Condition Monitoring: A Convinient Technique for Vibration Analysis of Tooth Failure in Gear Box

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Abstract— This dissertation work deals with the technique of condition monitoring to be applied to selected gearbox to assess the condition of gear teeth. Any change in condition of gear such as wear, a crack and lack of oil or failure of tooth during working may cause a corresponding change in the motion. The signals for known defect are collected by vibration accelerometer and sound pressure level probe (microphone) during working of gearbox. By introducing gears of known faults, the vibration and acoustic spectrum are collected by using Fast Fourier Transformer (FFT) and the corresponding changes in pattern are compared with the signals obtained from gear without faults. These changes in signals are then correlated to the faults of gear tooth.

Keywords-*sound pressure level,natural frequency,damping coefficient,decibel for sound measurement*

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I. INTRODUCTION

Today, most maintenance actions are carried out by either the predetermined preventive or the corrective approach. The predetermined preventive approach has fixed maintenance intervals in order to prevent components, sub-systems or systems to degrade. The concept of condition monitoring is to select measurable parameters on the machines, which will change as the health or condition of a machine. Regular monitoring is done and the change is detected. Once a change is detected it is possible to make a more detailed analysis of the measurements to determine what is the problem and hence arrive at a diagnosis of the problem. The parameters most often chosen to detect this change in conditions are either vibration, which tends to increase as a machine moves away from a smooth running condition into a rough mode with development of a fault, or an analysis of machine noise or acoustics, or machine lubricants where samples are tested for items such as wear debris from a developing fault. There are various sensors to detect and monitor the early signals of electrical, mechanical, electronic, pneumatic, hydraulic, etc, and provide an aid to fault diagnosis to establish an effective maintenance management procedure to predict and prevent system failure just in time. A well designed condition monitoring strategy reduces production costs, operating costs and labour costs.

II. LITERATURE REVIEW

N. Baydar & A. Ball have presented [1] "Detection of gear failures via vibration and acoustic signals using wavelet transforms". In their work they have used vibration and acoustic signals for detection failure of gear.

Yuji Ohue & Akira Yoshida have presented [2] "New evolution method on dynamics using continuous and discrete wavelet transforms". This paper deals with the new method of gear dynamics using the continuous and discrete wavelet transform. In order to evaluate the difference in the gear dynamics due to the gear materials, which are sintered & steel ones, the dynamic characteristics of gears were measured using a power circulating gear testing machine. The gear dynamics were analyzed in a time frequency domain by the continuous & discrete wavelet transforms.

Wen-xian Yang & Peter W. Tse have presented [3] "An advanced strategy for detecting impulses in mechanical signals". The appearance of overlapping in the results derived by continuous wavelet transform (CWT) smears the spectral features and makes the results difficult to interpret. This will significantly affect the accuracy of analysis of anomalous signals. Aiming at minimizing the undesired effect of overlapping a new soft-thresholding method in terms of exponential functions is proposed.

Peter W. Tse, Y. H. Peng, Richard Yam has presented [4] "Wavelet analysis and envelope detection for rolling element bearing fault diagnosis- Their effectiveness and flexibilities". This paper commences with technique of wavelet analysis and envelope detection for fault diagnosis. The components which often fail in a rolling element bearing are the outer race, the inner race, and the cage. Such failure generates a series of impact vibrations in short time intervals, which occur a Bearing Characteristics Frequencies (BCF).

D.F. Shi, W. J. Wang and L. S. Qu have presented [5] "Defect detection for bearing using envelope spectra of wavelet transform". This paper considers wavelet transform for defect detection of bearing. In order to overcome the shortcoming in the traditional envelope analysis in which manually specifying a resonant frequency band is required, a new approach based on the fusion of the wavelet transform and envelope spectrum is proposed for detecting and localized defects in rolling element bearing. This approach is capable of completely extracting the characteristics frequencies related to the defect from the resonant frequency band..

Jing Lin, Ming J. Zuo, Ken R. Fyfe have presented [6] "Mechanical fault detection based on the wavelet de-noising technique". This paper commences with technique of wavelet de-noising for mechanical fault detection. For gears and roller bearings, periodic impulses indicate that there are faults in the components. However, it is difficult to detect the impulses at the early stage of fault because they are rather weak and often immersed in heavy noise.

III. OBJECTIVES

- The different faults in gears can be detected without dismantling any gearbox for the diagnosis of faults.
- To match the FFT results with concerned faults to prove the correctness of condition monitoring is successfully conducted.
- To create particular precise defects in gears.
- To learn use of FFT instrumentation to know its various applications.

IV. GEARBOX DIAGNOSTIC TECHNIQUES

Manufacturing industry drives the world. Every manufacturing industry is having number of machines and gearboxes which are used for power conversion, speed reduction and torque amplification, can control many of them. It has been estimated that annually 10 million new gearboxes enter operation with a combined component value of more than 5 billion dollars. Economics of industries totally depend upon reliable operation of gear driven machinery and gearboxes.

Any defect induced in gear might costs high at the time of failure. For that, early prediction of breakage of gear tooth is essential to avoid stoppage of that machine thereby increase in utilization.

A. Noise and Vibration Sensing

Power losses in gearboxes are a normal consequence of less than perfect operating efficiency. These power losses results in energy dissipation as vibration and heat. The analysis for the detection of faults in the gearboxes is normally related to a change in the characteristics of the gearbox vibration. This change may be in overall vibration amplitude, change in the amplitude of certain frequencies of vibration, or in the pattern of the vibration signature. Changes in these signal amplitudes can be used to indicate degradation in these components and failure.

B. Acoustic Analysis Technique

The acoustic noise measurement can also be used for condition monitoring. Listening the noise of machines, as a means of detecting malfunction in them, the analysis of noise signal is carried out much the same way as vibration signal using similar instrumentation. By monitoring the acoustic conditions of plants and machineries at critical position in a mechanical manner, and by analyzing the acoustic signal in an intelligent way, it is possible to avoid the cost and avoidable breakdowns. In acoustical analysis technique either sound pressure measurement or sound intensity measurements are carried out. But sound intensity measurement is having distinct advantages. As it is vector quantity it gives sound pressure as well as direction of sound so it gives idea about the location of fault.

C. Oil Debris Detection

While vibration analysis may allow one to know gear faults, monitoring of the lubricating oil flow for metallic debris is a more direct method for the detection of wear and surface failure type faults in gearboxes. Two different approaches are commonly used. One involves the analysis of the oil samples and/or debris in an off line laboratory. The second involves detecting particles on line and in real time.
Oil debris detection can provide a good backup to vibration monitoring, especially in complex gearboxes or where vibration levels are high enough to render conventional vibration analysis ineffective

V. VIBRATION AND SOUND MEASUREMENT

A. Introduction

The measurement of vibration sound and its characteristics plays an important role in development of a systematic approach to vibration and acoustic analysis. In particular, the measurement of overall vibration and sound levels can be used to determine demand with regulations. These measurements can also be used to assess the effectiveness of various conditions monitoring technique and to establish realistic goals.

B. Fundamentals Of Vibration And Acoustics

- Vibrations are always resent in any rotating/ moving machine. These can't be eliminated but can be controlled. It is important to keep the vibrations in a machine within acceptable limits for its good health. Vibration as a parameter, therefore, can be used as an indicator of the health of a machine is considered good. However, when these levels become unacceptable, some malfunction in the machine is indicated.
- Accelerometers are seismic type transducers, which have to be attached to the vibrating object. Inside the accelerometer is a mass mounted on a spring and damper. These devices are used for the measurement of absolute vibration in those cases where a fixed reference for relative motion is not available as in the case of a moving vehicle. In many other situations measurement of absolute motion is easier and more desirable
- Sound pressure measurement in decibels is defined as:
  $LP = 10 \text{ Log } (P / Po)^2$ dB
  Where, 'P' is sound pressure measured and 'Po' is the reference sound pressure measured of 20 μPa. Pascal is N/m^2. Reference value of 20 μPa is chosen as it is the quantity that represents the threshold of hearing of an average person. The logarithmic scale of noise measurements is used to accommodate this large ratio. The sound pressure is a scalar quantity. In a free field condition (i.e. where there are no reflecting surfaces present) inverse square law applies according to which the Sound Pressure Level (SPL) decreases by 6 dB for each doubling of distance (i. e. if the SPL at 1 meter distance is 90 dB then at 2 meters it will be 84 dB)

VI. CAUSES OF GEARBOX VIBRATION AND NOISE

A. Transmission Error

Transmission Error is the error between teeth. Transmission Error (TE) is defined as the deviation of the relative angular position of two gear shafts from the position determined by the gear rotation and perfect conjugate mesh action. TE is a consequence of a torsion vibration of the gear system and it is a function of tooth profile errors, tooth meshing errors, tooth spacing errors, undercut, backlash, tooth surface roughness, misalignment of gear tooth and an elastic deformation of gear tooth.

B. Uniform Wear

There is sliding action between the contacting teeth on either side of pitch circle, but no sliding takes place at the pitch circle itself. Therefore the uniform wear tends to twist the harmonic nature of tooth mesh cycle and results into higher amplitudes of tooth mesh frequency and its harmonics. This effect does not become apparent until it becomes larger than the effect due to tooth deflection

C. Backlash

Excessive gear clearance or improper adjustment of backlash may result into frequency modulation and will give rise to excessive noise at gear mesh frequency. So far it has been assumed that the rotational speed of gear is constant, and tooth spacing perfectly uniform, but if either of the condition is violated, frequency modulation of the tooth meshing frequency may occur. If the gear clearances are within tolerances and gears are properly lubricated, the transfer of load from one tooth to next will be in the form of tooth impact and result will be increasing noise. If gear tooth clearances increases more, the initial tooth may cause the gear tooth to bounce in the clearances available, which results in sound or vibrating frequency at harmonics of gear mesh frequency. This is 1x, 3x …or perhaps even higher multiples of gear meshes frequency.

D. Eccentricity

Eccentricity occurs when shaft centerline does not coincide with the gear geometric centerline. It is common source of unbalance, resulting in more weight on the gear geometric centerline. It is common source of unbalance, resulting in more weight on one side of rotating centerline than on the other side. Eccentric gear can produce reaction forces because of cam like action against the meshing gear. Eccentricity of one gear or misalignment may give rise to amplitude modulation by frequency corresponding to its rotational frequency.

E. Cracked Tooth

As the gear rotates, the space left by the chipped tooth increases the mechanical clearance between the pinion and gear. The result is low amplitude sideband to the left of actual gear mesh frequency. When the next (i.e. undamaged) teeth mesh, the additional clearance results in higher amplitude as a result; the paired sidebands have non symmetrical amplitude, which is due to the disproportional clearance and impact.

F. Broken Tooth

Broken tooth results mechanical clearance between the teeth. While shifting load from one tooth to another, impact is going to occur, this results in increase the noise of gear box.

G. Improper Lubrication

Proper lubrication is essential for gear box because majority of the problems arise due to lack of lubrication. Due to lubrication problem, chip formation is developed on the tooth flank, leading to rough gear mesh and rapid deterioration occurs in spectrum near meshing frequency. There will be increase in the amplitude of fundamental frequency and its harmonics due to improper lubrication.

VII. Experimental Setup

The schematic diagram of vibration and acoustic measurement for fault diagnosis of gearbox shown in Fig.1 and a line diagram in Fig.2 The geared motor is rigidly mounted on concrete foundation to isolate vibration and acoustics from foundation.

Fig1-Test- rig of Gear Box Set up

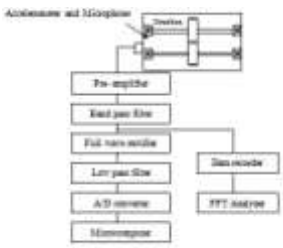

Fig.2 Schematic set up for vibration and sound pressure measurement

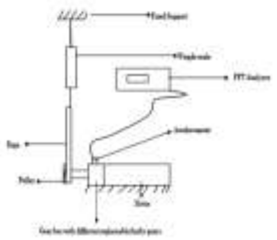

Fig.3 Line diagram for vibration and sound measurement

. In experimental procedure the gearbox is allowed to run at its rated power and speeds by applying different load condition of 0 kg, 2.5 kg, 5 kg, and 7.5 kg on rope break dynamometer having diameter of pulley 71.38 mm. . The positioning of sound pressure level probe is done properly on the top of the gear under consideration for measuring sound pressure. For vibration measurement accelerometer is kept on the top of gearbox. By making all above arrangements, readings are taken for non-defective gear and good lubrication condition. This data is stored in FFT analyzer for further analysis. Vibration and noise spectrums are taken for gears having various faults and the data is stored in computer for further analysis. For different condition of faults and different load conditions data is collected.

II. Data Acquistion Procedure

Fig 4 AE sensor located on pinion

The AE sensors used here is wide band type sensors with a relative flat response between 100 kHz and 1 MHz WD model, Physical Acoustics Corporation. An AE sensor was placed on the pinion (49 teeth), as shown in . The cable connecting the pinion sensor was fed into the pinion shaft to the pre-amplifier via a slip ring. This allows the AE sensor to be placed as close as possible to the gear teeth. Both the sensors are hold in place with mechanical fixtures. An 'IDM Electronics Ltd' manufactured PH-12 slip ring is used. The slip ring used sliver contact and could accommodate a maximum of 12 channels. The cooling air pressure for the slip ring is 1400 kg/mm2. Pre-amplification was set at 40dB. The signal output from the preamplifier is connected directly to a commercial data acquisition card. The data acquisition card could provide 10 MHz sampling rate and incorporated 16-bit precision giving a dynamic range of more than 85 dB. Prior to the analog-to-digital converter (ADC), the card uses anti-aliasing filters that can be controlled directly in software. A K-type thermal couple, rated from – 2000 C to 13780 C is used to measure the oil temperature for computation of oil film thickness. The oil bath temperature is measured through an opening on top of the gearbox casing using the specified thermal couple probe. This position for acquiring oil temperatures is adjacent to the gear mesh position as this is the closestposition the observer could get access.

VIII. RESULT ANALYSIS

A. Vibration SpectralAnalysis

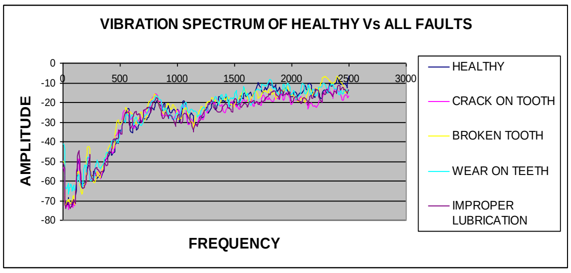

Fig.5 Vibration Spectrum of Healthy Vs all faults on tooth

Fig. 3 shows comparison of vibration signatures of all faults with healthy From this figure, it is also seen that the amplitude change of mesh frequency occurs during tooth wear. In terms of crack on tooth the amplitude at gear mesh frequency increases considerably. While improper lubrication results in only spikes i.e., momentary increases at meshing frequency and its harmonics, for worn-out teeth the amplitude level increases significantly.

B. Acoustic Spectral Analysis

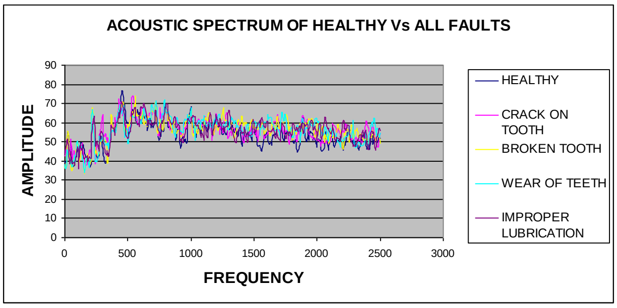

Fig.6 Acoustic Spectrum of healthy Vs all faults

Fig. 4 shows comparison of acoustic signatures of all faults,. From this figure, it is also seen that the amplitude change of mesh frequency occurs during tooth wear. In terms of crack on tooth the amplitude at gear mesh frequency increases considerably. While improper lubrication results in only spikes at meshing frequency and its harmonics. For worn-out teeth the amplitude level increases significantly. While diagnosing gearbox, gear mesh faults prove the importance of spectrum comparison. By monitoring changes over the time that the seriousness of developing problem can be estimated.

C. Effect of Load on Crack on One tooth

Various vibration and acoustic spectrums are taken for healthy gear at various loads and are discussed below. Below figures respectively shows comparison of cracked tooth at no load, at 2.5 kg load, at 5 kg load and at 7.5 kg load. As the load was given on the gear, it reflects the change in vibration spectrum. From above results following characteristics can be associated to varying load.

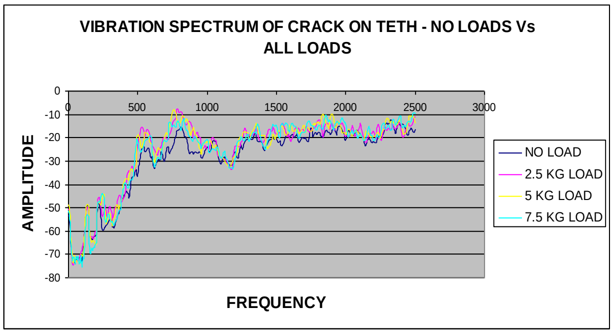

Fig.7Vibration spectrum of crack on teeth at no load Vs all load

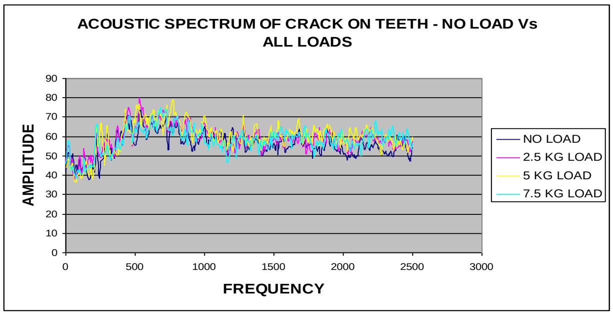

Fig.8 Acoustic spectrum of crack on teeth at no load Vs all loads condition

D. Effect of Load on Broken tooth

Various vibration and acoustic spectrums are taken for healthy gear at various loads and are discussed below. Below figures respectively shows comparison of broken tooth at no load, at 2.5 kg load, at 5 kg load and at 7.5 kg load. As the load is given on the gear, it reflects the change in vibration and acoustic spectrum. From above results following characteristics can be associated to varying load.

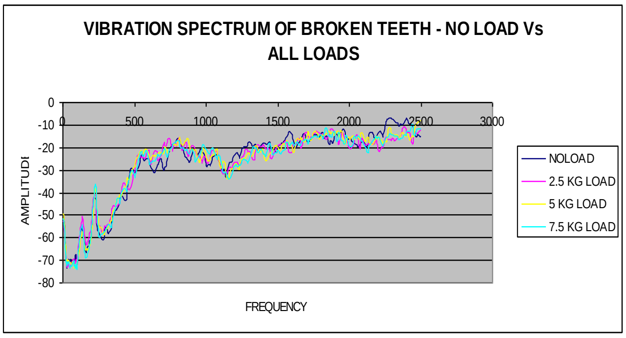

Fig.9 Vibration spectrum of broken teeth at no load Vs all load

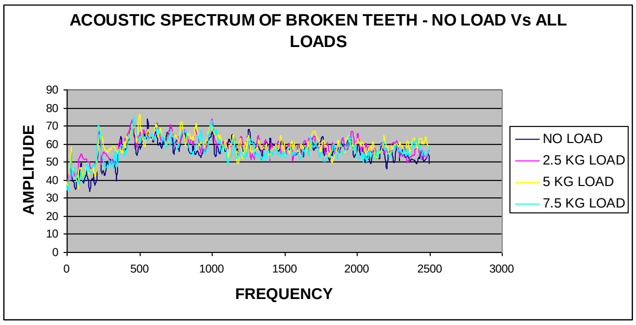

Fig.10 Acostic spectrum of broken teeth at no load Vs all load

VIII TIME DOMAIN ANLYSIS OF VIBRATION SIGNAL

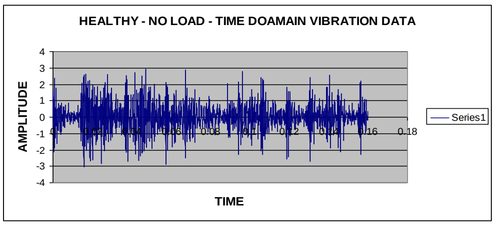

Fig. 11 Healthy-No Load-Time Domain Vibration Data

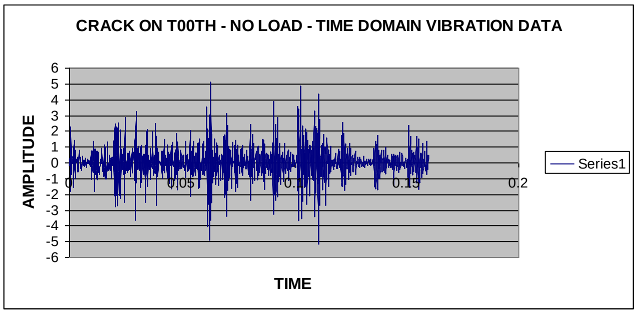

Fig. 12 Crack on tooth-No Load-Time Domain Vibration Data

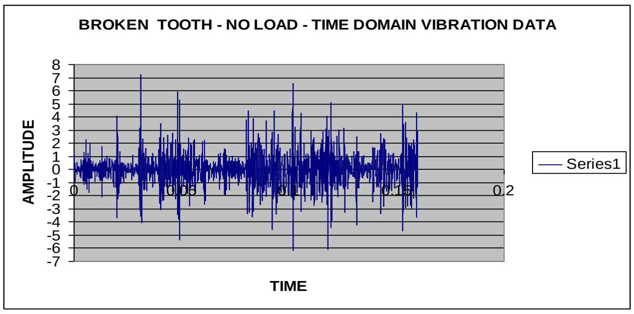

Fig. 13 Broken tooth-No Load-Time Domain Vibration Data

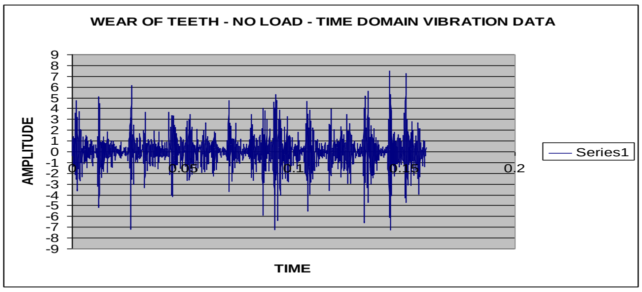

Fig14 Wear of teeth-No Load-Time Domain Vibration Data

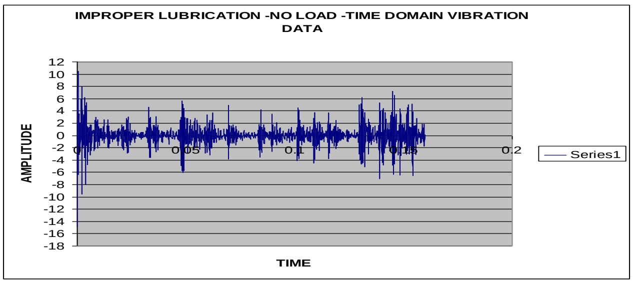

Fig. 15 Improper Lubrication-No Load-Time Domain Vibration Data

IX TIME DOMAIN ANALYSIS OF ACOUSTIC (NOISE) SIGNAL

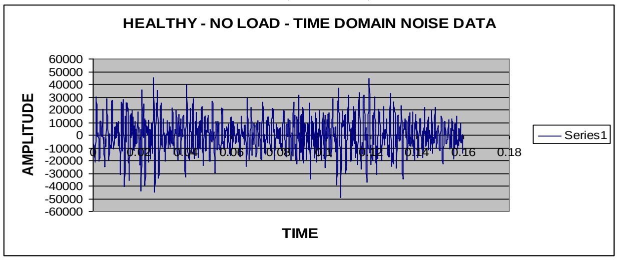

Fig. 16 Healthy-No Load-Time Domain Noise Data

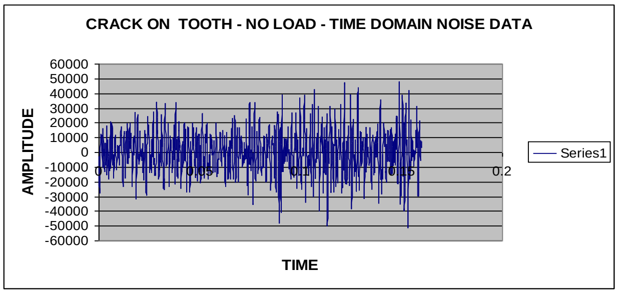

Fig. 17 Crack on tooth-No Load-Time Domain Noise Data

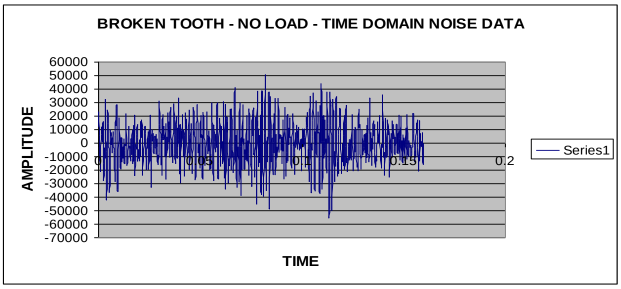

Fig. 18 Broken tooth-No Load-Time Domain Noise Data

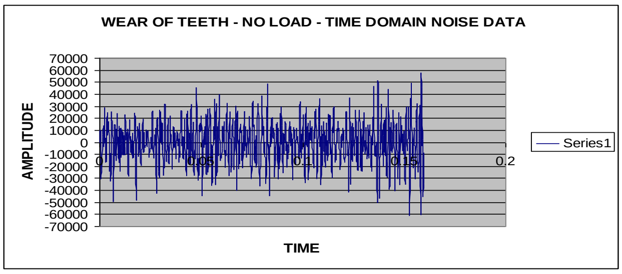

Fig. 19 Wear of teeth-No Load-Time Domain Noise Data

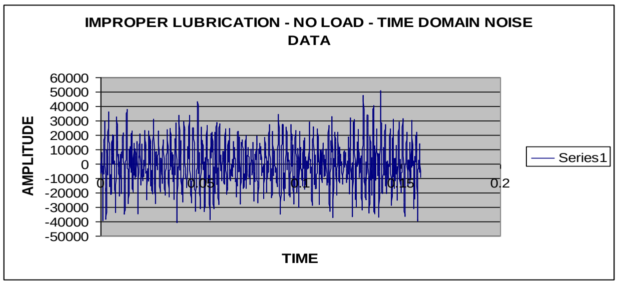

Fig. 20 Improper Lubrication-No Load-Time Domain Noise Data

X CONCLUSION

The condition monitoring of gears can significantly reduce the cost of maintenance. Firstly, it can allow the early detection of major faults, which could be extremely expensive to repair. Secondly, it allows the implementation of condition based maintenance rather than periodic or failure based maintenance. In these cases delaying scheduled maintenance can make significant savings until convenient or necessary.

Here vibration and acoustic signals were used for condition monitoring. It is shown that various types of gear failures can be detected successfully by both vibration and acoustic signals analysis.

In this dissertation work, experimentation is carried out to detect gear tooth defects through vibration and acoustic analysis and feasibility of practical application is seen. The acoustic and vibration spectrums obtained for different tooth defects are presented in previous chapter based on which following conclusion can be drawn.

With comparison of faulty crack on tooth and healthy gear spectrums, broken tooth and healthy gear, wear of teeth and healthy gear, improper lubrication and healthy respectively, it is shown that as the fault is produced on the gear, it reflects the change in acoustic and vibration spectrum. It is observed that from the amplitude of gear mesh frequency has increased considerably. From above results following characteristics can be associated to fault.

- The amplitude level increases considerably at gear mesh frequency.
- The amplitude level increases by small margin at side bands.
- It is also observed that as load is increased on the crack on tooth or broken tooth, there is change in acoustic and vibration spectrum.
- The amplitude level also increases at gear meshing frequency as load increases.

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