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Fault Diagnosis of Helical Gear through Various Vibration Techniques in Automotive Gearbox

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Abstract The main objective of this study is to detect gearbox fault signals through vibration analysis. Experimental tests are carried out using several sets of gears under different speeds and constant load. Initially, helical gears are fixed in the gearbox test rig and signals are recorded using data acquisition systems to establish the baseline behavior of normal gears. Then, the normal gears are replaced by defective gears and signals are recorded for each one of the cases separately under the same condition. After that, four proposed techniques of measuring vibrations, namely; time domain, root mean square, crest factor, and kurtosis are employed to evaluate the gearbox defects. From experimental results, it is found that the vibration signals play a significant role in evaluation defects of the gearbox. Also, it is noticed that the peak to the peak value of the time domain fluctuates around the x-axis and increases with the shaft speed. Moreover, it is found that at fluctuating speed conditions, the root mean square, crest factor, and kurtosis approaches are to be clearly distinguished from time domain for normal and defective gears. Finally, it is found that the vibration amplitudes of the gearbox are increased resulting in increased tooth breakage and wear at different gearbox speed.

Keywords: *time domain, root mean square, crest factor, kurtosis, gearbox fault diagnosis*

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1. Introduction

Gearboxes have been used to transmit the power from engine to the wheels in automotive industry. Gears are one of the most significant parts in mechanical transmission systems [1,2]. It is critical element in a variety of industrial applications, transportation, aerospace, energy, agricultural sectors, wind generation and other fields. Gears, however, usually cause mechanical shutdown even casualties due to its rugged working environment [3]. Therefore, the condition monitoring and fault diagnosis for gears are of great significance in ensuring the operational safety of systems [4].

Smooth operation and high efficiency of gears are necessary for the normal running of machines. Therefore, gear analysis is an important activity in the field of condition monitoring and fault diagnosis [5]. Early detection of local gear faults in industrial environments is very important to optimize the maintenance schedule and reduce the operating cost of gearbox damage [6]. Failures of the gearbox may cause injury to human beings and important economic losses. To avoid the consequences of any harmful accidents, several techniques are developed in condition monitoring to detect faults as early as possible. Vibration signal analysis is the most common gear detection technique for gear damage detection [7].

In the later studies, numerous signal processing techniques have been implemented as an approach to support condition monitoring and diagnostic procedures [8]. As still observed, a number of publications on vibration based gearboxes condition monitoring and fault diagnosis have been attracting in academic journals, conference proceedings and technical reports and have been reported in [9,10,11]. The vibration signals contain rich sources of information from the various mechanical components. By extracting fault characteristics of the gears embedded in these signals, the health condition and fault type can be confirmed. For machinery fault diagnosis, the vibration signals are widely updated and used. There are many research papers studying vibration-based fault detection and diagnosis [12,13]. Generated the vibration signals in the gearbox are induced due to fluctuate of the force on the gear surface and increased related to the number of gear teeth and the rotational speed of the gear shaft. After that, the vibration is transmitted to the structure and noise and vibration in the gearbox are emitted [14].

In this paper, gearbox test rig is developed to provide the necessary rotation speed for evaluating different gear defects under operational conditions. Firstly, an overall layout of the test rig is provided. Then, each of the components which make up the test rig is outlined. After that, information is provided on the type and severity of tooth breakage faults which are used. The influence of tooth width breakage and tooth wear is studied. Finally, vibration signatures of good gears and defective gears are obtained using the experimental facility created under different operating conditions.

2. Experimental Rig Setup

A complex test rig is developed in order to gather accurate and reliable data that can be used to evaluate gearbox through several signal processing techniques, as shown in Figure 1. The main objective of these experimental studies is to monitor the condition of automotive gearbox operating under different speeds. Piezoelectric accelerometer with sensitivity of 100 mV/g is placed on the casing to provide vibration signatures of gearboxes. The driving unit consists of a 7.5 kW Ac motor that has a maximum speed of 1500 rpm with a variable speed controller. The rotational speed is directly measured by a photo-type tachometer type S119-LT, with resolution of 0.1 rpm. Brake mechanism is fixed with the Ac motor through coupling and a mild steel shaft, which fixed on the frame by two ball bearings located between the motor and the brake assembly. The hydraulic braking mechanism with control valve is used to enforce the required load and display its value in pressure gauge.

A piezoelectric accelerometer, which directly mounted over the gearbox through a magnetic base, is used to gain the vibration outputs. The output signal of accelerometer is transferred to the five channels analyzer and saved as vibration signals. The saved data in the vibration analyzer is retrieved through cables to the PULSE software program. The Brüel & Kjær Vibro-Acoustics Data Acquisition System Type 3560-B is used. The gearbox is tested under no load condition to obtain reference signatures. Before conducting the experiment, the test rig vibrations are measured and verified to check the misalignment. The setup is run for 15 minutes to stabilize the vibration.

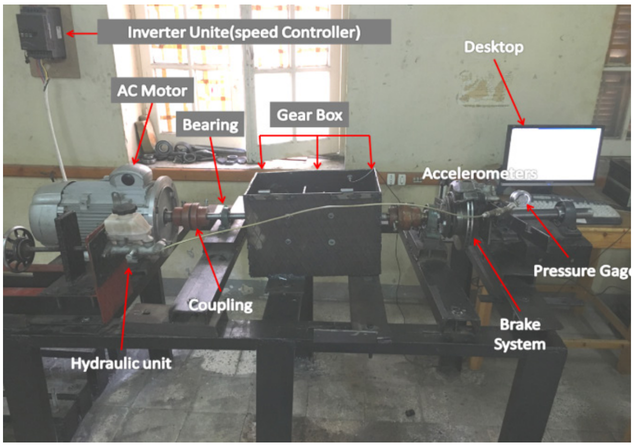

Figure 1. Gearbox fault diagnosis test rig

3. Results and Discussion

3.1. Time Domain Analysis of Normal Gear

In this section, the outputs of the normal gears are measured as no defect condition. Four different methods are considered and compared to evaluate the gearbox vibration namely; time domain, RMS, crest factor and kurtosis. The accelerometer output is directly fed into the dual channel vibration analyzer and it is stored as vibration signatures. The amplitude change of gearbox vibration signals along with time is displayed. Then, time domain signals are acquired at four different speeds. Figure 2 - Figure 5 illustrate the typical time waveform of the normal gear at 100, 200, 300 and 400 rpm, respectively. It is found that the peak to peak value of time domain increase with the increasing the shaft speed and fluctuate around the x axis. Also, It can observed that, the time domain signals displays a clear regular waveform with small peak less than 0.05, 0.06, 0.08 and 0.1 m/sec^2 in acceleration amplitude for 100, 200, 300 and 400 rpm, respectively.

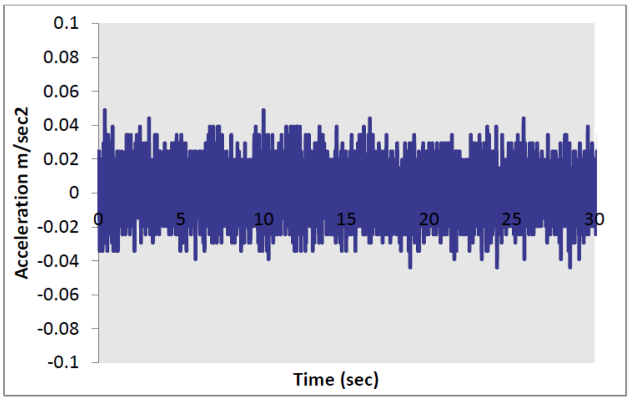

Figure 2. Time Domain Vibration Signal of the Normal Gear at 100 rpm

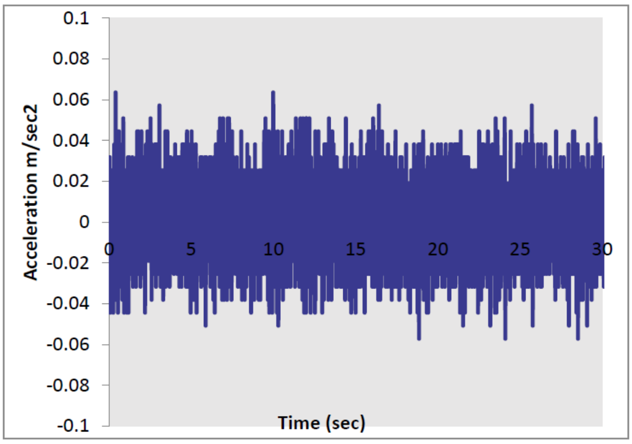

Figure 3. Time Domain Vibration Signal of the Normal Gear at 200 rpm

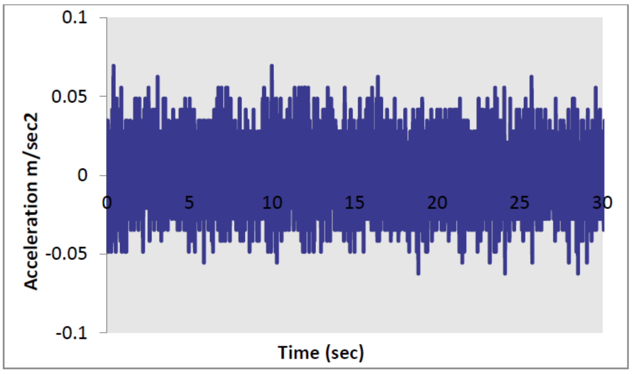

Figure 4. Time Domain Vibration Signal of the Normal Gear at 300 rpm

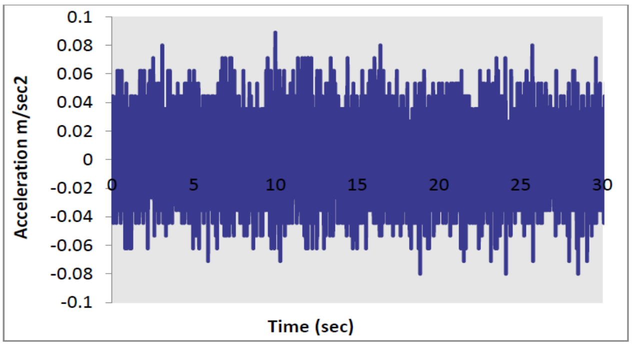

Figure 5. Time Domain Vibration Signal of the Normal Gear at 400 rpm

3.2. Evaluation Vibration of Normal Gear through Different Methods

Time domain vibration signal of the normal gear with different speed are difficult to compare and evaluate vibration generation of the proposed helical gear, as shown in Figure 6. Hence, in this section three different methods are used for making the comparison between several cases at rotational speed namely; root mean square (RMS), crest factor and kurtosis. RMS is used and plotted with changing rotational speed, as shown in Figure 7. It is served as index of average amplitude of time analysis signals. The experimental results are obtained at 100 rpm, 200 rpm, 300 rpm and 400 rpm, which are the speed settings available at the test facility. In the values of RMS obtained are less than 0.08 mm/s, which show that the gearbox is normal (defect-free). This may be means that the instant imperfections during the manufacturing process have low vibration amplitude. The crest factor of the vibrations at various rotational speeds as 100 rpm, 200 rpm, 300 rpm and 400 rpm is represented as shown in Figure 8. It is clearly found that the values of crest factor increase with increasing the gearbox shaft speed. Also, Figure 9 represents the kurtosis of the vibrations at various rotational speeds at 100 rpm, 200 rpm, 300 rpm and 400 rpm. It is found clearly that the kurtosis increase with increasing shaft speed. From the four different signal methods which are discussed and compared in order to evaluate the gearbox vibration namely; time domain, RMS, crest factor and kurtosis. It is found that the RMS, crest factor and kurtosis methods are easy to compared and used for the following section.

3.3. Evaluation Vibration of Tooth Breakage Defect

Tooth breakages faults are a very common happening in gear transmission because of high stress on gear roots that produces from bending loads on gear tooth [15]. This type of fault begins with single tooth which may have fabricating or material flaws. Because of the high overlap ratio of the helical gears, this type of fault only has a small effect on the overall power transmission of the gearbox. Previous works use conventional methods such as vibration signal analysis to diagnose the faults of tooth breakage in gearboxes, nevertheless such techniques have often proved unreliable to be in detecting the presence and severity of tooth breakage faults [16].

In this section, a gear tooth width breakage with four cutting percentages (25%, 50%, 75%, and 100%) of tooth breakage in the drive gear at the first stage of the helical gearbox. Before beginning the test, the gearbox is run for an hour at full load to warm up and reach to operational temperature of 50°C. The gearbox vibration signals are measured using RMS, crest factor and kurtosis techniques respectively, as shown in Figure 10, Figure 11 and Figure 12 respectively. The cutting percentage is varied from 25% to 100% of tooth breakage at various rotational speeds as 100 rpm, 200 rpm, 300 rpm and 400 rpm. It is found that the vibration signals indicating there is clearly an abnormality occurring in the system and the signals increase with the speed. From experimental results, it can concluded that the vibration of gearbox increase with increasing the tooth width reduction through RMS, crest factor and kurtosis techniques.

Figure 6. Proposed helical gear

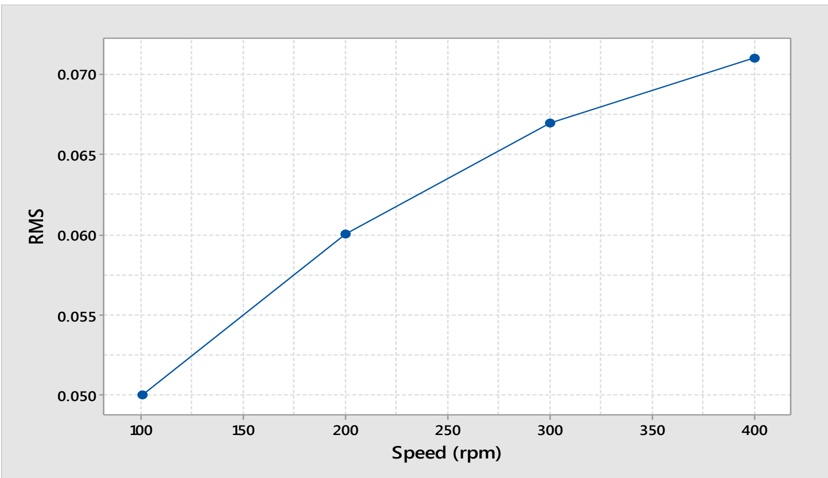

Figure 7. RMS of the Normal Gear with Different Speeds

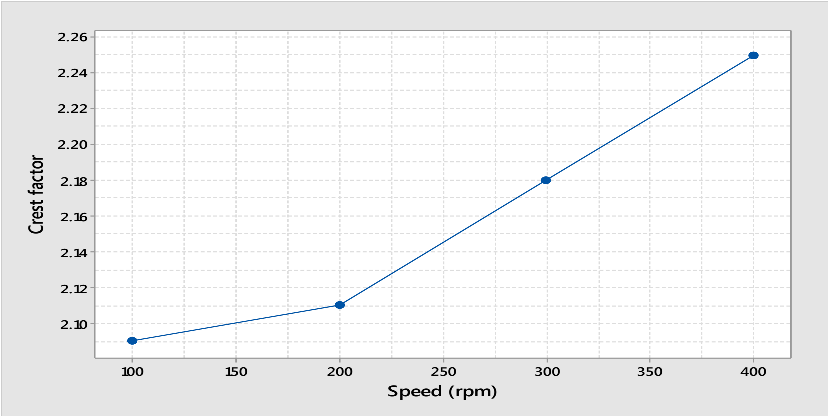

Figure 8. Crest Factor of the Normal Gear with Different Speeds

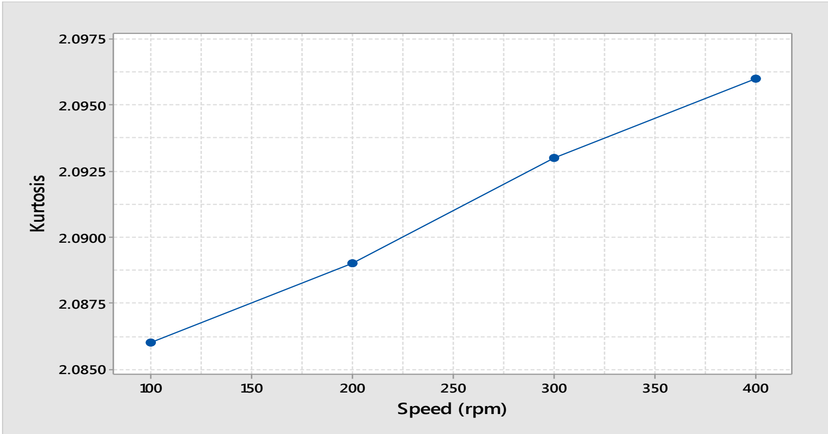

Figure 9. Kurtosis of the Normal Gear with Different Speeds

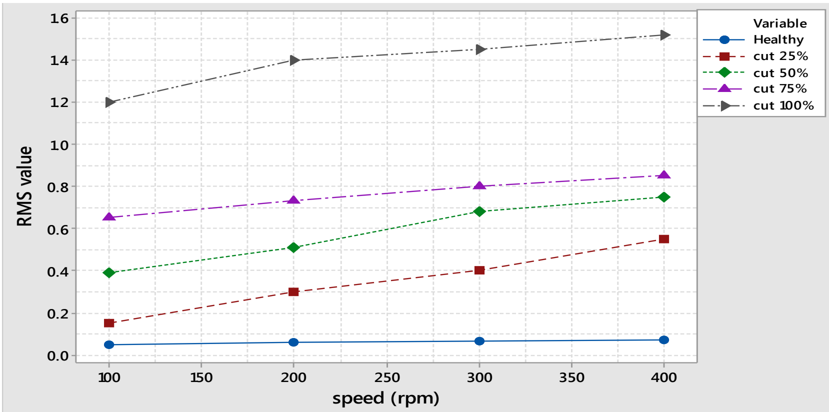

Figure 10. RMS Vibration Measurement Tooth Breakage Defect

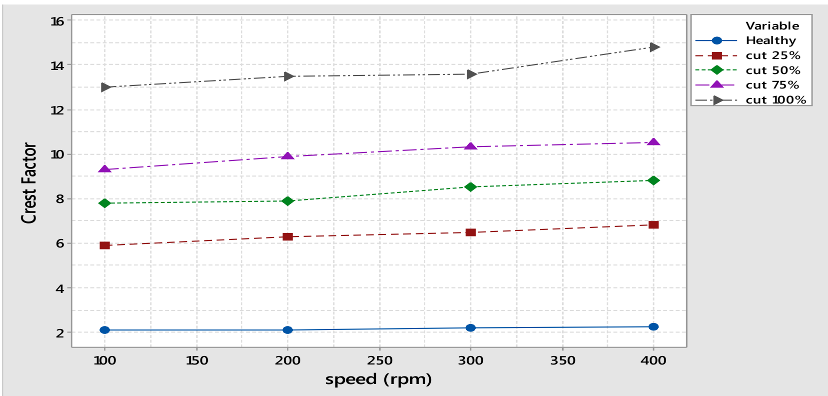

Figure 11. Crest Factor Vibration Measurement Tooth Breakage Defect

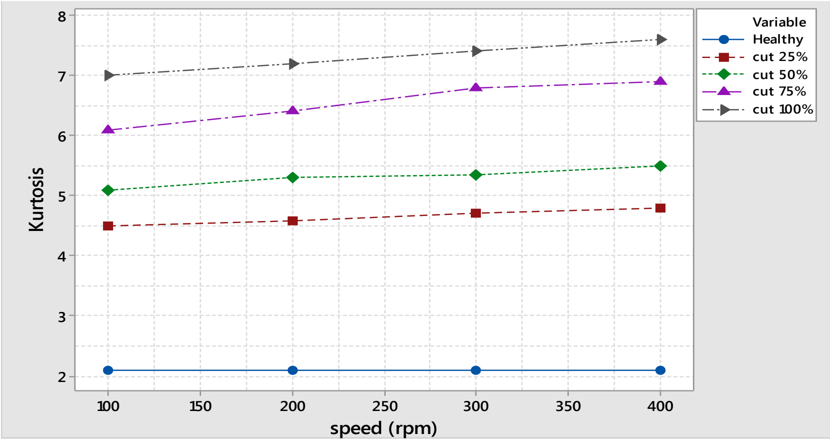

Figure 12. Kurtosis Vibration Measurement Tooth Breakage Defect

3.4. Evaluation Vibration of Worn Gear Tooth Defects

Of the most common causes of gear failures is the gear teeth wear that are exhibited to rolling and sliding contact under changing load conditions. The gear wear defect changes the tooth geometry and leads to different degrees of deflection of a faulty tooth and contributes to gear vibration. The gear defect of wear is progressively induced as represented in Figure 13 in four stages from 25% to 100% wear on one side of the selected tooth of a non-faulty gear. Figure 13 show the RMS of teeth wear percentage. It's found that the maximum RMS reflects the intensity of the defect it is recorded. The present investigation has carefully found the maximum RMS increasing in all wear percentage. Figure 14 show the crest factor of wear teeth percentage. It's found that the maximum value of crest factor reflects the intensity of the defect and it is increased for all teeth wear percentage. Figure 15 show the kurtosis of wear percentage. It's found that the maximum amplitude of kurtosis increase with the wear percentage increase.

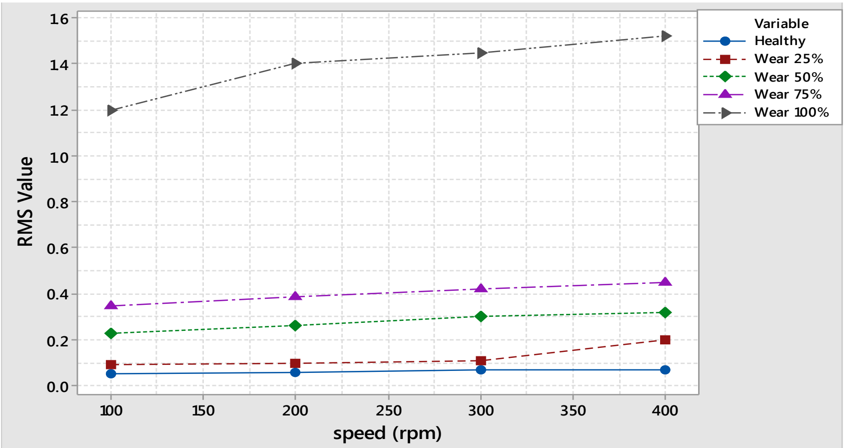

Figure 13. RMS Vibration Measurement Tooth Wear

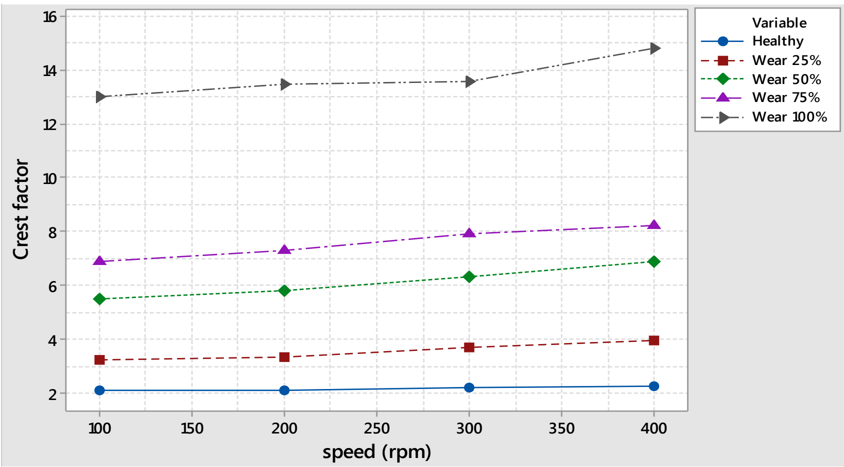

Figure 14. Crest Factor Vibration Measurement Tooth Wear

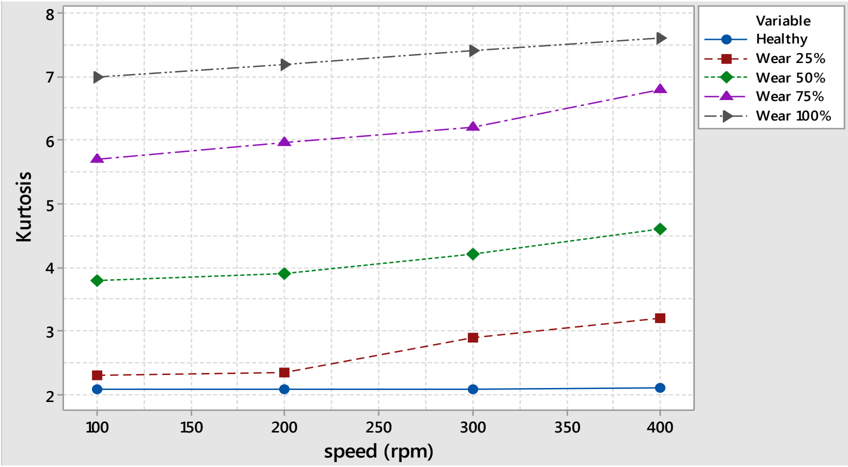

Figure 15. Kurtosis Vibration Measurement Tooth Wear

4. Conclusions

This paper presents experimental tests which are carried out on several sets of gears to examine the effect of tooth breakage and tooth wear defects on vibration generation of the gearbox. Based on the results from the experimental work, time domain provides useful information to analyze defects in gearboxes. Also, it is noticed that crest factor, RMS and kurtosis from the time domain technique for normal and defect gearboxes are obtained. It can be seen that the high signal of fault gear is increased compared with normal gear. All parameters have greater values in tooth breakage gear greater than normal gear. All parameters increase with increase in speed in breakage gear. Moreover, it is found that the RMS, crest factor and kurtosis ratios for acceleration response are suitable during defect faults while the time domain is not suitable during monitoring the faults. Also, it is observed that the RMS magnitude, crest factor and kurtosis ratios for both normal and defected gears tends to be higher for faster shaft speed.

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