reliability and speed of operation, size, weight, and costs of purchasing and operating machinery. Thus, there are
many types of bearings, with varying shape, material, lubrication, principal of operation, and so on.

For example, the use of spheres or cylinders rolling between the parts of rolling element bearing reduces the friction, thus allow tighter tolerances and provide a higher precision than a plain bearing. The machines accuracy increases over the time due to reduced wear.

Besides, the bearing’s performance and life may be altered intensely by the application of lubricants. For example, a lubricant may reduce the bearing’s friction and improve the life, but for applications like food processing a bearing cannot be used with a lubricant to avoid food contamination. The lubricants attract dust that spoils the bearings when continuous lubrication is applied to the situation.

1.2.1 Ball Bearing Vibrations

Rotating machinery is subjected to continuous loading at high rotational speeds. This induces vibration in the supporting bearings. Thus it is necessary to analyse the reason for these vibrations.

Rolling contact bearings represent a complex vibration system whose components (i.e. rolling elements, inner raceway, outer raceway and cage) interact to generate complex vibration signatures. Although rolling bearings are manufactured, using high precision machine tools and strict quality controls, they inevitably will have degrees of imperfection and generate vibration as the surfaces interact, through a combination of rolling and sliding. The following are the sources of vibration identified from the literature,
a) **Variable Compliance**

Under radial and misaligning loads, bearing vibration is an inherent feature of rolling bearings, even if the bearing is geometrically perfect. This type of vibration is often referred to as variable compliance and occurs because the external load is supported by a discrete number of rolling elements whose position with respect to the line of action of the load continually changes with time. Variable compliance vibration is heavily dependent on the number of rolling elements supporting the externally applied load, the greater the number of loaded rolling elements, the less the vibration. For radial loaded or misaligned bearings ‘running clearance’ determines the extent of the load region, and hence, in general, variable compliance increases with clearance.

b) **Surface Roughness**

Surface roughness is a significant source of vibration when its level is high compared with the lubricant film thickness generated between the rolling element-raceway contacts. Under this condition, surface asperities can break through the lubricant film and interact with the opposing surface, resulting in metal-to-metal contact. The resulting vibration consists of a random sequence of small impulses, which excite all the natural modes of the bearing and supporting structure.

c) **Waviness**

For longer wavelength surface features, peak curvatures are low compared with that of the Hertzian contacts and rolling motion is continuous with the rolling elements following the surface contours. The relationship between surface geometry and vibration level is complex and is dependent upon the bearing and contact geometry, as well as conditions of load and
speed. Waviness can produce vibration at frequencies up to around 300 times rotational speed but is usually predominant at frequencies below 60 times rotational speed.

Defects in bearing creates vibrations. The pattern of vibration signal depends on the defect. Generally the defects are of two types namely distributed defects and localized or discrete defects. The following are the sources of vibration in the defected bearing,

a) Distributed Defects

The nature of the manufacturing processes used to produce bearing components results in geometrical imperfections. Geometrical imperfections include surface roughness, waviness, and misaligned races and off size rolling elements. It will always be present to varying degrees depending on the accuracy class of the bearing.

b) Localized or Discrete Defects

Discrete defects refer to the damage of the rolling surfaces due to assembly, contamination, operation, mounting and poor maintenance, etc. These defects can be extremely small and difficult to detect and yet can have a significant impact on vibration-critical equipment or can result in reduced bearing life. This type of defect can take a variety of forms like, indentations, scratches along and across the rolling surfaces, pits, debris and particles in the lubricant.
c) **Raceway Defect**

A discrete defect on the inner raceway will generate a series of high energy pulses at a rate equal to the ball pass frequency relative to the inner raceway. Because the inner ring is rotating, the defect will enter and leave the load zone causing a variation in the rolling element-raceway contact force, hence deflections. While in the load zone the amplitudes of the pulses will be the highest but then reduce as the defect leaves the load zone resulting in a signal, which is amplitude-modulated at inner ring rotational frequency.

A discrete fault on the outer raceway will generate a series of high energy pulses at a rate equal to the ball pass frequency relative to the outer ring. Because the outer ring is stationary, the amplitude of the pulse will remain theoretically the same and hence will appear as a single discrete peak within the frequency domain.

d) **Rolling Element Defect**

Defects on the rolling elements can generate a frequency at twice ball spin frequency and harmonics and the fundamental train frequency. Twice the rolling element spin frequency can be generated when the defect strikes both raceways, but sometimes the frequency may not be that high because the ball is not always in the load zone when the defect strikes and energy is lost as the signal passes through other structural interfaces as it strikes the inner raceway. Also, when a defect on a ball is orientated in the axial direction it will not always contact the inner and outer raceway and therefore may be difficult to detect.
e) **Cage Defect**

Unlike raceway defects, cage failures do not usually excite specific ringing frequencies and this limits the effectiveness of the envelope spectrum. In the case of cage failure, the signature is likely to have random bursts of vibration as the balls slide and the cage starts to wear or deform and a wide band of frequencies is likely to occur.

### 1.3 VIBRATION MEASUREMENT AND DEVICES

Vibration measurement can be generally characterized as falling into one of three categories –

- Detection,
- Diagnosis and
- Prognosis

Detection generally uses the most basic form of vibration measurement, where the overall vibration level is measured on a broadband basis in a range. In machines, where there is little vibration other than that of from the bearings, the spikiness of the vibration signal indicated by the Crest Factor (peak/RMS) may imply incipient defects, whereas the high energy level given by the RMS (Root Mean Square) level may indicate severe defects. Trend analysis involves plotting of the vibration level as a function of time and using this to predict when the machine must be taken out of service for repair. Another way of using the measurement is to compare the levels with published vibration criteria for different types of equipment.

Vibration measurement can be done in several ways depending upon the defect to be detected. Bearing defects are measured by the overall vibration level and bearing signal analysis.
1.3.1 Overall Vibration Level

This is the simplest way of measuring vibration and usually consists of measuring the Root Mean Square vibration (RMS) of the bearing housing or some other point on the machine with the transducer located as close to the bearing as possible. This technique involves measuring the vibration over a wide frequency range e.g. 10-1,000Hz or 10-10,000Hz.

Although this method represents a quick and low cost method of vibration monitoring, it is less sensitive to incipient defects i.e. detecting defects in the advanced condition and has a limited diagnostic capability. It is easily influenced by other sources of vibration e.g. imbalance, misalignment, looseness, electromagnetic vibration etc. To have a realistic finding the other method called bearing signal analysis is preferred.

1.3.2 Bearing Signal Analysis

A bearing vibrating while in operation produces signal. Signals may be digital or analog depending on the transducer used for measurement. Time domain and frequency domain analysis are the two means of analysing the vibration signature of the bearing.

1.3.2.1 Time domain signal

Time domain is a term used to describe the analysis of mathematical functions, or physical signals, with respect to time as shown in Figure 1.5. In the time domain, the signal or function's value is known for all real numbers, for the case of continuous time, or at various separate instants in the case of discrete time. Though there are many equipments available to visualize the real-world signal, an oscilloscope is commonly used under time
domain visualization. The time domain graph represents a change of signal over time.

Figure 1.5 Sample time domain signal

1.3.2.2 Frequency domain signal

Frequency domain is a term used to describe the domain for analysis of mathematical functions or signals with respect to frequency, rather than time as shown in Figure 1.6. Speaking non-technically, a frequency-domain graph represents how much of the signal lies within each given frequency band over a range of frequencies. A frequency-domain representation can also include information on the phase shift that must be applied to each sinusoid in order to be able to recombine the frequency components to recover the original time signal.
The real-world signals are commonly visualized using a spectrum analyzer under frequency domain. Numerous mathematical transforms are used to analyze time functions and are referred to as frequency domain methods. The following list shows the most common transforms and the respective field of applications:

- Fourier series – Used for repetitive signals and oscillating systems
- Fourier transform – Used in no repetitive signals and transients
- Laplace transform – Used for electronic circuits and control systems
- Wavelet transform – Used for digital image processing and signal compression
- Z transform – Used for analyzing discrete signals and digital signal processing
The above transforms can be interpreted as capturing some form of frequency, and hence the transform domain is referred to as a frequency domain

1.3.3 **Vibration Measuring Devices**

The vibration measurement is done as direct measurement using hardware components. Besides the virtual instruments (VI) also used to measure the vibration. The features of vibration measuring devices are shown below.

1.3.3.1 **Vibration measurement using hardware devices**

1. Proximity Probe
   - Key phase marker
   - Shaft vibration measurement
   - Shaft centre line position
   - Best suited for measuring 1 To 500 Hz of vibration

2. Velocity Pick Up
   - For measuring bearing and structural vibration
   - Best suited for measuring 10 to 1000 Hz

3. Accelerometer
   - For high frequency range measurements
   - Best suited for measuring signals 1000 Hz onwards
1.3.3.2 Vibration measurement using virtual instrumentation

Virtual instrumentation uses the customizable software and modular measurement hardware to create user-defined measurement systems, called virtual instruments. The major difference between hardware instrumentation and virtual instrumentation is that a software is used to replace a large amount of hardware. Figure 1.7 explains the virtual instruments for measuring vibrations.

**Figure 1.7 Vibration measurement using virtual instrumentation**

Figure 1.8 shows an example of measured vibration signal using Labview guided user interface (GUI) window.

**Figure 1.8 Example of measured vibration signal using Lab view software**
1.3.4 **Data Acquisition (DAQ)**

Data acquisition begins with the physical phenomenon or physical property to be measured. Examples of this include temperature, light intensity, gas pressure, fluid flow, and force. Regardless of the type of physical property to be measured, the physical state which is to be measured must first be transformed into a unified form that can be sampled by a data acquisition system. The task of performing such transformations falls on devices called sensors. A sensor, which is a type of transducer, is a device which converts a physical property into a corresponding electrical signal (e.g., a voltage or current) or, in many cases, into a corresponding electrical characteristic (e.g., resistance or capacitance) that can easily be converted into an electrical signal.

The ability of a data acquisition system to measure differing properties depends on having sensors that are suited to detect the various properties to be measured. There are specific sensors for many different applications. DAQ systems also employ various signal conditioning techniques to adequately modify various different electrical signals into voltage which can then be digitized using an Analog-to-digital converter (ADC). Data acquisition systems are used to acquire, store and analyze vibration data received from sensors. Sensing Systems utilize state of the art computer based data acquisition systems. The equipment is optimized to sample at rates commensurate with the highest frequency expected during testing. Data may be acquired and submitted in different formats for further review and analysis by our customers. Filtering may be performed during acquisition or digitally following data acquisition. Data analysis such as Fourier Transforms may be performed following data acquisition.
DAQ hardware is what usually interfaces between the signal and a Personal Computer (PC). It could be in the form of modules that can be connected to the computer’s ports (parallel, serial, USB, etc.) or cards connected to slots (S-100 bus, Apple Bus, ISA, MCA, PCI, PCI-E, etc.) in the mother board.

The NI cDAQ-9172 (National Instruments) is an eight-slot USB chassis designed for use with C Series I/O modules shown in Figures 1.9 and 1.10. The NI cDAQ-9172 chassis is capable of measuring a broad range of analog and digital I/O signals and sensors using a Hi-Speed USB 2.0 interface.

**Figure 1.9 Outline View of DAQ kit**
Figure 1.10 Data Acquisition card

a) Specifications of NI 9233 module

The National Instruments 9233 are four-channel dynamic signal acquisition modules for making high-accuracy measurements from IEPE (Initialization For Integrated Electronic Piezoelectric) sensors shown in Figure 1.11.

Figure 1.11 NI 9233 Connector Assignments
The NI 9233 Series analog input modules deliver 102 dB of dynamic range and incorporate IEPE (2 mA constant current) signal conditioning for accelerometers and microphones. The four input channels simultaneously acquire at rates from 2 to 50 kHz. In addition, the modules include built-in antialiasing filters that automatically adjust to the sampling rate. Compatible with a single-module USB carrier and NI Compact DAQ and Compact RIO hardware, the NI 9233 are ideal for a wide variety of mobile/portable applications such as industrial machine condition monitoring and in-vehicle noise, vibration, and harshness testing. The specifications are shown below,

- 24-bit resolution
- 102 dB dynamic range
- 4 simultaneous analog inputs
- ±5 V input range
- Antialiasing filters
- TEDS (Transducer Electronic Data Sheet) read/write
- Supported in NI CompactDAQ, CompactRIO, and Hi-Speed USB carrier

b) Specifications of an Accelerometer

Precision industrial Integrated Circuit Piezoelectric (ICP) accelerometers are recommended for route-based vibration data collection and quantitative diagnostic measurements on industrial machinery. Figure 1.12 shows an accelerometer which has direct compatibility with the most commercially available vibration data collectors and Fast Fourier Transform (FFT) analyzers that supply excitation power for ICP sensors. This precision, shear-structured sensors offer tighter sensitivity tolerances than low-cost
series units and are supported with full NIST traceable calibration data that encompasses an extensive frequency range. All units are laser welded and leak tested to ensure a true hermetic seal. A shock protection to the level of 5000 g, guards against damage due to accidental overloads. A host of available options including velocity output, temperature output, and hazardous area approvals adapt the units for virtually any machinery vibration monitoring requirement. An accelerometer is connected with NI NI cDAQ-9172 module via NI – 9233 module.

![Figure 1.12 Illustration of an accelerometer](image)

c) Specifications of NI 9211 module

The National Instruments 9211 module contains 4-Channel Thermocouple Input Module modules for making high-accuracy measurements shown in Figure 1.13.
The thermocouple is connected with the NI 9211 to acquire input signals. The positive lead of the thermocouple is connected to the TC+ (Terminal Connection) terminal and the negative lead of the thermocouple to the TC− terminal. The COM terminal is internally connected to the isolated ground reference of the module. Figure 1.14 illustrates the typical shielding configuration. Table 1.1 shows the specifications of the thermocouple used in this work.
Table 1.1 Specifications of the K type thermocouple

<table>
<thead>
<tr>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple</td>
<td>K – type</td>
</tr>
<tr>
<td>Range</td>
<td>–328 to 2498 °F / –200 to 1370 °C</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1° from -328 to 990°F/-200 to 640°C</td>
</tr>
<tr>
<td></td>
<td>1° from 990 to 2498°F / 640 to 1370°C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±1° C</td>
</tr>
</tbody>
</table>

1.4 INTRODUCTION TO LUBRICANTS

The primary function of a lubricant is to prevent the wear of the rolling and sliding contacts of a bearing through hydrodynamic, Elasto hydrodynamic (EHD), or boundary lubrication. However, there are many other vital functions such as:

1. Minimizing the frictional power loss of the bearing
2. Acting as a heat transfer medium to remove heat from the bearing, or redistributing the heat energy within the bearing to minimize differential thermal expansions
3. Protecting the precision surfaces of the bearing components from corrosion
4. Removing wear debris from the roller contact paths
5. Minimizing the amount of extraneous dirt entering the roller contact paths
6. Providing a damping medium for cage dynamic motions

No single lubricant or class of lubricants can satisfy all the requirements for bearing operating conditions, from cryogenic to ultrahigh
temperatures, from very slow to ultrahigh speeds, and from benign to highly reactive operating environments. As for most engineering tasks, a compromise is generally exercised between performance and economic constraints. The economic constraints involve not only the cost of the lubricant and the method of application, but also its impact on the life cycle cost of the mechanical system.

1.4.1 Properties of Wet Lubricants

There are various properties that determine the quality of lubricant, the most important one is the viscosity of lubricant. The various other parameters are,

- Flash point
- Fire point
- Cloud point
- Pour Point
- Specific Gravity
- Viscosity
- Adhesiveness
- Cohesiveness
- Kinematic Viscosity
- Viscosity Index (VI*)
- Volatility
a) **Viscosity Index**

Viscosity index (VI*) is an arbitrary measure for the change of viscosity with temperature. It is used to characterize lubricating oil in the automotive industry. The viscosity of liquids decreases as temperature increases. The viscosity of a lubricant is closely related to its ability to reduce friction. Usually, the least viscous lubricant which creates a force between the two moving surfaces apart is desired. The higher viscous lubricant requires a large amount of energy to move (as in honey) and in the case of lubricant with low viscosity, the surfaces will rub and friction will increase.

As stated above, the Viscosity Index (VI*) focuses on how a lubricant's viscosity changes with variations in temperature. Many applications require the lubricant to perform across a wide range of working conditions. For example, in an engine, an automotive lubricants must reduce friction between engine components when it is started from cold (at room temperature 30°C) as well as when it is running (up to 200°C). The best lubricants will not produce much variation in viscosity over such a temperature range and therefore will perform well throughout.

The Society of Automotive Engineers (SAE) has graded the lubricant by assigning VI* scale to individual lubricants. The arbitrary reference temperatures of 100 and 210 °F (38 and 99 °C) were chosen to classify the lubricants. The original scale only stretched between VI* value of zero for (worst oil) naphthalene and VI* of 100 (best oil) for paraffin. But since the conception of the scale, better lubricants have also been produced, leading to VI* greater than 100. But the VI* of synthetic lubricants range from 80 to over 400.
1.4.2 **General Classification of Lubricants**

Numerous lubricants exist in the commercial market. The following Figure 1.15 provide the general classification of the lubricant.

![General Classification of Lubricants](image_url)

**Figure 1.15 General classifications of lubricants**

1.4.3 **Types of Lubrication Regimes**

Various regimes of lubrication was observed when the load increases on the contacting surfaces. The three distinct situations observed were explained below.

1.4.3.1 **Elasto-hydrodynamic lubrication**

The film of lubricant between the sliding surfaces separates the opposing surfaces. Due to the asperity contact and an elastic deformation on the contacting surface enlarging the load-bearing area whereby the viscous
The resistance of the lubricant becomes capable of supporting the load. The three mechanisms help to support the load under elasto-hydrodynamic lubrication.

- Elastic deformation of tribo-surfaces.
- Effect of increase in viscosity with pressure.
- Hydrodynamic lubrication

1.4.3.2 Boundary film lubrication

As the moving bodies come into closer contact at their asperities and heat developed by the local pressures causes a stick-slip thus leads to break off of some asperities. The chemically reactive constituents of the lubricant react with the contacting surface and forms a highly resistant tenacious layer called boundary film at elevated temperatures. This layer is capable of supporting the load and major wear or breakdown may be avoided. Boundary lubrication is also defined as that regime in which the load is carried by the surface asperities rather than by the lubricant as shown in Figure 1.16. There are several mechanisms by which the boundary lubrication film functions. Some of them are sacrificial layer, low shear interlayer, friction modifying layer, shear resistant layer and load bearing glasses. These mechanisms operate in different regimes controlled by the environment and operating conditions.

Figure 1.16 Boundary lubrication
1.4.3.3 Partial or mixed lubrication regime

Speed of rotation is low and load is high or the temperature is sufficiently large to significantly reduce the lubricant’s viscosity – when any of these conditions occur, the tallest asperities of the bounding surfaces will protrude through the film and occasionally come in contact which produces the partial or mixed film lubrication regime.

1.4.4 Strubeck Curve

The Strubeck curve relates the friction coefficient as a function of a parameter $\eta V/P$, where $\eta$ is viscosity, $V$ is speed and $P$ is load as shown in Figure 1.17. Boundary lubrication is a result of the combination of low viscosity, low velocity and high load.

![Figure 1.17 Strubeck Curve](image)

This type of lubrication is characterized by insufficient amounts of a lubricant in the interface region and thus by a large direct surface contact. This leads to a high friction coefficient in this region on the Strubeck curve. For increased velocity and viscosity the separation of the contacting surface is
happened by the film of lubricant instead of the boundary film. So this regime carries the higher load, when compared to the boundary lubrication.

1.4.5 Lubricant Additives

The purification and manufacturing processes impact good qualities to lubricating oils. But still they cannot be used directly. They will be prone to contamination and decomposition in the exact working conditions. Hence certain chemical compounds and other agents which are termed as additives are added to the oil. Use of chemical additives in lubricants is very wide.

Additives are used in the lightest instrument and spindle oils to the thickest gear lubricants, automotive lubricants, cutting oils and hydraulic fluids. There are over 50 characteristics of lubricating base oils which can be improved by the additives. Generally speaking the additives must have the following properties and their properties are presented in Table 1.2.

Table 1.2 Various types of additives

<table>
<thead>
<tr>
<th>Additive Used</th>
<th>Purpose of Additives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-oxidant</td>
<td>Increases oil and machine life and prevents oxidation</td>
</tr>
<tr>
<td>Corrosion Inhibitor</td>
<td>Protects against chemical attack of alloy bearings and metal surfaces</td>
</tr>
<tr>
<td>Detergents</td>
<td>Cleanliness of lubricated surfaces.</td>
</tr>
<tr>
<td>Rust Inhibitor</td>
<td>Eliminates rusting in the presence of water and moisture</td>
</tr>
<tr>
<td>Pour depressant</td>
<td>Improves low-temperature fluidity</td>
</tr>
<tr>
<td>Viscosity Index</td>
<td>Lowers rate of change of viscosity improver with temperature change</td>
</tr>
<tr>
<td>Anti-foam agent</td>
<td>Prevents stable foam formation.</td>
</tr>
<tr>
<td>Extreme Pressure agent</td>
<td>Improves film strength and load carrying capacity</td>
</tr>
</tbody>
</table>
1.5 **NANOMATERIALS**

Nanomaterials are chemical substances or materials which are manufactured and used in a very small scale. They are down to 10,000 times smaller than the diameter of a human hair. When material is made into nanoparticles, its reactivity increases. Smaller the particle size, higher the surface area. Nanoparticles have a very high surface area to volume ratio. Due to this a higher percentage of atoms (in nanoparticles) can interact with other matter. Therefore surface area (measured in Square meters per gram) is the most important unit of measure for a nano lubricant. Higher the surface area, higher the lubricity. Nanomaterials are developed to exhibit other novel characteristics (such as increased strength, chemical reactivity or conductivity) compared to the same material without nanoscale features. Hundreds of products containing nanomaterials are already in use and the examples are batteries, coatings and anti-bacterial clothing etc.

1.5.1 **Classification of Nanomaterials**

Nanomaterial’s are extremely small in size having at least one dimension 100 nm or less. Nanomaterials can be in nano scale in one dimension (e.g. surface films), two dimensions (e.g. strands or fibres), or three dimensions (e.g. particles). They can exist in single, fused, aggregated or agglomerated forms with spherical, tubular, and irregular shapes. Common types of nanomaterials include nanotubes, dendrimers, quantum dots and fullerenes. Nanomaterials have applications in the field of nano technology, and display different physical and chemical characteristics from normal chemicals (i.e., silver Nano, carbon nanotube, fullerene, photo catalyst, carbon Nano, silica). Nano structured materials are classified as Zero dimensional, one dimensional, two dimensional and three dimensional nanostructures as shown in Figure 1.18.
1.5.2 Manufacturing process of nanoparticles

There are four fundamental routes for making nano materials.

a) Form in place

These techniques incorporate lithography, vacuum coating and spray coating.

b) Mechanical

This is a ‘top-down’ method which reduces the size of the particles by attrition, for example, ball milling or planetary grinding.

c) Gas phase synthesis

This includes plasma vaporization, chemical vapour synthesis and laser ablation.
d) **Wet chemistry**

This is the range of technique which is mostly applicable for characterization by light scattering techniques. These are fundamentally ‘bottom-up’ techniques, i.e. they start with ions or molecules and build these up into larger structures.

Chemical reduction, micro emulsion (colloidal) techniques, sono-chemical reduction, electro-chemical, microwave-assisted, sol-gel, aquas precipitation, hydrothermal syntheses and biosynthesis are the main techniques for the synthesis of nanoparticles through the chemical approach.

In principle it is classified as the wet chemical synthesis of nanomaterials into two broad groups,

1. The top down method where single crystals are etched in an aqueous solution for producing nanomaterials. For example, the synthesis of porous silicon by electrochemical etching.
2. The bottom up method consisting of sol-gel method, precipitation etc. where materials containing the desired precursors are mixed in a controlled fashion to form a colloidal solution.

**1.5.3 Nano Fluid Preparation**

Dispersion of nano powder into other media is critical, because the nano particle tends to aggregate. The size of the aggregate is usually larger than the size of the particle. Ultra-sonication technique is used to disperse the particle in the media. The sonication speed, frequency and time of sonication are the major significant factors affecting the formation of aggregates of nano particle.
1.5.4 Size Measurement Techniques for Nanoparticles

Nano particle size and shape are characterized by any of the following techniques. Selection of process is based on the required accuracy and application.

- Transmission Electron Microscopy (TEM)
- Scanning Electron Microscopy (SEM)
- Atomic Force Microscopy (AFM)
- Photon Correlation Spectroscopy (PCS)
- Nanoparticle Surface Area Monitor (NSAM)
- Condensation Particle Counter (CPC)
- Differential Mobility Analyzer
- Scanning Mobility Particle Seizer (SMPS)
- Nanoparticle Tracking Analysis (NTA)
- X-Ray Diffraction (XRD)
- Aerosol Time of Flight Mass Spectroscopy
- Aerosol Particle Mass Analyzer (APM)

In this research SEM and XRD techniques were used for the characterization of the developed nano material.

1.6 OBJECTIVE OF THE RESEARCH

Absolute damping of vibration is not possible in any situation. This research is focused on proving the vibration damping ability of the lubricant under experimental conditions. The scope of the research is to develop a nano
particle mixed lubricant and testing the vibration damping ability, while lubricating the ball bearing.

The experimental techniques adopted in the present work are focused on, measurement of vibration, characterization of nano-particle and damping ability of the lubricant. The following are the specific objectives of the research,

- To measure the vibration of the ball bearing with different defect and lubricated under oil lubrication using an accelerometer and virtual instrumentation
- To select the lubricant which dampens the vibrations mostly by applying different viscosity grade lubricant to the bearing
- To synthesis the nano-copper oxide particle using aqueous precipitation method and characterization of the prepared nano particle.
- To prepare nano-fluid by dispersing surfactant coated nano-particle into the lubricant and interpreting the vibration of ball bearing under nano-fluid lubrication and base lubricant.
- To compare the vibration of the bearing running with nano-fluid over the conventional lubricant and prove the damping ability of the nano-fluid.
- To study the wear characterization of the balls running with conventional and nano-fluid lubricant which is tested using four ball wear tester and verified with an optical and Scanning Electron Microscopy.
1.7 PROBLEM DEFINITION

A rolling-element bearing, also known as a rolling bearing, is a bearing which carries a load by placing rolling elements (such as balls or rollers) between two bearing rings called races. The relative motion of the races causes the rolling elements to roll with very little rolling resistance and with little sliding. A bearing with different defect exhibits different vibration pattern and is measured using accelerometer. Ball bearing is a type of rolling element bearing, (SKF 6205) is selected for diagnostics with different defects, loads and speeds. Different defects are introduced in the ball, inner and outer races of bearing by spark erosion and electrode discharge machining process. The bearing vibration response was measured using an accelerometer connected with the DAQ kit. Time and frequency domain analysis was used to identify the nature and amplitude of the defect and correlated with mathematical equation.

Most of the bearings are lubricated with the semi-solid lubricant such as grease. The importance given for the bearings lubricated under liquid lubricants is sufficiently less. In this thesis, an attempt has been made to select the proper lubricant which significantly increases the damping property among the various lubricant grades available in the market.

Additives are the elements which increase the physical and chemical properties of the lubricant, when mixed with minimum quantity. Recent research works proved that, use of a nanoparticle along with lubricating oil provides better tribological properties when compared to the conventional method of lubrication. Though there are different nano particles mixed with the lubricant, nano CuO particle seems to provide better tribological properties. Synthesis of the CuO nano particle is done by aquas precipitation method and the characterization is done by XRD, Zeta potential, SEM with Energy Dispersive X-Ray Analysis (EDX) tests.
Lubricant reduces the wear rate and friction coefficient which also reduces the vibration of the lubricating element. The work has been taken to study the vibration of the bearing lubricated with the CuO nano particle mixed lubricant and its influences on vibration damping.

The nano-CuO particle mixed lubricant’s wear and friction characteristics have performed as per American Society for Testing and Materials (ASTM) standard tests using four ball wear tester.

1.8 OUTLINE AND ORGANIZATION OF THE THESIS

This thesis totally consists of seven chapters. The following session explains the methodology adopted to solve the identified problem and outline of the thesis. The first two chapters (chapter 1 and chapter 2) have the detailed discussion on selection of nano copper oxide as an additive to lubricant, overview of vibration synthesis techniques, extensive studies on applications of vibration measurements in detecting faults of rolling element bearing and an elaborate analysis of work related to the present investigation available in the literature.

In the third chapter, experimental setup used for measuring ball bearing vibration, usage of instruments and vibration signature analysis for identifying the bearing defect has been presented.

The fourth chapter explains the experimental results of vibration bearing running with lubricants of three different viscosities. A detailed analysis have been done to represent vibration as a function of MOFT and lubrication factor. The different regime of lubrications developed during the running of bearing in lubricant have been outlined and analysed, to select a lubricant which reduces the vibration to the maximum extent possible.
Fifth chapter focused on the synthesis and characterization of nano
copper oxide particle. XRD, PSD, Zeta potential and SEM have been utilized
to characterize the morphology of the nano-CuO particles. Surfactant
treatment has been done using oleic acid under controlled condition to
improve uniform dispersion of nano particle in the lubricant.

The sixth chapter emphasises on the preparation of nano-fluid by
suspending nano-CuO particles in the ISO 68 lubricant. The viscosity of
different lubricants under varying temperatures have been measured and
analysed. Vibration analysis tests have been carried out with healthy and
defective bearing under nano-fluids lubrication at different speeds for a
specified period of time. However, the interaction effect of lubricant on
vibration have been found while using nano fluid as a damping factor. The
significant of the lubricant in dampening the vibrations have been illustrated
in the bar chart. Thermal response of both the lubricants have been recorded
to study the thermal stability of the nano fluid. Tribo-mechanical studies
outline the anti-friction and anti-wear property of the nano fluid. The surface
characterization of wear tested balls using SEM and SEM with EDX have
been utilized to clarify the mechanism of damping and wear during the nano
fluid lubrication.

In the seventh chapter, the conclusion have been drawn from the
above studies and the scope for future work has also been presented.

The overall project methodology has been depicted in Figure 1.19.
Figure 1.19 Project methodology