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On the application of non-destructive testing techniques on rotating machinery.

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Abstract

The diagnosis of artificial defects in a single stage gearbox using two non-destructive techniques (vibration and AE) and advanced signal processing techniques to discriminate between different load and defect states is the scope of the present study. Wavelet based techniques were developed and utilised in order to evaluate the vibration signals and extract diagnostic information out of them. A new concept of AE transducer mounting on rotating structures, without the use of the expensive solution of the slip-ring is presented. The AE signals are analyzed and their root-mean-square (RMS) values are calculated. The capability of the new approach of AE acquisition in discriminating between different loading and damage states is shown and discussed. Interesting findings on the effect of the oil temperature upon AE recordings only speculated theoretically so far are also presented. Both methods yielded interesting results and showed an ability to distinguish between healthy and defected gears.

1. Introduction

Gearboxes are very important in many industrial applications. Thus the interest for their health monitoring is growing and effective diagnostic techniques and methodologies are the objective of previous studies. Vibrations have been used and well established for many decades. There is a great number of works in the literature where vibrations together with conventional or more advanced signal processing techniques have been used towards the health monitoring of rotating machinery and gearboxes.

Baydar and Ball [1] have used the instantaneous power spectrum and have shown that it is capable of detecting local tooth faults in standard industrial helical gearboxes. The progression of local faults was monitored by observing changes in the features of the distribution. They claimed that not only is detection of fault possible, but also its location by observing the location of energy in the power spectrum. Baydar et al [2] used multivariate statistics based on principal components analysis towards gear fault detection in rotating machinery. The same authors have also applied the Wigner-Ville distribution [3] as well as the wavelet transform [4] on vibration and acoustic signals for the same purpose. Wang and McFadden [5,6] utilized time-frequency techniques and showed that the spectrogram has advantages over Wigner-Ville distribution for the analysis of vibration signals for the early detection of damage in gears. They have also employed the wavelet transform [7,8] to analyze the local features of vibration signals and showed that unlike the time-frequency distribution which incorporates a constant time and frequency resolution the wavelet transform can display simultaneously both the large and small sizes in a signal enabling the detection of both distributed and local faults.

The interest for applications of acoustic emission for condition monitoring in rotating machinery has grown significantly over the last decade. In an area where vibration monitoring dominates for several decades successfully in many industrial applications, acoustic emission offers some attractive advantages over vibrations. First of all, as AE is a non-directional technique, one AE sensor is sufficient to perform the task in contrast to vibration monitoring which may require information from three axes. Since AE is produced at microscopic level it is highly sensitive and offers opportunities for identifying defects at an earlier stage when compared to other condition monitoring techniques. As AE mainly detects high-frequency elastic waves, it is not affected by structural resonances and typical mechanical background noise (under 20 kHz). Sources of AE in rotating machinery include asperities contact, cyclic fatigue, friction, turbulence, material loss, cavitation, leakage, etc. For instance, during the interaction of the surface asperities the oil film that covers the teeth locally increases its pressure generating a varying pressure profile. This transient pressure profile generates elastic waves that propagate on the surface of the material as Rayleigh waves and the displacement of these waves is measured with an AE sensor. In addition to this continuous type AE from the asperities contact, any crack initiation and pitting type of damage can also give rise to significant AE that is captured by the data acquisition board.

Acoustic emission has attracted attention and was applied to rotating machinery only since 1990 [9]. Al-Balushi et al. [10] extracted energy-based features from AE transients and related them with damage, broken teeth and pitting of gears. Tandon et al. [11] applied AE to spur gears in a gearbox test-rig. They simulated pits of constant depth but variable size and AE parameters such as energy, amplitude and counts were monitored during the test. AE was proved superior over vibration data on early detection of small defects in gears. Singh et al. [12] also applied AE technique in condition monitoring of test rig gearboxes while vibration methods was also used for comparative purposes by placing accelerometers on the gearbox casing. They also concluded that AE provided early damage detection over vibration monitoring.

Singh et al. [13] also investigated the possibility of AE to detect crack initiation and growth and found that AE has successfully monitored the crack onset while vibration methods could detect the crack growth only. Sentoku [14] attempted to establish the function between AE signal descriptors and the health monitoring of gearboxes. The test showed that AE amplitude and energy increased with an increase in pitting. Toutountzakis et al. [15] investigated the influence of oil temperature and of the oil film thickness on AE activity and on AE signals captured during continuous running of a back-to-back gearbox test-rig. It was observed that the AE RMS varied with time as the gear box reached a stabilised temperature and the variation in AE activity RMS could be as much as 33%.

2. Experimental procedure

Figure 1 shows the experimental setup utilised for this study. The test rig consists of two gears made from 045M15 steel with a module of 3 mm, pressure angle 20^{o}, which have 53 and 25 teeth. The axes of the gears are supported by two ball bearings each (a low speed for the gear and high speed for the pinion). All the above are settled in an oil basin in order to ensure proper lubrication. The gear box gets power from a motor and consumes it on a generator. Their characteristics are as follows:

Motor: Single phase type MY 90L-4, 2 HP power, operates at 220 volts, 9.0 A with a current frequency of 50 Hz and rotates at 1400 rpm.

Generator: Single phase, rotates at 3000 rpm. Under operating voltage of 115 V produces 36.5 A current whereas at 230 V produces 18.3 A.

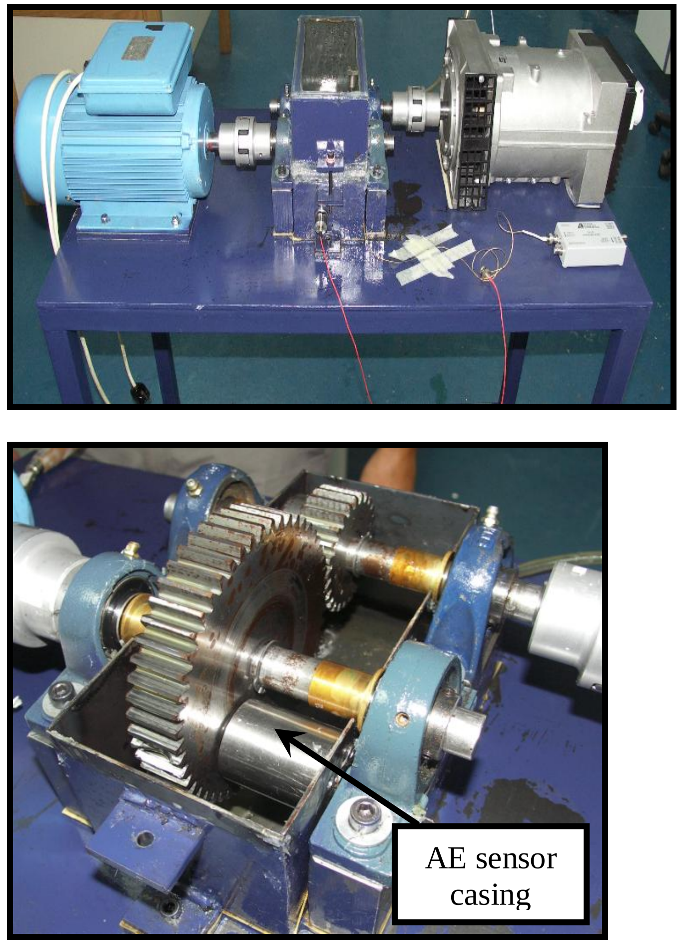

Figure 1: Experimental setup

Prior to testing, the gear box operated for at least 2 hours under 1 kW load until the lubricant temperature was stabilized i.e. did not change over 1 ^{o}C for at least 10 minutes. Stabilization of lubricant temperature was of prime importance since previous studies [5,6] have suggested that acoustic emission is highly affected by the oil temperature. After the temperature stabilization the gear box operated for half an hour in every damage and loading case. Acoustic emission was recorded during the whole procedure. Three states of damage were introduced in the large gear. No defect, 1 defected tooth and 2 defected teeth. The gear box operated in three different loadings for each damage state namely a) no load b) 0.5 kW load on the axis c) 1 kW load. Onwards with [A], [B], [C] we shall denote the three damage states of no defect, 1 defected tooth and 2 defected teeth respectively. Loads 0, 1, 2 correspond to no load, 0.5 kW load on the axis and 1 kW load. Table 1 summarizes the notations.

Table 1: Loads and defects notation

Defect notation	Corresponds to:	Load notation	Corresponds to:
[A]	No defect	0	No load
[B]	1 defected tooth	1	0.5 kW load
[C]	2 defected teeth	2	1 kW load

Vibrations and AE are recorded since the very beginning of the testing procedure and until the lubricant temperature is stabilised. The AE sensor is directly mounted on the gear through a special casing (see details in Figure 2). The design incorporates two hollow steel cylinders (Figure 2): the one is mounted onto the gearbox case (1) and the other (2) is sliding inside the first one until its outer face (3) contacts the surface of the gear. The constant contact force needed is applied through a spring (4) located inside the first cylinder which pushes the smaller cylinder against the contact surface (3). This contact surface of the small cylinder is made out of bronze to reduce wear and local temperature increase due to friction. The AE sensor (5) (pico sensor, Physical Acoustics Corporation) is mounted inside the small cylinder (which is hollow as well), against the bronze head (3). The gear is rectified on the contact location.

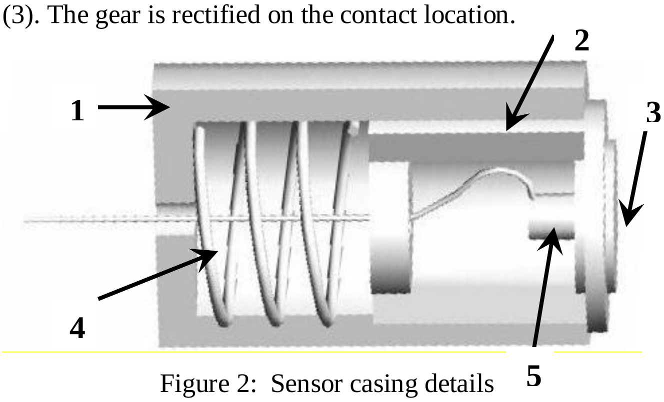

Figure 2: Sensor casing details

A four channel PCI-2 data acquisition system by Physical Acoustics Corporation (PAC) was utilised for the AE recording. A pico sensor by PAC with pre-amplification of 40 dB was used for this study. A sampling rate of 5 MHz was used. The waveform length was selected so as to record continuous AE during one full gear revolution, giving a waveform of 40 msec duration at 1500 rpm revolution speed of the large gear.

3. Wavelet analysis

Wavelet transform (WT) has introduced new aspects in signal and image processing over the last twenty years. A wavelet is a localized wave which instead of oscillating forever it drops to zero rather quickly. Wavelets stem from the iteration of filters and filter banks (with rescaling) so they are inherently orthogonal or biorthogonal. Fourier analysis consists of breaking up a signal into sine waves of various frequencies. Similarly, wavelet analysis is the breaking up of a signal into shifted and scaled versions of the original (or *mother*) wavelet. There is a wide variety of available wavelets with different properties and characteristics. The major advantage of wavelets is their inherent ability to perform local analysis with varying precision. Wavelet transform treats low frequencies with low resolution and high frequencies with high resolution. Consequently they are ideal candidates to analyze transient signals, reveal trends, highlight noise etc. Wavelet transform can mainly be applied in two ways: discrete wavelet transform DWT and continuous wavelet transform CWT.
The continuous wavelet transform considers dilation and translation factors for continuous time and time-scale parameter and can be defined as:

$$CW(a,b)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{+\infty} f(t)\cdot\psi^{*}\left(\frac{t-b}{a}\right)dt \qquad (1)$$

with the inverse transform being expressed as:

$$f(t)=\frac{1}{C_{\psi}}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} CW(a,b)\cdot\frac{1}{a^{2}}\cdot\psi\left(\frac{t-b}{a}\right)dadb \quad (2)$$

where α represents scale (or pseudo-frequency) and b represents time shift of the mother wavelet. ψ^{*} is the complex conjugate of the mother wavelet ψ.

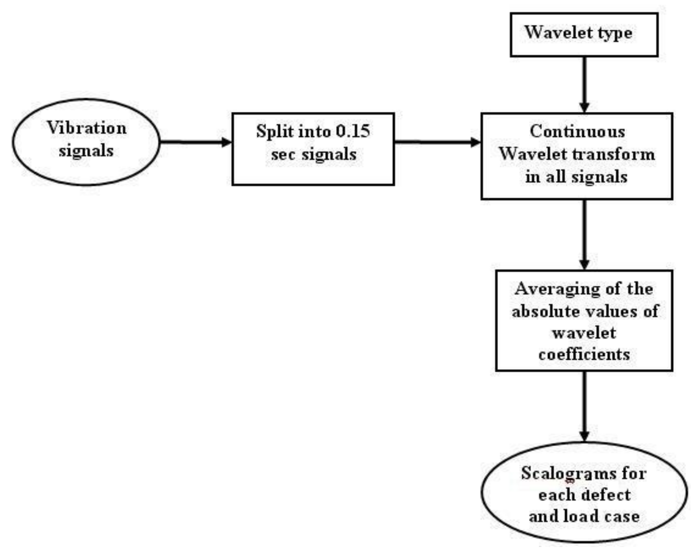

Figure 3: CWT procedure

The flow-chart of the applied methodology is depicted in figure 3 and comprises the use of continuous wavelet transform (CWT) upon the vibration signals. The 3 collected 0.9-sec duration signals are very large and thus are splitted in 0.15 seconds duration signals. Then continuous wavelet transform is applied upon all the 0.15 sec signals and the coefficient matrix is obtained for each signal. Averaging of the absolute values of the (complex) coefficient matrices follows and scalograms representative for each defect and load case are drawn. Characteristic differences in these scalograms are expected to give diagnostic value to this technique.

4. Results

AE load discrimination ability

RMS proved efficient among other AE descriptors in discriminating between different damage and loading states. The results follow in graphs of RMS versus time. For the defect state [A] (no defect) figure 4 shows the complete experimental procedure. The gearbox started to operate under load 2 for about 2.5 hours or about 9000 seconds, until the lubricant temperature was stabilised at about 44 ^{o}C. This figure also proves how drastically acoustic emission (RMS) changes under the increasing oil temperature and confirms the conclusions of Toutountzakis et al [7,9] and Tan [8] who supported in their works that oil temperature variations affect significantly acoustic emission recordings and should always be taken into account. Figures 5,6 correspond to the defects [B] and [C] respectively.

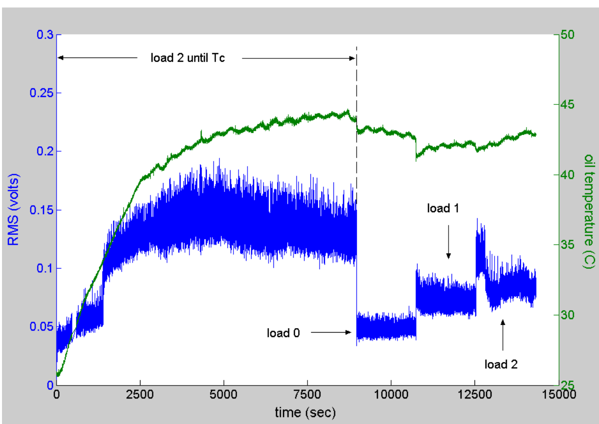

Figure 4: RMS level for defect [A] - all loads

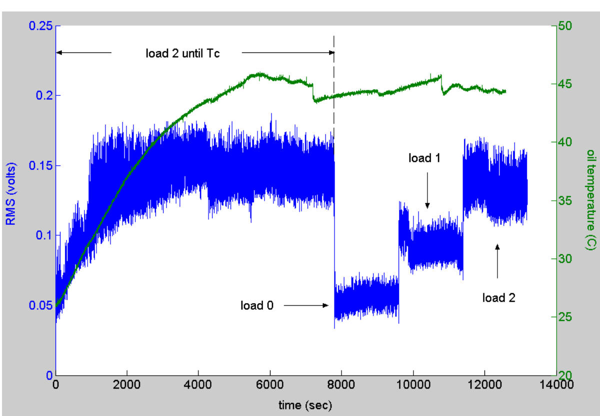

Figure 5: RMS level for defect [B] - all loads

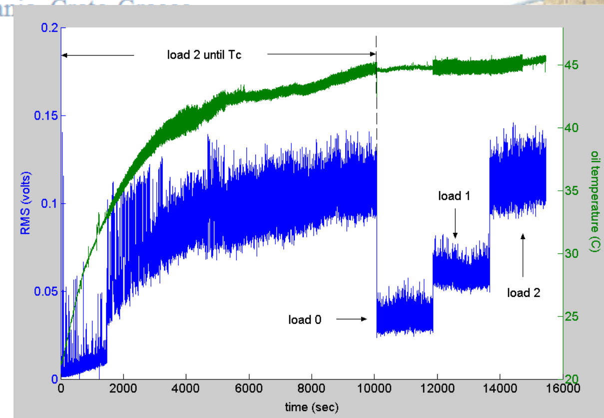

Figure 6: RMS level for defect [C] - all loads

4.2 CWT-based methodology

The second methodology, based on the continuous wavelet transform, provided with the scalograms of the vibration signals in each load and defect case. Figures 7-9 present the scalograms for the load 1 case and for all types of defects. The results are impressive as the differences among the different defects are outstanding. When damage in the gear increases some higher scales seem to enhance. In the case of defect [B] scales around 200 (175-225) are significantly enhanced. From the theory of wavelets we recall that scale is inversely proportional to frequency, which means that high scale corresponds to low frequency. For the certain type of wavelet (complex Morlet) scales 225-175 correspond to frequencies 0.44-0.57 kHz. In the defect [C] case apart from scales 175-225, scales 110-140 also seem to be enhanced. These correspond to 0.71-0.91 kHz frequency domain.

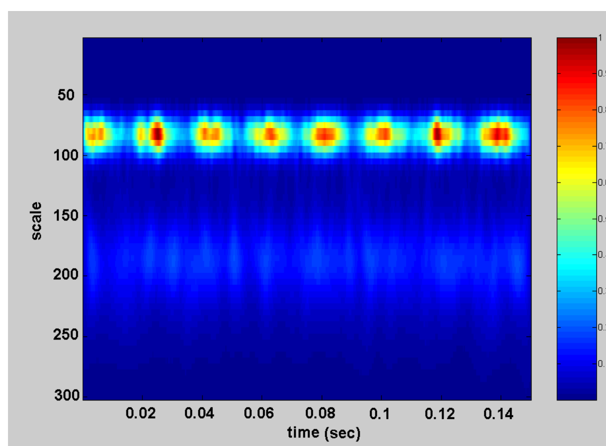

Figure 7: cwt for [A] load 1

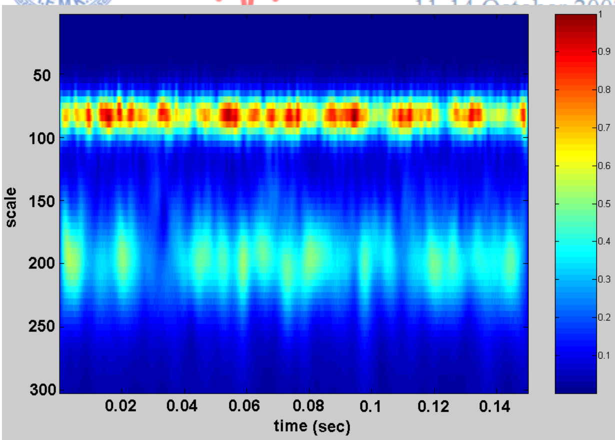

Figure 8: cwt for [B] load 1

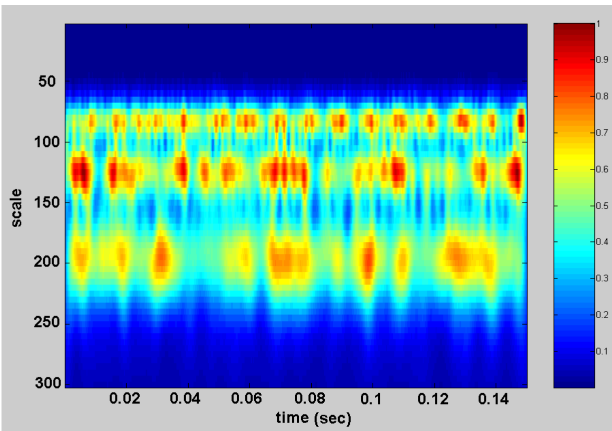

Figure 9: cwt for [C] load 1

Conclusively what is observed as frequency modulation by other authors can be clearly be seen in wavelet scalograms and thus provide with a far more clearer mean of discriminating gear defects than FFT where multiple frequency peaks cannot be easily separated.

5. Conclusions

Two non-destructive testing methodologies namely AE and vibration were utilized in order to monitor the operation of a single stage gearbox under various loads and defect types and extract information of diagnostic value. Advanced signal processing techniques such as the wavelet transform were used to process the vibration recordings. The oil temperature was observed to play a significant role affecting seriously the AE recordings. Thus steady oil temperature is suggested for the field monitoring.

The continuous wavelet transform upon the averaged 0.15 sec duration signals yielded the wavelet scalograms. There it was evident how the scalograms were differentiated under the various defect types by enhancing modulating frequencies, non-existent in the healthy gear case.

Conclusively both techniques managed to discern among the diverse defect types and their diagnostic power was proven by the obtained results. In the future more subtle experiments are designed with more realistic operational characteristics i.e. varying loads, smaller defects etc. The goal is to utilize non-destructive techniques for online monitoring of operational gearboxes in industry, helicopters and every gearbox application that suffers from frequent breakdowns and failures.

6. Acknowledgements

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7. References

[1] N. Baydar, A. Ball, Detection of gear deterioration under varying load conditions by using the instantaneous power spectrum, Mechanical Systems and Signal Processing (2000) 14(6), 907-921

[2] N. Baydar, Q. Chen, A. Ball, U. Kruger, Detection of incipient tooth defect in helical gears using multivariate statistics, Mechanical Systems and Signal Processing (2001) 15(2), 303-321

[3] N. Baydar, A. Ball, A comparative study of acoustic and vibration signals in detection of gear failures using Wigner-Ville distribution, Mechanical Systems and Signal Processing (2001) 15(6), 1091 1107

[4] N. Baydar and A. Ball, Detection of gear failures via vibration and acoustic signal using wavelet transform. Mechanical Systems and Signal Processing (2003) 17(4), 787–804

[5] W.J. Wang, P. D. McFadden, Early detection of gear failure by vibration analysis – I. Calculation of the time-frequency distribution, Mechanical Systems and Signal Processing (1993) 7(3), 193-203

[6] W.J. Wang, P. D. McFadden, Early detection of gear failure by vibration analysis – II. Interpretation of the time-frequency distribution using image processing techniques, Mechanical Systems and Signal Processing (1993) 7(3), 205-215

[7] W.J. Wang, P. D. McFadden, Application of orthogonal wavelets to early gear damage detection. Mechanical Systems and Signal Processing (1995) 9(5), 497-507

[8] W.J. Wang, P. D. McFadden, Application of wavelets to gearbox vibration signals for fault detection, Journal of Sound and Vibration (1996) 192(5), 927-939

[9] Sato. Rotating machinery diagnosis with acoustic emission techniques. Electrical Engineering Japan 1990; 110 (2): 115-127

[10] Al-Balushi KR, Samanta B. Gear faults diagnosis using energy based features of acoustic emission. Journal of Systems Control Engineering 2002; 216:249-263

[11] Tandon N, Mata S. Detection of defects in gears by acoustic emission measurements. Journal of Acoustic Emission 1999;17(1-2):23-7

[12] Singh A, Houser DR, Vijayakar S. Early detection of gear pitting. Power transmission and gearing conference, ASME, DE 1996;88:673-8

[13] Singh A, Houser DR, Vijayakar S. Detecting gear tooth breakage using acoustic emission: a feasibility and sensor placement study. Journal of Mechanical Design 1999;121:587-93

[14] Sentoku H. AE in tooth surface failure process of spur gears. Journal of Acoustic Emission 1998;16(1-4):S19-S24

[15] T. Toutountzakis, C.K. Tan, D. Mba. Application of acoustic Emission to seeded gear fault detection. NDT&E international (2004) 1-10