Experimental Study of Worm Gearbox Faults using Acoustic Emission Signals

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Abstract

This paper assesses the performance of Acoustic Emission (AE) signals for condition monitoring and fault detection in low-speed gearboxes. One normal gearbox and one faulty gearbox from a gearbox-driven roll forming line, each consisting of a worm drive and four spur gears, were used in this study. An AE sensor was placed on top of each gearbox using magnetic mounts and the signal was collected using a PCI-II board. The collected signals were processed and analyzed via AEwin software. Hit-based, time domain, and frequency domain AE parameters were compared to determine their effectiveness. The count rate, absolute energy and signal strength were found to be the hit-based parameters that resulted in the clearest distinction between good and faulty gearboxes. The absolute energy was observed to be the best time domain parameter followed by RMS. Both frequency and time-frequency analysis results indicated that the faulty gearbox has higher spectral peaks in the lower frequency range, which was confirmed numerically by calculating the frequency centroid difference. AE was shown to be useful for condition monitoring and fault detection in low-speed gearboxes, with numerous AE parameters identified as showing significant differences between normal and faulty gearbox conditions.

Keywords: Gearbox, Worm Gear, Acoustic Emission, Fault Detection

Introduction

Gearboxes are widely used in industry applications to provide speed and torque conversion [1]. Unexpected gearbox failures can result in significant costs due to lost production and ruined products. Therefore, different condition monitoring (CM) methods have been developed for gearbox fault detection. Many experimental studies have been performed to identify and compare the effectiveness of CM methods on gearboxes, however, few of them involve gearboxes for low-speed machinery, particularly of speeds less than 50 revolutions per minute (rpm). Low speed machines are typically found in cooling towers, ball mills, wind turbines, and roll forming machinery. These machines are critical to the production process and normally have high value. Therefore, one normal gearbox and one faulty gearbox from a gearbox-driven roll forming line, each consisting of a worm drive and four spur gears, were selected as the object of this study.

Vibration analysis is one of the most popular methods for gearbox condition monitoring, but there are limitations in its application in slowly rotating gearboxes [2]. A high frequency signal analysis technique referred to as Acoustic Emission (AE) has increasingly been proposed as a powerful fault detection tool in applications where other techniques fail to yield useful results, such as in low speed gearboxes. AE refers to the transient elastic waves within a material (typically metal), which are generated by the rapid release of localized stress energy caused by material deformation under mechanical loading [3]. The AE techniques have the advantage of allowing identification of early stage defects since AE is produced at the microscopic level and is highly sensitive.

In addition, AE is a result of only high frequency elastic waves, which means it is relatively insensitive to typical mechanical background noises at lower frequencies [4]. These advantages make the AE technique a good choice for monitoring of gearboxes, particularly in low speed applications. However, most published work report focuses on experimental studies identifying damage in spur and helical gears and very little work has been done involving AE based CM of worm gear drives.

For a worm gear drive, which is a gear arrangement consisting of a worm meshing with a worm gear, the transfer of power involves a predominantly sliding motion and it normally results in significant sliding friction. Many studies have been conducted to investigate the relationships between AE and sliding. Dornfeld and Handy [5] investigated the sensitivity of AE to the onset of motion when slip occurs. Lingard et al [6] studied sliding wear using AE and concluded that AE signals are related to the wear rate, the frictional work inputs, and established tribological contact variables. As sliding is the dominant motion of a worm drive, AE offers the opportunity for worm gear fault detection. Elforjani *et al.* [7] reported on a comparison of AE based condition monitoring tests versus vibration based fault detection and diagnosis techniques. Their work used worm gears with artificially seeded faults and showed that the AE based methods provided superior detection and diagnostic results for both “small” and “large” defects on worm gear tooth.

Methods

Apparatus

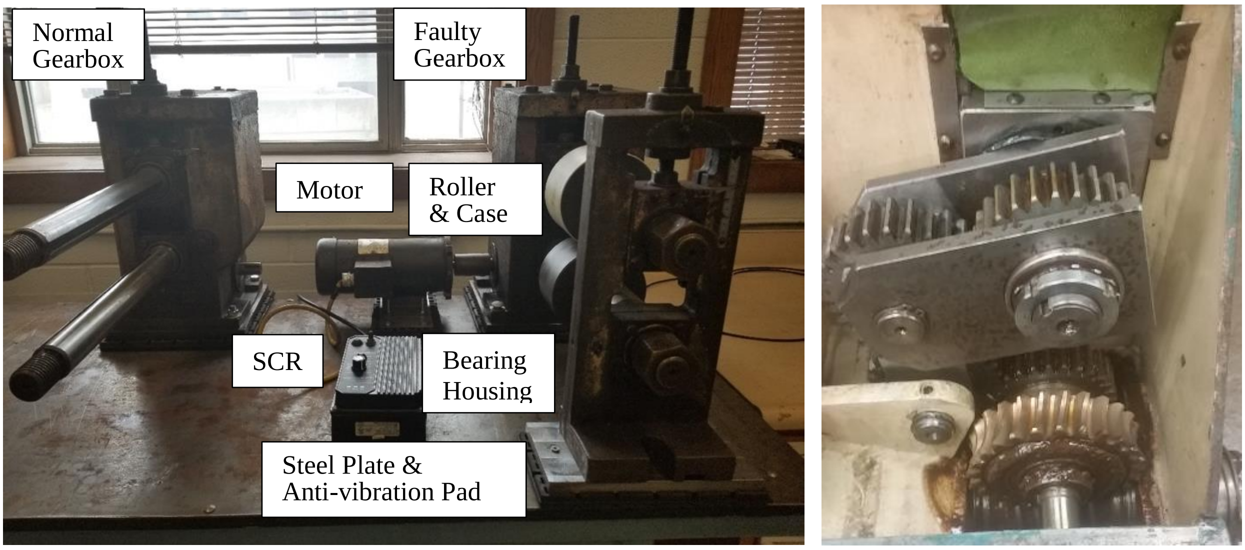
Experimental facilities were set up as shown in Figure 1(a). Two gearboxes were mounted securely to a rigid table. Each gearbox contains a worm drive, which drives the gearbox input shaft that in turn drives parallel spur gears that then rotate the rollers (see Figure 1(b)). A 3/4 HP LEESON Motor was connected to run one gearbox for each test. The KBPC-240D SCR (Silicon controlled rectifier) was used with the motor to control the input power. Steel plates with different height were placed under the motor, gearboxes and bearing housing to meet the connection requirement. To reduce the amount of vibration transmitted through the table, anti-vibration pads were placed between the table and motor/gearbox/bearing housing. In addition, casings were placed over one roller to simulate the metal strip passing between the rollers.

The “normal-state” gearbox was recently refurbished with new gears throughout. The “faulty-state” gearbox had recently been removed from regular production use on the metal forming line. No specific fault was identified by the maintenance technicians, only that it was removed from production because it no longer met performance specifications. No details on the performance specifications used to judge gearbox worthiness were available.

Instrumentation

The PCI-II based AE system produced by Physical Acoustic Corporation (PAC) was used for AE signal collection. This system includes a sensor, preamplifier, cables, PCI-2 (Peripheral Component Interconnect) card and the AEwin software. The R15α used for AE tests is a narrow band resonant sensor with high sensitivity and low-frequency rejection. It was mounted to the top of the gearbox housing using a magnetic mount (see Figure 2). The connected preamplifier is 2/4/6 type with in-line differential and in-line signal ends. It is applied to condition sensor outputs to be acceptable for inputs on the PCI-2.

The gain level of the preamplifier was set at 40 dB and the in-line single end was used. The sampling rate was set to 1 million samples per second (MSPS), which resulted in a measurable frequency of up to 500 kHz. The threshold level, which is a reference line used to define an AE “hit”, was set to 27 dB to ensure that only one or two events would be detected for every five (5) seconds at stopped operating condition. This limit was deemed ideal to maximize the sensitivity to events while at the same time reducing spurious events not related to gearbox operation. Around seven (7) seconds of signal were collected for each measurement. The time domain rate, which controls the frequency of the time domain parameters to be recorded, was set at 10 ms. The AE waveforms contain 10,000 samples each and were saved for further frequency analysis. A high pass filter of 40 kHz was used to reject the unwanted parts of each signal for all AE tests.



(a) *(b)*

Figure 1. Pictures of (a) overview of experimental set-up and (b) gearbox structure.

Figure 2. Sensor installed at the gearbox housing top

For the AE tests, three loading conditions were simulated by adjusting the contact condition of the two rollers (fully separated, just contacting, and full contact), which were achieved by changing the location of the upper shaft as indicated by a ruler attached to both gearbox and bearing housing. The rotating speed of the output shaft was adjusted from around 3 rpm to 35 rpm by the SCR drive. The results shown are for the just contacting condition. The results for the other load conditions showed similar results.

Results and Analysis

Hit-based AE analysis

The plots shown in Figure 3 compare the faulty-state and normal-state data by using different hit-based parameters, including the RMS, peak amplitude, count rate, signal strength and absolute energy over the duration of 1 second. The averaged parameter values collected under each shaft rotating speed are presented as circle dots, and the trend lines were plotted using the curve fitting function in MATLAB. The red and green colors represent data collected from the faulty and normal gearboxes respectively. The parameter values for gearboxes rotating at 25 rpm were marked for comparison, the faulty-state and normal-state gearbox could be clearly distinguished by the parameter gaps.

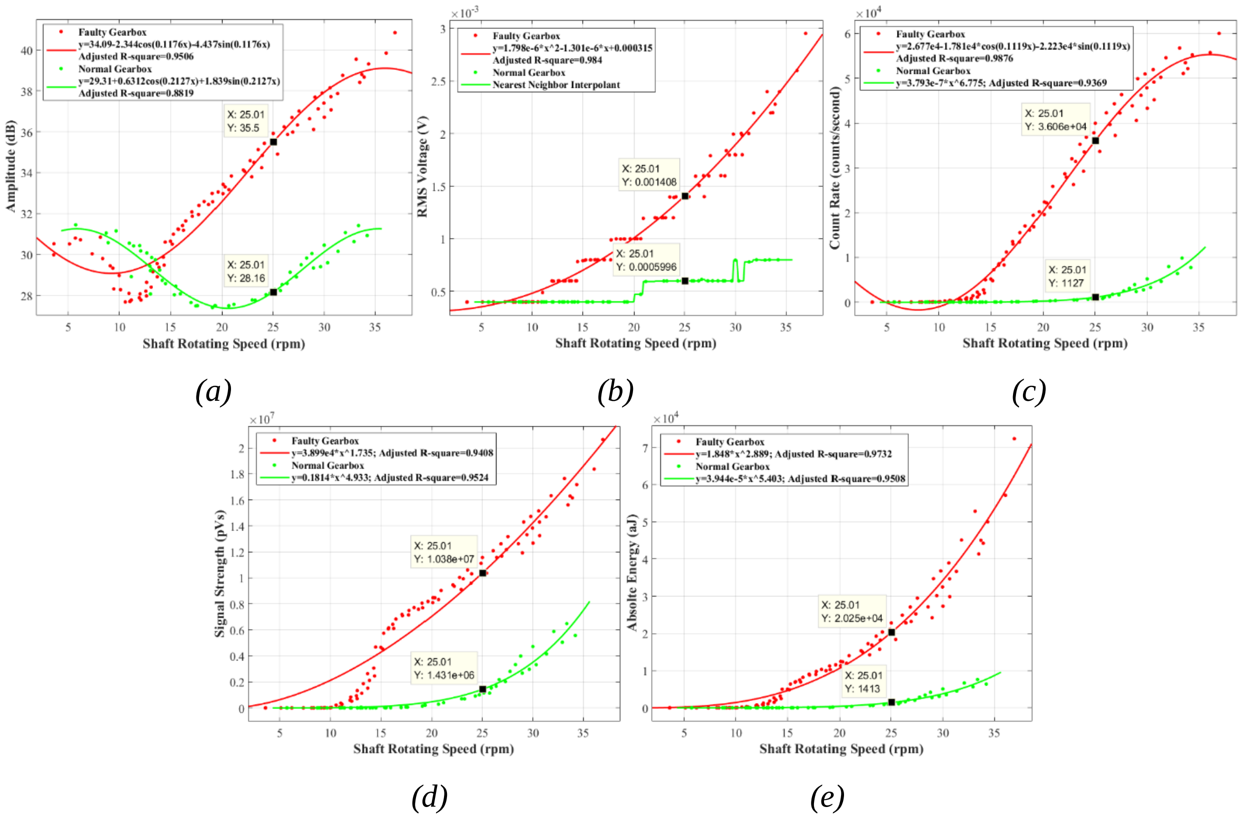


Figure 3. Hit-based parametric comparison of AE signals from the faulty and normal gearbox: a) Amplitude, b) RMS Voltage, c) Count Rate, d) Signal Strength and e) Absolute Energy. (Curves are to highlight trends only.)

To compare the performance of hit-based AE indicators, the Parameter Difference (PD) was calculated to show the relative difference of each parameter between the faulty and normal gearboxes.

$$\mathrm{PD} = 20\log_{10}\frac{P_{Faulty}}{P_{normal}}\ (\mathrm{dB})$$

where P_{Faulty} and P_{normal} represent the average parameter values of the faulty and normal signals respectively.

Since the shaft rotating speed was controlled by rotating the turn-button at the SCR, not all faulty gearbox signals have the corresponding normal gearbox signal at exactly the same shaft rotating speed. To handle this problem, the parameters were averaged per 1 rpm speed range before calculating the PD. The results are presented in Figure 4.

The absolute energy, signal strength and count rate are better hit-based AE parameters for fault detection as they present larger differences than the RMS and amplitude at all speeds. The PD value for these three parameters reaches the maximum (40 to 50 dB) at around 16 rpm, however, the value decreases steeply at speeds above 16 rpm. Instead, the PD of RMS increases steadily over the whole speed range. The RMS-based PD reaches around 10 dB at 34 rpm, which matches the PD level of signal strength. The results show that absolute energy, signal strength and count rate are useful parameters for condition monitoring of gearbox faults at speeds lower than 35 rpm. It is anticipated that RMS will be a good indictor to distinguish the faulty gearboxes at high rotating speeds (which were not included in this study due to the relatively low speed application focus).

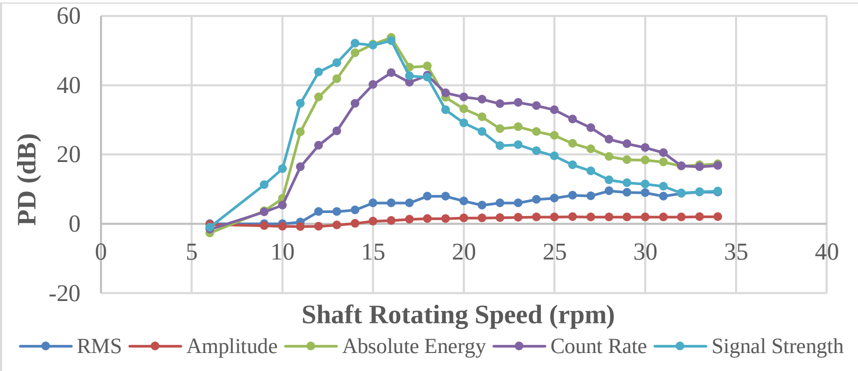


Figure 4. Comparison of PD of hit-based AE parameters

Time domain AE analysis

Figure 5 shows the time domain AE signals collected from the normal and faulty gearboxes rotating at 21.2 rpm and 20.9 rpm respectively. It was observed that the faulty gearbox signals were obviously stronger than the signals collected from the normal gearbox rotating at similar speed.

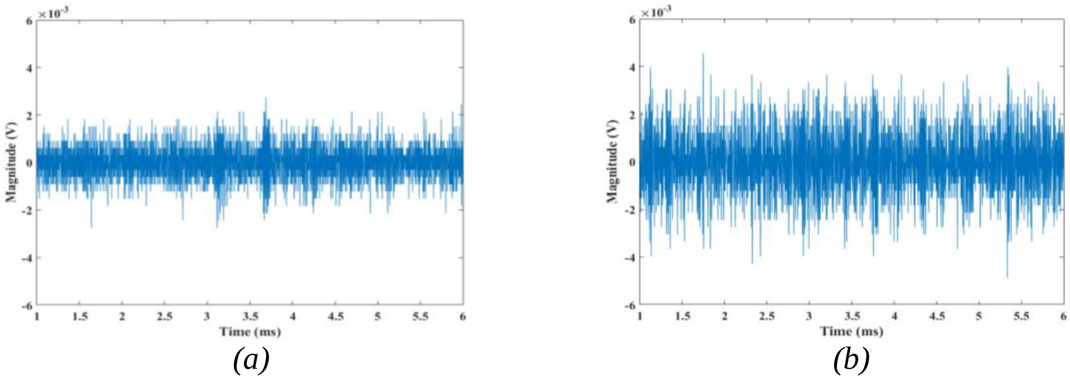


Figure 5. Comparison of AE signals of (a) normal gearbox and (b) faulty gearbox

Figure 6 presents the time domain parameters including the RMS, absolute energy, Kurtosis and Crest Factor as a function of the shaft rotating speed. The RMS and absolute energy were recorded by the AE system at every 10 ms, while the Kurtosis and Crest Factor were obtained by analyzing the waveforms using MATLAB. As can be seen from Figures 6 (a) and (b), the faulty gearbox has higher RMS and absolute energy, and the difference becomes more obvious as speed increases. No clear trend lines were obtained for Kurtosis and Crest Factor plots as shown in Figures 6 (c) and (d), the Adjusted R-square value of the fitting lines are all below 0.5. In addition, both faulty and normal gearboxes tend to have stable and similar Kurtosis (around 3) and Crest Factor value (around 3.5) at speeds above 15 rpm.

The performance of each parameter can be more clearly observed from the PD plot as shown in Figure 7. The negative PD of Kurtosis and Crest Factor in the speed range from 5 to 15 rpm indicates that more outliers are presented in the normal gearbox signals under low rotating speed. The PD stays at around 0 for Kurtosis and Crest Factor when the rotational speed increases, therefore these two parameters are not ideal for gearbox fault detection. Instead, the RMS and absolute energy are good indicators as they have positive and increasing PD values over the whole speed range. It is obvious that the absolute energy is the best parameter for fault detection since it has the highest PD level at all measured speeds. At this stage it is not clear exactly the absolute energy provides the best trending ability. This will be the focus of future study.

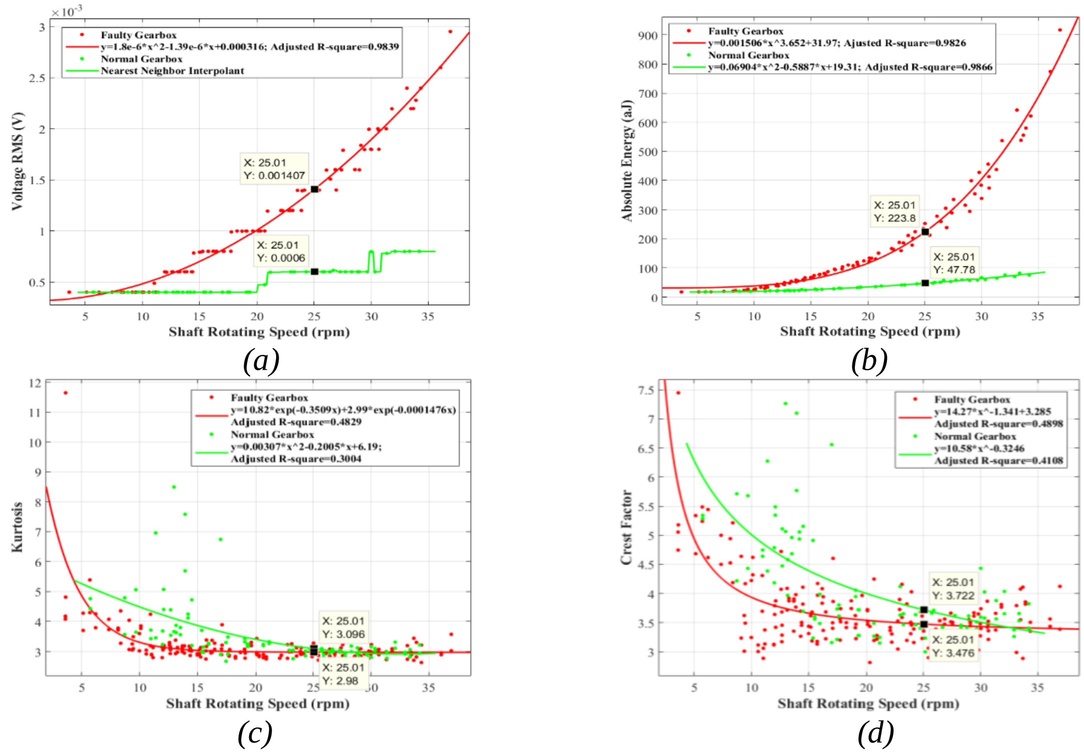


Figure 6. Time-driven parametric comparison of AE signals from the faulty and normal gearbox: a) RMS Voltage, b) Absolute Energy, c) Kurtosis and d) Crest Factor

Frequency domain AE analysis

The spectrum plots of the AE signals collected from the faulty and normal gearboxes at all speeds (from around 3 rpm to 35 rpm) have similar distribution but different amplitudes. Two plots were chosen as examples and are shown in Figure 8. The concentration of high amplitude frequency components was found in the region of 50 to 100 kHz. Most frequency peaks occur at around 95 kHz. No clear dominant frequency component can be directly extracted from the frequency spectra. As stated by Mba and Rao [8], one possible reason is that the transient impulses associated with the relative motion of material excite a broad frequency range. However, a marked increase in amplitude of broadband frequency components was observed with the appearance of gearbox wear.

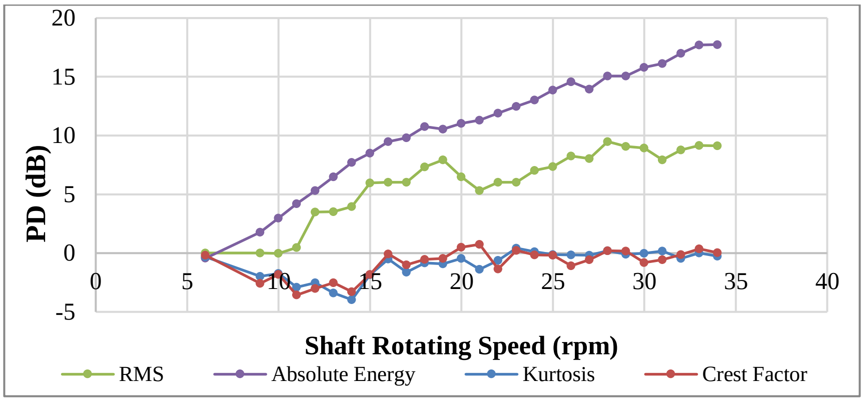
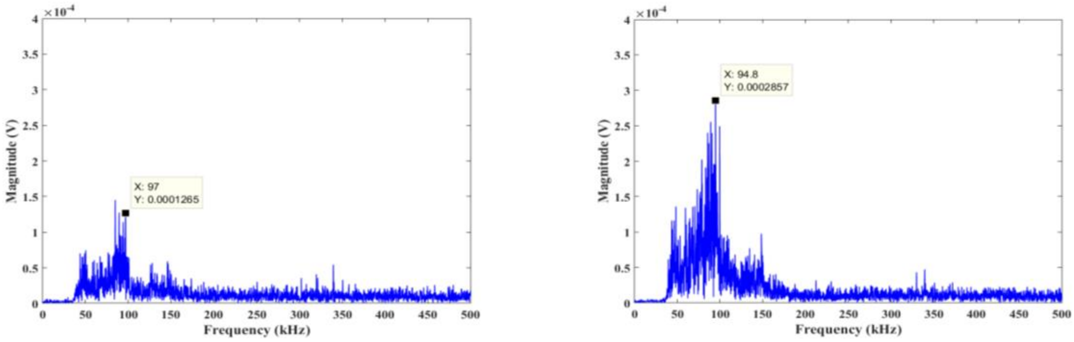


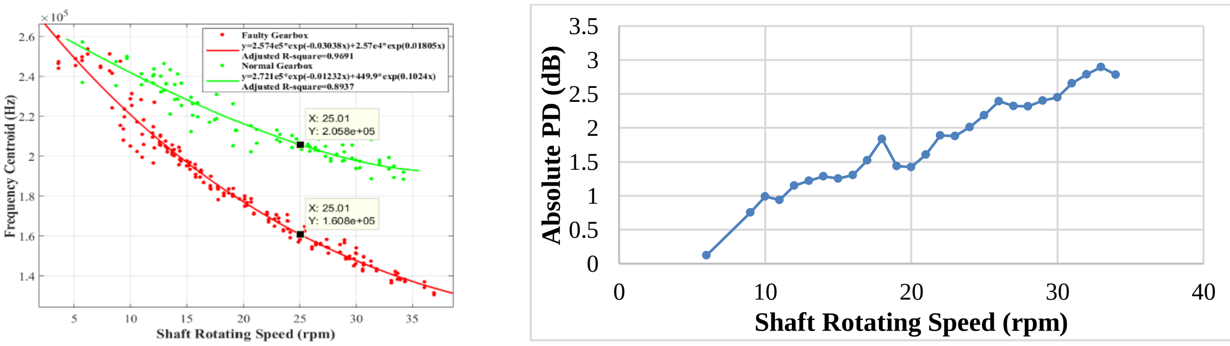
Figure 7. Comparison of PD of time-driven AE parameters



(a) *(b)*

Figure 8. Spectrum plots of AE signals from (a) normal gearbox rotating at 21.2 rpm and (b) faulty gearbox rotating at 20.9 rpm

The frequency centroid is the first moment of inertia of frequency, which measures the center of mass of the frequency spectrum. It can provide useful information about the shape change of the frequency spectrum. As can be observed from Figure 9 (a), the centroid frequency level decreases with increasing shaft rotating speed for both the faulty and normal gearboxes, and the signals collected from the normal gearbox have higher frequency centroid values at all speeds. This indicates that more high frequency responses are present in the low frequency range for the faulty gearbox, which was consistent with the frequency spectra observations. That is, the faulty gearbox has higher peaks in the lower frequency range (50 to 100 kHz), while both faulty and normal gearboxes have low amplitude frequency responses in the higher frequency range.



(a) *(b)*

Figure 9. Plots of (a) comparison of frequency centroid and (b) PD of frequency centroid

Negative PD values were obtained due to the higher P_{normal} value compared to the P_{faulty} value. The absolute PD values are plotted in Figure 9 (b) to present the difference level of frequency centroid as a function of shaft rotating speed. The frequency centroid is a good indicator for fault detection as it can present the shape of the frequency spectrum numerically with the increasing absolute PD value over the whole speed range.

Summary and Conclusions

Table 1 summaries the trends from different indicators and the PD values at the typical operating speed of the gearbox shafts during production (25 rpm). It was observed that three hit-based AE parameters including count rate, absolute energy and signal strength have more than 10 dB PD at a shaft speed of 25 rpm. The count rate is therefore considered the best hit-based AE parameter for condition monitoring of the gearboxes operating in the forming line as it shows the largest difference at a shaft speed of 25 rpm.

For the time domain parameters, Kurtosis and Crest Factor do not show clear differences between normal and faulty conditions at all speeds, and the absolute energy is the best parameter followed by the RMS value. The frequency centroid is a good frequency domain parameter to present the change of signal shape as the damage develops in the gear material.

Table 1. Summary of PD values for different parameters

Parameter Type	Parameter	Gearbox Condition	Value at 25 rpm	PD value at 25 rpm (dB)
Hit-based AE parameters	RMS Voltage (V)	Normal	0.0006	
		Faulty	0.0014	7.36
	Count Rate (Counts/sec)	**Normal**	**1127**	
		Faulty	**36060**	**30.10**
	Peak Amplitude (dB)	Normal	28.16	
		Faulty	35.5	2.01
	Absolute Energy (aJ)	Normal	1413	
		Faulty	20250	23.13
	Signal Strength (pVs)	Normal	$1.43*10^6$	
		Faulty	$1.04*10^7$	17.21
Time-driven AE parameters	RMS Voltage (V)	Normal	0.0006	
		Faulty	0.0014	7.36
	Absolute Energy (aJ)	**Normal**	**47.78**	
		Faulty	**223.8**	**13.41**
	Kurtosis	Normal	3.1	
		Faulty	2.98	-0.33
	Crest Factor	Normal	3.72	
		Faulty	3.48	-0.57
Frequency domain parameter	**Frequency Centroid (kHz)**	**Normal**	**205.8**	
		Faulty	**160.8**	**-2.14**

In summary, an AE-based technique has been shown to be a good method for low-speed worm gearbox fault detection, as was demonstrated by the high PD values of hit-based, time domain, and frequency domain parameters. Constant oil temperature tests under different load conditions will further investigate the relationship between AE activities and load level.

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