INTRODUCTION

1.1 Background and Motivation

Rotating machineries are backbone of modern human civilization. From household appliances to large industries, they are present everywhere. Due to higher demand of speed and operations, most of rotating machineries frequently face premature failure. Condition monitoring technique deals with the above problem so that a rotating machine can run without any premature failure. Condition monitoring is basically defined as a technique of measuring machine condition and provides preventive measures before failure occurs. Thus the technique not only reduces machine downtime but also saves time and money in machine maintenance by identifying the damaged equipment beforehand. Several techniques have been developed to monitor the rotating machineries such as oil debris analysis, vibration signal analysis, motor current signal analysis, acoustics signal analysis etc. Each one of these techniques have been developed to measure the condition of the machine and identify the minimal behavioral changes of the machine as early as possible so that preventive measures can be taken within a set time. Among these techniques, the vibration signal analysis is most widely used technique, as the vibration signal carries plenty of information related to the machine. However, many a times the vibration signal carries structure borne noise which reduces the strength of the signal. Moreover, the position of the vibration sensor has tremendous importance for condition monitoring purpose because amount of structure borne noise attenuation primarily depends on positioning of the vibration sensor. Condition monitoring technique requires signal with a high signal to noise ratio so that the technique becomes more effective and efficient. It is a well-known fact, that presence of defect changes the rotating dynamics of the machine and it affects the speed variation. Recently, analysis of speed variation has become a promising technique for condition monitoring of rotating machines as the speed signal carries less structure borne noise since it is directly measured from the rotating shaft. With this, the rotational speed signal can be measured that carries plenty of information due to direct response of the rotating dynamics and it is measured directly from the output shaft of the machine by a low cost speed measuring device like an incremental rotary encoder.

1.1.1 Importance of Condition Monitoring

In today's competitive market, it is very essential that a product must fulfill many objectives. It has to be economic, reliable and as well as it has to satisfy the customer's requirements. Therefore machines are becoming complex and automatic day by day. Beside this, for maximization of industry's profit, these machines are running for a longer period of time. Therefore, occurrence of fault is inevitable and this can lead to a sudden machine failure and subsequent results are production loss, economic loss and a question of operator's safety. Today in an industry, condition monitoring is an essential tool which takes care of the condition of the machine. Preventive measures can be taken as early as possible if condition monitoring techniques are implemented early. Thus, it increases maintenance efficiency and helps an industry from huge economic losses during failures or fault conditions.

1.1.2 Importance in a Gearbox System

Gearbox is an important machine component used for power transmission between two shafts. It finds its application from small industry to heavy industry. In power transmission system, there are other methods also such as friction wheel, belt, chain, linkage etc. However, the choice of a particular method depends upon many factors such as maximum power transmission capacity, minimum transmission ratio, dimension, cost, efficiency, and load on bearing etc. Moreover, selection of particular method also depends on type of machine used in the power transmission system. It may be possible that the belt drive is a most suitable one for a particular power transmission system. Therefore, the main idea of using a particular method for a power transmission is that it can increase the performance of a machine. Recently, a study on various power transmission methods has been portrayed in the paper (Giberti et al., 2012), which is shown in Table 1.1.

Table 1.1: Typical characteristics of mechanical transmissions

	Power max (kW)	*τ minimum	Dimensions	Cost	Efficiency	Load on bearings
Friction wheels	1/6	20	Low	Medium	0.90	high
Spur gears	750	1/6	Low	high	0.96	low
Helical gears	50000	1/10	Low	high	0.98	low
Worm gears	300	1/100	low	high	0.80	medium
Belt	200	1/6	high	low	0.95	high
Trapezoidal belt	350	1/6	medium	low	0.95	high
Toothed belt	100	1/6	medium	low	0.90	low
Linkages	200	1/6	medium	medium	0.90	low

* τ is Transmission ratio

From above Table 1.1, it is evident that why the gearbox system is so important in the area of power transmission. Further use of helical gearbox has higher demand due to highest power transmission capacity. Any fault presence in the gearbox will readily hamper the smoothing operation. Hence, condition monitoring of the gearbox is always necessary. However, the gear may face various kinds of fault like tooth wear, spall, tooth broken etc. Identification of fault at its earlier stage under different operating condition and taking the necessary action is always a challenging task for the researchers. In practical situations, the severity of a fault in gearbox depends on contact ratio. A small fault may be severe for spur gearbox but in case of helical gearboxes that fault is not severe because of higher contact ratio. Hence, the measured signal from the helical gearbox may not contain much information related to fault. Furthermore, the type of fault generation depends on gear manufacturing process. Gear manufacturing generally goes through heat treatment process, shot peening process etc. The heat treatment is generally done to increase the strength of the gear tooth and shot peening is done to improve fatigue strength. Higher amount of heat treatment increases the brittleness of the gear tooth; therefore the automobile gearbox mostly undergoes sudden tooth breakage. Beside the fault severity, applied load on the gearbox has tremendous importance in fault identification process. In practical condition, with the gearbox operating under steady load condition, the output responses such as vibration signal shows the characteristic of non-stationarity (Kar and Mohanty, 2007) due to time varying and nonlinear internal factors. These factors basically evolve from the type of gear used, geometrical error of the gear etc., therefore, time to time gear condition monitoring is essential. However the conventional gearbox fault detection system is mostly based on vibration signal. Since the vibration signal is degraded by structure borne noise, it is necessary to develop a speed signal based condition monitoring technique to monitor gearbox faults.

1.1.3 Importance in an Internal Combustion Engine

Internal combustion (IC) engine is a widely used component in the area of power generation. The conversion of energy in an IC engine is done by two processes viz. spark ignition process and compression ignition process. In these two processes, heat addition takes place by spark ignition in a spark ignition (SI) engine whereas compression ignition (CI) engine relies on air-fuel compression ratio. Moreover, in spark ignition process, the heat addition takes place at constant volume whereas in compression ignition process, the heat addition takes place at constant pressure. The heat addition during ignition leads to engine firing. The accomplishment of proper engine firing depends on many factors such as proper spark, correct air fuel ratio, rich compression ratio etc. (Heywood, 1988). As the power output from the IC engine totally depends on proper combustion in the engine; therefore detection of engine firing over a cycle is an important issue. In the spark ignition IC engine, the most common fault is engine misfire due to spark plug fault. The engine misfire interrupts the continuous mechanical energy transmission. Therefore, continuous condition monitoring of IC engine is utmost necessary to provide continuous power to the system. In vibration signal based condition monitoring, an accelerometer is mainly placed on the cylinder head to capture the vibration. Monitoring has been done either by direct analysis of vibration signal or by reconstructing the cylinder's pressure. Here too, the vibration signal is contaminated by structure borne noise. Recently, few researchers have started to analyze the engine behavior by analysis of instantaneous angular speed (IAS) of the output shaft. In the present work, an endeavor has been put forward to detect the engine firing and study the behavior of IC engine based on engine output shaft rotation speed signal.

1.2 Analysis of Gearbox System with Fault

1.2.1 Geometric Error

Smooth operation of gearbox is an important aspect in power transmission system. Therefore, precision of gear has vital role. Manufacturers try their best to fulfill this aspect. However in practical situation, it can never be achieved. A certain amount of geometric error will always be present. The geometric error includes tooth profile error, tooth tracing error, pitch error etc. The geometric error not only hampers smooth operation but also causes huge stress generation on gear tooth. Further it leads to gear tooth crack.

1.2.2 Wear

Failure of a gear not only depends on gear root stress, surface pressure and crack, but also gear tooth wear which sometimes leads to severe damage. In gear wear, layers of metal are removed from tooth flank (Shipley, 1967). However, initially the tooth wear creates problem in smooth operation of the gears and as time goes on the tooth wear leads one or more tooth failures. There are two types of gear wear which takes place during gear operation viz. abrasive wear and corrosive wear. The first one takes place due to the splashing action of foreign particles such as metallic debris, sand particles etc. whereas the corrosive wear takes place due to chemical reaction of lubricating oil, acid, moisture etc. Thus, wearing action generally produces scratch like marks on gear tooth surface

1.2.3 Pitting

Pitting is a fault in gear generated due action of fatigue loading on the gear tooth (Shipley, 1967). Under the fatigue loading while the fatigue strength of the gear tooth becomes lesser than the contact stress, then the metal from the gear tooth gets removed. Pitting is generally non progressive in nature and generally occurs in gears. Over time, the pitted surface gets smoothed out by the repetitive action of tooth movement. Sometimes, pitting becomes destructive in nature. The pitting when distributed all over the tooth weakens the tooth leading to breakage.

1.2.4 Spall

Spall is a kind of damage where flakes of material get removed from the tooth surface (Feng et al. 2009). The spall occurs due to high contact stress at the mating gear surfaces. Based on size, the spall is divided into three categories viz. minor spall, moderate spall and severe spall. The minor spall is where the wear length is about 2~4 mm and width is 0.5~2mm, moderate spall is of length 5~13 mm and width 3~5 mm. Severe spall is where the wear length is about 20 mm and width is 8 mm. Tooth spall leads to tooth failure under dynamic loading during gear operation.

1.2.5 Tooth Broken

Tooth of a continuously running gear is always subjected to a repetitive loading or fatigue loading. Under the action of this load, a crack is initially initiated on the tooth flank, which progresses over time and suddenly the tooth fails. This broken tooth changes the meshing stiffness of the gear, which leads to higher vibration during operation. Tooth breaking of the gear causes also missing of contact lines. Therefore, a sudden impulse force is created by the gear tooth during gear operation. The tooth breakage generally occurs at the root of the tooth as the maximum stress is generated there.

1.3 Organization of the Thesis

In 2nd chapter, a literature review is presented. The chapter covers detection and monitoring techniques based on IAS signal, vibration signal, for rotating machineries such as gearbox, rotor, IC engine and other machineries.

Chapter 3 covers various techniques for measuring instantaneous angular speed (IAS) from encoder pulse signal. The chapter mainly focuses on analog to digital converter based IAS estimation technique. Each and every analog to digital based technique has been compared with each other. Later, a suitable technique has been considered for the IAS estimation. This IAS signal is further analyzed by various signal processing techniques to monitor a multistage helical gearbox and an SI engine.

Chapter 4 describes the detail of the experimental setup used in the research.

Chapter 5 deals with the analysis of IAS signal from a multistage helical gearbox under different speeds, loads and defect severity conditions. Different signal processing techniques have been employed to extract the hidden information from the IAS signal. In this chapter, a comparison between various signal processing techniques has been shown and an epilogue has been drawn for gearbox monitoring.

Chapter 6 encompasses the time synchronous averaging of IAS signal to enhance quality of fault detection process in multistage gearbox.

Chapter 7 deals with engine firing detection in SI engine. Moreover, the chapter focuses on characteristic analysis of SI engine by analyzing the speed variation estimated from rotary encoder signal and vibration from laser vibrometer.

Further chapter 8 presents the summary with concluding remarks.