CHAPTER 2

# Literature Review

## 2.1 Introduction

This chapter presents an overview of the state of art of the existing diagnostic and prognostic procedures used in SHM. In today's competitive environment, very precise and safe operations of rotating machines are of prime importance. This can be achieved by proper health monitoring. Two main stages of health monitoring of SHM systems are fault diagnosis and fault prognosis. In the first stage, i.e., diagnosis, the forthcoming or early efficiencies/imperfections in the process and system are identified. In the second stage, i.e., prognosis, the life of the system and component at a particular time (under certain operational conditions) is estimated or predicted and the remaining time is known as remaining useful life (RUL). Both of the stages can be further classified based on the type of techniques as model-based techniques and data-driven techniques. In model-based techniques, detailed physical modelling of the system is carried out, and it required through the understanding of the dynamics of the rotor SHM systems. In data-driven techniques, a variety of data, such as vibration, sound, temperature, lubricant, etc., are extracted with the help of some suitable sensors.

These data are processed to interpret them in meaningful results. Various machine learning techniques, such as an artificial neural network (ANN), decision tree, random forest, Self-Organizing Map (SOM), Support Vector Machine (SVM), etc. are used for the analysis of collected data. On the other hand, some techniques utilize both; model-based techniques and data-driven techniques. In this chapter, the existing research related to health monitoring of SHMs has been reviewed and summarized. The various signal processing methods and their diagnostic capabilities can be divided into three stages:

## 2.2 Diagnosis of SHM Systems

### 2.2.1 Model-Based Analysis Techniques

Several modal based techniques for health monitoring of SHM systems have been proposed in previously published literature. SHM systems are one of the major sources of nonlinearity in rotating machines, which considerably affects the performance of the system. This motivates researchers to focus on nonlinear analysis of SHM systems. Having various sources, the nonlinearity in the rotor SHM system arises mainly due to the presence of radial clearance, damping, stiffness, etc. Many other imperfections such as localized and distributed defects are also responsible for nonlinear behaviour of the rotor SHM systems. Moreover, SHM systems generate vibrations, even if it is healthy, and the system is balanced. It is due to the use of the finite number of rolling elements to carry the load.

The various signal processing methods and their diagnostic capabilities can be divided into three stages:

First stage corresponding to the articles published before the year 2001, the Second stage refers to the articles published during the period 2001 to 2010,

and the Third stage pertains to the articles issued during the year 2011 to till date

## 2.2.2 Data-Driven Analysis Techniques

A variety of data-driven approaches have been developed and proposed for the last several years. These methodologies utilized the data, extracted using various techniques such as; vibration measurement, sound measurement, stator/motor current, and voltage signature, tribological observations, etc. Due to the ease of use, sensitivity towards faults, less time consuming, robustness, wide available range, and other several advantages, about 82 The signals, collected from rolling element bearings for health monitoring are broadly categorized into three domains; time domain, frequency domain, and time-frequency domain. Performance of health monitoring using various data-driven techniques depend upon the extracted data and assume that a healthy system has some relatively constant frequencies and statistical parameters. During operation, over some time, any malfunction in the system results in the variation of temporal and spectral features. The transient signals can be investigated using time-frequency domain techniques, such as Short Time Fourier transform (STFT), Wigner-Ville-distribution (WVD), and Wavelet Analysis (WA).

**Time domain analysis techniques** Time domain analysis is one of the most widely used techniques due to its simple pre-processing, speed independency, and ease of use. The investigations of rolling element bearings using time domain analysis are very simple as looking at the vibration signal. Alternatively, time domain statistical parameters such as peak value, Root Mean Square (RMS), peak-to-peak amplitude, kurtosis, skewness, crest factor

(CF), shape factor and synchronous averaging can be calculated. Dyer and Stewart (1978) and Mathew and Alfredson (1984) carried out experimental investigations on a taper roller bearing. The authors performed temporal analysis and extracted various statistical moments, i.e., mean, RMS, skewness, and kurtosis from the extracted vibration signals. The study proposed that although all the extracted temporal features are good indicators, kurtosis provides more information about the system. Tandon (1994, 1999) and Howard (1994) comprised the effectiveness of various time domain indicators for rolling element bearings. Martin and Honarver (1995) and Honarver and Martin (1997) have further investigated various temporal moments and concluded that time domain analysis is an economic tool for maintenance and quality control of rolling element bearings. Several temporal features such as; mean, RMS, skewness, kurtosis, crest factor, peak value, peak-to-peak amplitude, shape factor, form factor and many more have been successfully employed in various investigations of rolling element bearings. Williams *et al.* (2001) studied three time- domain indicators, i.e., RMS, kurtosis, and crest factor for the health monitoring of rolling element bearings and observed significant variations in the responses of these indicators. Samanta and Al-Balushi (2003) and Samanta *et al.* (2003) analysed the third and fourth central moments, i.e., skewness and kurtosis. The authors employed ANN and SVM for the diagnosis of bearing faults and summarized that both the even and odd moments are equally capable of representing bearing health effectively. The authors also concluded that the extracted temporal features characterize good separability between healthy and various defective conditions of bearing. Stack *et al.* (2004) studied the effect of generalized roughness on bearing components. In this work, the authors highlighted that before the formation of any known defect, the roughness of the surface increases, and its response is different from the other types of defects. Malhi and Gao (2004) classified the various fault severities in rolling element bearings. The authors considered defects in the inner race and outer race of the bearings and employed principal component analysis (PCA) for the selection of extracted temporal, spectral, and wavelet-based features. Results highlighted that selected features improved the fault severity classification. Ericsson *et al.* (2005) proposed a framework for fault detection of rolling element bearings, in which kurtosis and crest factor are utilized as condition indicators. Saxena and Saad (2007) extracted first and fourth central moments of time domain for the investigations of rolling element bearings.

The authors utilized a Genetic Algorithm (GA) along with ANN and summarized that the proposed approach is a powerful technique for bearing health monitoring. Zhang and Nandi (2007) proposed a Genetic Programming (GP) based framework for the classification of bearing faults. The authors employed three machine learning techniques viz. ANNs, SVMs, and GAs for the analysis. Central to the explanation, binary GP scheme provides good classification performance over the others. Abbasion *et al.* (2007) classified the single-level fault severities in rolling element bearings. The author's employed wavelet transform (WT) for the denoising of vibration signals. The classification has been performed using SVM and faults in various components have been classified.

Lei *et al.* (2008) developed a fault diagnosis methodology based on statistical analysis and adaptive neuro-fuzzy interface system. The authors extracted several statistical features and employed distance evaluation technique for the selection of features. Results highlighted that the performance of the classifier could be improved significantly in the presence of extracted features. Xu *et al.* (2009, 2016) developed an improved fuzzy ARTMAP (IFAM) framework for the diagnosis of faults in rolling element bearings. The authors extracted various temporal features and utilized the modified distance discriminant technique for the selection of most appropriate features. Results highlighted that the proposed technique provides reduced training and testing time of the classifier.

Wang *et al.* (2009, 2013) proposed a Gaussian mixture model and a hidden Markov model for bearing fault classification. The authors consider three fault severities in bearing components and observed accurate results. Samanta and Nataraj (2009) used linear and nonlinear Proximal Support Vector Machine (PSVM) for the fault detection of rolling element bearings. The authors employed Particle Swarm Optimization (PSO) to select the extracted temporal features and concluded that nonlinear PSVM provides improved diagnosis results. Various statistical features viz. kurtosis, standard deviation, range, mean value are also utilized for the diagnosis of rolling element bearings (Kankar *et al.*, 2011 (b); Kappaganthu and Nataraj, 2011). These investigations utilized SVM and ANN and proposed that the selected features are sensitive to provide considerable fault identification accuracy. Wang *et al.* (2012) classified the faults in rolling element bearings using Hyper-Sphere-Structured Multiclass Support Vector Machine (HSSMC-SVM). The authors summarized that the Empirical Mode Decomposition (EMD) approach is an effective scheme for fault classification and requires less time. Zhang *et al.* (2013) and Bordoloi and Tiwari (2013) employed SVM for the fault classification in rolling contact elements. The authors considered various temporal features in their investigations and observed significant improvements.

Recently, Gangsar and Tiwari (2014) and Bordoloi and Tiwari (2014 (a)) classified various faults in rolling element bearings and gears using improved SVM. The authors employed SVM and v-SVM for the investigations and used the grid search technique, GA and Artificial Bee Colony Algorithm (ABCA) for the SVM parameter optimization. These works proposed that the classification performance of SVM is more superior at high speeds than the lower ones. Wang *et al.* (2015) extracted various dimensionless temporal features such as shape factor, crest factor, impulse factor, clearance factor, and others along with various conventional temporal features for fault diagnosis of rolling element bearings. Singh and Kumar (2015) utilized ANN and SVM for the diagnosis of rotor faults. The authors performed experimental investigations and extracted time domain indicators for the examinations. Results highlighted that under similar conditions, SVM outperforms than the ANN.

Catastrophic failure of the bearing and the associated system can be reduced significantly with known defect severity. Moshou *et al.* (2010) have extracted statistical features for the defect severity estimation in rolling element bearing. The authors have quantified the defect severity by graphical representation of SOMs. Jiang *et al.* (2012) have extracted residual signals and statistical features from the conducted experiments to quantify the defect severity. The Multi-Frequency Band Energies (MFBEs) are also extracted from the acquired signals and summarize that varying trend of residual signals can be a useful tool for defect severity estimation.

Various feature ranking techniques have been used in the literature on rolling element bearing applications. Feature ranking techniques improve the computational efficiency and rank the features based on the information content about the states of the system. In this process, the features are ranked in such a way that the feature which carries the most significant information is ranked at the top. A variety of feature ranking techniques have been used and reported in the literature. Malhi and Gao (2004) proposed the principal component analysis-based framework for the selection of appropriate features. Samanta *et al.* (2006) utilized GA for the selection of appropriate features for bearing fault diagnosis. The authors employed ANN for the analysis and summarized that significant improvements could be obtained using the proposed feature selection technique. Sugumaran *et al.* (2007) used SVM and Proximal Support Vector Machine (PSVM) for the fault diagnosis of rolling element bearings using statistical measures. The authors utilized a decision tree technique for the selection of optimal features. The study summarizes that SVM and PSVM show superior performance in the presence of optimally selected features.

Zhao *et al.* (2010) conducted an extensive study and proposed various feature ranking techniques such as Chi-square, information gain (IG), and Relief. The authors also compared the performance of these ranking techniques. Kappaganthu and Nataraj (2011) proposed the concept of mutual information for the ranking of features. The authors conducted experimental investigations and found that the proposed approach helps find out the most appropriate features which significantly improve fault diagnosis efficiency.

**Frequency domain analysis techniques** Frequency domain analysis provides a more informative signature and has the advantage to locate the fault in bearing components. The frequency domain analysis deals with the examination of vibration signals involving frequency analysis and often considers the periodicity of impulse in vibration due to defects. The bearing generates frequencies during the operation and each bearing component, i.e., inner race, outer race, and rolling elements, has its distinct frequency called bearing characteristic frequencies. These characteristic frequencies have predetermined values for a specified bearing at a particular speed. Whenever any defect is generated in any of the bearing components, impulses are generated because this defect strike during operation and characteristic defect frequency in the frequency spectrum appear due to these impulses. This frequency can be calculated with the help of bearing geometry and its rotating speed. In frequency domain analysis, these excitations are used to detect the defect in rolling element bearings. Due to these advantages, frequency domain features are preferred and employed for precise investigations.

Braun and Datner (1979) utilized various bearing characteristic frequencies for the analysis of bearing vibrations. Liu and Mengel (1992) examined the performance of ball bearing using frequency domain parameters. The authors extracted three frequency domain features, i.e., the peak amplitude of frequency domain, percent power, and peak RMS and employed ANN for the investigations. Results highlighted that spectral features, along with the ANN, can successfully diagnose the bearing condition. Tandon and Choudhury (1999) reviewed some vibration and acoustic methods for the detection of defects in rolling element bearing and summarized the advantages of frequency domain techniques over the other. Williams *et al.* (2001) examined ball and roller bearings at varying speeds using bearing characteristic frequencies. The authors observed that characteristic frequencies are useful in the identification of defective bearing component. Abbasion *et al.* (2007), Hao and Chu (2009), Zhu *et al.* (2009) and Kappaganthu and Nataraj (2011) presented an experimental study for the diagnosis of localized faults in rolling element bearings. The authors utilized various bearing characteristic frequencies and observed the superior performance of the classifier.

Lei *et al.* (2008) proposed an Adaptive Neuro-Fuzzy Interface System (ANFIS) for the detection of faults in rotating machinery. The authors extracted several frequency domain statistical characteristics from the available vibration signals and observed an enhancement in the generalization performance of the classifier. An improved fuzzy ARTMAP (IFAM) framework for the diagnosis of rolling element bearings was suggested by Xu *et al.* (2009). The authors extracted several frequency domain parameters such as mean frequency, coefficient of variability, frequency domain skewness, frequency domain kurtosis, RMS ratio, etc. for the investigations and proposed that the extracted features have significant contribution in fault diagnosis. Zhang *et al.* (2013) utilized Kernel Principal Component Analysis (KPCA) and Particle Swarm Optimization Support Vector Machine (PSO SVM) for the identification of bearing health. The authors used several frequency domain features viz. frequency centre, RMS frequency, standard deviation frequency, spectrum peak ratio inner, and spectrum peak ratio outer for the investigations. Results highlighted that the proposed methodology identifies the state of bearing and performance of degradation successfully. Li *et al.* (2013) investigated and classified the localized faults in cylindrical roller bearing. The authors utilized bearing characteristic frequencies and kurtosis for the examination and observed good classification efficiency. A fault diagnosis framework, in which the extracted spectral features are reduced using Statistical Locally Linear Embedding (S-LLE) dimensionality reduction technique, was proposed by Wang *et al.* (2015). The authors employed K-Nearest Neighbour (KNN) classifier and SVM for the investigations and observed promising results.

**Time-frequency domain analysis techniques** Several time-frequency analysis techniques have been proposed in the last two decades for the health monitoring of rolling element bearings. The time-frequency domain analysis can be performed basically in three ways as; Short Time Fourier Transform (STFT), Wigner-Ville distribution (WVD) and Wavelet Analysis (WA). These techniques analyse the signal in both the time domain and frequency domain simultaneously. These techniques are very useful for the signals in which the signal to noise ratio is low, and there is no clear peak of excitation. However, due to the better time-frequency resolution of WA over the STFT and WVD, it is the most widely used time-frequency analysis technique (Tse *et al.*, 2001).

Brotherton *et al.* (1992) investigated the fault detection in rolling element bearings and gears using STFT and WA and employed ANN for the analysis. Mori *et al.* (1996) proposed a Discrete Wavelet Transform (DWT) framework for the rolling element bearings. The authors investigated the presence spalling on bearing components and summarized that WA is a useful tool even for the detection of pre-spalling. Paya *et al.* (1997) performed experimental investigations for the diagnosis of faults to bearings. The authors employed WT and ANN for the examinations. This work proposed that the combination of WT and ANN is an intelligent way for the diagnostics of rotary machines. Tse *et al.* (2001) carried out an experimental analysis for the investigations of rolling element bearings. The authors used WA for the analysis and summarized that WA is a simple and flexible inspection method for health monitoring. Prabhakar *et al.* (2002) used DWT for the identification of defects in races of the ball bearing. Results highlighted that DWT is an effective tool for the detection of single and multiple faults in ball bearings. Chen and Mo (2004) proposed an intelligent fault diagnosis framework for the health monitoring of rotating machinery. The authors examined the system using WT and ANN and highlighted the good generalization capability of the proposed method. Abbasion *et al.* (2007) employed SVM along with WA for the classification of faults in rolling element bearings. The authors used discrete Mayer wavelet and obtained good classification efficiency of the classifier. Wang *et al.* (2008) used a time-varying autoregressive model for the classification of faults. The authors utilized a time-frequency spectrum for the analysis and concluded that the proposed methodology is capable of identifying the faults accurately.

Guo *et al.* (2008) investigated the Hilbert envelop spectrum and SVM for classification of faults in bearings. The authors performed experimental investigations and summarized that the proposed framework is capable of diagnosing the multiclass severities effectively. Wang and Kanneg (2009) investigated the performance of a geared system using wavelet energy. The authors proposed an integrated classifier which consists of the neural network. The authors performed experimental investigations for the validation of the methodology and obtained encouraging results. Hong and Liang (2009) and Wang *et al.* (2013) used Lempel-Ziv complexity and Continuous Wavelet Transform (CWT) based model to quantify the defect severity. The authors concluded that Lempel-Ziv measure, as the nondimensional index can be used for fault severity estimation.

Rafiee *et al.* (2010) examined 324 mother wavelets for their effectiveness towards the gear and bearing fault diagnosis. The authors carried out experimental investigations for the analysis and concluded that Daubechies 44 (db44) is one of the most efficient mother wavelets for the investigations of rolling contact elements. Kankar *et al.* (2011 (c), (d)) proposed a wavelet selection criterion for the investigations of rolling element bearings. The authors utilized CWT and suggested energy to Shannon energy ratio framework for the analysis. In this work, the authors employed SVM, ANN, and SOM and observed the best performance of SVM for the bearings. Yaqub *et al.* (2011) presented a defect severity estimation model based on wavelet packet decomposition and SVM. The authors also extracted various statistical features for the severity estimation. Bordoloi and Tiwari (2014 (b)) optimized the parameters of SVM for the classification of faults in gears. The authors used a genetic algorithm and the artificial bee colony (ABC) algorithm for the optimization and utilized a Wavelet Packet Transform (WPT) for the analysis. Results highlighted that SVM, along with WPT, provides significant improvements.

Based on the advantages and suggestions of literature, the authors utilized temporal features and some measures of uncertainty for the multi-fault classification of localized faults in rolling element bearings. Besides that, the advantages of various feature ranking techniques motivated the authors to explore their applicability in fault severity estimation. In present work, a generalized approach is proposed for the selection of extracted features, based on ten-fold cross-fold validation, which provides statistically unbiased results.

## 2.3 Prognosis of SHM systems

### 2.3.1 Model-Based Analysis Techniques

Relatively few attempts have been made towards the model-based approaches of RUL estimation. Model-based techniques include detailed physical modelling of the system, which can provide accurate results. However, it is challenging to model the real-world system accurately because of the stochastic nature of the failure. Ioannides and Harris (1985) proposed a fatigue life model for bearings. In this work, the authors have developed a statistical relationship between the probability of survival and the fatigue life of the bearing and proposed that the developed model is also compatible with other fatigue-prone machine elements. Zaretsky *et al.* (1996) compared various life models theories of bearings such as; Weibull (1939), Lundberg and Palmgren (LP) (1947) and Ioannides and Harris (IH) (1985). Harris and

McCool (1996) have also presented a comparative study between two life prediction theories, i.e., LP theory and IH theory. The authors summarized that IH model is better for both of the ball and cylindrical roller bearing applications. Li *et al.* (1999 (a), 1999 (b)) proposed an adaptive framework for the prognosis of bearings. The authors utilized the deterministic defect propagation model based on the Pariss formula and a fine-tuned adaptive algorithm for the prediction of defect propagation. The authors performed numerical simulations and experimental investigations for the analysis and observed good synchronization between the obtained results.

Li *et al.* (2000) developed a stochastic defect progression prognosis model for SHMs. The authors performed theoretical investigations and concluded that the proposed model provides the early predictions for the life of bearings. Later, Yu and Harris (2001) proposed a stress-based fatigue life model for ball bearings. The authors compared the developed model with the previous studies, i.e., the LP model and IH model and summarized that the proposed model outperforms than the previous studies. Zhang *et al.* (2001) examined the RUL of bearing using the damage curve approach. The authors presented an SHM prognostic model and performed experiments for the analysis. Results highlighted that the life of the SHM system could be effectively estimated by proper monitoring and analysing of vibration signals. Qui *et al.* (2002) proposed a similar approach as Zhang *et al.* (2001) for the prognostics of bearings, based on the damage curve approach. However, the authors observed a relationship between the spectral features, bearing running time and the bearing lifetime and proposed that the life of bearing can be examined effectively through the vibration signals of SHM. *et al.* (2006) presented the proportional hazard model and the logistic regression model for the RUL examination of bearings. The authors also provided a statistical interface in this work and observed encouraging results. Marble and Morton (2006) proposed a spall propagation model for the bearing examinations. The authors considered the surface roughness and statistical parameters in the analysis and obtained good accuracy in the results. Wang (2007) developed a two-stage prognosis model for ball bearings. In this model, the author assumed the first stage as a healthy period and second stage as a defect development, progression, and failure period. The authors performed several theoretical investigations and summarized that the proposed model is useful for vibration-based monitoring applications in which the two-stage life process is observed.

### 2.3.2 Data-driven analysis techniques

Broadly, the data extracted for RUL assessment can be divided into two categories; instantaneous data and Condition Monitoring (CM) data. Instantaneous data contain information about the particular event, and these are less useful. On the other hand, CM data contain useful information for RUL prediction (Si *et al.*, 2011). Further, CM data can be subcategorized into two categories; direct CM data and indirect CM data, as shown in Figure 2.1. Direct CM data comprise indicators such as wear and crack growth. These indicators, if possible, can be monitored directly and used to estimate the RUL of the system. However, indirect CM data includes the data which provide insight into the system. A variety of data such as; lubricant properties, temperature, vibration, acoustic emission, current, voltage, loading conditions, pressure, humidity, moisture, etc. are considered in indirect CM data for assessment of RUL. The performance of data-driven techniques relies upon the condition monitoring data and assume that a healthy system has some relatively constant frequencies and statistical parameters. During operation over some time, any faults in the system result in variation of spectral and temporal features (Kim *et al.*, 2012).

Shao and Nezu (2000) proposed a progression-based approach for the investigations of bearing life. The authors used ANN and Autoregressive Moving Average (ARMA) for the analysis and utilized RMS value as an indicator. The authors highlighted that under various fluctuating conditions, the proposed framework has better prediction capabilities over ARMA models.

Williams *et al.* (2001) performed a run-in-failure lifetime testing of bearing. The authors analysed the system using various sensors such as; thermocouple, pressure flow transducer, magnetic contact probe, wear site sensor, vibration, and an acoustic sensor. This work provides insight into various statistical parameters with the fault propagation. Zhang *et al.* (2002) performed accelerated life testing on tapered roller bearing considering the environmental effects for the prognosis. The authors assumed only the stresses of acceleration for the investigations and observed very fewer residual errors in the study. Qiu *et al.* (2003) employed WT and SOM for the life assessment of bearings. The authors utilized Morlet wavelet for the de-noising of the signals and observed that the proposed methodology indicates the state of the system. Later, Qiu *et al.* (2006) proposed a prognosis framework for bearings. The authors presented a wavelet filter bank methodology for the extraction of weak signals from the acquired vibration

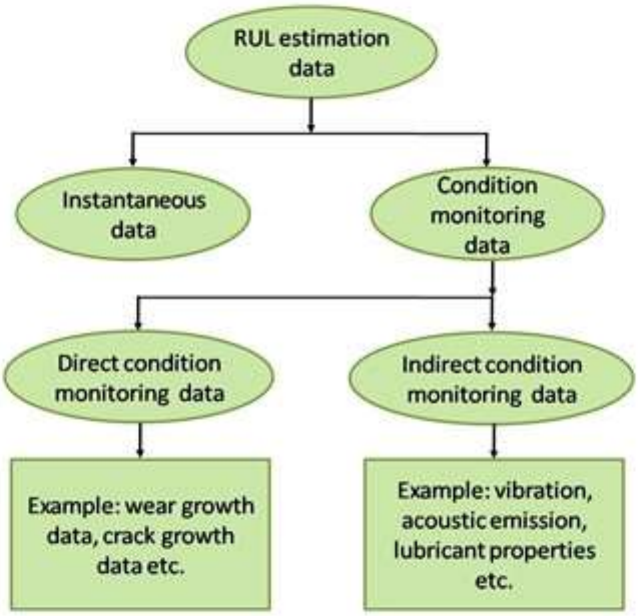


Figure 2.1: Classification of data acquired for RUL prediction

signals. Results showed that the weak signals provide significant information before the failure of the system.

Wang *et al.* (2004) carried out experimental investigations for the assessment of gear health. The authors studied and compared the prediction capabilities of the neuro-fuzzy (NF) method and Recurrent Neural Networks (RNNs) to predict RUL of geared system. Results showed that the NF approach has better capabilities than that of RNN method. Gebraeel *et al.* (2004, 2008) conducted experimental investigations for the prognosis of bearings. The authors utilized histories of partially degraded bearings and ANNs for the analysis. The authors used the remaining updated life of bearing and concluded that the proposed methodology has good synchronization between actual and predicted results. Samanta and Nataraj (2008) used Support Vector Regression (SVR) and ANFIS for the prognosis of gears. The authors examined various conditions of gears and highlighted the effectiveness of the methodology. Tian *et al.* (2010) and Tian (2012) developed an ANN-based model for the remnant life of SHMs. The authors used various failure and suspension histories to train the proposed model and highlighted that the prediction capabilities of neural networks could be improved significantly by reducing the noise level of vibration data.

Benkedjouh *et al.* (2013) suggested a data-driven framework for RUL analysis of bearings. The authors used isometric feature mapping technique for the dimensionality reduction of extracted features. Results showed that RUL prediction accuracy could be improved significantly through the optimally parameterized process. Loutas *et al.* (2013) used various spectral and temporal features for the analysis of bearings. The authors employed SVR for the examination of RUL, along with various prognostic performance measures.

Li *et al.* (2014) proposed a Strong Tracking Particle Filter (STPF) technique for the life calculations of bearings. Various statistical features viz. mean, arms, skewness, etc. are extracted for health monitoring of bearing. The authors employed SVR and reduced the dimensionality of features using local linear embedding (LLE) dimensionality reduction technique. Results highlighted that the proposed framework provides a satisfactory life prediction of SHMs. Hong *et al.* (2014) utilized a data-driven model for health assessment and life estimation of SHM using Empirical Mode Decomposition (EMD) and SOMs techniques. The authors investigated various health stages of bearing for life calculations using the confidence value at each stage and concluded that the proposed methodology provides higher prediction accuracy.

Soualhi *et al.* (2014) suggested an adaptive methodology for RUL examinations based on Artificial Neuro-Fuzzy Interface System (ANFIS) and HMMs. The authors utilized statistical features for the analysis and found them suitable for stable state analysis. The authors summarized that the proposed approach provides satisfactory results when the prior knowledge of bearing degradation stages is available.

Singleton *et al.* (2015) analysed Extended Kalman Filtering (EKF) approach for the life assessment of SHMs. The authors used various time, and frequency domain features to assess bearing faults. A comparative study between EKF and regular Kalman filtering (KF) approach was carried out for the investigations. The applicability of some features was also analysed under various operating conditions for the life examination. Results showed that the prediction capabilities of EKF were superior over regular KF approach.

Ali *et al.* (2015) proposed an ANN-based framework for the RUL prediction of bearings. The authors employed Weibull distribution and utilized temporal features viz. RMS and kurtosis for the investigations. The authors summarized that the proposed methodology provides satisfactory RUL estimations. Recently, Lei *et al.* (2016) presented a two stepped module for RUL estimation of bearings. In the first module, the authors constructed an indicator, while in the second stage, the RUL predictions have been performed. Results show that the proposed method outperforms among the other compared methodologies.

Quian et al. (2016) investigated the remaining life using Phase Space Warping (PSW) and Paris crack growth model for the analysis. The authors concluded that the presented approach effectively estimates the RUL of bearing with good reliability.

In the proposed literature of RUL of SHM systems, the investigations have been carried out using the features of vibration, temperature, etc. However, in previous studies of RUL, the wear propagation has not been considered. In present work, besides the life assessment, the authors also analysed the possible causes of wear of the bearing and examined the three components of bearing, i.e., inner race, outer race, and rollers, at various operating hours of the bearing. It helps in detailed and insight analysis of the system. This work also utilizes diffusion mapping (DM) dimensionality reduction (DR) technique due to its various advantages over the other considered techniques in the literature (Maaten *et al.*, 2009) for the reduction of extracted features.

## 2.4 Outcome of Literature Review

The review part indicates the possibility of researching various dimensions listed as follows:

(1) Most of the signal analysis methods concentrate on the single point defects only and therefore, present study is focused towards the simultaneous detection of multiple faults i.e. compounded faults.

(2) There is a growing need of setting up signal processing methods, adaptive to the continuously changing defect conditions, during the bearing degradation phases.

3) There is a need of customized artificial intelligence techniques such as artificial neural networks, support vector machine, deep learning CNN etc. for dealing with big data size of diagnosis and prognosis.

(4) If one intends to apply machine learning methods for structural health monitoring by using vibration signal, there has been no available criteria for the minimum size of data required for the diagnosis. Moreover, if the data size falls insufficient, how could it be modified for feature extraction and feature selection?

This gap of machine learning process is addressed in the present work.