DETECTING CHANGES IN GEAR SURFACE ROUGHNESS USING VIBRATION SIGNALS

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Abstract

The detection of gear wear from vibration signals is generally achievable once the wear has progressed to a 'macro' level, in which the tooth profile has changed appreciably. A typical example is the 'double scalloped' wear pattern – involving substantial material loss either side of the (largely unaffected) pitchline – which is diagnosable from an increase in the amplitude of the second harmonic of gearmesh frequency. Yet macro level wear is often preceded and accompanied by micro-level surface roughness changes, arising from either abrasive wear or contact fatigue pitting. These micro- and macro-level phenomena interact with one another, and so to be able to accurately predict wear rates in operating gears requires knowledge of their surface roughness state – information not easily obtainable without stopping the machine and taking detailed measurements.

This paper investigates the use of vibration signals for estimating gear tooth surface roughness. Measurements from a laboratory spur gearbox test rig are used, and the rig is fitted with gears of modified surface roughness. It is proposed that changes in surface roughness would be detectable from the nature of amplitude modulation of the random vibrations produced from asperity contacts between the teeth when they slide against one another. Such a signal – random but with cyclic modulation – is known as second-order cyclostationary, and the study finds that the degree of second-order cyclostationarity in the measured signals is strongly correlated with gear surface roughness. In comparison, the RMS and kurtosis of the vibration signal are found not to be as strongly correlated with roughness. The findings will be very important for gear prognostics, where knowledge of wear rate is critical in estimating the remaining useful life of gears.

1. Introduction

Gear transmissions are one of the most important forms of mechanical transmission, and the life and reliability of gears play a key role in the total life and reliability of mechanical equipment. Gear systems are widely used in many applications, including the mining industry, (petro-)chemical industry, rail and road transport, helicopters, and wind turbines (WT), where they account for 21% of downtime "with the highest rate of downtimes per component among all the wind turbine components" [1]. On a worldwide scale, monitoring and maintenance of gears has an enormous safety and economic impact on society. The use of reliable gear monitoring techniques allows for the early detection of gear damage, which if left undetected often leads to damage to other components, and sometimes even to catastrophic failure.

Wear is an important failure mode of gears, with the two main wear mechanisms being abrasive wear and surface fatigue [2]. The combination of these mechanisms, eventually leading to failure, is a very complex process because of changes in operating conditions (e.g. load and speed), lubrication regimes (full, mixed or boundary lubrication), and tooth geometry (tooth profile and surface topography). Both wear mechanisms change the micro-level tooth surface topography, which in turn affects the rate of wear.

It is widely recognised that macro-level wear (changes in tooth geometry of the order of millimetres) can be detected using well-established vibration analysis methods such as Fourier analysis and time synchronous averaging (TSA) [3, 4]. However, most value comes not in being able to detect wear, but rather to predict it, and to use the prediction to estimate the remaining useful life (RUL) of gears. RUL prediction is the least developed of the condition monitoring tools but has by far the biggest potential for economic savings (through maintenance optimisation) and for the elimination of unforeseen catastrophic failures (including consequential damage), with huge potential gains in safety, the minimisation of production losses and great reduction of the need to replace valuable assets.

The accurate prediction of gear wear requires knowledge of the wear conditions and wear rate, and for this the surface roughness state of the gears must be known – information not easily obtainable without stopping the machine and taking detailed measurements. Thus a valuable tool in gear prognostics would be the ability to detect changes in gear tooth surface roughness using only vibration signals, and this paper investigates this possibility.

Despite most of the energy being found in the periodic part of gear vibration signals, it has been shown that significant random components exist whose instantaneous power varies cyclically with the gear meshing [5, 6]. Such signals are known as *second-order cyclostationary* (CS2), and a widely accepted hypothesis [5] ascribes a portion of these CS2 components to friction and asperity contacts, which would have a negligible effect on the periodic part of the signal, the latter generally dominated by macro-level phenomena.

Though hypothesised, the relationship between surface roughness and CS2 signal content has not yet been investigated. This paper presents such an investigation using data from a small gear test rig at the University of New South Wales (UNSW) Australia.

2. Gear Surface Roughness and Cyclostationary Signals

2.1 Cyclostationary signals

A signal is defined to be cyclostationary at the *n*th-order if its *n*th-order statistical properties are periodic with respect to time [5]. Thus for a first-order cyclostationary (CS1) signal, its mean value is periodic. This includes for example pure periodic signals with additive noise, which tends to be the dominant signal type in gear vibrations.

A second-order cyclostationary signal has a periodic autocorrelation function (or variance), a typical example of which is a cyclic repetition of random bursts. It is important to note that CS2 signals are random signals, such that their cyclic structure (i.e. periodic variance) is not apparent in the ordinary frequency spectrum. For such cases, cyclostationary signal processing techniques must be applied to uncover the underlying cyclic nature of the signal.

More information on cyclostationary signals in mechanical applications can be found in [7, 8].

2.2 Gear surface roughness and its effect on vibration signals

All gear operations involve some form of sliding contact between the mating gear surfaces. This sliding contact can produce random vibrations from the asperity contacts between the gears, the nature of which is dependent on a number of factors, such as the speed and load, the lubrication conditions and the micro-geometry of the surfaces. While the energy of this phenomenon might be very low in comparison with macro-geometric effects of the gears, it is thought that with appropriate signal processing it may be possible to detect changes in gear surface roughness purely from the vibration signal.

It is proposed here that this surface roughness information would be most easily detected in the second-order cyclostationary part of the vibration signal. Changes in surface roughness would no doubt affect the overall vibration (e.g., rms) level and its frequency characteristics, but it would be very difficult to distinguish surface roughness from other effects.

The rationale for studying the CS2 part of the signal is explained in Figure 1. The illustration is for a hypothetical spur gear pair with a contact ratio of 1.5, but the concept applies more broadly. Figure 1(a) shows the number of tooth pairs in contact as a function of the gear rotation angle, and Figure 1(b) shows the (approximate) sliding velocity at the mesh point over the same angle. Note that for constant speed operation the x-axes could equally be scaled in time units. It can be seen that for each meshing pair, there is zero sliding velocity when there is pitchline contact, and a (near) linear increase as the mesh point moves away from the pitchline. This produces in the sliding velocity a periodicity corresponding to the gearmesh frequency.

Shown in Figure 1(c) is the sort of resultant amplitude modulation effect that might be expected from this varying sliding velocity. The carrier signal in this case is the random vibration from the asperity contacts between the mating gears, which, though unknown in its frequency characteristics, can be distinguished from other parts of the signal by precise knowledge of its modulating (cyclic) frequency.

It should perhaps be noted here that the meshing force would also modulate this random vibration, but it too has a (predominantly) periodic structure corresponding to the gearmesh frequency. This arises from the parametric excitation from the time-varying numbers of teeth in mesh. When a new gear tooth pair comes into mesh, the mesh stiffness jumps suddenly, but the system cannot reach its new equilibrium position instantaneously, and thus a sudden increase in the contact force results. The opposite occurs when a tooth pair exits its mesh.

While other effects may also be subject to this modulation at gearmesh frequency, it is thought that under similar system and operating conditions (speed, load, alignment, macro-geometry of the gear teeth, etc.), tooth surface roughness should be correlated with the degree of second-order cyclostationarity at gearmesh (cyclic) frequency. This paper investigates the possibility of detecting gear surface roughness changes using one of the indicators of cyclostationarity defined below.

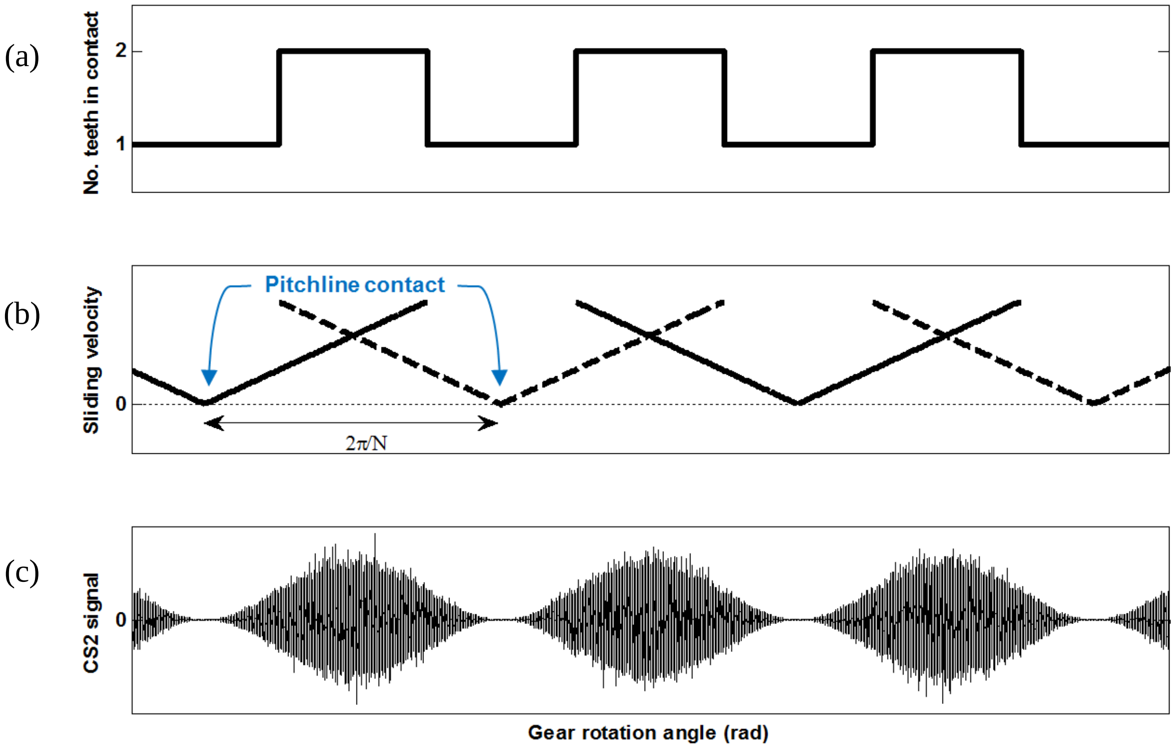

Figure 1. CS2 signal generation from varying sliding velocity in mating gears; (a) number of tooth pairs in contact; (b) approximate sliding velocity; (c) possible amplitude-modulated random signal (CS2) generated from varying sliding velocity (N = number of teeth on the gear)

2.3 Indicators of cyclostationarity

Raad et al. [9] developed robust indicators to measure the degree of cyclostationarity in a signal (up to the fourth order), based on cyclic cumulants (rather than moments). The indicator of second-order cyclostationarity (ICS2) is related to the envelope spectrum, whose enveloping operation is a natural estimator of the cyclic variance of CS2 processes. ICS2 is defined as the ratio between the fault symptomatic peaks and the zero-frequency peak of a full-band envelope spectrum:

$$ICS2 = \sum_{k\in\mathbb{Z},k\neq 0} \frac{\left|C_{2x}^{k\alpha_0}(0)\right|^2}{|C_{2x}^{0}(0)|^2} \tag{1}$$

where $C_{2x}^{0}(0)$ represents the mean-square power of the 'centred signal' x_c, obtained by subtracting the synchronous average from the raw signal. $C_{2x}^{k\alpha_0}(0)$ is theoretically defined as the second-order cyclic cumulant for the set of all cyclic frequencies α $(= k\alpha_0)$, multiples of a fundamental frequency α_0 representative of the cyclic behaviour of the CS2 signal (frequency of the modulation). Raad et al. [9] showed that a consistent estimator of $C_{2x}^{\alpha}(0)$ for a discrete signal $x(k)$ of length N is given by the components at frequencies α in its envelope spectrum, in this case calculated using the squared signal as a proxy for the squared absolute value of the analytic signal:

$$C_{2x}^{\alpha}(0) = \lim_{N\to\infty} \left\{ N^{-1} \sum_{k=0}^{N-1} x_c^2(k) e^{-j2\pi n\alpha\Delta t} \right\} \approx N^{-1} DFT\{x_c^2(k)\}(\alpha) \tag{2}$$

where $DFT\{x(k)\}(\alpha)$ stands for the N-point discrete Fourier transform of signal $x(k)$ calculated at frequencies α, and Δt is the sampling period.

As outlined in [9], the indicators of cyclostationarity are dimensionless and are asymptotically zero for a purely stationary function. ICS2 should be applied to the residual signal obtained by removing the synchronous average from the raw signal.

Stemming from the theory outlined in Section 2.2, ICS2 is applied here with α_0 equal to the gearmesh frequency. This is quite different to previous applications of the indicator to gear condition monitoring, where the cyclic frequency was defined as the shaft speed, the objective being to monitor variations in shaft-speed modulation, as might arise for example from local gear faults (e.g., tooth cracks or spalls). To the authors' knowledge, such an approach has not been applied to monitor modulations at the gearmesh frequency arising from micro-level surface phenomena.

3. Methodology

3.1 Experimental set-up

The UNSW gearbox test rig shown in Figure 2 was used to investigate the effects of gear surfaces with different roughnesses. On the rig, power is supplied to the single-stage spur gearbox by an electric motor, and the output shaft of the gearbox is connected to a water pump, which provides a torque load. The speed of the motor can be controlled using a variable frequency drive (VFD) so that tests can be run at different speeds.

The gears used in the tests were KHK steel spur gears of 46 and 25 teeth (models SS2-46 and SS2-25) for the input and output, respectively. The input shaft speed was set to 23 Hz and an average torque load of 14 Nm was applied.

Vibration signals were measured using a B&K 4370 accelerometer connected to a National Instruments CompactDAQ and Module 9234. A tacho signal was recorded from the free end of the output shaft using a magnetic probe and a slotted disc. The sampling frequency was 51 kHz, giving a usable frequency range of about 20 kHz.

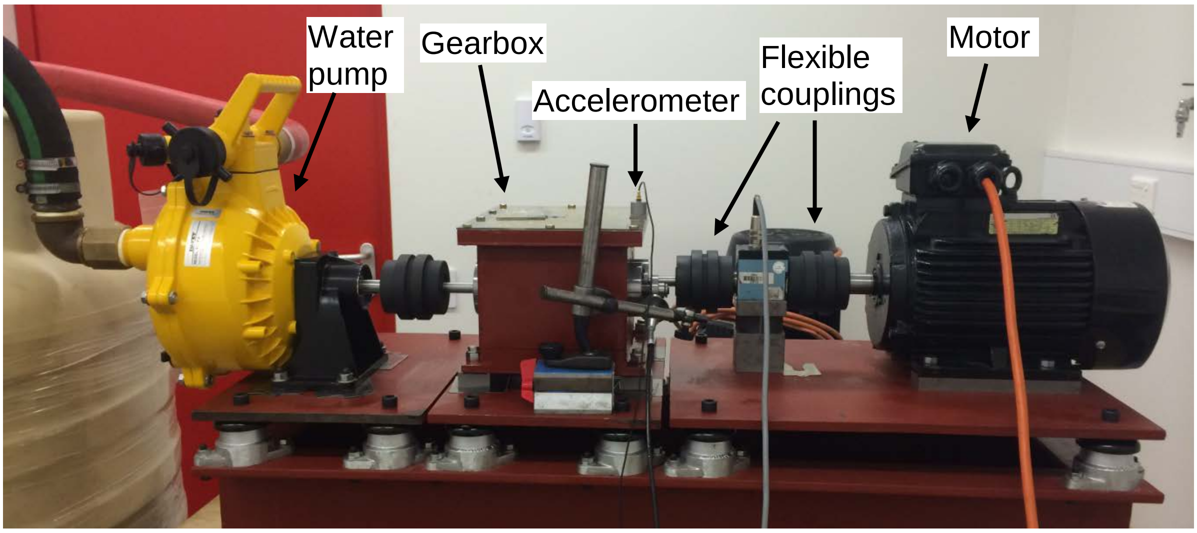

Figure 2. UNSW gearbox test rig

3.2 Test program

The test program comprised two long-running tests: Test 1 ran for 88 hours, and Test 2 for 24 hours. Vibration signals were recorded at regular intervals (ranging from 30 minutes to two hours) throughout both tests. At the beginning and end of each test, and at one point three hours into Test 2, the gear surface roughnesses were measured, as explained in the following section. The basic outline of this test program is shown in Table 1.

As shown in the table, this test program provides six instances (vibration measurements) of known surface roughness to investigate the potential of the proposed roughness indicator, ICS2. In addition to these points of known roughness level, data from throughout Test 2 will also be studied because, as seen in Table 1, the surface roughness decreased quite significantly during that test, especially during the first three hours. It is speculated here that the surface roughness is likely to have followed a trend similar to an exponential decay, with the more pronounced asperities removed early in the wear process, and a progressively lower rate of change in surface properties. A check for this characteristic will be made in the Results section.

Table 1. Test program and gear surface roughness values

Test	Measurement number	Surface roughness, *Ra* (μm) gear / pinion / **average**	Comment
1	1A	0.50 / 0.60 / **0.55**	Start of Test 1 (0 hrs)
	1B	0.57 / 0.49 / **0.53**	End of Test 1 (88 hrs)
2	2A	1.47 / 1.45 / **1.46**	Start of Test 2 (0 hrs)
	2B	1.05 / 1.19 / **1.12**	Before disassembly; 3 hrs into Test 2
	2C	1.05 / 1.19 / **1.12**	After disassembly; 3.5 hrs into Test 2
	2D	0.94 / 1.09 / **1.02**	End of Test 2 (24 hrs)

3.3 Surface roughness processing and measurement

Gear surface roughness measurements were made using a Perthometer, and Ra, the arithmetic average of absolute values of surface deviation, was chosen as the roughness parameter. In each case, the surfaces of about half of the gear teeth were measured, and a few measurements along each tooth were made. All the measurements were then averaged to obtain an average surface roughness value for each gear. In some cases the surface roughness was modified manually, and care was taken to ensure the roughness was quite uniform across all the teeth for each gear.

To modify the roughness of the gear surfaces, two main mechanisms were used: sandpaper was used to increase roughness, and simply running the gears for a long period under load was used to modify (generally reduce) the roughness. Gears were obtained with initial roughness values, Ra, of 0.5 to 0.6 μm, and one pair of gears was used in this condition for Test 1. For Test 2, the gear surfaces were first roughened manually using sandpaper, after which the gears were blown with compressed air to remove any debris. As seen in Table 1, at the start of Test 2 the gears had an average roughness of about 1.5 μm.

3.4 Signal processing

As explained in Section 2.2, surface roughness information would be carried in the random part of the recorded vibration signals, and so deterministic components synchronous with the shafts were removed from the signals using time synchronous averaging. The resulting residual signal was then used to calculate the ICS2 indicator according to Equations 1 and 2.

In addition to ICS2, the RMS and kurtosis of the residual signal were also calculated for comparison. RMS characterises the overall power level of the signal, so the RMS of the residual signal would likely show a positive correlation with surface roughness, since increased roughness would increase the energy of random vibration components.

Kurtosis, defined as the normalised fourth order moment of a signal, gives a measure of a signal's impulsivity. For an *N*-sample record, *x*, the kurtosis is given by:

$$K = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^4}{[\sum_{i=1}^{N}(x_i - \bar{x})^2]^2} \tag{3}$$

It was only recently shown [10] that kurtosis is actually closely related to the envelope signal: it is given by the sum of all components in the squared envelope spectrum normalised by the square of the mean-square power in the signal. In that sense it is very similar to ICS2, but by including all components in the envelope spectrum and not only those at multiples of the cyclic frequency, it is expected that kurtosis will be much less sensitive than ICS2 to surface roughness changes.

4. Results and Discussion

4.1 Correlation of indicators with surface roughness for Tests 1 and 2

Plots of ICS2, RMS and kurtosis of the residual signal for the six measurements of known surface roughness are shown in Figures 3, 4 and 5, respectively (ref. Table 1). The correlation coefficient is given for each plot, showing a very strong positive correlation between ICS2 and roughness. For the other indicators, the correlation – positive for RMS and negative for kurtosis – is significant but not as strong.

Note that points 2B and 2C have the same roughness level because they correspond to just before and after taking a roughness measurement. At this point the gearbox was disassembled, partly to conduct the measurement, and partly because a problem with looseness was identified on the rig. This occurred at some point between the start of the test (Test 2) and the three-hour mark. It is thus considered that measurements taken in this period are quite unreliable because they reflect an abnormal state in the operation of the gearbox. Accordingly, point 2B, recorded in this period, was omitted from the correlation calculation, but is included in the plots for completeness. This is discussed further in Section 4.2.

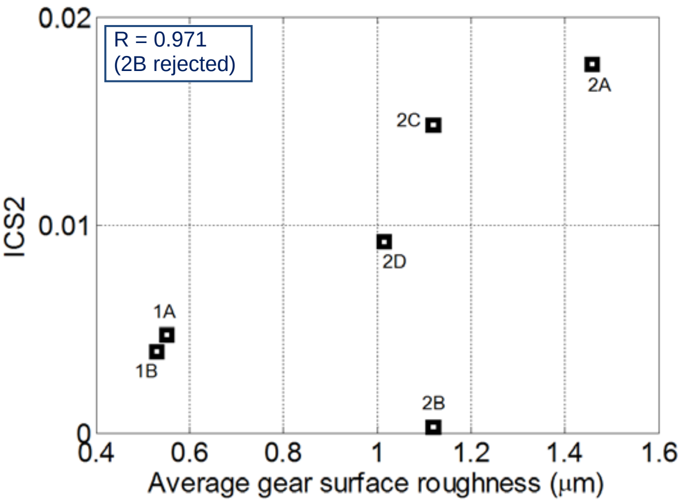

Figure 3. ICS2 vs average gear surface roughness

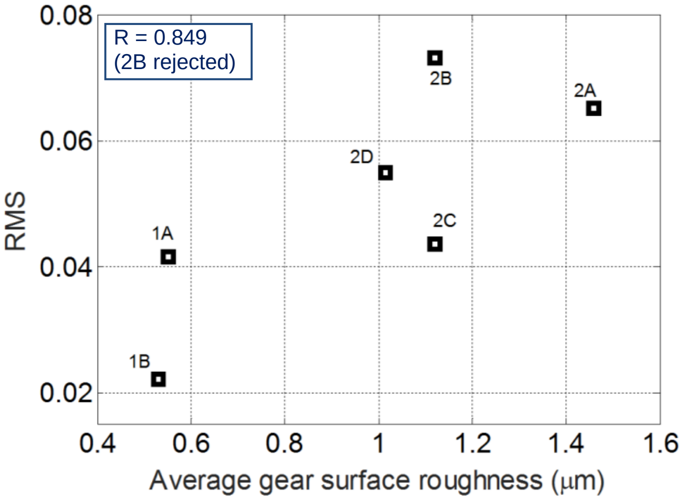

Figure 4. RMS vs average gear surface roughness

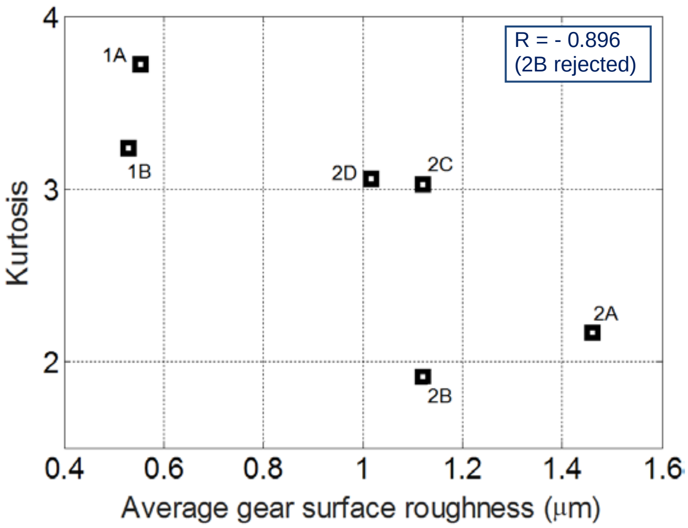

Figure 5. Kurtosis vs average gear surface roughness

4.2 Trend of indicators over time for Test 2

Since the roughness levels of the gears changed markedly during Test 2, it was decided to study the trend in the parameters over that time. As noted in Section 3.2, it is thought the roughness may have followed an exponentially decaying trend in that time.

Figures 6, 7 and 8 show, respectively, the ICS2, RMS and kurtosis plots vs time for the duration of Test 2 (24 hours). The points where the roughness was known (measured) are labelled on the plots (ref. Table 1).

The change due to disassembly of the rig just after the three-hour mark can be seen clearly, especially in the ICS2 and kurtosis plots. As mentioned, measurements taken after the start of the test and before the disassembly are considered unreliable. Leaving these points aside, the ICS2 curve shows a very strong exponentially decaying pattern, with only small fluctuations about the general trend. By contrast, RMS and kurtosis, though previously found to be quite strongly correlated with roughness (albeit with only a small number of data points), do not show any meaningful trend. The RMS fluctuates seemingly randomly throughout the record, while the kurtosis, post-disassembly, is very stable at about three, indicating the residual signal has an essentially Gaussian distribution. Therefore the expectedly lower kurtosis sensitivity is in this case dominated by the non-roughness related characteristics and does not show the CS2 component.

Though more testing with different gear surface roughness levels is required, these results certainly suggest that ICS2 is a very promising indicator of gear surface roughness.

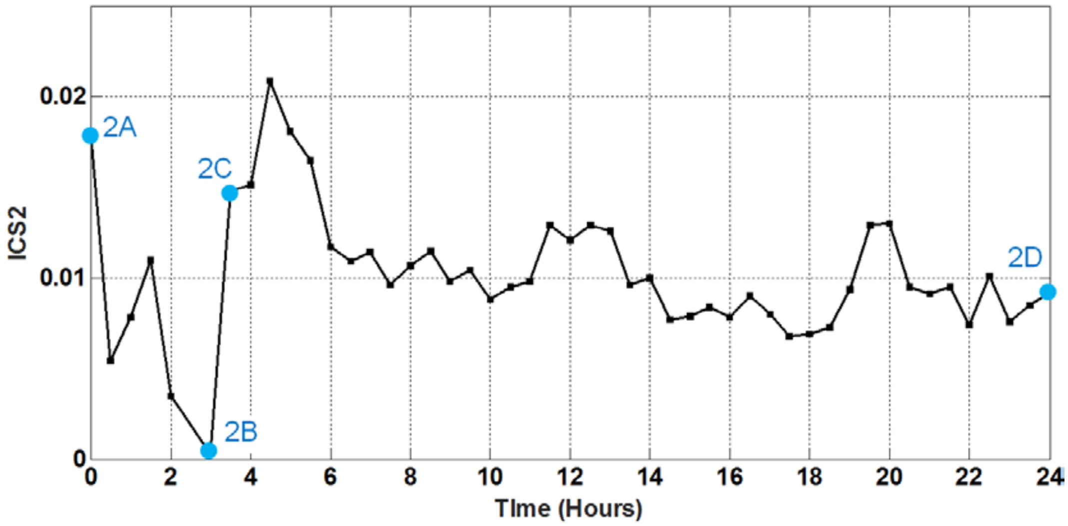

Figure 6. ICS2 vs time for Test 2

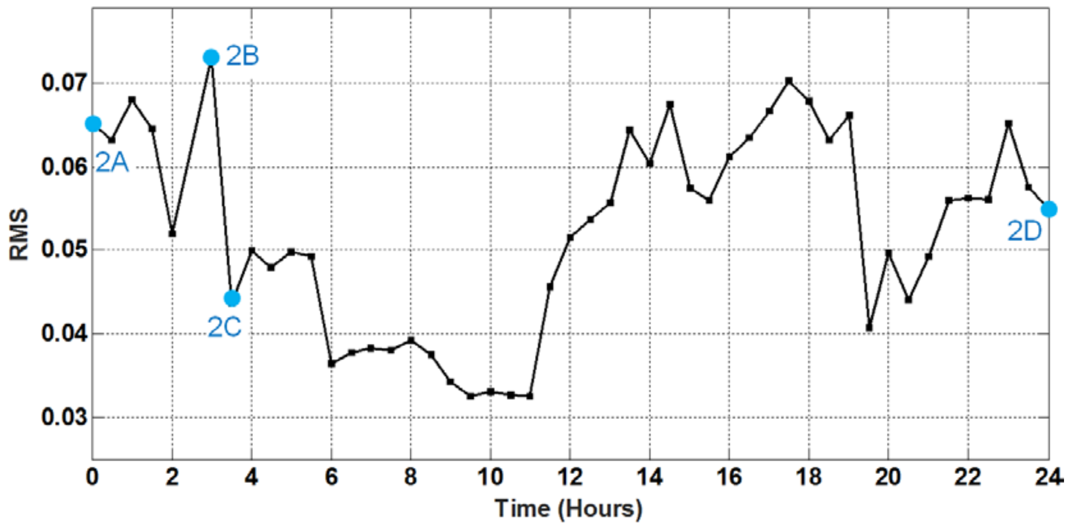

Figure 7. RMS vs time for Test 2

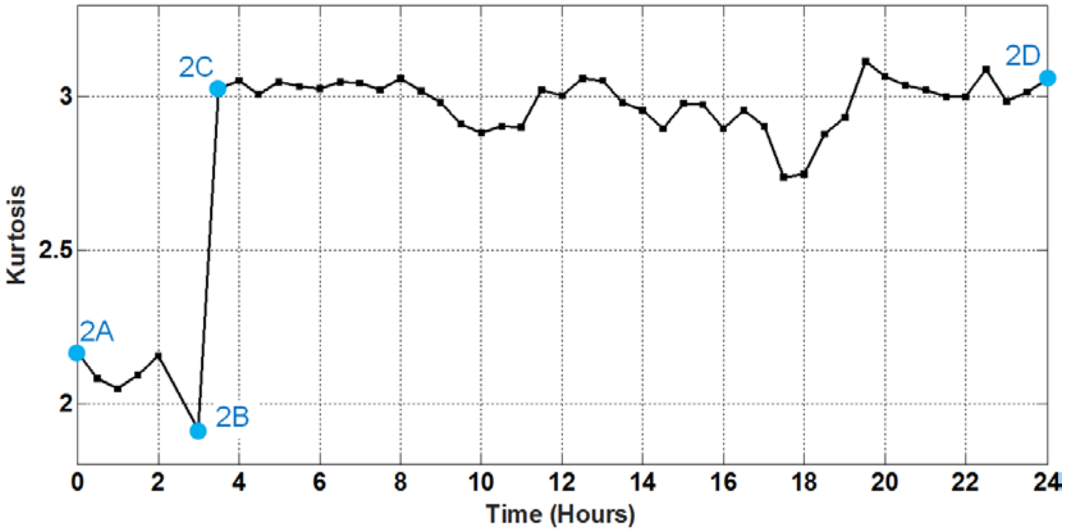

Figure 8. Kurtosis vs time for Test 2

4. Conclusion

This paper investigated the use of vibration signals to detect changes in the roughness of gear tooth surfaces. It was proposed that this might be achievable using established cyclostationary signal analysis tools, because it is thought the roughness of the surfaces would affect the nature of amplitude modulation of the random vibrations produced from asperity contacts between the teeth when they slide against one another, this being a second-order cyclostationary (CS2) signal. Using measurements from a gearbox test rig installed with gears of various surface roughnesses, it was found that indeed the degree of second-order cyclostationarity in the measured signals was very strongly correlated with surface roughness. By contrast, the RMS and kurtosis of the measured signals were found to be less strongly correlated with roughness, and in fact are much less selective indicators than CS2 content and could easily be affected by unrelated events or changes in system condition.

Surface roughness is an important parameter in estimating and predicting gear wear, and so the findings will be very useful for gear prognostics, where knowledge of wear rate is critical in estimating the remaining useful life of gears.

Acknowledgement

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