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Design and Analysis of fault diagnosis system using vibration analysis and fuzzy logic

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Abstract: Gears are most important component in mechanical industry and are used in several high precision applications. Gear manufacturing industry acquires a significant portion of mechanical industry. In order to sustain market competition, it is mandatory to reduce operations and maintenance cost. Despite the immense progress in the field of predictive maintenance and condition monitoring approaches, gear manufacturing industries mostly rely on scheduled maintenance. The drawback of these practices is that faults are not identified unless they manifest and may lead to catastrophic failure of the machine and unexpected downtime. The aim of this paper tips to present a method for detection of faults in gear hobbing by nature-inspired analysis of acceleration data. MEMS acceleration sensor (MPU6050) was used to acquired acceleration data from an in-situ gear hobbing machine. A novel data analysis approach is developed using nature-inspired computing to differentiate normal operation from erroneous conditions. The vibration data is analyzed on the basis of approximate entropy. Fuzzy logic is used to establish a relationship between acceleration and different faults, namely loose bearing error, improper assembly, misalignment, and improper lubrication.

Keywords: *Gear Hobbing, Vibration Analysis, Fault Diagnosis, Fuzzy Logic etc.*

I. INTRODUCTION

Gears are integral part of motion and power and motion transmission systems. Gears are core mechanical parts of several important industries such as automobiles, aerospace, high speed rails and intelligent manufacturing. Reliability and performance of equipment used in these industries is determined by the quality of gears. Gear manufacturing industry is largest and most important part of mechanical field. Gear hobbing is the leading process for manufacturing high quality gears [1]. As shown in figure1, hobs are used as cutting tools in gear hobbing to generate the geometry into gear blanks. A typical gear hobbing process s shown in Fig 1. The gear geometry is generated by two rotating shafts (hob and work piece). The hob feeds vertically to the gear blank. The gear blank rotates while maintaining meshing relation with the hob. Gear hobbing is more efficient than other manufacturing processes like end milling [2]. Gear hobbing machines are classified on the basis of placement of gear blank and hob. Gear hobbing is a rough machining process, as a result the hob tool is subjected to high axial feed rate and large radial cutting depth. This results in huge cutting force and stress on the hob. This in turn leads to development of extreme thermal and vibrational stresses, which significantly affects the gear quality.

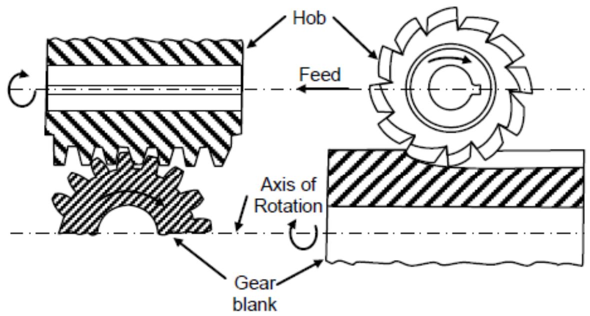

Fig 1 : Gear hobbing process[2]

Machine tool vibration can be mainly divided into two categories, forced vibration and regenerative vibration. Forced vibrations are caused by repeated impacts of hob teeth on the surface of the workpiece during machining, and this phenomenon is unavoidable . Regenerative vibrations are result of self-excitation mechanism that occur during chip generation process [3]. Gear hobbing process is subjected to two impact frequencies, as shown in Figure 2 [2].The first impact frequency(f_1) is also called tool passing frequency and is evaluated by equation (1) in terms of tool rotational speed (n)and number of teeth in one column of hob cutter(z). It is a result of rotational motion of hob.

$$f_1(HZ)=[z.n(RPM)]/60 \qquad (1)$$

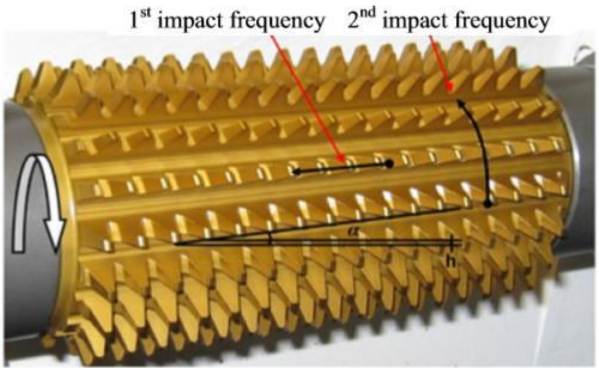

Fig 2.:Impact frequencies in hobbing process[3].

Longitudinal motion of hob give rise to second impact frequency (f_2). It is mathematically represented by equation (3), where v_c represents cutting speed and h represents height difference between teeth. Height difference is a function of helix angle(α) and pitch (p) and can be calculated by using equation (2).

$$h = p.sin\alpha \qquad (2)$$

$$f_2(HZ) = \frac{50}{3}.\frac{v_c[mm/min]}{h[mm]} \qquad (3)$$

Vibration analysis has been proven to be solid and effective in gear related fault diagnosis [5]. The vibration of the hob provides alternative possible approach for gear quality evaluation [6]. The vibration data for a hobbing process is typical sequence data and can be treated as one group (or more groups) of highly coupled vibration segments. In order to perform vibration diagnosis, vibration signal of machine must be converted into electrical signals that can be recorded and analyzed to determine if a machine needs attention. The most widely used approach for predicting vibration is identifying normal frequency modes of a system [7]. Normal frequency modes can be determined either experimentally or by finite element analysis. Accelerometer and impact hammer are used to experimentally extract the frequency modes experimental [8]. In this approach the results can be obtained quickly with significant reliability but with periodic interruption of the operation. FEM is an automated approach but it is a highly demanding process and extensive knowledge related to geometry, contact conditions and materials is required [9]. Vibration analysis for fault inspection is a multidisciplinary field. Recently machine learning algorithms are applied for vibration monitoring. Fourier and wavelet transformation were used to identify defects in gear box and induction machines in [10]. The effect of feature selection techniques on learning patterns is demonstrated in [11]. A data driven approach for fault diagnosis can be found in [12]

Design of a fault classifier requires condition monitoring for offline training and high quality data. The introduction of simple, low cost and high-performance MEMS accelerometers and gyroscopes has completely redefined the industrial vibration monitoring. MEMS is abbreviation for Micro Electro Mechanical Systems and refers to tiny mechanical structures that can interface with electronics. Much research has been conducted to testify the efficiency and usage of MEMS.

In the context of gear production much information about sources of vibration and modes is available for end milling process[13]. Gear hobbing is the most dominant process for manufacturing high quality gears, but the literature related to vibration characteristics of the same is limited. The aim of this paper is to develop a vibration analysis system for industrial gear hobbing machine by Using Micro Electro Mechanical Systems and soft computing approaches. The research is validated on real time collected dataset. The aim of this paper is to develop a vibration analysis system for industrial gear hobbing machine by Using Micro Electro Mechanical Systems and soft computing approaches. The research is validated on real time collected dataset.

Figure 3: Acquiring vibration signatures with accelerometer

II. MATERIALS AND METHODOLOGY

The experiment was conducted on shop floor of Capstan meters Private Limited, Jaipur. Morat Vertical Gear Hobbing machine is used in this industrial facility for manufacturing spur gears. The chemical and mechanical properties of a type of gears manufactured by this organization are mentioned in Table 1 and Table 2 respectively. The properties of Hob tool are mentioned in Table3.

The objective of this research is to develop a diagnostic algorithm that can identify faults by analyzing the vibrational behavior of the machine and prevent catastrophic breakage of Hob Tool. Errors were imitated on the gear hobbing machine and vibration signature was recorded for both normal and abnormal operating condition. The errors studied in this experiment are : spindle bearing error, hob with broken tooth, misalignment , welded chips and assembly error. Vibration signature were recorded through a data acquisition device , which consists of assembled circuit of MEMS accelerometer sensor (MPU6050) and Arduino UNO microcontroller. The sampling time was 30 seconds. The data acquisition device was fixed at an appropriate position , as shown in Figure 1 and vibration signature of different operating conditions were recoded in computer for further analysis.

TABLE I

PROPERTY	VALUE
SPECIFICATION	BS 249
COPPER	56-60
LEAD	2-3.5
TIN	-
IRON	-<=0.35
NICKEL	-
ALUMINIUM	-<
MAGNESIUM	-
ZINC	REMAINDER
OTHER IMPURITIES	<0.70

TABLE II

PROPERTY	VALUE
SPECIFICATION	BS 249
DIAMETER	12 mm
TYPE	CYLINDRICAL SPUR GEAR
ULTIMATE TENSILE STRENGTH	39.4 MINIMUM
PERCENTAGE ELONGATION	15 .0 MINIMUM

TABLE III

PROPERTY	VALUE
HAND AND NUMBER OF STARTS	RH SINGLE
DIAMETER	24
LENGTH	12
BORE	8
CLASS	AA DIN 3698
MATERIAL	ASP 2030

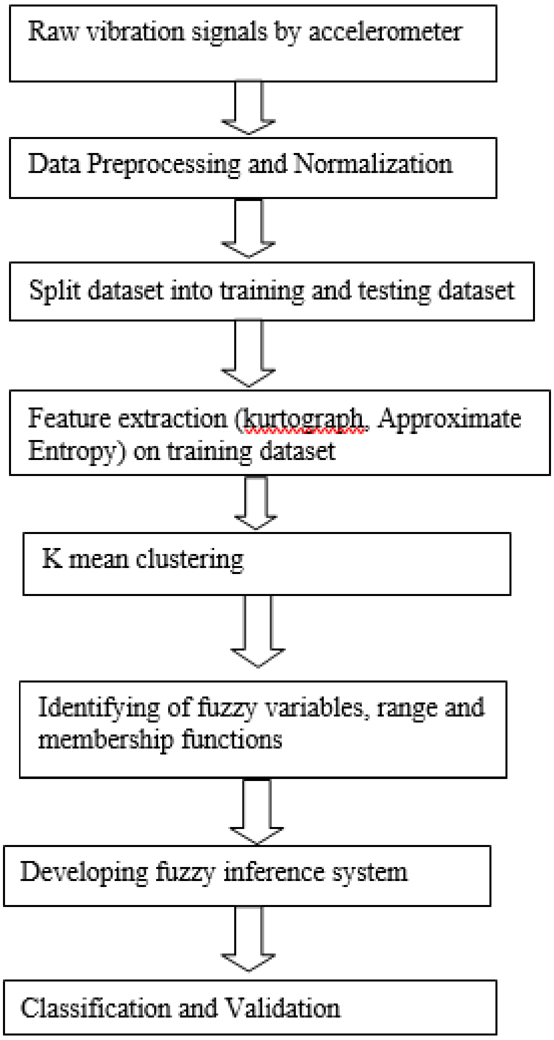

Figure 4: Schematic diagram of proposed methodology

III FEATURE EXTRACTION AND CLASSIFICATION

The methodology adopted in this research is shown in Figure 4. Raw vibration signals acquired from accelerometer must be preprocessed and normalized to remove noise.

3.1. **Data preprocessing :** Gear hobbing, like any other machining operation contains white Nosie or Gaussian noise in vibration signals because of relative motion. These disturbances may hide actual fault signature (certain peaks may pass unnoticed due to presence of noise) and therefore must be removed from the acquired signals. Spectral kurtosis is used for this purpose. Spectral Kurtosis is defined as a fourth-order spectral analysis tool for detecting and characterizing non stationarities in a signal. According to spectral kurtosis each signal is associated with an optimal frequency or frequency resolution at which maximum kurtosis is observed and the same must be detected. Spectral kurtosis is used to enhance the skewness or peakedness of the signal. Optimal window size is used in calculation of spectral kurtosis. The optimal window size is decided by plotting fast kurtogram, as shown in Figure 5-6.

The Fast Kurtogram is a method based on Spectral Kurtosis. Kurtogram is used for finding the optimal frequency band to rotating machinery fault diagnosis by calculating kurtosis and represents the window in which the spectral kurtosis parameters are maximum. It can be observed from Figure 3-4 that high level frequency bands are present abnormal machining condition as compared to normal machining. The optimal window size refers to the length of window where maximum deviation is observed. The above-mentioned parameters are extracted for each time series data, fused together in form of array and stored in a separate database. The database is further divided in train and test datasets in ratio of 7:3. Fuzzy inference system is developed on the basis of features extracted on train dataset, whereas test dataset is used for validation.

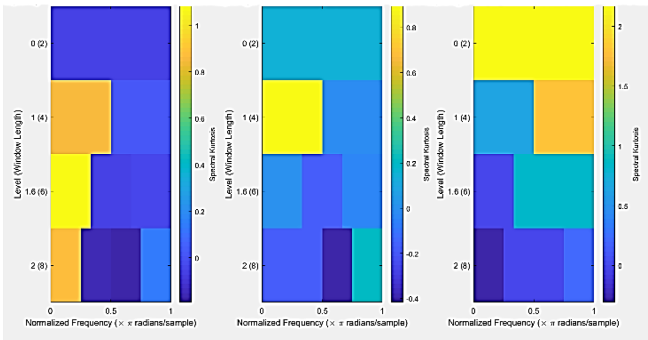

Figure 5: fast kurtogram for abnormal machining(Misalignment error case)

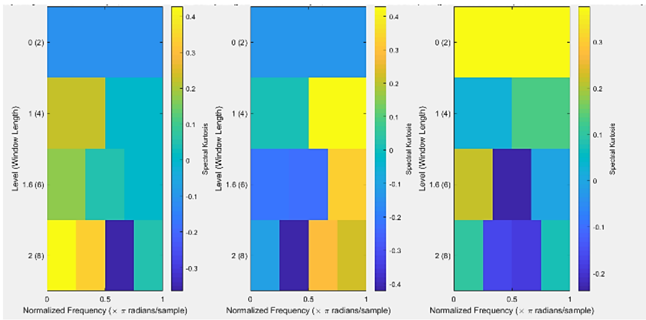

Figure 6: fast kurtogram for normal machining

3.2. **Feature extraction** : The features are extracted from segmented parts of normalized data where a segment refers to a number of consecutive accelerometers reads. In most of the machining operations no prior knowledge is available about activity boundaries therefore segments of fixed length are analyzed. In the proposed research a segment is composed of 300 accelerometer reads. An overlap of 50% in length is allowed between two consecutive accelerometer reads.

The features represent the unique characteristics of the vibration signatures and are used to determine the operating condition of gear hobbing machine. Abnormal or erroneous operation will have different vibration signatures as compared to a normal operation. However, multi level classification (classification of different types of faults) cannot be performed solely on basis of vibration signatures . Approximate entropy is used for this purpose. Approximate entropy (ApEn) is a technique used to quantify the amount of regularity and the unpredictability of signal over time-series data. Consider a finite time series composed of N data points. The value of Approximate Entropy (ApEn) can be calculated by using equation 4.

$$ApEn(m,r,N)=\emptyset m(r)-\emptyset m+1(r) \qquad 4$$

Here, the discrete and consecutive data points are denoted by m , predetermined tolerance value is denoted by r and ∅ denotes function of similarity. Approximate entropy is calculated on all three axis in all types of vibration signatures (error and normal). K mean clustering is then applied to obtain the range of approximate entropy in different conditions in the 3 axis. The value of centroid obtained as a result of K means clustering shown in figure 7. The achieved Centroids are used in deciding the range of fuzzy input and output variables.

3.3 Classification

Mamdani Fuzzy Logic is used as the classifier. Nine input and one output variables were used in the proposed fuzzy inference. An appropriate rule matrix was developed using the values of approximate entropy feature after K means clustering . The details of developed fuzzy logic classifier is shown in Table 4.

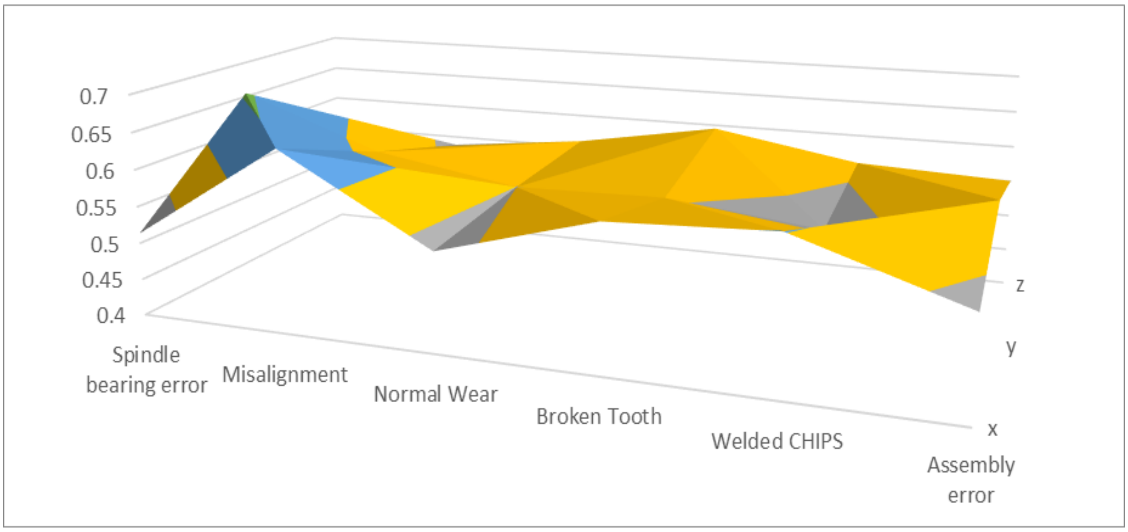

Figure 7 Centroid of Approximate entropy for different operating conditions

IV RESULTS AND DISCUSSION

Experimental investigation has been carried out on gear hobbing machines exhibiting different types of faults. The vibration signatures are preprocessed using spectral kurtosis. In order to highlight all possible peaks, optimized window size is used for spectral kurtosis. Approximate entropy is extracted from the normalized signal. K mean clustering is applied to obtain a range of approximate entropy for different fault conditions and normal working conditions. Consequently, fuzzy logic is implemented to differentiate between different type of faults. Fuzzy model is validated with 120 trials. The confusion matrix is presented in Table 5. It can be observed that the proposed method is a best performing one. Four classes (Spindle bearing error, Welded Chips Assembly Error, Normal) show ideal accuracy. The false positive and false negatives in the other classes are within tolerance range.

TABLE IV

Variable	Type	Range	Membership functions
Approximate entropy x	Input	0.51-0.59	Low
			Medium
			High
Approximate entropy y	Input	0.52-0.65	Low
			Medium
			High
Approximate entropy z	Input	0.51-0.59	Low
			Medium
			High
Error	Output	0-1	Normal
			Spindle bearing error
			Misalignment
			Broken tooth
			Welded chips
			Assembly error

TABLE V

PREDICTED CASE	ACTUAL CASE					
	Spindle bearing error	Misalignment	Broken Tooth	Welded Chips	Assembly Error	Normal
Spindle bearing error	20	0	0	0	0	0
Misalignment	0	19	0	0	0	0
Broken Tooth	0	1	18	0	0	0
Welded Chips	0	0	2	20	0	0
Assembly Error	0	0	0	0	20	0
Normal	0	0	0	0	0	20

V CONCLUSION

Vibration analysis system for fault diagnosis for an industrial gear hobbing machine, using MEMS accelerometer is developed in this research. The developed system can identify different faults which may occur during gear hobbing process with high accuracy. Spectral kurtosis with optimal window length plays a significant role in enhancing the peak in vibration data and consequently improves the data analysis. The proposed approach is different from previous approaches as extensive data analysis and soft computing techniques are the primary concern. In this research work a novel approach for preventive maintenance is presented. The developed algorithm can decrease the maintenance cost to a huge extent it and can prevent catastrophic failure. The proposed research work is highly suited for ubiquitous computing and continuous monitoring as required in Industry 4.0. In future the author will try to integrate the proposed methodology with advanced data analysis techniques such as deep learning. The author will also see the feasibility of the proposed approach with internet of things for remote control.

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