Fault diagnosis and health assessment of rolling element bearings via vibration signature analysis has gained importance since the vibration signature always carries the dynamic information of the system under investigation. Health assessment also referred as condition monitoring involves the application of techniques for investigating the physical state of machinery and its subsystems. The primary objective of vibration based condition monitoring is predictive maintenance to gather information about incipient faults and then deciding the direction for corrective action to prevent sudden or total failure of machine components and in a way to plan replacement time of machine components.

Rolling element bearings are frequently encountered in rotating machinery due to their load carrying capacity and low friction characteristics. Rolling element bearings work under different conditions and are frequently under heavy loadings generated in the machinery subjected to time and space varying dynamic loads. A damaged bearing in a machine act as a vibration generator and has a great impact on the performance of the entire system. Machine tool bearings are very accurately engineered components and as such they are very important to the successful performance of the machine tool. Rolling element bearings in machine tool spindle permits relative motion between the work piece and the cutting tool necessary for material removal. Premature failure of these bearings is a serious concern since it results in enormous loss of production and costly downtime. This outlines the need for monitoring the health of bearings from time to time to avoid sudden failure of the system as a whole since bearing failure results not only in its own but also failure of the entire system. The damage in a bearing is due to different defects present on races and rolling elements. The manufacturing process itself may give rise to these defects or these may develop during the service conditions. There are numerous failure modes associated with rolling element bearing such as contact fatigue, plastic flow, wear type failure etc. Defects in bearing are broadly classified as localized and distributed defects. Localized or discrete defects are present on races of the bearing or any of the rolling elements. Physically these are sharp discontinuities on the elements of
the bearing causing impulsive nature of vibration signature. As opposed to this, misalignment, eccentricity and geometrical imperfections such as race or element waviness and off-sized rolling elements are the distributed defects.

All machines whether in healthy or degraded condition vibrate since vibration is the exchange of energy between mass and spring. Overall vibration levels in the initial span of life is low and upon usage, over a length of time, wear of machine elements occurs causing change in the dynamic response during operation. Vibration based signature analysis techniques are based on periodic monitoring of the machine elements to assess their health. As such this technique is suitable for the elements which show periodic degradation upon usage. Gear and bearing are the machine elements which deteriorate over a length of time. This is the basis of vibration based signature analysis and has been the focus of predictive maintenance programs in a wide array of industries. Over the years there has been a revolutionary development in the electronic field encouraging the application of many signal processing techniques in bearing fault diagnostics and thus making the domain of vibration based signature analysis highly interdisciplinary.

### 1.1 Motivation for Present Work

When a defect strikes its mating surface, a pulse of short duration is generated as a result of sudden change in the contact stress. It is the frequency of pulse generation which is to be monitored and it describes the location of fault. This is the basis of Fast Fourier Transform (FFT) being adopted by many researchers over the years. Fourier transform is a classical tool for converting data into a form that is useful for analysing frequencies. When a defect present on one of the elements strikes its mating surface, corresponding defect frequency is excited referred as ball pass frequency of the corresponding surface. However FFT based approach is suitable for analysis of vibration signals that are produced by some periodic process. Fourier transform has limited success when the measured signal is buried in background noise or mixed with other signatures (for example, the signature of cutting process in machine tools like lathe). Additionally, the measured bearing vibration signal can also change because of fluctuating load condition. Due to change in dynamic response of the system, the vibration signature attains a non-stationary nature.

Several researchers have carried out theoretical investigations to demonstrate the mechanism of vibration generation in rolling element bearings due to single point and
multiple point defects. The mathematical model developed by McFadden and Smith [1, 2] describes the vibration produced by a single point and multiple defects on the inner race of a rolling element bearing. The vibration generated by bearing was modelled as a series of impulses at the rolling element passing frequency. The results of the theoretical model were verified through experimentation. Tandon and Choudhury [3] proposed an analytical model to predict the vibration frequencies of rolling element bearings and the amplitude of frequency components due to the presence of localised defects in different elements of a bearing. In few such theoretical studies, the impulse generated at the defect is modelled by half sine wave or triangular pulse. There are many such studies on the development of theoretical model and verification by experimental methods for bearing fault diagnostics.

For dynamic signal analysis, wavelet transform has been increasingly applied for system health monitoring. Peng and Chu [4] have presented a detailed review on the application of wavelet transform in machine condition monitoring. Several significant aspects discussed in the paper are time-frequency analysis of signals, the fault feature extraction, the singularity detection of signals, denoising of signals etc. While performing time-frequency analysis wavelet transform is best suited to extract fault features, de-noising and extraction of weak signals and singularity detection. Presence of periodical impulses indicates the presence of faults in bearings. However at the early stage of fault, these impulses are difficult to detect due to their weakness or these impulses may be buried in noise. In some studies, this issue is addressed by using wavelet based denoising methods and a method based on wavelet packet transform. While processing a signal with wavelet transform, selection of mother wavelet is a key step. Some researchers have proposed methods of selecting the best mother wavelet based on energy and Shannon entropy and their ratio. However in majority of the studies reported, the process of mother wavelet selection has remained ad hoc. While selecting a mother wavelet among multiple wavelet selection criteria, each criteria results in altogether different base wavelet making decision making on mother wavelet selection extremely challenging.

In view of this, the present study endeavours to establish guidelines for the selection of appropriate mother wavelet taking into consideration multiple wavelet selection criteria and mother wavelets from different wavelet families for processing the bearing vibration signals acquired from the experimental set up. Further this newly developed
technique is extended to present case studies on fault diagnosis of bearings of lathe machine tool and a pump. Secondly, it is noticed based on the theoretical studies that there is a scope for applying curve fitting techniques for modelling the impulse generated by striking of the defect as per the physical phenomenon as opposed to existing smooth impulsive nature of the pulse such as triangular, half sinusoidal or rectangular wave etc. This is achieved through a theoretical model which incorporates the blending functions of the cubic hermite spline to model the impulse generated due to impact at the defect.

1.2 Scope of Work

As discussed in the previous section, the present study focuses on the application of curve fitting techniques for modelling the mechanism of pulse generation caused by impact at the defect. Using such a technique helps in generating a pulse as per the physical happenings taking place inside the bearing when the defect gets struck. In the experimental domain, there are no comprehensive views on selection of mother wavelet among multiple selection criteria for processing the vibration signals acquired from the bearing. A detailed plan of the research work is as follows:

- To develop a mathematical model for studying vibrations of a ball bearing simulating localized defects on the outer and inner race using blending functions of cubic hermite spline.

- To develop a computer program in MATLAB incorporating cubic hermite spline for modelling the defect pulse and to study the effect of location of defect on the characteristic frequencies.

- To study the effect of defect size, load, change in angular position of the defect, presence of multiple defects on the vibration amplitude using above model.

- To design and fabricate an experimental setup for testing different defect free and defective ball bearings at different speeds and loads.

- To study the effect of degradation of bearings (effect of defect size), effect of variation of load on the vibration amplitude.
• To apply an advanced signal processing tool such as wavelet transform for fault diagnosis of rolling element bearings.

• To establish guidelines and propose a new strategy for selection of mother wavelet for processing vibration signals and the diagnosis of bearing faults.

• To extend the above strategy for condition monitoring and fault diagnosis of bearings of lathe machine tool and a pump.

1.3 Organisation of The Thesis

Chapter 1 deals with the introduction to rolling element bearings and sets the scope of work. Chapter 2 provides a comprehensive review of the literature on fault diagnosis of rolling element bearings and related systems. In this chapter along with the relevance of the study, different theoretical studies for explaining the vibration generation in bearings carried out by earlier researchers are discussed. The type of defects and the causes of vibration in bearing are also discussed. This is followed by the discussion on experimental studies in this field using FFT and wavelet transform based methods. Chapter 3 describes the theoretical model developed in this research for explaining the mechanism of vibration generation due to localized defects on the races of bearing. A detailed explanation of the curve fitting technique for modelling the defect pulse is presented and equations of motion are derived. Chapter 4 describes the experimental setup and instrumentation used for acquiring the vibration signature from rolling element bearings. This is followed by the description of case studies on fault diagnosis of bearings of lathe machine tool and a pump. Chapter 5 gives a detailed explanation of the methodology adopted in the research work for fault diagnosis. In chapter 6, the results of the theoretical model incorporating cubic hermite spline for studying ball bearing vibrations are presented. Secondly, the results of experimental studies performed on the setup incorporating the new strategy of mother wavelet selection are presented. Finally experimental results of pump bearing and bearings of lathe are discussed. Chapter 7 summarizes the conclusion drawn based on the mathematical model, experimentation and the case studies. This is followed by a brief discussion on the possible extensions to the developed mathematical model and the experimentation on bearing for future studies.