Vibration Signature Analysis and Fault Diagnosis of Machines Using Neural Networks: A Literature Review

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Abstract: Machine maintenance is a key to every manufacturing unit as machine performance ultimately affects the output which determines the operational efficiency and productivity. The major constituents are the different types of faults being generated leading to downtime, rejections, rework apart from the waste of resources such as material, manpower, energy/power, capital etc. As an attempt to improve the operational effectiveness of a machine it is essential that the faults may be detected and diagnosed well before its occurrence to avoid breakdown during machine operations. Amongst many ways of detecting the health of machine, vibration analysis is one of the best means to detect fault occurring in machine due to variation in its parameters. The vibration signature analysis is useful in identifying the likely occurrence of fault during condition monitoring of machines. In this paper a literature review is carried out as an objective to assess the development and contribution by researchers in the field of machine fault diagnosis based on vibration signature analysis using neural network.

Keywords: Machine Fault diagnosis, Vibration signature, Pattern recognition, Time and Frequency domain analysis, ANN

1 Introduction

In modern industry, equipment and machinery are very important part of the total productive effort. A higher machinery cost doesn't permit breakdown time. Plant maintenance is a vital service function wherein condition monitoring gained wider acceptance. The use of human senses and other sensitive instruments like audio gauge, sound, vibration analyzer, and amplitude meter etc. are used to predict troubles before failure. Vibration signature analysis uses the real time vibration signals from machines for analysing machine health & fault diagnosis. To check the mechanical and operating condition, vibration is the sensitive, accurate and reliable indicators of machine. With appropriate sensor it can identify the specific source or the defective part.

1.1Research Motivation: The contribution by researchers revealed the work carried out to identify the defects/faults, source of occurrence and causes by diagnosis of vibration signals. The vibration measurement, and fault detection methods used were tedious and not cost effective. The vibro-sensors were costly and the set up required for interfacing were complicated. Fault diagnosis is a common and regular affair in big industries whereas a systematic procedure is used for the maintenance as the rejection and poor quality of the product does not allow the manufacturer to compromise. In SMEs the awareness and facilities available are very limited and hardly any attention is paid in this regard. A suitable cost effective fault detection system may help these SMEs to identify faults in machines and could enhance their productivity and cost effectiveness. The present research work aims to help out SMEs from the problems of fault diagnosis. It includes development of a system which shall detect, measure, and diagnose the problems in small capacity machines like lathe by recording real time vibration signal.

The machining process on lathe machine is invariably accompanied by vibration in the tool, workpiece, machine elements as drives, bed, tool post etc. The vibration may occur due to inhomogeniety in work material, tool condition, cutting parameters, machine loading conditions, lubrication, chatter, imbalance mechanism etc. Machining is subjected to both static and dynamic loads. The dynamic forces act to cause forced, free or self-excited vibration. Dynamic rigidity and stability is key [2] which adversely affect on the performance of machine.

It is imperative to diagnose and avoid failure of any possible kind in machines. Each machine generates a unique vibration signals for a typical failure has its own frequency base. This has encouraged to develop vibration signal based fault diagnosis system..

The research work under consideration is to develop a fault diagnosis system based on vibration signature analysis using artificial neural network. In this regard a comprehensive literature study conducted in the area of vibration bahaviour by condition monitoring, vibration monitoring, pattern recognition, vibration signature analysis, fault detection from vibration signature analysis and vibration signal time domain, frequency domain, time-frequency domain analysis, analysis of the statistical parameters and the application of the concept artificial neural network in each.

1.2 Lathe machine faults and identification: Lathe is widely used for machining purpose. Driving mechanism, spindle and spindle mountings, slide and slide-ways, tool holding device, carriage etc. are majorly responsible for the performance of the machine. The failure of any or combination of these may produce defective parts. Also cutting parameters and work material are responsible for defectives. The defectives thus produced are due to the faulty conditions emerged in the machine due to variation in one or combination of these or failure of the machine parts. The faults observed are many and a particular fault is very difficult to associate with failure of an independent machine part. All machines vibrate under normal operating condition which has no implication on the performance but variation in any of the parameter causes the machine to vibrate beyond the normal range leading the machine to fall under faulty condition, forcing for early break down, reduced life, more defectives etc.

1.3 Condition Monitoring: It is an effective mean for detecting faults by monitoring condition or health of machine by extracting the feature and classification of fault condition. It assess the state of a machine and determine the reason for malfunction through observation (William et al., 1992).[1] The vibration-based condition monitoring approach is based on the ideology that all systems produce vibration. On no fault condition, vibration is small and constant; however, when faults emerges and dynamics in the machine changes, the vibration spectrum changes (Marwala, 2001) [2].

1.4 Vibration Analysis: Vibratory motion is inherent to all types of machinery typically measured in terms of either physical response or sound produced. The vibrations may be mechanical and acoustic Vibration behavior is a prime indicator of machinery condition and so plays a key role in machinery diagnostics and health monitoring.[10]

Vibrations is a serious problem influencing manufactured parts quality, precision, tool life, machine performance and cutting rates[31]. Tools wear data shows that the severity of chatter greatly reduces the life of cutting tools. [32] Taylor suggested, chip formation is responsible for chatter. Kudinov and Shteinberg considered, periodic effect of built-up-edge formation can excite vibration.[33] Braun S. and B. Datner[19] described a method aimed at detecting localized defects. Pratesh Jayaswal [20] made specific contribution in the field of vibration based machine fault signature analysis for different machine parts. **C**omparing frequency spectra recorded at different times on the machine can effectively detect fault at early stage. A reference spectrum compared with current spectrum, as individual frequencies or frequency ranges diagnose the rate of fault deterioration. In measuring and trending vibration signal's, crest factor is a good indication of the condition machine parts [21]. Kirby and Chen, (2007) determined mean amplitude of vibration using accelerations in both directions along the axes. Taskesen (2005) proposed on-line vibration control system in turning to measure the relative vibration between tool and work piece.

An experiment shows the variation and influence of cutting conditions on vibration frequency of machine and its relationship to the cutting condition [34]. The variation in material, tool, machine parts, mechanism, lubrication condition, disturbances from adjoining machines causes vibration being introduced.[35]. Experiments revealed that cutting parameters have an effect on the amplitude and natural frequency of vibration in tool. M. Thomas et al 2003, observed that increase in cutting parameters increases vibration, [36]. K Sampath, et al 1988 studied a cutting sound prediction model to relate vibration by scaling the effect of different machining parameters and its impact on changing conditions. Lars Hakansson, observed a frequent problem of vibration induced by metal cutting [37]

2.1 Fault detection: Vibration analysis is useful to evaluate current machine condition, diagnose faults, monitoring and trending behaviour. This includes vibration measurements and frequency analysis. Renwick & Babson [28] achieved significant results in diagnosing machinery problems. Weqerich demonstrated a non-parametric model using smart signal for detecting faults in rotating machinery via extracted features from vibration signals [29]. Lei [30] addressed damage diagnosis approach for time series analysis of vibration signals for the structural health monitoring problem.

2.2 Vibration signature analysis; It is used to analyse vibrations in various parts of a machine and provides data and graphical pattern to predict or analyse life of the component. Vibration signature analysis gives the permissible limit of vibrations for a particular component beyond which the component may fail. Vibration signature analysis can monitor and supervise any component of a machine and give the mathematical reasons for quick maintenance and fault finding.

2.3 Pattern recognition: Pattern recognition is the study of how machines can observe the environment, learn to distinguish patterns of interest from their background, and make decisions about the categories of the patterns. Pattern recognition is intended to continually monitor the health of the machine by recording systematic signals or information derived in the form of mechanical vibrations, noise signals, change in smell, relative displacement, and so on [25].

Mann [26] explored the benefits of such methods compared with traditional one. Nandi and Toliyat [27] presented a review on fault diagnosis of machines based on pattern recognition.

Machine recognition, description, classification, and grouping of patterns are important issues in variety of engineering and scientific fields. A pattern could be anything (e.g. a trend, signals images etc). Pattern recognition includes supervised and unsupervised classification [23]. A long series of researches still could not bring out a general purpose pattern recognizer. Human are still the best recognisers though how mankind does is yet not known. Ross [39] emphasizes the contribution of Nobel Laureate Herbert Simon on pattern recognition for decision making: Better and relevant pattern leads to better decision. A pattern recognition system comprises of data acquisition and preprocessing, data representation and decision making. Some of the pattern recognition approaches are template matching, statistical classification, structural matching, and neural networks. Among these statistical approach has been more popular and widely adopted. The addition of ANN theory succeeded in gaining attention as pattern recogniser. [22].

2.4 Statistical Analysis: Vibration signal can be well manipulated to get pattern using time and frequency domain analysis. The statistical approach to both time and frequency analysis make them more predominant. Time domain are sensitive to impulsive oscillations, such as peak level, (rms) value, crest factor, kurtosis and many more. (Ocak and Loparo, 2004[5]; Li et al., 2000)[6] Ericsson et al. (2004) showed that unlike frequency domain analysis, the time-domain analysis is less sensitive to suppressions of the periodicity. The frequency domain involves frequency analysis of vibration signals monitor at periodicity of high frequency transients. In the processes, the frequency domain methods search for repetitions occurring at any of the characteristic defect frequencies. The time-frequency domain analysis showed how the frequency contents of the signal changes with time. The examples of such analyses are: Short Time Fourier Transform (STFT), the Wigner-Ville Distribution (WVD) and most commonly the Wavelet Transform (WT).

3. Data Acquisition system:

Condition monitoring is one of the most effective mean for detecting faults in machines and equipments. This can be achieved by extracting the features and classification of fault condition. It involves collection, processing, and interpretation of data relating to the condition of critical components in the machine to predict the fault in advance thus reducing the frequency of breakdowns. This not only identifies the failure of a system, but also predicts its symptoms (Wang, 1989) [17]. Vibration signals are used to compare the signals of a machine running in normal and faulty conditions. In experiments conducted on lathe, vibration signal in tangential and axial direction for machine variables were measured through a vibrometer data acquisition system. The effect of cutting parameters were evaluated to observe that vibration velocity level increases as the cutting speed, depth of cut and feed rate increases.

3.1 Measurement Sensor Systems: Many sensors are available for tool condition monitoring system namely; touch sensors, power sensors, vibration sensors, temperature sensors, force sensors, vision sensors, flow sensors, acoustic emission sensors and so on. Many researchers conducted case studies and experiments in the areas of vibration monitoring of turning machine to review the techniques of faults diagnosis using sensors and analysis vibration signatures. S. S. Abuthakeer's developed an experiment showing the behavior of the machine for given cutting condition within the operating range. Julie and Joseph, 2008[18] demonstrate tool condition monitoring approach in machining operation based on the vibration signal collected through a low-cost, microcontroller-based data acquisition system. Marlon C. Batery and Hamid R. Hamidzadeh, 2007 has done analytical and experimental vibration analyses for a lathe system to detect the possibility of faults and to develop an accurate cutting process to analyse the vibration signatures and to determine cause of inaccuracy in the manufacturing process and faulty components. Kirby and Chen,(2007) determine mean amplitude of vibration using acceleration in both direction along the axes. Taskesen (2005) proposed a vibration control system for turning operation to measures the relative vibration between the cutting tool and the work piece using accelerometer and active vibration controller. Jagadish M. S. and H. V. Ravindra proposed data acquisition for lathe to measure vibration severity for different spindle speed.

4. Data Analysis

As a part of research activity the efforts are focused on a lathe machine wherin the potential for variety of fault conditions makes it an ideal case. A lathe consisting of headstock, tailstock, carriage, feed mechanism, electrical and coolant systems and each system has several elements. For fault diagnosis the identification of ailing systems could be based on the data available on failures and their frequencies. Many parameters for monitoring a machine is proposed by Johansson [6]. Machine condition monitoring by vibration measurement has emerged as trustworthy method in manufacturing.

Signal processing techniques analyse the time and frequency spectrums, by determining the normal and defective frequencies of various machine parts. The amplitude of vibration signature gives an indication of the severity of the problem, while the frequencies indicate the source of the defect. The difficulty in identifying wide range of defect frequency in spectrum, time and frequency domain methods are developed [2].Time domain methods usually involve indices that are sensitive to impulsive oscillations, such as peak level, rms value, crest factor analysis, kurtosis and shock pulse counting [3]. Since it is difficult to identify defect in direct spectrum many spectral techniques such as Adaptive Noise cancellation, HFR Technique or Envelope Detection and Wavelet Transform are applied. A comparative study of some vibration parameters for defect detection [8] has shown encouraging results. The researches in manufacturing have reported for condition monitoring using vibration signals for cutting tools [9] bearings and other failures in machine tools. This exemplifies that emphasis is on qualitative interpretation of vibration signatures both in the frequency and time domain, the useful reviews of which are available in text form, including detailed charts of machinery fault analysis [10-12]. Statistical methods are more common ways to assess the presence and level of damage [13-14] where the statistical pattern recognition procedure encompasses vibration-based damage detection methods and applications. This enables quantitative evaluation of the presence of damage, type, location and degree.

5 Artificial Neural Networks

Neural networks had proved its ability in pattern categorization. A well trained ANN system can precisely identify different types of faults from emerging vibration signals. The capacity of ANN to imitate and replicate human expertise makes them ideally fit for the purpose. Neural networks are able to learn expert knowledge by being trained using a representative set of data [40].

A neural network predictor approach applied for analyzing vibration parameters for two different working conditions. The simulation results obtained convinced that ANN was able to represent different types of ball-bearing systems. The neural network was trainable to analyse system with two conditions to predict the phenomenon [38]. Effectiveness of ANN and SVM classifiers are used for fault diagnosis. The characteristic features of vibration signals was run in its normal and faults introduced condition as input to ANN and SVM classifiers. The statistical features i.e. standard deviation, skewness, kurtosis etc. of the time-domain vibration signal segments along with peaks of the signal are used as features to input the ANN. The researchers have applied ANN [4] to machinery fault diagnosis. In case study on effectiveness of ANN for fault diagnostics using time-domain as well as frequency spectrum features the vibration signals obtained from normal condition induced with faults are subjected to processing for extraction of features to be used as inputs to the ANN diagnosing condition machine. In this, the normalized features are used so that the change of magnitude in signals due to change process parameters, the diagnostic results remains unaffected till signal patterns remain unchanged. The features are obtained from measured vibration signals in terms of single values like crest factor, kurtosis and peaks for the undivided signals. The effects of different types of faults are studied.

6 Conclusion

A widespread review of outcome of researchers reveals that vibration signature analysis and pattern recognition techniques are very popular and with use of soft computational tools become more effective and analysis as learnt from the studies above. The researches disclosed the application for fault diagnosis for either moving parts especially bearings or one of the cutting parameters with little efforts paid on other machine operational characteristics to include effect of coolants, lubrication and externally excited vibration.

A brief review of various types of faults and fault detection carried out. The traditional and newer techniques are discussed at length for fault vibration signature analysis. On review it is concluded that vibration signature analysis is very useful in fault identification. Better analysis is possible by converting the vibration analog signal in discrete data followed by use of time domain and frequency-domain features for further investigations. Expert system based ANN could be a robust fault classifying technique using extracted features from vibration signal. The outcome has motivated to further research and develop a more robust ANN based fault detection system incorporating other faults prone condition.

The present research work aims at including the faults emerging out due to cutting parameters, operational characteristics, work material and other sources of vibration. To record the vibration signals a data acquisition system shall be developed interfaced with computers enabling data storage and retrieval in assistance with a soft computing tool as MATLAB. The feature extraction procedure shall be applied to ascertain the normal and faulty condition classification. A systematic study of vibration signature and pattern recognition assisted with statistical analysis for time and frequency domain shall be helpful in identifying the normal and faulty condition. To make it more effective a new system may feature a real time data acquisition system to extract features and doing the necessary analysis followed by its training on artificial neural network and developing an effective fault diagnosis system. This ANN based fault detection system shall assist in identifying the condition of machine on real time basis.

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