Use of Cyclostationarity to Detect Changes in Gear Surface Roughness Using Vibration Measurements

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Abstract Wear in gears can usually be detected from the vibration signal once the wear has reached a 'macro' level—millimetre-scale variations from the original involute profile. Macro level wear is often preceded and accompanied by micro-level surface roughness changes (micrometre scale), arising from either abrasive wear or contact fatigue pitting. These micro- and macro-level phenomena interact with one another, and so knowledge of surface roughness is needed to be able to predict macro-level wear. It was recently suggested that it may be possible to use the cyclostationary properties of the vibration signal as an indicator of gear surface roughness, and the present paper examines this possibility further. It is thought that roughness information is carried by random high frequency vibrations that are modulated by the gearmesh cycle, and so any speed changes in the system should change both the carrier and modulating frequencies. The paper tests this hypothesis by studying laboratory measurements from a spur gearbox running at different speeds and with gears of different roughnesses. The findings will be very important for the further development of gear prognostics methods.

1 Introduction

Wear is one of the most common failure modes of gears, with abrasive wear and fatigue being the main wear mechanisms. Gear wear is a very complex process that is influenced by many factors, such as lubrication, temperature, operating conditions, material properties and tooth geometry. It has been established that vibration-based techniques can be used to detect macro-level wear (millimetre scale

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variations from the original involute profile), through changes in the amplitudes of gearmesh harmonics, in particular the second harmonic [7, 9]. However, most of the techniques were developed for fault detection and diagnosis, rather than for prognosis and remaining useful life (RUL) prediction. Predicting RUL is the least developed aspect of gear condition monitoring, but it carries perhaps the greatest potential benefits, both economic and safety related. The wear and lifespan of gears is related to tooth surface roughness [6]; however, information about tooth surface roughness is very difficult to obtain without stopping the machine and taking detailed measurements. As such, establishing a relationship between surface roughness and vibration would provide a very valuable tool for the diagnosis of the gear wear state and for the calculation of remaining useful life.

It was recently proposed that such a relationship could be established through the use of cyclostationary (CS) signal analysis [10], and the present paper explores this possibility further. It is widely known that most of the power in gear vibration signals resides in the periodic components, such as the gearmesh frequency harmonics, but it is thought that important information is also carried in the second-order cyclostationary (CS2) components—in this case random vibrations that are modulated by the gear meshing process [4, 5]. One source of these random vibrations in gears is from the friction and asperity contacts that occur between the sliding surfaces of the meshing teeth, and it is thought that the strength of these vibrations would be closely related to tooth surface roughness. This paper investigates the relationship between gear surface roughness and cyclostationarity using data obtained from a laboratory spur gearbox test rig. In particular, the effect of running speed on the frequency distribution of the cyclostationary content is examined for a number of different surface roughness levels. This will allow for more targeted metrics of surface roughness to be developed in the future.

2 Gear Surface Roughness and Cyclostationarity

2.1 Cyclostationary Signals and Their Indicators

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 [4]. The most relevant case here is that of a second-order CS signal, which has a periodic autocorrelation function (or variance), a typical example of which is a cyclic repetition of random bursts. 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.

The degree of cyclostationarity in a signal can be measured by established indicators [8]. The indicator of second-order cyclostationarity (ICS2) is defined as:

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

where $C_{2x}^{0}(0)$ is the mean square power of the 'centred signal' x_c, obtained by subtracting the synchronous average from the raw signal. $C_{2x}^{k\alpha_0}$ is the second-order cyclic cumulant for the set of all cyclic frequencies α ($= k\alpha_0$). According to Raad et al. [8], a consistent estimator of $C_{2x}^{\alpha}(0)$ for a discrete signal $x(n)$ with length N is given by the components at frequencies α in its envelope spectrum, in this case using the squared signal as an approximation for the squared envelope:

$$C_{2x}^{\alpha}(0) \approx N^{-1} DFT\left\{ x_c^2(n) \right\}(\alpha) \tag{2}$$

where $DFT\{x(n)\}(\alpha)$ stands for the N-point discrete Fourier transform of signal $x(n)$ calculated at frequencies α.

While ICS2 gives an indicator of the overall level of second-order CS content in a signal, it does not indicate its spectral frequency distribution. For this, one must employ more comprehensive tools such as the Spectral Correlation (SC), $S_x(\alpha,f)$, defined as the double discrete Fourier transform of the instantaneous autocorrelation function (itself a function of both time and time lag for CS signals) [2]. The Spectral Correlation indicates the power distribution of the signal with respect to both the spectral frequency f and the cyclic frequency α [1]. In this paper we employ a normalised version of the SC, the Spectral Coherence, defined as [2]:

$$\gamma_x(\alpha,f) = \frac{S_x(\alpha,f)}{\sqrt{S_x(0,f) S_x(0,f-\alpha)}} \tag{3}$$

where $S_x(0,f)$ represents the ordinary power spectral density at frequency f. I.e., the CS content at frequency f is normalised by the power at frequencies f and f–α in the stationary part of the signal. The Spectral Coherence can also be interpreted as the SC of the whitened signal, which tends to magnify weak cyclostationary signals [2].

2.2 *Effect of Gear Surface Roughness on Vibration Signals*

As explained in [10], the rationale for employing cyclostationary analysis in this context arises from the periodic variation in sliding velocity (and contact forces) inherent in meshing gears. The variation in the number of meshing tooth pairs and the cyclic trend in the sliding velocity of the meshing pairs as a function of gear rotation angle result in possible CS2 components generated from the random asperity contacts on the gear tooth faces. As shown in the same reference, a periodicity in the sliding velocity is produced corresponding to the gearmesh frequency. It is likely that the strength of the vibrations arising from random asperity contacts would be closely tied to sliding velocity (and level of roughness), leading to the amplitude modulation effect experienced in [10]. Note that even though this vibration (the carrier signal) is random, with unknown frequency content, it can be separated from other parts of the signal using CS tools because the modulation signal is both known and periodic, with a cyclic frequency equal to gearmesh frequency.

3 Methodology

3.1 Experimental Setup

Data was collected from a number of tests conducted on the UNSW gearbox test rig, shown in Fig. 1. The gearbox consists of a single parallel gear stage and is powered by an induction motor connected to a variable frequency drive (VFD). A water pump is connected to the output shaft to apply a torque load, and a tacho (twice-per rev) is connected to the free end of the output shaft. The drive and driven gears are KHK mild steel spur gears, with 46 and 25 teeth, respectively.

The vibration signal was collected using a B&K 4370 accelerometer stud-mounted on the top of the gearbox casing. The signal was recorded using a National Instruments CompactDAQ with an NI-9234 module. The sampling frequency was 51 kHz.

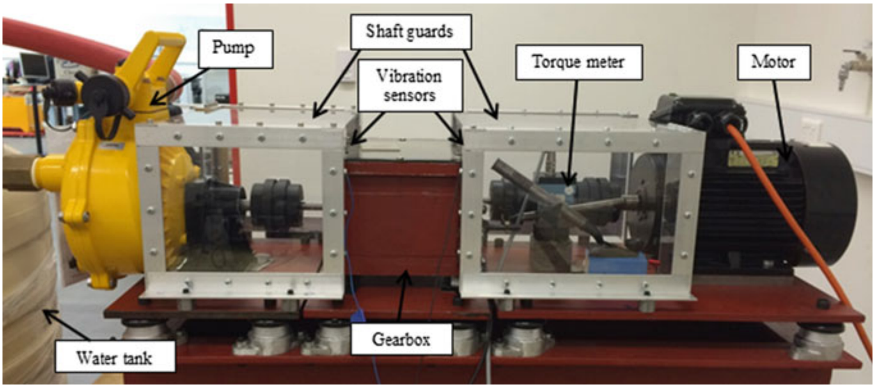

Fig. 1 UNSW gearbox rig

3.2 Test Program and Surface Roughness Measurement

Three sets of tests were conducted, each with different gear pairs. Before some tests the meshing surfaces of the gears were roughened manually (see below). Each test consisted of a long running period (88, 24 and 45 h for Tests 1, 2 and 3, respectively), in which the tooth surfaces were allowed to evolve (generally smoothen) naturally over time, and periodically the vibration signals were recorded and the tooth surfaces measured again to obtain the roughness level corresponding to each vibration signal. In total, 15 measurement points were used: two in Test 1 (points 1A and 1B), four in Test 2 (2A-2D) and nine in Test 3 (3A-3I). The rig was run with an input shaft speed f_{in} of 23 Hz and a torque load of 14 Nm, but at each measurement point signals were also recorded at 15 Hz/7 Nm.

Sandpaper (grit 120, 220 and 320) was used to roughen the gears at the start of Tests 2 and 3. (In Test 1 the gears were as-supplied.) The gears in Tests 1, 2 and 3 had initial surface roughnesses (R_a values) of 0.6, 1.5 and 3.2 μm, respectively, and these roughnesses reduced to 0.5, 1.1 and 1.5 μm over the duration of the tests.

Surface roughness was measured using a Mahr M1 Perthometer (cut-off wavelength 0.8 mm), with measurements taken along a number of teeth (randomly selected), and multiple measurements taken along the same tooth. The measured R_a values were then averaged to give the reported value. At the start of Tests 2 and 3, with manually roughened surfaces, a consistent roughness was achieved by ensuring that the R_a values of all measurements fell within ±0.1 μm of the mean value.

3.3 Signal Processing

As explained in Sect. 2.2, it is hypothesised here that surface roughness information would be carried in the random part of the vibration signal (and modulated by a periodic function associated with gearmesh), so order tracking and time synchronous averaging were applied to remove deterministic components synchronous with both shafts. The residual signal (obtained by subtracting the two TSA signals from the order-tracked signal) was then used to calculate ICS2 according to Eqs. (1) and (2), with the cyclic frequency set to the gearmesh frequency ($\alpha = f_{gm}$). The residual signal was also used to calculate the Spectral Coherence (again at $\alpha = f_{gm}$), as defined in Eq. (3), using a new fast computation code developed by Antoni et al. [2, 3].

4 Results and Discussion

4.1 Correlation of CS Indicator and Surface Roughness

Figure 2 shows the plots of ICS2 vs surface roughness for all the measurement points for both input shaft speeds (15 and 23 Hz). The data from Tests 1 and 2 in the high speed case was in fact presented in [10], where a very good correlation between ICS2 and roughness was observed. It was explained in that paper that point 2B was thought to be unreliable because looseness had developed in the rig, so that point was discarded in the regression analysis. The plots shown here, with a greater range of roughness levels and a new speed/load, suggest a more complex relationship. Certainly, the monotonic trend previously observed in the high speed case (right plot) seems to break down around R_a = 2 µm. It is possible that for the outlying measurement points at higher roughness levels (the first four measurements from Test 3) there is a fundamental difference in the interaction of the contacting surfaces. For example, a higher R_a value—obtained using coarser grit sandpaper—may mean a larger average wavelength in the surface asperities, and beyond a certain point this could lead to a reduction in the rate of asperity breakage and deformation, and hence a lower ICS2 value. However, this explanation is at odds with the fact that throughout Test 3 (45 h), the average surface roughness of the gears did change considerably (from R_a = 3.2 to 1.5 µm). Implicit in this point is that R_a alone is not an adequate metric to completely characterise a random surface, and this is one area that will be examined in future analyses on the cyclostationarity/roughness relationship.

In the case of low speed/load (left plot), there is no observable trend, even from the Test 1 and 2 data points. A likely reason for the poorer correlation in the low speed case is due to the very low torque load (7 Nm), which could not be controlled

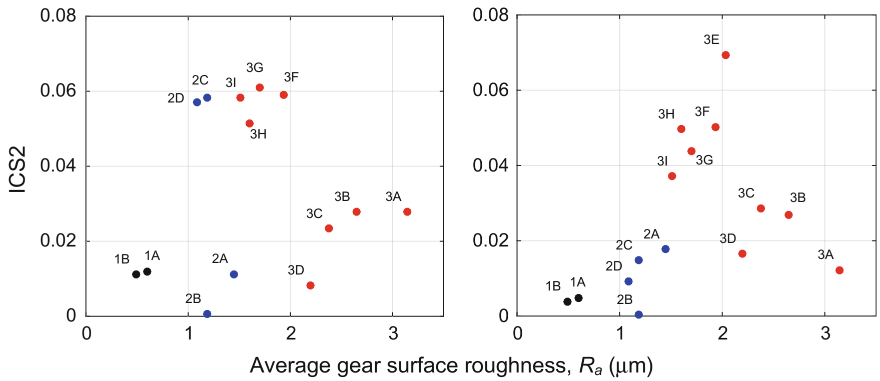

Fig. 2 ICS2 (calculated at $\alpha = f_{gm}$) versus gear surface roughness; left: f_{in} = 15 Hz; right: f_{in} = 23 Hz

independently of speed with the rig setup at that time. Future testing will address this issue.

4.2 Effect of Running Speed on Cyclostationarity

One way of improving on ICS2 as a potential roughness indicator is to develop a more targeted metric that examines the spectral frequency range carrying the most roughness information. This section contributes to that by studying the effect on CS content of the machine running speed. The rationale for using CS processing tools to examine surface roughness (see Fig. 1) was based on variations in sliding velocity between the contacting surfaces throughout the mesh cycle, and so it seems likely that running speed (which dictates the range of sliding velocities) would have a direct effect on the frequency of the CS content. This CS spectral content was investigated using the Spectral Coherence defined in Eq. (3), expressed as $|\gamma_x|^2$ to give values ranging from 0 to 1. Four measurement points were chosen for analysis—1B, 2A, 3A and 3F—representing a range of roughness and ICS2 levels. Figure 3 shows the Spectral Coherence for these points over the 0–25 kHz spectral frequency range. This represents the power of the signal content modulated at the gearmesh frequency normalised by the power in the stationary part of the signal. To give a clearer indication of the spectral distribution, the first order spectral moment (or 'mean frequency') for each coherence plot is shown as a dotted line on the graphs, and the results for the two speed cases are plotted on the same axes.

It is clear in every plot that the average frequency of the CS content increases with the running speed, almost in direct proportion, with the average change in mean frequency found to be about 1.4, while the speed ratio was around 1.5. That is, not only does the cyclic frequency change with running speed, but so does the range of dominant carrier frequencies. This indicates that the main carrier signals are indeed tied to sliding velocity and the rate of interaction of the asperities, and not, for example, fixed frequency resonances such as might be excited in the presence of a bearing fault. Note that this analysis is complicated by the fact that the machine speed only changes the range (or average) of the sliding velocity, i.e. the sliding velocity still spans a range from zero to the maximum.

To develop a more effective roughness indicator further work is needed to establish the frequency range over which most roughness information is carried, over a wider range of speeds, roughnesses and torque loads. However, the finding that the 'mean' carrier frequency seems closely related to sliding velocity helps in the development of more sophisticated tools, for example to isolate frequency modulation effects.

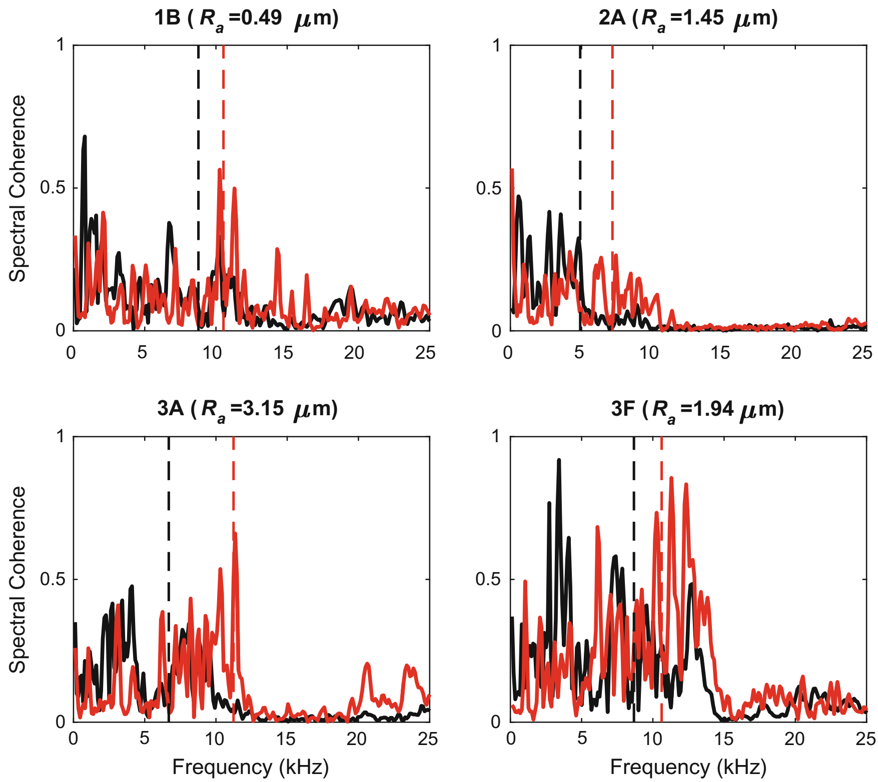

Fig. 3 Spectral coherence $\left|\gamma_x\left(\alpha = f_{gm}, f\right)\right|^2$ obtained at different operating speeds corresponding to measurement points 1B (top-left), 2A (top-right), 3A (bottom-left) and 3F (bottom-right). Black lines: f_{in} = 15 Hz; red lines: f_{in} = 23 Hz. Dashed lines represent first-order spectral moments

5 Conclusion

This paper investigated the possibility of using the cyclostationary (CS) properties of vibration signals to detect changes in gear tooth surface roughness. It was previously proposed that information about the surface roughness of meshing gears would be carried in the random vibrations generated from asperity impacts, and these vibrations would be modulated by the gear meshing cycle, which is entirely deterministic. This creates a second-order cyclostationary (CS2) signal, and a previous study found a strong correlation between CS2 content and surface roughness. The present paper, using new data covering a much larger range of roughness levels, found this relationship to be more complex than originally thought, with a negative correlation between these two variables observed beyond a certain roughness level (R_a = 2 μm). More work is needed to understand the physics underlying this observation.

The paper also used Spectral Coherence to study the frequency content of that part of the vibration signals modulated at the gearmesh frequency, and how it is affected by running speed. For the four measurement points studied, covering a range of surface roughnesses, it was found that the mean frequency of the coherence varied almost in direct proportion to the running speed, indicating that the main carrier signals in the CS2 content were based on sliding velocity, such as impacting asperities, and not on fixed frequency resonances. This provides useful information for the development of more targeted roughness metrics in the future.

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