Vibration Signal Based Machine Fault Diagnosis through Statistical Approach to Frequency Domain Analysis

Sanjay Asati
Mechanical Engg Dept
M Patel Institute of Engg & Tech, GONDIA (M.S. India)
e-mail: name@xyz.com

Dr. P. M. Bapat
Department of Mechanical Engineering
V.P.S. College of Engg & Tech., Lonavala (Pune, M.S. India)

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 for it is variety of waste being generated including the downtime, rejections, rework apart from the waste of resources such as material ,manpower, energy/power, capital etc. To eliminate these wastes and increasing the output it is essential to maintain the machine and identifying and recognizing the fault prior to its occurrence. Condition monitoring is an effective method to identify such faults. To make condition monitoring more effective vibration signature analysis plays a crucial role wherein the vibration signal acquired and extracted features defines and exhibit the trend for variation. In this paper, a research work conducted on an experimental set up for data acquisition is utilized for vibration signal acquisition and feature extraction for the functioning of a lathe machine for its various cutting and operational parameters. Frequency domain analysis carried out and statistical approach adopted to determine different statistical parameters as variance, skewness, kurtosis, crest factor. The analysis includes determining statistical parameters for fault and no-fault condition of machine. This analysis determines when machine becomes operational ineffective and termed for faulty condition. The objective is to set the parameters for machine to classify the condition of machine as fault or no-fault to be further used for input for developing intelligent system based on neural networks.

Keywords: *Fault diagnosis, cutting parameters, Time domain, frequency domain, statistical parameters*

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I. INTRODUCTION

In modern time industries, equipment and machinery are important part of the total productive effort making plant maintenance a vital service function wherein condition monitoring gaining wide recognition. Condition monitoring [1,2] is aided with many measuring instruments assisting identification and diagnosis of faults prior to its occurrence. Many tools & techniques are available leading to diagnosis of machine performance and machine faults. In the recent past number of instruments developed which sense health of machine and monitor performance. Machine unable to perform as per pre-specified criteria and standards are termed as underperforming and may be a result of variation in any of the operational parameters resulting in defective parts. Such conditions are faulty one and need to be addressed with reasons and sources. Sometimes machine produces unfamiliar and unwanted sound or vibrate with greater amplitude. These unwanted variations are results of deviation from the ideal condition for machine performance. Among various means to diagnose faults in machines, vibration signal based machine fault diagnosis system gained wider popularity over the years.[3-9]

II. .LATHE MACHINE FAULTS AND IDENTIFICATION:

In this paper, lathe machine is under consideration for different known fault conditions. Lathe, a very common machine being used for variety of machining operation across the industries. The performance of machine is based on its cutting and operational parameters. It observed that for given constant cutting speed and feed rate, beyond a certain depth of cut machine starts vibrating significantly resulting in poor surface finish and dimensional inaccuracies. Such is the case common for different combination of cutting parameters. Further cutting tool condition, tool material and tool geometry also affects machine performance. As the tool starts wearing out the vibration characteristics changes and reaches to maximum extent for the completely worn out tool. Thus in between the grounded and worn out tool condition a vibration characteristic may be obtained to define and identify the good and bad tool condition responsible for normal or abnormal machining condition.[10-12]

Driving mechanism, spindle and spindle mountings, slide and slide-ways, tool holding device, lubrication, coolants etc. also contribute majorly to the performance of the machine. The failure of any or combination of any of these may produce defective parts. 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.[13-15]

III. METHODOLOGY

The experimental study evaluated different fault conditions using accelerometers mounted at prominent position in proximity to the source and connected with interfacing device to computer. The accelerometer measured the axial and radial accelerations from the source as per the conditions demanded. The data obtained was processed using MATLAB software.

Time domain and frequency domain analysis carried out to determine the vibration signature in terms of aplitude and frequency by acquiring spectra for various established fault conditions. To further strengthen claim statistical analysis carried out with the data obtained by time domain and frequency domain analysis for fault detection and recognition. A series of statistical parameter as rms value, standard deviation, variance, kurtosis, skewness, crest factor obtained tabulated and plotted for evaluation.

IV. DATA ACQUISITION SYSTEM:

A vibration signal data acquisition system is developed using MEM type accelerometer plugged in the sound port of PC backed with MATLAB software to acquire the sound wave file. The data acquired is normalized and conditioned to suitably meet the requirements. The data is obtained using time domain analysis and the characteristics of vibration signals obtained as plot of time against acceleration. The associated numeric values also obtained and analysis carried out to ascertain the known normal and faulty condition being well validated. Numerous sets of data collected for different defined normal and fault condition further tested on statistical parameters to validate the result obtained using time domain analysis. As even the results obtained from time domain analysis are well supportive to the objective pre-defined but measuring the characteristics only on one amplitude parameter may not always be true and need to be tested on other front. Vibrations signals are characterized for amplitude and frequency. Vibration signal can be well manipulate to get pattern using time and frequency domain analysis. The statistical approach to both time and frequency analysis make them more predominant.[16-19]

It refers to display or analysis of the vibration data as a function of frequency. The time-domain vibration signal is transformed into the frequency domain by applying a fast Fourier transform (FFT) where further analysis is carried out, The principal advantage of this format is that the repetitive nature of the vibration signal is clearly displayed as peaks in the frequency spectrum at the frequencies where the repetition takes place.

This allows for faults, which usually generate specific characteristic frequency responses, to be detected early, diagnosed accurately, and trended overtime as the condition deteriorates. [20-24]

5.1 Frequency Domain Analysis: It refers to analyzing a mathematical function or signal with respect to the frequency widely used in the areas as control systems, vibration signal and statistics. It is mostly used to signals or functions that are periodic over time. The significant concept in frequency domain analysis is the transformation which is used to convert a time domain function to a frequency domain function and vice versa. Frequency domain methods use the Fast Fourier Transform (FFT) to convert the time signal into its' corresponding frequency components.[25]

The commonly used transformation in the frequency domain is the Fourier transformations. Fourier transformation convert a signal of any shape into a sum of infinite number of sinusoidal waves. Analyzing sinusoidal functions is easier than general shaped functions makes this method very suitable.

Energy in vibration signal distributes over a range of frequencies. Frequency analysis separates these individual frequency components in a complex signal and indicates amplitude of each. For real time data analysis a quicker method widely adopted is FFT analysis which uses FFT (Fast Fourier Transform) algorithm to calculate spectra of group of data.. The FFT algorithm efficiently calculates discrete fourier transform. The relationships used to transform data from time domain to frequency domain is Fourier transform pair. The main indicator is the characteristic defect frequencies in frequency domain analysis. Spectral analysis of vibration signal is widely used in fault diagnostics. It was found that frequency domain methods are generally more sensitive and reliable methods [26,27]

Time domain is 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 collected vibration signal data is tested for frequency domain analysis.

To overcome the drawbacks of time domain analysis, obtained data tested over frequency domain to test frequency of occurrence of vibration signal. The Fast Fourier Transformation (FFT is applied to) for getting the frequency of the signal acquired. Each acquired signal is transformed into frequency spectrum for all the established fault condition. FFT is applied for all the known normal and abnormal data and the numeric value for each acquired signal is obtained. The frequency domain analysis test for the frequency of occurred signal. in the frequency spectrum it observed that for the normal set of data the frequency peaks are less and they are not clustered closely while in case of abnormal data where the intensity of vibration signal is more in terms of amplitude and frequency the frequencies are more clustered and are more closer. The frequency rate is too high and observed that in some cases it is crossing the resonance frequency. The frequency analysis is carried out for the following conditions which beyond certain develop faulty machine condition. They are due to variation in cutting speed, feed rate, depth of cut, tool wear and bearing failure.

5.2 Data Collection: Data collected by the developed data acquisition system[28] and stored as wave files for the following defined fault condition as..

Case I: The fault emerges due to excessive depth of cut

Case II: Higher feed rate results in chatter and other dimensional inaccuracies

Case III: Higher operating cutting speed generates more vibration.

Case IV: Worn out tool results in enhanced chatter.

Case V: Damaged bearing introduces shocks

There are few other faults also identified but at this stage it is worth analysing the key fault areas.

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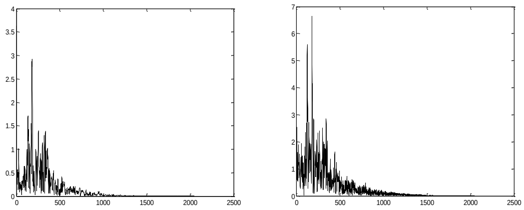
The faulty conditions were introduced in the machine and data acquisition done for various fault condition by setting various cutting conditions.

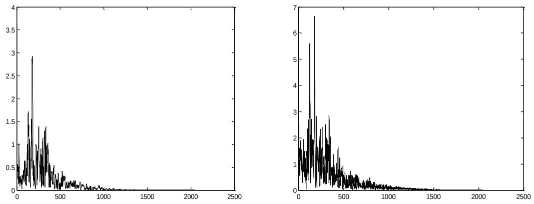
5.21 Case I: The cutting speed and feed rate kept constant and the depth of cut varied (0.2mm to 3mm) over a period of time to acquire vibration signal.



Normal Faulty

Fig5.2.1;Frequency spectrum for variation in depth of cut for constant speed and feed rate

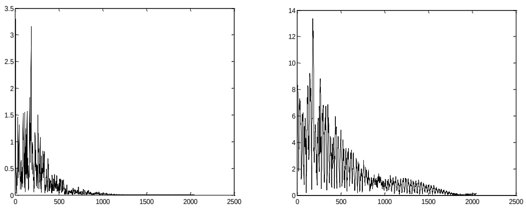
5.22 Case II: The cutting speed and depth of cut kept constant and feed rate varied (0.05 mm/rev to 0.4 mm/rev) over a period of time to acquire vibration signal. Fig2 shows the frequency spectra for normal and abnormal conditions. The spectra indicatese



Normal Faulty

Fig5.2.2; Frequency spectrum for variation in feed rate for constant speed and feed rate

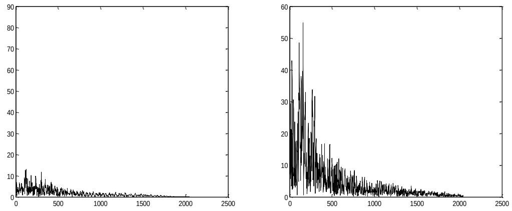
5.23 Case III: The feed rate and depth of cut kept constant and cutting speed (15 to 50 m/min) varied over a period of time to acquire vibration signal.



Normal Faulty

Fig5.2.3; Frequency spectrum for variation in cutting speed for constant depth of cut and feed rate

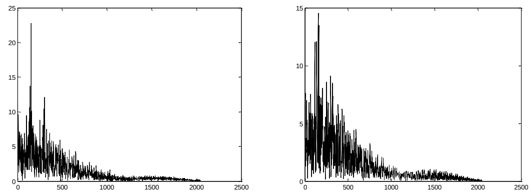
5.2.4 Case IV: For constant known cutting parameters the behavior of cutting tool observed and vibration signals acquired to monitor the variation in vibration signals with wearing cutting tool. The cutting tool ground to geometry ideal for machining It is observed that w.r.t. to tool wear vibration signals become more intensified affecting surface finish and dimensional inaccuracy



Normal Faulty

Fig5.2.4; Frequency spectrum for varying tool condition for constant cutting parameters

5.25 Case V: Bearing plays important role in proper functioning of the machine. Bearing failure occurs due to failure of races, cages or balls. In this case only ball failure is considered by introducing intentional fault during the course of data collection. This is done by progressively damaging the balls by tempering. The vibration signals are acquire for this condition by establishing other parameters to stay normal and stable. The initial vibration signal acquired represents ideal condition where vibrations ha minimum amplitude and low frequency. As fault is introduced rise in amplitude and frequency is observed which after a certain limit become excessive to describe as abnormal condition characterised by higher peaks of amplitude and closer clusters of frequency to result poor surface finish and operational noise.



Normal Faulty

Fig5.2.5;Frequency spectrum for bearing failure

5.3 Statistical Analysis: Statistical analysis is vital to all experimentations using statistical approach. It approximates the solutions when the actual process is complex or unknown in its true form.

Statistical analysis describes the nature of the data under analysis and explores relation of data to population. The statistical parameters create a model summarizing and exhibiting relationship of data to population. It is the useful tool to validate the data and the established model and emerges out to establish relationship, trends and patterns to indicate future phenomenon and actions.

5.31Statistical parameters: The statistical parameters determined to process the data based on the features it able to extract includes;

i. RMS value measure magnitude of a varying quantity and very useful when the variates are positive and negative
ii. Standard deviation indicate variation or dispersion exist from the mean value.
iii. Variance measures how far a set of numbers spread out from the mean.
iv. Kurtosis is a measure of the peakedness of the probability distribution of a real-valued random variable

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v. Skewness measures the extent to which a variable positioned to either side of mean.

vi. Crest Factor is a measure of a waveform, showing the ratio of peak values to the average value.

Table1 : Frequency Domain Data ,Depth of cut(mm)

Data Type	Depth of Cut	Statistical Parameter					
		RMS	Kur	SD	Var	SkF	CrF
Normal	o.2	0.48	15.45	0.43	0.18	2.58	6.77
	0.4	0.77	11.38	0.65	0.43	2.74	5.75
	0.6	0.46	11.30	0.41	0.17	2.64	6.16
	0.8	0.49	13.18	0.43	0.19	2.29	7.44
Abnormal	1	0.50	20.04	0.43	0.19	2.98	7.40
	1.2	0.87	21.09	0.72	0.52	3.21	7.44
	1.5	0.52	21.96	0.47	0.22	3.48	9.13
	2	2.03	17.72	1.60	2.57	3.48	8.33
	2.5	2.32	23.71	1.78	3.17	3.76	10.49
	3	8.41	32.04	4.10	18.44	5.07	12.63

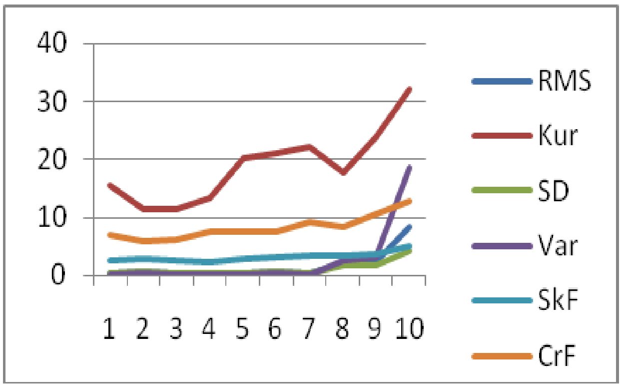

Fig 5.3.1 Statistical behavior for variation in depth of cut

Table2: Frequency Domain Data ,Feed rate(mm/rev)

Data Type	Feed rate	Statistical Parameter					
		RMS	Kur	SD	Var	SkF	CrF
Normal	0.05	0.44	16.05	0.36	0.13	2.68	8.42
	0.75	0.41	15.68	0.32	0.10	3.19	9.50
	0.10	0.40	20.40	0.36	0.13	3.21	8.90
	0.13	0.35	23.50	0.39	0.15	3.12	8.27
Abnormal	1.50	0.41	24.92	0.36	0.13	3.61	7.36
	0.18	0.43	26.51	0.32	0.10	3.96	9.37
	0.20	0.42	28.76	0.38	0.14	3.54	11.87
	0.25	0.72	25.94	0.37	0.14	4.56	10.21
	0.30	0.60	29.07	0.55	0.30	4.25	11.76
	0.40	0.76	41.69	0.64	0.41	4.74	10.02

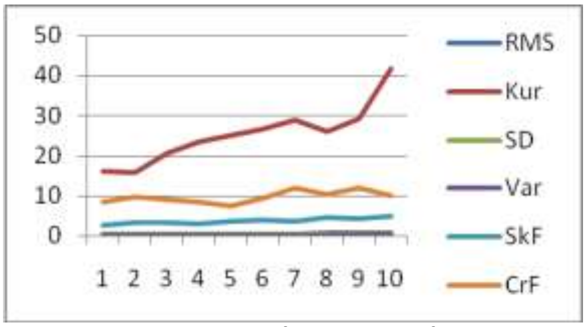

Fig 5.3.2: Statistical behavior for variation in feed rate

Table3: Frequency Domain Data ,Cutting Speed rate(Min/min)

Data Type	Cutting Speed	Statistical Parameter					
		RMS	Kur	SD	Var	SkF	CrF
Normal	15	0.50	13.08	0.44	0.19	2.85	6.86
	20	1.03	7.49	0.71	0.50	1.90	4.94
	23	0.61	13.85	0.53	0.28	2.96	7.97
Abnormal	26	0.50	13.30	0.43	0.19	2.85	7.05
	30	1.11	14.55	0.76	0.58	2.54	6.71
	33	0.35	26.28	0.32	0.10	3.06	6.51
	36	0.74	14.46	0.64	0.41	3.05	6.28
	40	2.60	8.11	2.01	4.04	2.08	5.13
	45	0.46	32.05	0.42	0.17	4.43	10.92
	50	0.25	43.34	0.23	0.05	4.73	14.74

Fig 5.3.3: Statistical behavior for variation in cutting speed

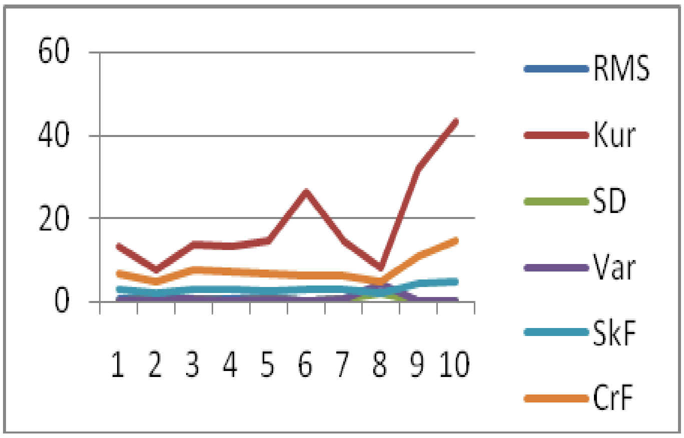

Table4:Frequency Domain Data ,Tool Wear Condition

Data Type	Stage	Statistical Parameter					
		RMS	Kur	SD	Var	SkF	CrF
Normal	1	2.3	40.5	1.9	3.6	4.5	12.8
	2	8.4	14	7	48.6	3	6.5
	3	5.6	25.5	4.7	22.5	3.7	11.3
Abn orm al	4	3.2	10.3	2.6	7	2.5	6.2
	5	3.5	37.7	2.8	7.6	3.8	12.9
	6	0.7	46.8	0.6	0.4	5.3	11.5
	7	14.1	55.7	12.2	150	5.9	13.4
	8	3.3	344.5	2.8	8	14.5	24.6
	9	5.4	194.3	4.8	22.6	10.1	21.6
	10	19.2	142.3	17.6	309	10	19

Fig 5.3.4: Statistical behavior for tool wear condition

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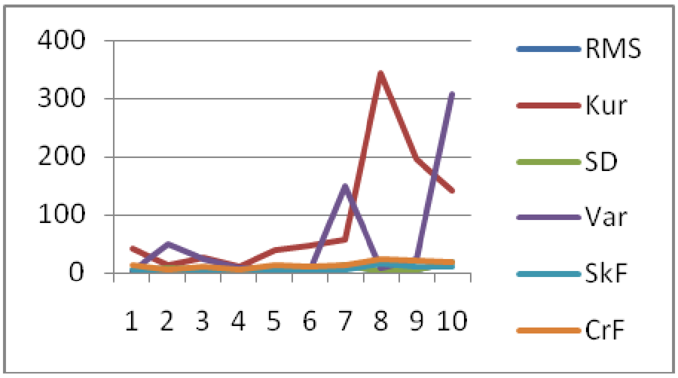

Table5: Frequency Domain Data ,Bearing Failure Condition

Data Type	Stage	Statistical Parameter					
		1	2	3	4	5	6
Normal	1	2.06	7.89	1.62	2.62	2.18	5.60
	2	2.39	10.35	1.87	3.49	2.36	6.10
	3	2.16	7.70	1.69	2.86	1.98	5.46
Abnormal	4	3.06	7.46	2.33	5.42	1.96	5.55
	5	3.17	11.47	2.44	5.97	2.43	6.85
	6	2.42	9.71	1.91	3.64	2.34	5.58
	7	2.73	9.48	2.07	4.30	2.19	5.90
	8	2.59	12.23	1.99	3.95	2.55	6.26
	9	3.60	9.92	2.86	8.19	2.38	6.53
	10	2.53	17.89	2.04	4.17	2.98	8.99

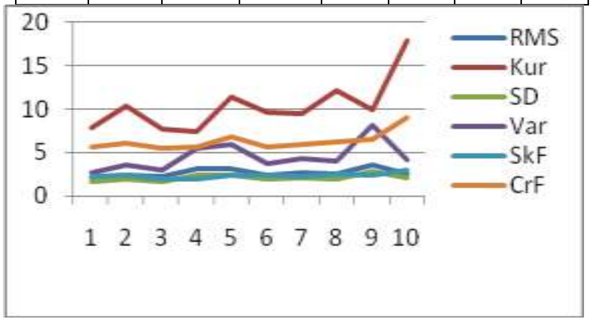

Fig 5.3.5: Statistical behavior for bearing failure

vi. DISCUSSION

Case I: From frequency domain analysis it observed(fig 2.2.1) that for lower depth of cut value machine is stable and intensity of vibration is low which further rose with increase in depth of cut. Beyond a certain limit frequency domain spectrum the signals shows behavior which no longer be termed as normal as it started affecting machine performance and surface finish leading to dimensional inaccuracy. Such conditions are faulty conditional and machine is termed to be behaving abnormally. Table 1 & Fig5.3.1 support the fact that the statistical parameter are uniform and nearly stable for normal condition and sharply increases as abnormality leads to failure. The peakedness is more and the data more skewed.crest factor value is on the rise. This differentiates the two conditions as normal and faulty.

Case II: Fig 2.22 shows how frequencies are clustered closer for normal while for fault condition it is spreaded and more frequency peaks are seen. From table 2 and fig 5.3.2 the variation support the fact about normal and fault condition. As feed increases more vibration frequency peaks observed and peakedness rises.

Case III: Fig 2.2.3 exhibits the frequency domain analysis for variation in cutting speed. Table 3 and fig 5.3.3 supports the characteristics of frequency domain analysis. Kurtosis and crest factor are prominent parameters to support the established fact.

Case IV: Fig 2.2.4 shows the frequencies for normal and faulty behavior of cutting tool. For new grounded tool the frequency is low and rms value, skewness and variance (table 4 and fig 5.3.4) are uniform and constant which sharply rises as tool starts wearing and rose to maximum when worn out. The statistical behavior establish a trend for variation in parameters with the tool wear condition.

Case V: This is a very crucial fault condition need to be judged precisely. Fig 2.2.5 shows the deteriorating bearing condition. Initial when bearing was in good condition the frequencies were low and but the damaged bearing resulted high frequencies and larger peaks. Table 4 and fig 5.3.4 reveals bearing failure is a progressive phenomenon and a gradual worsening pattern is observed in terms of kurtosis & crest factor.

vii. CONCLUSION:

An exhaustive data collection and analysis carried out for frequency domain analysis assisted with statistical analysis. The developed data acquisition system proved to be handy consistent and precise. The system has produced the result with finer accuracies. The analysis concludes that the introduced fault conditions are accurately identified and recognized supported the stand that every fault has some unique characteristics in terms of vibration signals. The unknown fault conditions tested positively and were accurately classified as type of fault and fault condition in term of normal and abnormal. Thus each type of fault can be clearly distinguished and models may be developed to understand unknown fault conditions emerged in machine over a period of its functioning. The outcome finds its suitability to develop an intelligent system manipulating the acquired data and the results obtained for fault diagnosis and classification.. Frequency domain analysis is tested over time domain analysis for amplitude and frequency verses time. The amplitude Vs frequency remain untested and their behavior shall be interesting to monitor prior to develop any diagnostic model,

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