Chapter 3

Methodology

'An experiment is a question which science poses to nature, and a measurement is the recording of nature's answer.'

-Max Planck

It is often important to pose proper questions in order to get useful answers. Over the years, researchers have been asking many questions for bearing fault diagnosis - Is the fault present? What is the nature of the fault? Can it be diagnosed under varying conditions? How fast and early can we diagnose it? This research hypothesises that with modified envelope detection, most of these questions can be adequately answered.

Highlights:

- This chapter defines the objectives of this research and discusses details of public datasets and in-house experiments.
- The cases from these datasets include diagnosis under constant and variable speeds, diagnosis for different fault sizes, diagnosis using primary and secondary accelerometers and diagnosis using microphone signals.
- Specifications of the sensors, acquisition card and processing hardware are also provided. Details of the experiments and data acquisition are given.
- The datasets explained here, CWRU-2013, UOO-2018 and BITS-2021, are used throughout the thesis.

It is evident from the literature survey that bearing fault diagnosis is a multifaceted problem and demands comprehensive study and experimentation. Several standard datasets on bearing fault diagnosis are publicly available with different objectives. In this chapter, the objectives of this research are defined, the details of the experimental procedure are provided and the overall methodology is explained. The proposed bearing fault diagnosis algorithms are also briefly introduced.

3.1 Research Objectives

The central objective of this thesis is to develop a signal processing framework to diagnose bearing fault signatures from vibration and sound signals under constant as well as variable speed conditions. Bearing fault diagnosis is a widely explored topic and it can be broadly classified into model based [164], signal processing based [165] and data-driven [166] approaches to diagnosis. The scope of this thesis is limited to signal processing based algorithms of bearing fault diagnosis. The objectives of this research are -

1. Development of a framework for diagnosis of bearing faults under constant as well as variable speed conditions.
2. Enhancement of existing signal processing methods for bearing fault diagnosis using modified enveloping techniques.
3. Design of appropriate fault features for selecting appropriate algorithmic parameters and thereby increasing the accuracy of diagnosis.
4. Design of a set of experiments for bearing fault diagnosis using vibration and sound signals and testing of proposed approaches on this dataset.
5. Validation and testing of proposed algorithms on public dataset for variable speed and in-house experimental dataset.

3.2 Public Datasets

Bearing fault datasets are important for validating the performance of proposed algorithms vis-à-vis the existing algorithms. Following datasets are publicly available and widely accepted in the research domain.

- Case Western Reserve University (CWRU-2013) [167],
- Huang *et al.*, University of Ottawa (UOO-2018) [168]

3.2.1 Case Western Reserve University (CWRU-2013)

This is a most widely accepted dataset for studying bearing fault diagnosis [167] and is benchmarked in [169]. The test rig has a $2hp$ electric motor with control circuitary, an encoder for speed measurement, accelerometers for vibration measurements and a dynamometer for applying load of 0 to $3hp$. The bearing under test (BUT) is either located at the drive end or the fan end of the motor. An accelerometer is mounted at both ends to capture the signature for adjacent bearings. The data was collected under constant speed around $1700rpm$. Depending on the load exerted by the dynamometer, slight variations in the rotational speed are observed.

Different sizes of faults, $7,\ 14,\ 21$ *mil* are induced in the inner raceway, outer raceway and the rolling element of the BUT by electro-discharge machining. As the outer raceway is fixed during rotation, the data for faults at $3,\ 6,\ 12$ O'Clock positions are recorded. In all, its a comprehensive dataset for bearing fault diagnosis under constant, medium rotational speeds. There are two types of bearings under test and their fault characteristic frequencies (FCF) are as follows -

6205-2RS JEM SKF (Drive End Bearing):

$$\begin{aligned}\text{Inner Raceway}(f_{ir}) &= 5.42\ f_r \\ \text{Outer Raceway}(f_{or}) &= 3.58\ f_r \\ \text{Rolling Element}(f_{re}) &= 4.71\ f_r\end{aligned}$$

6203-2RS JEM SKF (Fan End Bearing):

$$\begin{aligned}\text{Inner Raceway}(f_{ir}) &= 4.95\ f_r \\ \text{Outer Raceway}(f_{or}) &= 3.05\ f_r \\ \text{Rolling Element}(f_{re}) &= 3.99\ f_r\end{aligned}$$

3.2.2 University of Ottawa (UOO-2018)

This dataset is published in 2018 and contains bearing vibration signals acquired under variable speed conditions [168]. The speed variations are mainly in the low to mid range, that is around $10-30Hz$. The acquisition rate is $200KHz$ and four different types of speed variations are tested - increasing, decreasing, increasing then decreasing, decreasing then increasing. Three different experiments are performed under each speed variation. Thus, overall, 36 signals, of $10sec$ each, are included in this dataset - 12 healthy cases, 12 inner raceway defects and 12 outer raceway defects. The fault size, however, is not known and there are no variations in it.

The main objective of this dataset is to diagnose bearing faults under variable speed conditions. The bearing under test is ER16K and has following fault characteristic frequencies (FCF) -

$$\begin{aligned}\text{Inner Raceway}(f_{ir}) &= 5.43\ f_r \\ \text{Outer Raceway}(f_{or}) &= 3.57\ f_r\end{aligned}$$

The fault cases in this dataset are named as *'XYN'*, where *X* is the fault type (H - healthy, I - inner race fault and O - outer race fault), *Y* stands for speed variation (A - increasing, B - decreasing, C - increasing then decreasing and D - decreasing then increasing) and *N* is an integer representing experiment number. For example, *IA1* is the first experiment of inner race fault case under increasing speed.

3.3 In-house Experiments (BITS-2021)

Based on the objectives of these publicly available datasets, a similar set of experiments is designed and a dataset is created. This dataset is referred to as 'BITS-2021'.

3.3.1 Experimental Set-up

The experimental test rig is shown in Fig. 3.1. It consists of an electric motor with speed control electronics and two bearing posts. One nearer to the motor has a healthy bearing, while the second which is away from the motor, has Bearing Under Test (BUT).

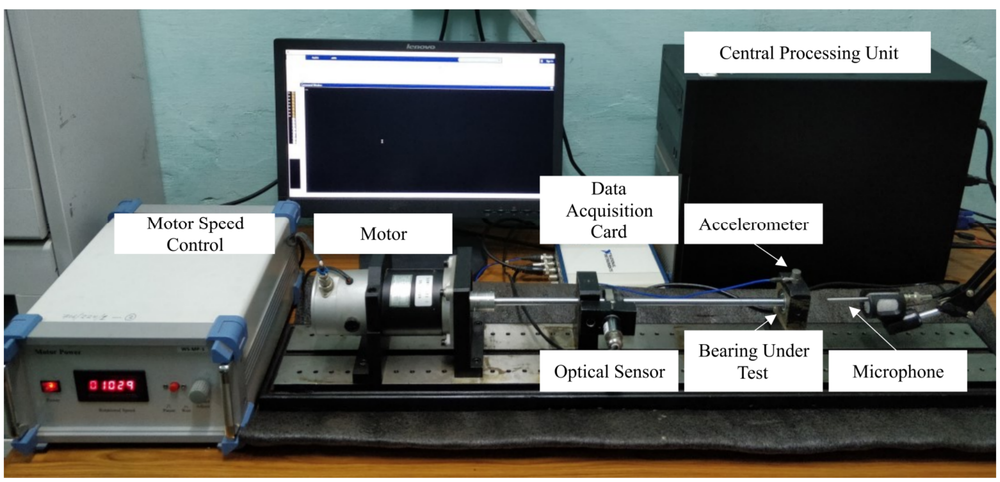


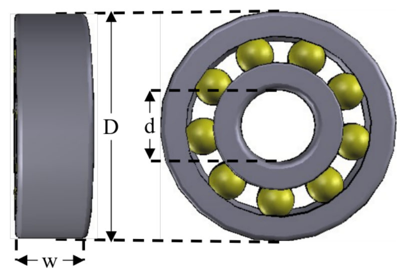
Figure 3.1: Experimental set-up of bearing fault diagnosis

3.3.2 Bearing Under Test (BUT)

SKF 1200 ETN9 is used as the bearing under test. The faults are created using wire-cut electro-discharge machine (EDM) induced fault in the inner raceway, the outer raceway or the rolling element. Two fault sizes, 0.6 mm and 0.7 mm (23.62 and 27.56 mil respectively) are introduced separately in the BUT. The geometric specifications of the BUT are given in Table 3.1.

Table 3.1: Specifications of Bearing Under Test

Specification	Value
Outer Diameter (D)	30 mm
Bore Diameter (d)	10 mm
Width (w)	9 mm
Limiting Speed	36000 rpm
Dynamic Load Rating	5.53 kN



The fault characteristic frequencies of this bearing can be calculated as the multiples of rotating speed (f_r). -

$$\begin{aligned} \text{Inner Raceway}(f_{ir}) &= 5.55\ f_r \\ \text{Outer Raceway}(f_{or}) &= 3.45\ f_r \\ \text{Rolling Element}(f_{re}) &= 3.96\ f_r \end{aligned}$$

3.3.3 Sensors

Three sensors are used to acquire data from the BUT. An accelerometer sensor (ICP® (352C33)) is mounted on the housing of the BUT. A microphone (GRAS 40PP CCP Free-field QC Microphone) is placed near the BUT and an optical sensor is used to measure the rotational shaft speed.

ICP® is a PCB® registered trademark that stands for "Integrated Circuit Piezoelectric" and identifies sensors that incorporate built-in microelectronics.

Table 3.2: Specifications of the accelerometer

	Sensitivity	100 mV/g
	Measurement Range	± 50 g peak
	Frequency Range	0.5 Hz to 10 KHz
	Weight	5.8 gm
	Mounting	On the bearing housing with a screw

Table 3.3: Specifications of the microphone

	Sensitivity	50 mV/Pa
	Measurement Range	33 to 128 dB
	Frequency Range	10 Hz to 20 KHz
	Weight	24 gm
	Mounting	On a stand near the bearing housing (non-touching)

3.3.4 Data Acquisition

The data is collected under different operating speed conditions. For each experiment, a BUT is fixed in Bearing Post 2. The motor speed is varied over a range of 1000 to 2000 rpm. The details of speed variation are given below.

Costant Speed: 1000, 1200, 1400, 1600, 1800 and 2000 rotations per minute

Variable Speed: 1200 to 1500, 1500 to 1200, 1700 to 2000 and 2000 to 1700 rotations per minute

The vibration and sound signals are simultaneously acquired for a duration of 10 sec using *National Instrument's* NI USB 4432 with a sampling rate of 20000 samples/sec. Similar experiments are performed with same setting for different types of bearing faults. Thus the designed dataset BITS-2021 has 100 cases (50 vibration signals and 50 corresponding sound signals, which represent 10 healthy cases, 10 inner race cases of 0.6 mm, 10 inner race cases of 0.7 mm, 10 outer race cases of 0.6 mm and 10 outer race cases of 0.7 mm) under different operating speeds.

Table 3.4: Specifications of the data acquisition card

	• 24 bit Delta-Sigma Analog to Digital Converter • Simultaneous sampling mode • Sampling rate up to 102400 samples per second • ± 40 V peak input range • Direct support integrated electronics piezo-electric (IEPE) sensors

3.3.5 Processing Hardware

All the processing is done on MATLAB® R2020b and Intel® Core™ i5-1035G1 processor of 1.19 GHz, with 8 GB RAM. The data is acquired using

3.4 Summary

Based on the gaps in existing research, discussed in Chapter 2, the objectives of this research are first defined. Two widely accepted datasets - one for constant speed and other for variable speed condition - are chosen for study. A similar set of experiments is performed in-house with vibration as well as microphone sensors to capture the bearing condition. The cases from these datasets will be used in further part of this thesis for investigating the applicability of proposed algorithms and comparing their performance with existing methods.

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