Pitting detection in worm gearboxes with vibration analysis

Elasha, F. , Ruiz-Cárcel, C. , Mba, D. , Kiat, G. , Nze, I. and Yebra, G.

Pitting detection in worm gearboxes with vibration analysis

F. Elasha[1], C. Ruiz-Cárcel [2], D. Mba[2], G. Kiat[2], I. Nze[3], G. Yebra[3]
[1] School of Mechanical, Aerospace and Automative, Coventry University, Coventry, UK
[2]Cranfield University, Cranfield, UK
[3]Transport for London, UK

ABSTRACT

Diagnostics of worm gear defects with vibration analysis is challenging and this is reflected in the limited number of publications. However, these gears are commonly used in many applications such as escalators, mills, conveyors, etc., and significant cost may arise from their down time due to unidentified defects. This paper aims to apply various vibration analysis techniques to diagnose the presence of naturally developed faults within worm gearboxes.

The condition of three different worm gearboxes were assessed using various vibration signal analysis techniques including a few statistical measures, Spectral Kurtosis and enveloping. This was undertaken in an attempt to identify the presence of defects within the worm gearboxes. It is shown that irrespective of the predominantly sliding motion of the gears, diagnosis of faults is feasible as long as the appropriate analysis technique is employed. In addition the results show sensitivity to the direction of vibration measurement.

Nomenclature

Bw	Band Width
D	Difference signal
DE	Drive End
Fc	Central frequency
K	Kurtosis
K_{max}	Maximum Kurtosis
N	Number of the points in the signal
NDE	Non-Drive End
r.m.s	Root mean square
SK	Spectral Kurtosis

* Corresponding author Email address: Faris.elasha@coventry.ac.uk

1 INTRODUCTION

In a worm gearbox the worm meshes with a wheel to transmit motion between crossed shafts, usually perpendicular to each other. Worm gearboxes are generally used for applications requiring large gear reduction ratios; they have the advantage of taking up little space and are simpler in configuration compared to the other gears types of the same reduction ratio. Other advantages of worm gears include the self-locking effect, low backlash, damage tolerance as well as quiet operation. However, worm gearboxes have some disadvantages; they generate high friction compared to the other gears types due to their sliding action (as opposed to rolling) which results in heat generation and hence lower efficiency. Also the sliding motion gives rise to inevitable abrasive wear and scuffing, therefore worm gearbox wheels are usually made of a softer material (usually bronze) and worms are most commonly made of a harder steel [1]. Due to their unique properties, worm gearboxes have found their niche in a variety of industrial applications such as rolling and saw mills, mining machinery and escalators.

With a gradual shift towards condition-based maintenance for greater operational effectiveness, condition assessment via vibration analysis is common practice. However, it is seldom employed for the condition assessment of worm gears due to the inherent challenges involved in the analysis of worm gear vibration. Compared to other gears types where defects manifest as periodic impacts in the form of side-bands around the gear mesh frequencies [2; 3], such distinctive defect symptoms are not obvious for worm gear sets due to their continuous sliding interactions [4]. Consequently, the literature on this topic is relatively scarce.

Peng et al. [5, 6] combined the use of oil and vibration analysis to establish detection methods in a worm gearbox; they concluded that wear analysis remains a useful tool for the detection of gear wear while the vibration analysis was more suited to identifying bearing failures. Vähäoja et al [4] also reiterated the need to combine vibration and oil analysis to effectively diagnose defects in worm gearboxes. Other technologies that have been employed to diagnosis worm gearbox defects include Acoustic emission (AE), this has been used for fault detection in worm gearboxes where parameters such as r.m.s and AE energy were found to be reliable indicators of the presence of defects [7]. The number of successful applications of vibration analysis to worm gearboxes is very limited as reflected in the avaliable literature. Furthermore, to date there have been no applications of Spectral Kurtosis and FM4* to worm gearbox diagnosis. This paper aims to examine the effectiveness of such vibration analysis techniques, amongst others, in detection of faults in operational worm gearboxes employed for escalators.

2 Vibration analysis techniques

Whilst there are varied vibration diagnostic techniques available to the user this paper focuses on three techniques: Spectral Kurtosis, envelop analysis and a few statistical measures such as Kurtosis, r.m.s and FM4*. The techniques selected for this investigation employed a very established diagnostic technique (Enveloping), a relative modern diagnostic technique (Spectral Kurtosis) and a few traditional statistal measures. In relation to the latter, the r.m.s and Kurtosis were selected because they are commonly used vibration diagnostic techniques, in addition the statistical measure FM4* is known to be effective in diagnosing gears pitting [8].

2.1 Statistical metrics

2.1.1 Root Mean Square (r.m.s)

One commonly used statistical measure for analysis of vibration is the root mean square (r.m.s). This parameter tends to provide measurement of the effective energy of the vibration signal with the damaged component expected to produce high vibration energy and hence higher r.m.s [3]. The r.m.s is expressed mathematically by:

$$r.m.s = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i{}^2)} \tag{1}$$

Where N is the total number of samples in the waveforms, x_i is waveform samples

2.1.2 Kurtosis

Kurtosis is defined as the degree of peakness of a probability density function *p(x)* and mathematically it is defined as the normalized fourth moment of a probability density function [9]:

$$K = \frac{\int_{-\infty}^{\infty}[x-\mu]^4 \, p(x)dx}{\sigma^4} \tag{2}$$

Where x is the signal of interest with average μ and standard deviation σ. Kurtosis is one of the widely used condition indicators principally due to its correlation with impulsive type signatures which can occur with bearing defects [10-12].

*2.1.3 FM4**

FM4* is a relatively simple method used to detect changes in the vibration pattern resulting from damage on gear teeth. The FM4* parameter is the ratio between the Kurtosis of the difference signal to the squared variance of a healthy gearbox's difference signal. The difference signal is computed by extracting gear mesh, shafts frequencies, their harmonics and associated side-bands from the vibration signature. As a defect progresses on a tooth, vibration peaks will increase in the difference signal and as a consequence the Kurtosis value will exceed 3, and this will lead to increase of FM4* . This metric is calculated as [13, 14]:

$$\mathrm{FM4}^{*} = \frac{N \sum_{i=1}^{N}(d_i - d')^4}{{M_2}^2} \quad \textbf{(3)}$$

Where d is the difference signal, d' is the mean value of the difference signal, N is the total number of the samples, and M_2 is the variance of the difference signal in good condition. This metric has been applied for vibration diagnosis of helicopter gearboxes even during torque variation [13, 15, 16].

2.2 Envelope analysis

Envelope analysis is applied extensively in vibration diagnosis of bearings and gearboxes [10, 17, 18]. As impacts due to the defects excite resonance at a higher frequency it is possible to identify the frequency of the impacts with the use of envelop analysis. In application the vibration signal is filtered at high frequencies (structural resonance frequencies) and then the signal is passed through an envelope detector and a low pass filter. The envelope signal is either presented in the time domain or transformed into the frequency domain in order to identify fault frequency components [3].

2.3 Spectral Kurtosis (SK)

The basic principle of this method is to determine the Kurtosis at different frequency bands in order to identify non stationaries in the signal and determine where they are located in the frequency domain. Obviously the results obtained strongly depend on the width of the frequency bands Δf [19]. The Kurtogram [9] is a representation of the calculated values of the SK as a function of f and Δf. However, exploration of the entire plane (f, Δf) is a complicated computational task, though Antoni [19] suggested a methodology for the fast computation of the SK.

The frequency band where the SK is maximized provides information which can be used to design a filter in order to extract the part of the vibration signal with the highest level of impulsiveness. Antoni et al. [20] demonstrated how the optimum filter, which maximizes the signal to noise ratio, is a narrow-band filter at the maximum value of SK. Therefore the optimal central frequency fc and bandwidth Δf of the band-pass filter is found as the values of f and Δf which maximise the Kurtogram. The filtered signal can be finally used to perform an envelope analysis, which is a widely used technique for identification of modulating frequencies related to bearing faults. In this investigation the SK computation and the subsequent signal filtration and envelope analysis were performed using the original Matlab code programmed by Antoni [19].

3 On-site gearbox measurements

Gearboxes vibration measurements were undertaken on three operational escalator worm gearboxes (A, B and C). Vibration measurement was taken in the vicinity where the worm meshes with the wheel and in all three directions, see figure 1. The worm gearbox was of the right-angle type with 85 teeth on the wheel gear and 3 threads on the worm. The gearbox had a nominal output speed of 870 rpm and a rated power of 38 kW.

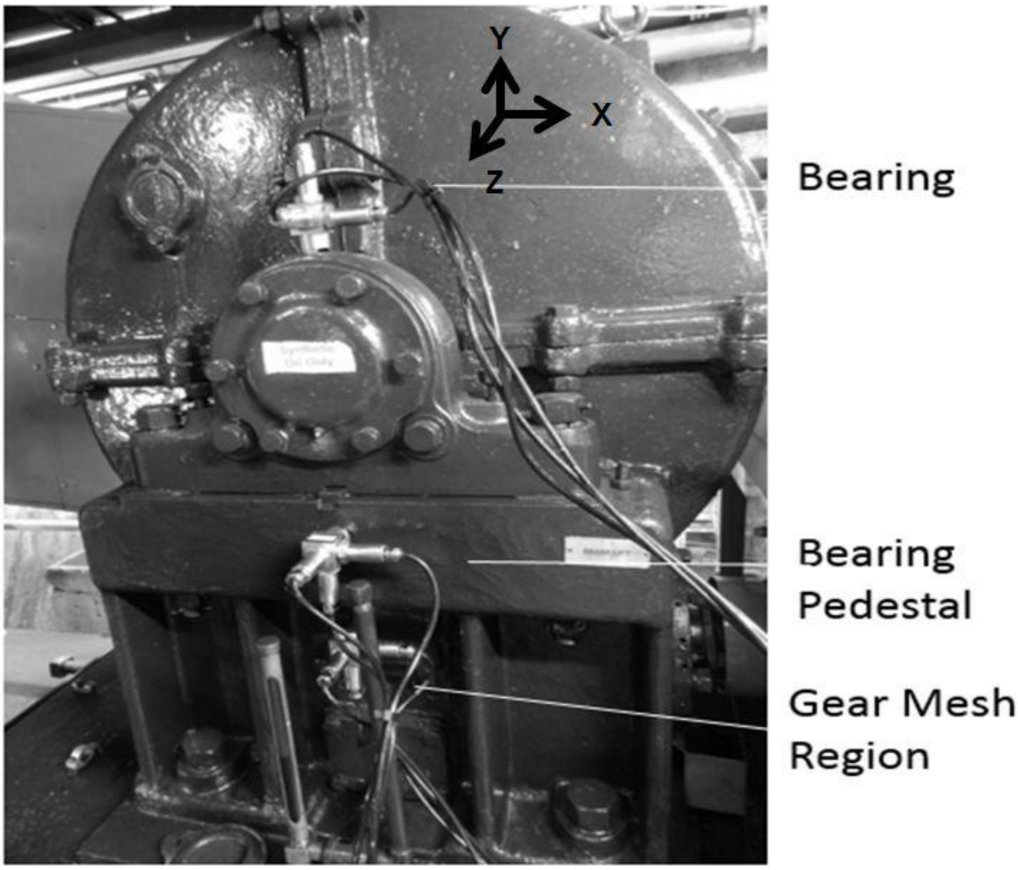

Figure 1 Positions chosen for mounting accelerometers

The Y-axis of the tri-axial accelerometer arrangement was oriented in the vertical direction; the X-axis refers to the axis parallel to the worm shaft, and the Z-axis is parallel to the wheel shaft (axial) and in the direction of sliding motion. It was anticipated that vibration measurements in this direction would yield the most prominent indications of the presence of pitting.

For each vibration measurement 300-seconds of data was captured at a sampling frequency of 12 kHz using Monitran MTN/1100W accelerometers, configured in a tri-axial arrangement and mounted on a Monitran M8 (AA008) block with a magnetic attachment adaptor (Monitran MTN/MM001). The accelerometers had an operating frequency range of 0.8 Hz to 12 kHz. The acquisition system employed two National Instruments (NI) PXI-4472B cards (8-channel, 24-bit resolution). These cards were configured in a NI PXI 1031 chassis with a NI PXI 8360 MXI express remote controller that enabled interface to a LabVIEW signal express software program.

Of the three gearboxes investigated it was known that Gearbox B was in good condition following a recent overhaul, therefore this gearbox (B) was considered as the healthy reference condition. To aid diagnosis, all characteristic vibration frequencies were determined, see table 1. These included the worm shaft speed with its harmonics and bearings defects frequencies. Each gearbox was supported by four bearings. The bearing defect frequencies for each gearbox were calculated and referenced to the rotating speed. The frequencies are listed in table 1.

Table 1 Gearbox reference frequencies

Reference Frequencies (Hz)	A	B	C
Gear mesh frequency GMF		43.5	
Wheel NDE Cage		0.205	
Wheel DE Cage		0.215	
Wheel NDE Roller Spin		1.32	
Wheel DE Roller Spin		1.73	
Wheel NDE Outer Race		3.28	
Wheel DE Outer Race		4.09	
Wheel NDE Inner Race		4.72	
Wheel DE Inner Race		5.41	
Worm DE Cage	6.04	6.07	6.16
Worm Shaft (1X)	14.14	14.22	14.42
Worm NDE Roller Spin	32.635	32.82	33.28
Worm DE Roller Spin	47	47.2	47.9
Worm NDE Outer Race	73.882	74.3	75.345
Worm NDE Inner Race	109.94	110.56	112.116
Worm DE Outer Race	121	121	123
Worm DE Inner Race	162	163	165

4 Results of vibration investigation

4.1 Statistical metrics (Kurtosis, r.m.s and FM4* Analysis)

Observations of r.m.s and Kurtosis are detailed in table 2. The Kurtosis values for all vibration measurement directions were relatively similar across all three gearboxes whilst r.m.s values was highest for gearbox A, notably 100% higher than r.m.s levels for Gearbox B (reference gearbox) in Z-direction. Values of r.m.s in X- and Y-directions indicated no discernible changes. The r.m.s was calculated over 10 seconds time span.

Table 2 result of vibration r.m.s and Kurtosis

Gearbox	**r.m.s** (V)			**Kurtosis**		
	Z	**X**	**Y**	**Z**	**X**	**Y**
Gearbox A	0.048	0.022	0.027	3.18	3.06	2.99
Gearbox B	0.024	0.023	0.021	2.98	2.99	2.85
Gearbox C	0.033	0.026	0.016	2.96	2.99	3.06

Figure 2 shows the results of the FM4* analysis for each gearbox revealing comparatively high levels for Gearbox A. The value FM4* under healthy conditions (Gearbox B) ranged from 2.8 (X-direction) to 5 (Z-direction) for all vibration measurement directions, with the highest level noted in the Z-direction. FM4* levels for Gearbox A were relatively high in Z and Y directions, 36 and 12 respectively, whilst the level in the X-direction was relatively low at 3. The FM4* levels of Gearbox C were comparative to levels noted on Gearbox B except for the Z-direction were a value of 11 was noted.

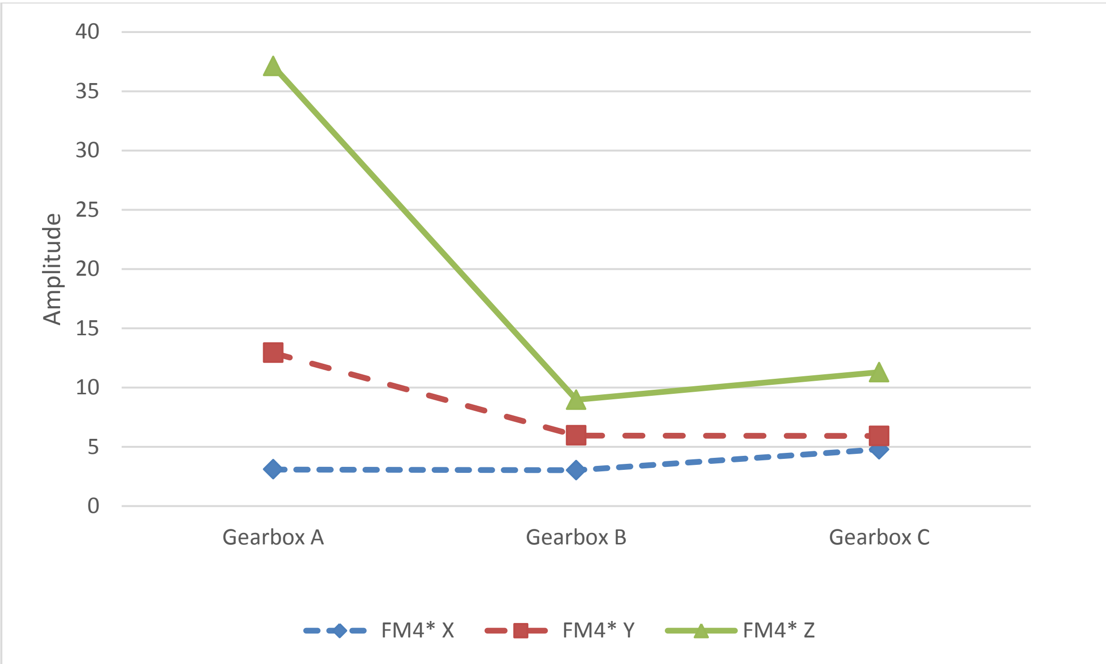

Figure 2 FM4* values for all gearboxes

4.2 Spectral Kurtosis

The Spectral Kurtosis analysis was undertaken on data sets collected from all three gearboxes and this yielded the frequency bands and center frequencies which were then used to undertake envelope analysis, see table 3. A typical kurtogram from measurement taken on Gearbox A (Z-direction) is shown in figure 3. The region circled represents the highest value of the Kurtogram from which filter characteristics are determined. In this particular instance the Band Width (Bw) is 187.5 Hz and the Centre Frequency 5343.75 Hz. Spectral plots of enveloped vibration signals following filtration, whose characteristics were determined with the aid of the kurtogram, are shown in figures 4 to 6 for the data collected in all three directions.

Table 3 Summary of Spectral Kurtosis frequencies

	Fc(Hz)	BW (Hz)
Gearbox A (Z)	5343	187.5
Gearbox B (Z)	5875	250
Gearbox C (Z)	5875	250
Gearbox A (Y)	5343.75	187.5
Gearbox B (Y)	5875	250
Gearbox C (Y)	5875	250
Gearbox A (X)	726.6	46.9
Gearbox B (X)	5953	93.75
Gearbox C (X)	820	46.9

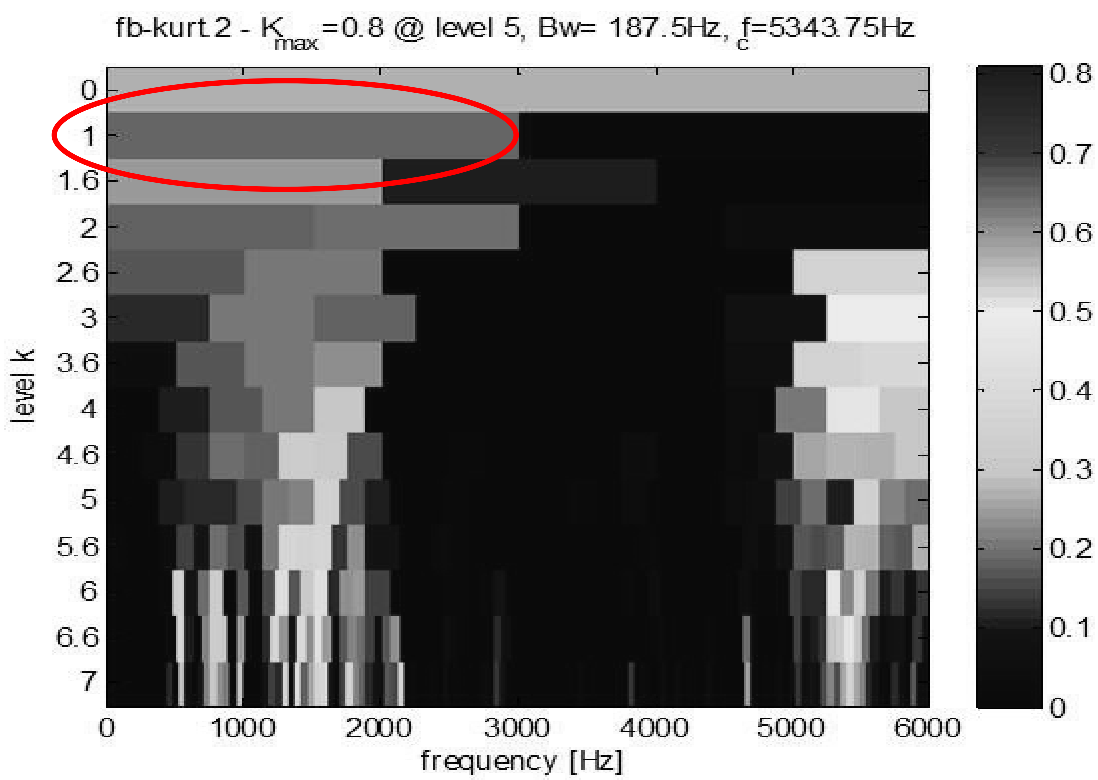

Figure 3 Kurtogram for Gearbox A (Z-direction)

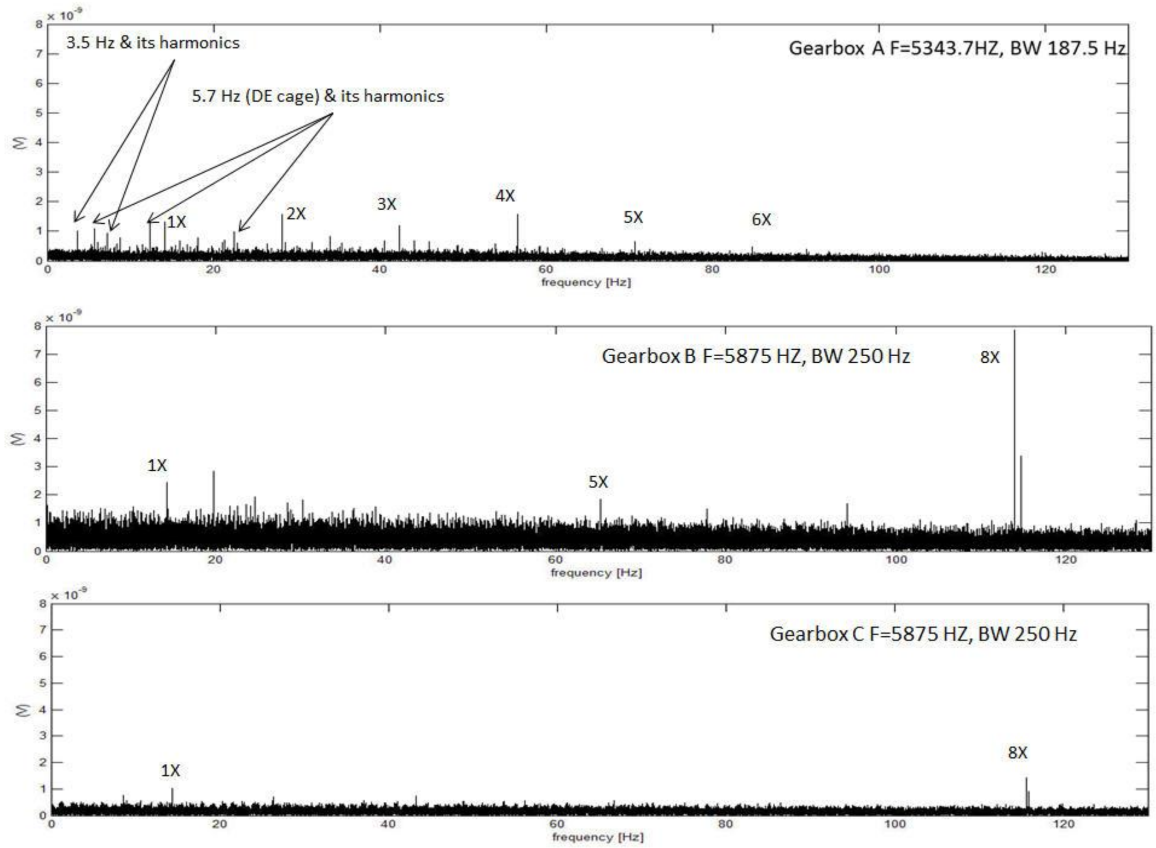

Figure 4 Envelope spectra for all gearboxes based on filter characteristics estimated Spectral Kurtosis (Z-direction)

Observation from the spectra of the enveloped signal in the Z-direction, see figure 4, showed interesting characteristics. Gearbox A showed worm shaft frequency and several harmonics. Such phenomenon is known to be associated with gear pitting [21]. This was not observed in the envelope spectra of the other gearboxes. Bearing frequencies observed included the wheel NDE outer race (3.5 Hz) and a harmonic, and wheel DE inner race (5.7 Hz) for Gearbox A. Result in Y-direction also showed worm shaft harmonics and bearings frequencies for gearbox A (see figure 5) which reinforces the observations in the Z-direction. Observations from gearboxes B and C in Y- and X-directions were similar in pattern. Noted was the presence of a frequency component at 7.8 Hz, and its harmonics (Gearbox A and C) which corresponded to the 2nd harmonic of outer race wheel DE (see figure 6). The vibration amplitude of gearbox B was significantly low compared to the others gearboxes.

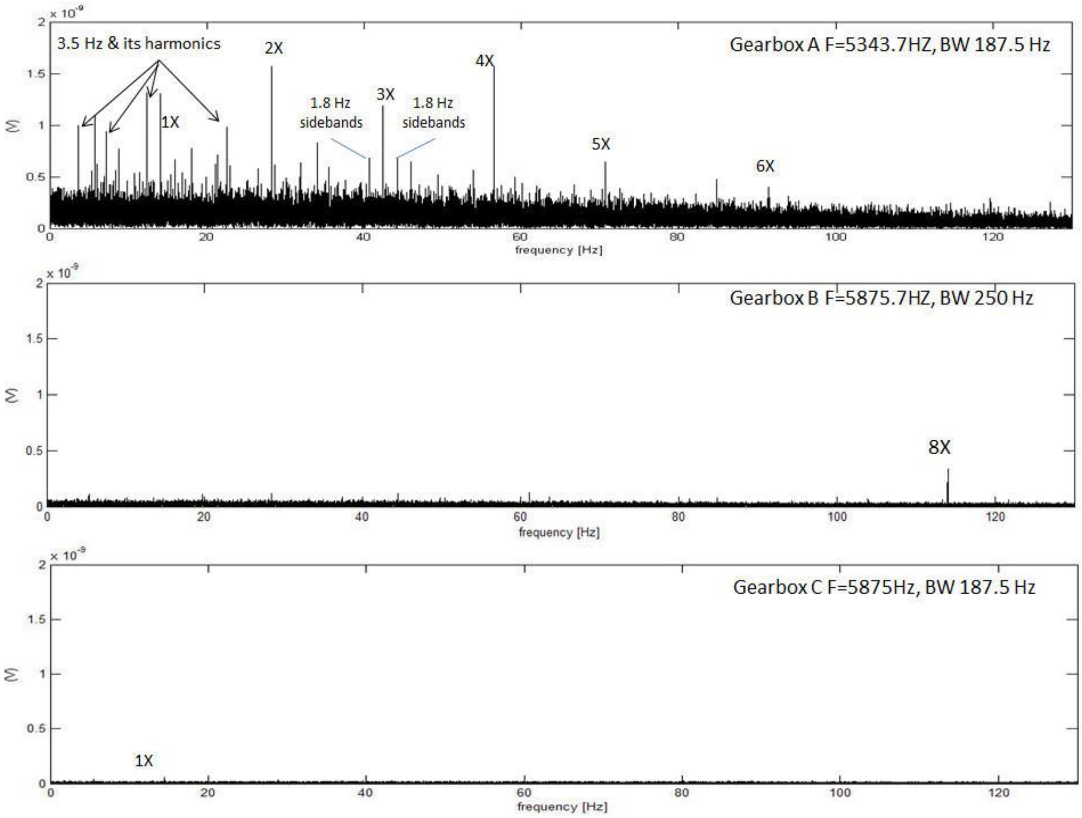

Figure 5 Signal envelopes from Spectral Kurtosis in Y-direction

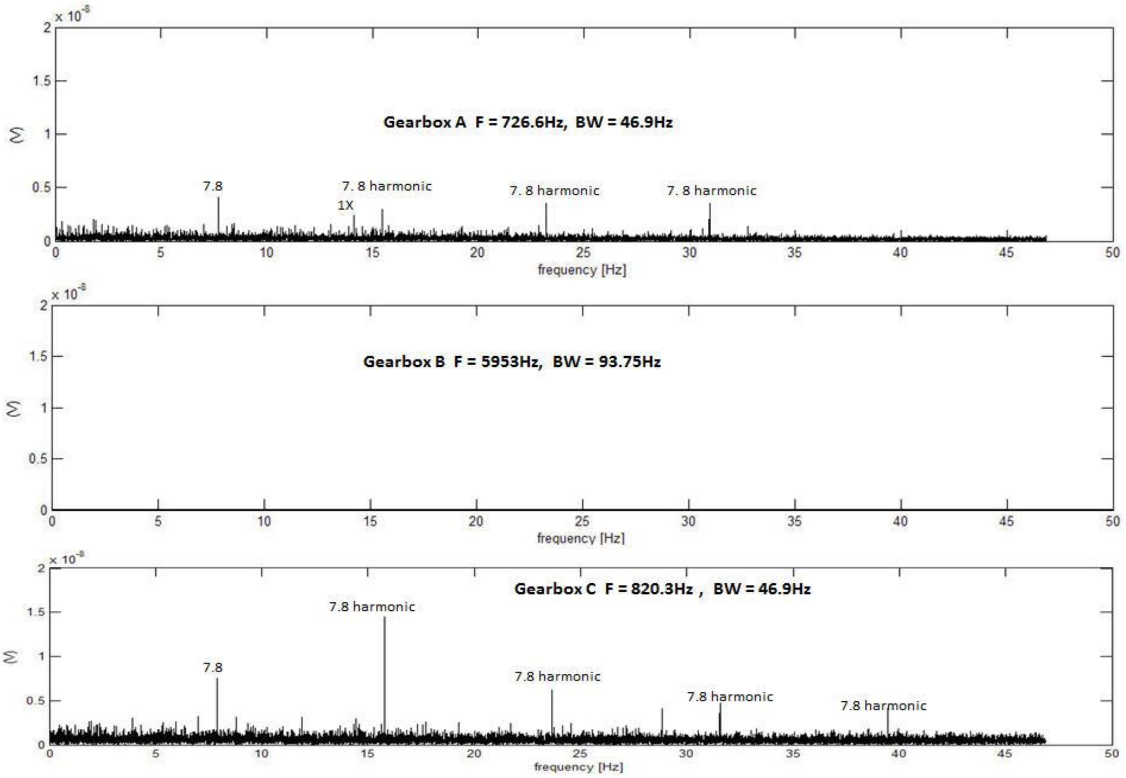

Figure 6 Signal envelopes from Spectral Kurtosis in X-direction

4.3 Enveloping analysis

Observations of the frequency spectra of measured vibration data showed the presence of high frequencies, ranging between 500 Hz to 1500 Hz and 2500 Hz to 3500 Hz, see figure 7. These highly active regions are attributed to structural resonant conditions. In order to investigate the presence of any modulating frequencies due to presence of defective rotating components, envelope analysis was undertaken at these defined frequency bands. These regions of relative high amplitudes in frequency spectrum varied depending on the measurement direction. The regions of interest selected included the following regions:

- X-direction 500 – 1500 Hz & 3000 – 4000 Hz
- Y-direction 500 – 1500 Hz & 3500 – 4500 Hz
- Z-direction 500 – 1500 Hz & 2500 – 3500 Hz

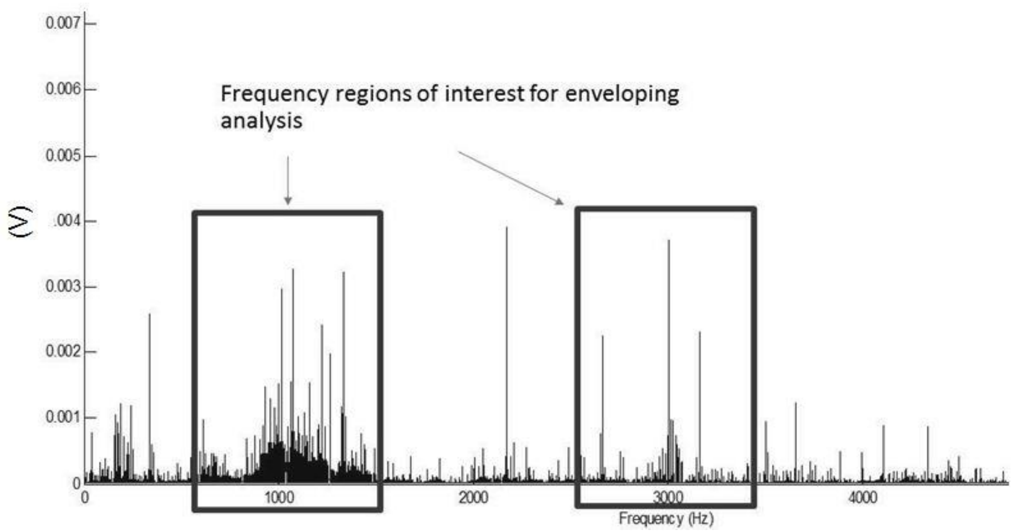

Figure 7 Frequency spectrum of Z direction gearbox A

For envelope spectrums in the Z-direction (see figure 8), distinctive harmonics of worm shaft and gear mesh frequencies were observed for Gearbox A in the 500 Hz-1500 Hz frequency band, again indicating the presence of pitting damage. This characteristic was not observed in any of the other gearboxes, nor from envelope data taken in the range of 2500 Hz-3500 Hz. The envelope analysis between the frequency band of 2500 Hz to 3500 Hz revealed various bearing defect frequencies, including the wheel DE inner race (5.41z) for gearboxes A and C, and the wheel NDE Roller Spin (1.32 Hz) for Gearbox A (see figure 8).

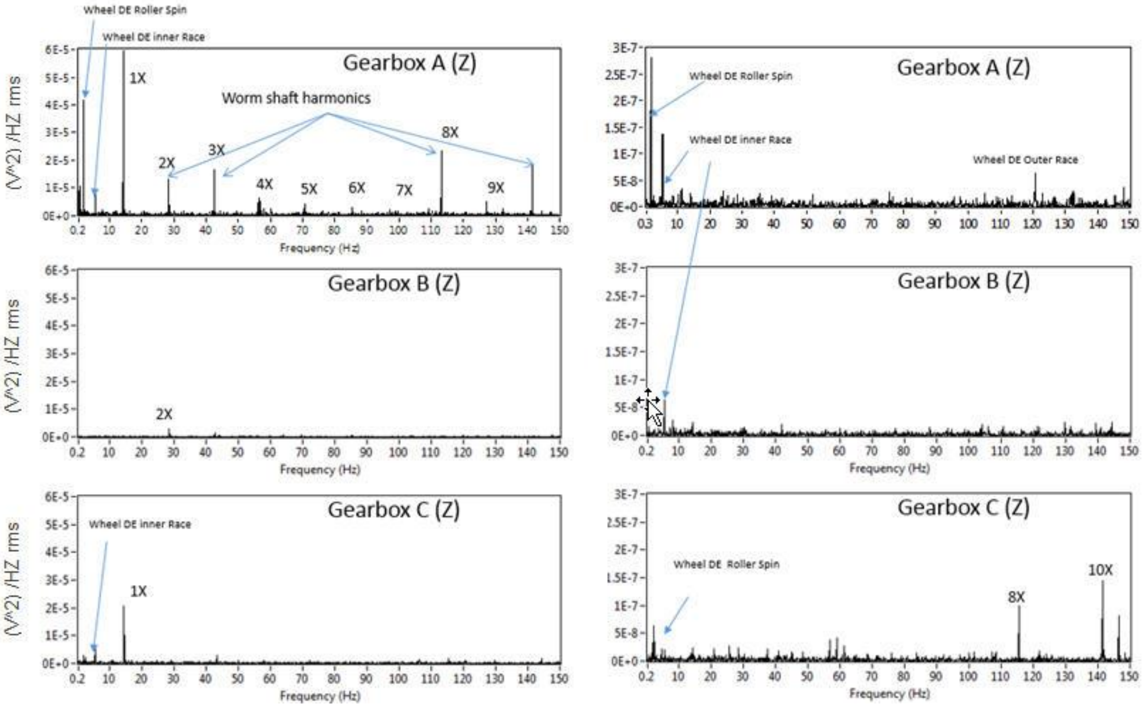

Figure 8 Comparison of gearboxes A, B, C (Z) envelopes for 500-1500 Hz (left side) and 2500 Hz-3500 Hz (right side)

Observations of the envelope spectrums in the Y-direction (see **figure 9**) between 500 Hz to 1500 Hz showed several harmonics of worm shaft and gear mesh for all gearboxes. In addition, evidence of bearing frequencies, including the wheel DE bearing inner race defect frequency (5.41Hz) was observed for all gearboxes in this range (500-1500 Hz). Envelope analysis performed in Y-direction for frequency range between 3500 Hz-4500 Hz showed a prominent wheel DE outer race (121Hz) in Gearbox A only.

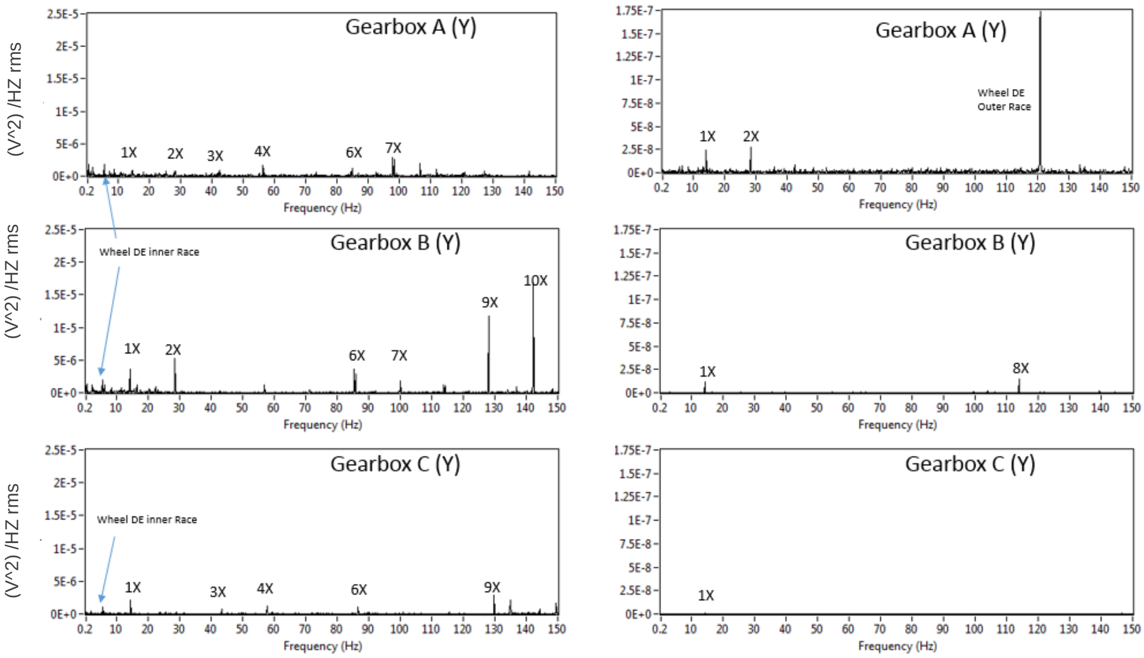

Figure 9 Comparison of gearboxes A, B, C (Y) envelopes for 500-1500 Hz (left) and 3500-4500 Hz (right)

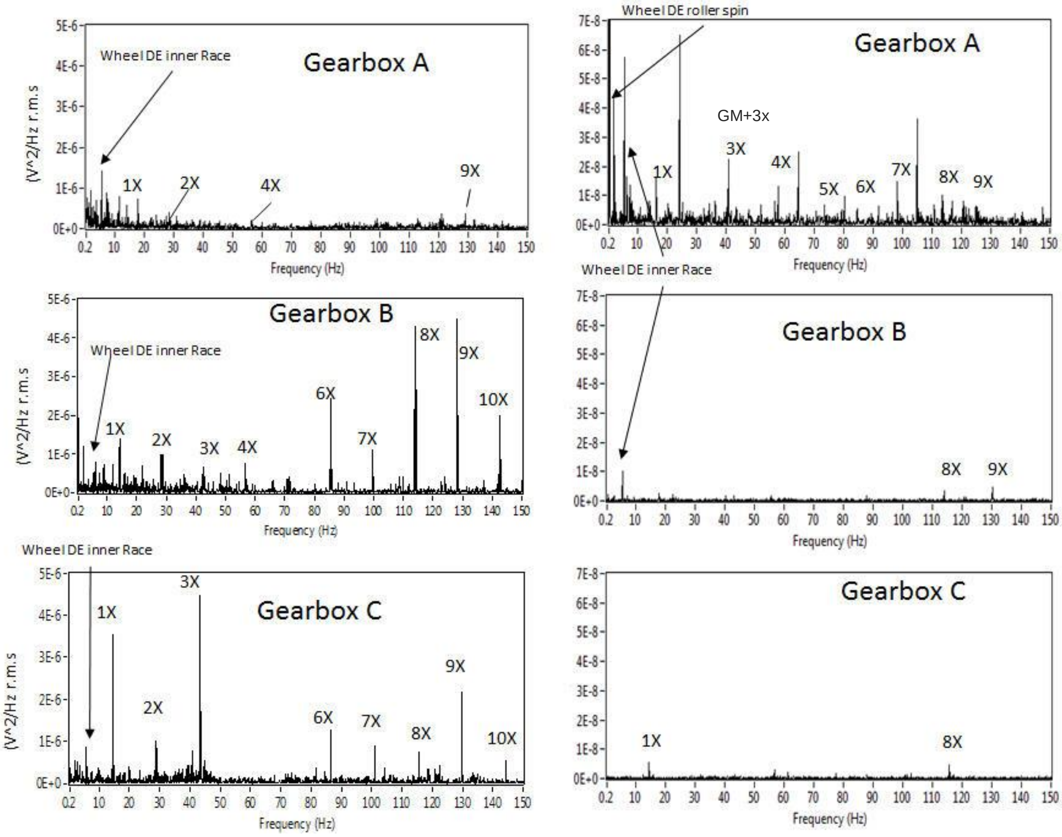

Figure 10 Comparison of gearboxes A, B, C (X) envelopes for 500-1500 Hz (left) and 3000-4000 Hz (right)

No defect frequencies of any bearing were noted in the enveloped spectrums from the X-direction at 500 Hz-1500 Hz range, see figure 10. Harmonics of worm shaft frequencies (X-direction) were observed in the envelope spectra performed in a range of 500 Hz-1500 Hz for all gearboxes though with relatively lower amplitudes for Gearbox A. Observations of the envelope spectrums in the range of 3000 Hz-4000 Hz showed the Gearbox A (X) vibration signatures contained several harmonics of worm shaft speed and gear mesh compared to Gearboxes B and C. Furthermore, the bearing frequency of the wheel DE inner race was identified at 5.41Hz.

5 Discussion

A suite of techniques were employed for the vibration analysis of the worm gearboxes. Three statistical metrics were considered for vibration analysis including r.m.s, Kurtosis, and FM4*. The result of Kurtosis showed no distinctive differences between all three gearboxes. However, the r.m.s and FM4* levels showed relatively higher values for Gearbox A. The high levels associated with the r.m.s and FM4* of Gearbox A pointed to the presence of gearbox damage, particularly the FM4* level (36) in the Z-direction. It would appear that results in Z-direction are more sensitive to the gear pitting fault conditions compared to other directions. This wasn't surprising as the direction corresponded to the sliding direction of the mating teeth.

Comparison of results from the envelope and Spectral Kurtosis analysis showed both techniques were able to identify the presence of pitting and bearing defects in Gearbox A based on observations in the Z-direction. A summary of defect frequencies identified is presented in table 4. Spectral Kurtosis analysis results of Gearbox B (healthy gearbox) in all directions showed no existence of defect frequencies whilst Gearbox A was fraught with harmonics of the worm shaft frequency, a typical symptom associated with worn gears. The ability of SK analysis to identify the presence of worn gears is based on the identification of particular frequency regions with high impact energy; these impacts are due to presence of gears pitting which affect gears sliding motion. Interestingly only the envelop analysis in the Z-direction was able to support the fault conditions inferred from the SK analysis, i.e., Gearbox A was defective. Observations of enveloping analysis for all gearboxes in the X- and Y-directions displayed multiple peaks of shaft speed.

Given diagnosis of worm gearboxes with vibration analysis is dependent on the integrity of the relative sliding surfaces, any discontinuity in the gear profiles, due to pitting, will lead to impacts and such energies will be more sensitive across particular frequency bands. For this reason the SK analysis is ideally suited for diagnosis of worm gearboxes.

Table 4 Summary of defect frequencies observed from the envelope and SK spectrum

Gearbox	Spectral Kurtosis	Envelope analysis (Z-direction only)
Gearbox A	Presence of numerous bearing defect frequencies (all directions) Shaft frequencies and its harmonics (all directions)	Presence of numerous bearing defect frequencies Shaft frequencies and its harmonics
Gearbox B	-	-
Gearbox C	A bearing defect frequency (X-direction only)	A bearing defect frequency

Visual inspection revealed that gearbox A has visible pitting and bearing damage, while no obvious pitting damage was found on the wheel teeth of gearboxes B and C, see figure 11. These observations infer that statistical metrics (r.m.s and FM4*) can be used to set fault alarm levels with further diagnosis undertaken with Spectral Kurtosis. Such an alarm level may be set at an FM4* level of 15, based on observations presented in figure 2 though a generic level can only be set after a statistically significant number of gearboxes have been investigated.

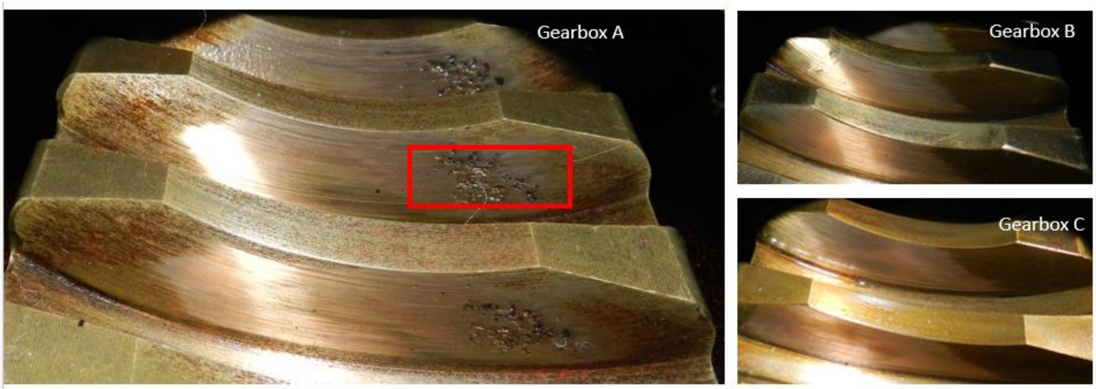

Figure 11 Visual inspection of gearbox wheel teeth

6 Conclusion

Various vibration signal analysis tools were employed in this study. All techniques were able to present features which indicated pitting damage on one gearbox (Gearbox A). The presence of a defective gear was confirmed by visual inspection, see figure 10. All techniques applied for diagnosis were sensitive to the direction of measurement with measurements taken horizontally and parallel to wheel shaft axis (Z-direction) proving most sensitive. more reliable results. The FM4* was deemed effective for the detection of pitting presence, the advantage of such a technique is its simplicity in implementation. SK and envelope analysis were valuable for the identification of both bearing and gears defects frequencies, though the SK analysis was less susceptible to the direction of measurement, making this technique relatively more robust. In conclusion, the conditions of three worm gearboxes were assessed; surface pitting has been identified in gearbox (A) wheel teeth, while no visible damage were identified for gearboxes B and C.

REFERENCES

[1] Black, A. (2014), *The Ins and Outs of worm gears*, available at: http://www.machinerylubrication.com/Read/1080/worm-gears (accessed January, 16).

[2] Rao, B. (1996), *Handbook of condition Monitoring*, Elsevier, Oxford, UK.

[3] Alan, D. (1998), *Handbook of the condition monitoring techniques and methodology*, First edition ed, Chapman and Hall, London UK.

[4] Vahaoja, P., Lahdelma, S. and Leinonen, J. (2006), "On the Condition Monitoring of Worm Gears", in Mathew, J., Kennedy, J., Ma, L., et al (eds.) Springer London, , pp. 332-343.

[5] Peng, Z., Kessissoglou, N. and Cox, M. (2005), "A study of the effect of contaminant particles in lubricants using wear debris and vibration condition monitoring techniques", *Wear*, vol. 258, no. 11, pp. 1651-1662.

[6] Peng, Z. and Kessissoglou, N. (2003), "An integrated approach to fault diagnosis of machinery using wear debris and vibration analysis", *Wear*, vol. 255, no. 7, pp. 1221-1232.

[7] Elforjani, M., Mba, D., Muhammad, A. and Sire, A. (2012), "Condition monitoring of worm gears", *Applied Acoustics*, vol. 73, no. 8, pp. 859-863.

[8] Zakrajsek, J. J., Townsend, D. P. and Decker, H. J. (1994), "An analysis of gear fault detection methods as applied to pitting fatigue failure data", *The Systems Engineering Approach to Mechanical Failure Prevention*, Vol. 16, Apr 1993, Virginia Beach, Virginia, USA, NASA, USA, pp. 199.

[9] Randall, R. B. (2011), *Vibration-based Condition Monitoring*, first ed, John Wiley and sons Ltd, UK.

[10] Randall, R. B. and Antoni, J. (2011), "Rolling element bearing diagnostics—A tutorial", *Mechanical Systems and Signal Processing*, vol. 25, no. 2, pp. 485-520.

[11] Dwyer, R. (1983), "Detection of non-Gaussian signals by frequency domain kurtosis estimation", *Acoustics, Speech, and Signal Processing, IEEE International Conference on ICASSP'83.* Vol. 8, IEEE, pp. 607.

[12] Sawalhi, N., Randall, R. B. and Endo, H. (2007), "The enhancement of fault detection and diagnosis in rolling element bearings using minimum entropy deconvolution combined with spectral kurtosis", *Mechanical Systems and Signal Processing*, vol. 21, no. 6, pp. 2616-2633.

[13] Decker, H. J. and Lewicki, D. G. (2003), *Spiral Bevel Pinion Crack Detection in a Helicopter Gearbox,* NASA/TM—2003-212327-- ARL–TR–2958, Glenn Research Center, NASA, USA.

[14] Lebold, M., McClintic, K., Campbell, R., Byington, C. and Maynard, K. (2000), "Review of vibration analysis methods for gearbox diagnostics and prognostics", *Proceedings of the 54th meeting of the society for machinery failure prevention technology, Virginia Beach, VA,* pp. 623.

[15] Sait, A. and Sharaf-Eldeen, Y. (2011), "A Review of Gearbox Condition Monitoring Based on vibration Analysis Techniques Diagnostics and Prognostics", in Proulx, T. (ed.) *Rotating Machinery, Structural Health Monitoring, Shock and Vibration, Volume 5,* Springer New York, , pp. 307-324.

[16] Halim, E. B., Shah, S. L., Zuo, M. J. and Choudhury, M. A. A. (2006), "Fault detection of gearbox from vibration signals using time-frequency domain averaging", *American Control Conference, 2006,* pp. 6 pp.

[17] Wang, W. (2001), "Early detection of gear tooth cracking using the resonance demodulation technique", *Mechanical Systems and Signal Processing*, vol. 15, no. 5, pp. 887-903.

[18] McFadden, P. D. and Smith, J. D. (1984), "Vibration monitoring of rolling element bearings by the high-frequency resonance technique — a review", *Tribology International,* vol. 17, no. 1, pp. 3-10.

[19] Antoni, J. (2007), "Fast computation of the kurtogram for the detection of transient faults", *Mechanical Systems and Signal Processing,* vol. 21, no. 1, pp. 108-124.

[20] Antoni, J. and Randall, R. (2006), "The spectral kurtosis: application to the vibratory surveillance and diagnostics of rotating machines", *Mechanical Systems and Signal Processing,* vol. 20, no. 2, pp. 308-331.

[21] Teng, W., Wang, F., Zhang, K., Liu, Y. and Ding, X. (2014), "Pitting Fault Detection of a Wind Turbine Gearbox Using Empirical Mode Decomposition.", *Strojniski Vestnik/Journal of Mechanical Engineering,* vol. 60, no. 1.