Planet bearing diagnostics under variable speed operation

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Abstract

The detection and diagnostics of faults in planet gear bearings constitute a problem in the diagnostics of planetary gearboxes, possibly because of the tortuous and time varying path the signals must take in reaching externally mounted accelerometers. The problem is made even more difficult when the speed of the machine is continuously varying, such as with wind turbines. Many forcing functions vary with the speed of the machine, whereas structural responses have fixed resonance frequencies. Our group has therefore studied this problem using a small planetary gearbox in a test rig at UNSW with a localised notch inserted into the outer race of one of the planet bearings. Tests were done at fixed and varying speed. It was found that in all cases the bearing fault was carried by a very high resonance frequency (~ 50 kHz) but this band was not found by the conventional fast kurtogram. It was however found by a newly developed cyclostationary processing tool. One of the central points of the paper is that for varying speed the correct domain must be used for each processing step, so a typical analysis may involve switching several times between the time and angle domains, for example to remove deterministic signal components in the latter, or to conduct bandpass filtering in the former. The fault diagnosis was clearest for the constant speed test, with harmonics of BPFO surrounded by sidebands at the relative speed of the planet and planet carrier, which is the rate at which the outer ring passes through the load zone. However, the diagnosis could also be made for the variable speed case.

1 Introduction

Faults in planet bearings are often very difficult to detect and diagnose, especially in cases involving variable speed and load, such as in wind turbine transmissions. There have been many instances where faults in such bearings have not been found, not least in the diagnostic contest run in conjunction with the CMMNO conference in Lyon in December 2014 [1], where none of the participants were able to locate the fault. One problem is very likely the tortuous and time varying path the signals must take in reaching externally mounted accelerometers, meaning that special techniques must be found to separate the weak bearing signal from the background noise from gears etc. Bearing signals are typically carried by high frequency resonances, which remain fixed as speed varies, but the repetition rates of impulse responses (IRs) generated by the faults are tied to machine speed. A powerful procedure to separate the bearing signals from masking signals, for constant speed machines [2], involves first removing discrete frequency components, for example from gears, by a method recognising that the bearing signals are stochastic, because of a small random variation in the spacing of the IRs, meaning that their correlation length is short with respect to that of deterministic discrete frequency signals. Even after that, it is usually necessary to find a frequency band dominated by the bearing IRs, which tend to be highly impulsive. Most often, the fast kurtogram [3] is able to do this, by finding the optimum combination of centre frequency and bandwidth to maximise the spectral kurtosis (SK) of the bandpass filtered signal. There are a small number of cases, however, for which the bearing signal is not the most impulsive, but then other tools, based on cyclostationarity, are still able to achieve separation [4]. This is because bearing fault signals are very similar to second order cyclostationary signals, since their second order statistics are almost periodic, even if the signal as a whole is stochastic. A signal is second order cyclostationary (CS2) if its squared envelope is periodic, and even though in the case of bearing signals this is not strictly true, because of the 1-2% variation in repetition frequency, the first few harmonics of such “frequencies” are sufficiently localised to allow diagnosis [5]. The major tool used in [4] is the spectral correlation diagram, where carrier frequency components of modulated signals (which can be broadband for CS2 signals) are located on one axis, and cyclic modulating frequencies are found at discrete locations on the other.

When the machine speed varies, many signals, including bearing fault signals, become so-called *cyclo-non-stationary* (CNS), and there have been a number of recent advances in the theory behind their analysis [6, 7]. Most importantly, it has been realised that CNS signals required joint treatment in the angle/time (or order/frequency) domains to fully capture the characteristics of the signal [6]. It is shown that a diagram similar to the spectral correlation can be obtained, where the carrier frequency axis (usually encompassing fixed resonance frequencies) is in terms of frequency, but the modulating component axis is in terms of harmonic orders.

This paper shows how these concepts can be incorporated easily into a conventional envelope-based diagnostic approach, by passing between the time/frequency and angle/order domains. Figure 1 illustrates how the benchmark method in [2] has to be modified when speed varies, such that the harmonic order axis is no longer simply a re-scaled version of the frequency axis.

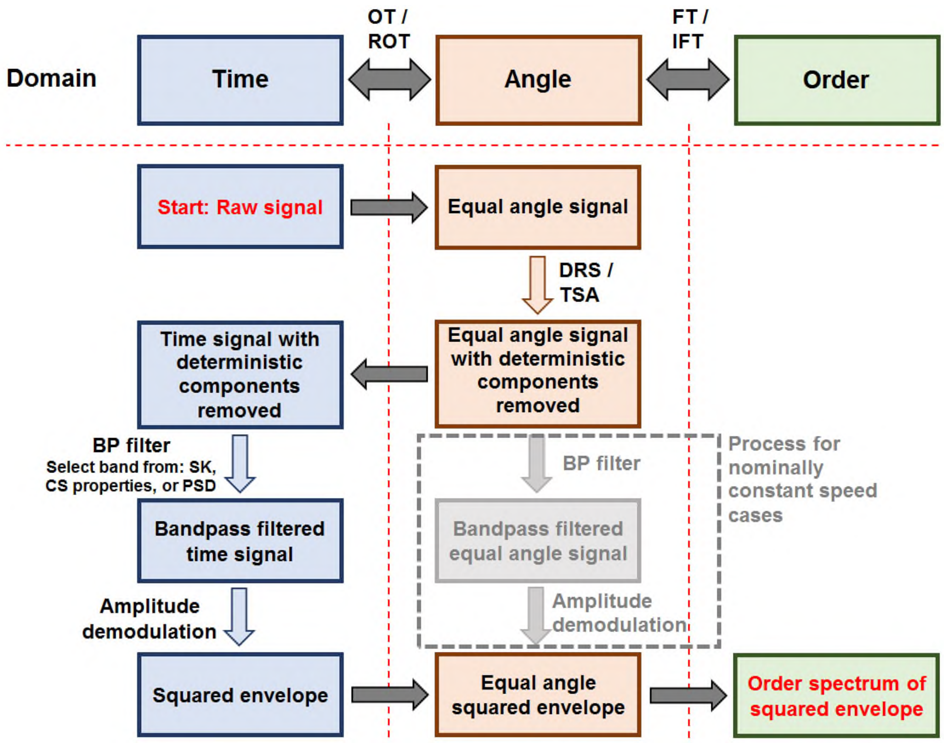

Figure 1: 'Benchmark' method for bearing diagnostics in variable-speed conditions;
(R)OT: (reverse) order tracking; (I)FT: (inverse) Fourier transform;
DRS: discrete/random signal separation; TSA: time synchronous averaging;
BP: bandpass; SK: spectral kurtosis; CS: cyclostationary; PSD: power spectral density

Since the first necessity is usually to remove deterministic components related to machine speed, the signal must first be converted to the (rotation) angle domain by order tracking, where the localised order components can be removed using a technique such as DRS (discrete/random separation), TSA ("time" synchronous averaging), or possibly a cepstral liftering method [8]. Since the bearing signals are usually carried by high frequency resonances, it is then necessary to return to the time/frequency domain to apply techniques such as spectral kurtosis (SK), using the fast kurtogram. Another technique known as minimum entropy deconvolution (MED), which is another component of the benchmark method in [2], must also be applied in the time domain, since it generates an inverse filter to counteract the extent of smearing of IRs, these having constant length in the time domain, even if their spacing varies (with variable speed). At this stage, the bearing signal should have been extracted from the total signal, with maximum impulsiveness, and the deterministic (squared) envelope of the IRs can be generated. Since the spacing of these will vary with speed, the envelope signal must be transformed back to the angle domain by another order tracking process, before finally obtaining the squared envelope spectrum (SES) in the order domain. Note that this will distort the length of each pulse (governed by the damping time constant), but the spacing will dominate the envelope spectrum.

2 Methodology

2.1 Experimental Setup and Test Program

The data under analysis was obtained from the UNSW planetary gear rig, which consists of one parallel and one planetary gear stage, as shown in Fig. 2 (left). The planet carrier forms the input to the planetary stage, and the sun the output, with the ring fixed. Tooth numbers are shown in the figure. Acceleration was measured using a B&K 4394 accelerometer stud-mounted on the top of the ring gear, as shown in Fig. 2 (right). The planet bearings (IKO model NAF 122812) consist of 11 needle rollers with pitch and roller diameters of 19 mm and 3 mm, respectively. A large slot was seeded in the outer race of one of the planet bearings, as shown in Fig. 3 (left). A phase reference signal was recorded from a tachometer placed on the free end of the drive shaft (with respect to which all ‘order’ figures are given), and both signals were sampled for 30 s at 150 kHz using a B&K Pulse analyser. The high sampling rate was used because it was found in previous investigations [9, 10] using the same rig but with slightly smaller planet bearings, that seeded bearing faults were only diagnosable at very high frequencies (~ 40 kHz). The expected fault frequency, BPOO (ball pass order, outer race) is approximately 12.3 orders, with the fault passing in and out of the load zone at a rate of 2.66 orders (planet gear speed relative to the carrier). Two tests were conducted: one nominally constant speed, with the input shaft rotating at 5.4 Hz, and one variable speed, with an input speed ranging from 2.9 to 4.2 Hz, as shown in Fig. 3 (right).

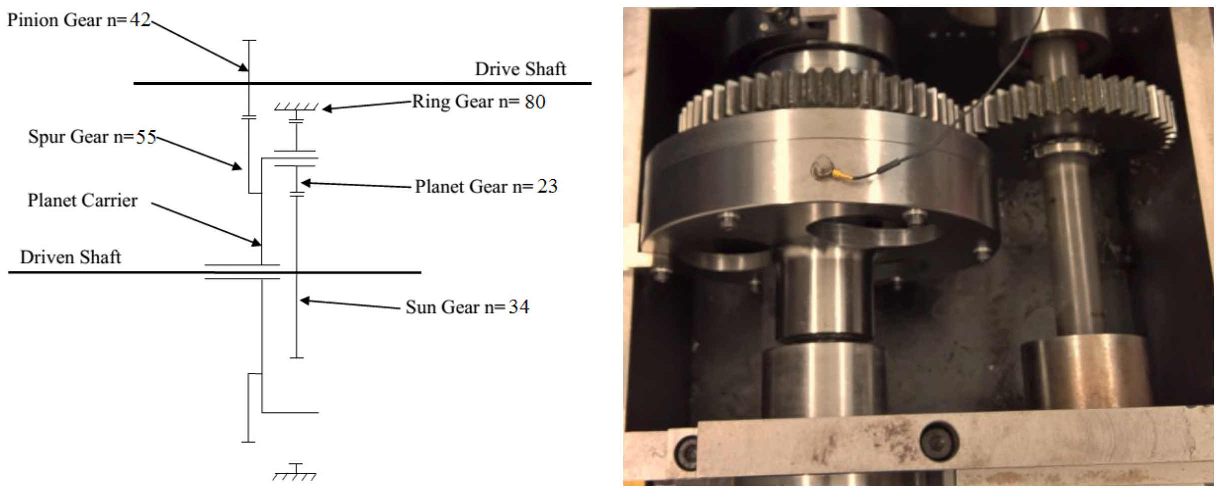

Fig. 2: Planetary gearbox test rig. Left: gear diagram; right: top view of gearbox showing accelerometer on top of ring gear

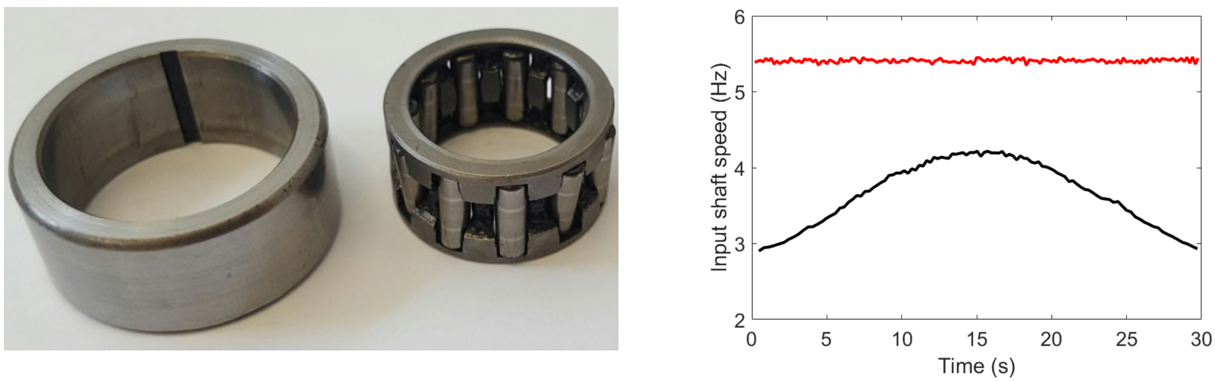

Fig. 3: Left: disassembled planet needle roller bearing showing seeded fault (slot) on the outer race; right: measured input shaft speed profiles, constant (red) and variable (black)

2.2 Signal Processing Approach

The first step was to remove deterministic components, and this was done using discrete-random separation DRS [11]. For the variable speed case, the procedure of Fig. 1 was followed, meaning that order tracking was used to transform the data into the angle domain. It was then reverse order tracked to the time domain to find the optimum demodulation band for envelope analysis.

Initially, the fast kurtogram [3] was tried, but as shown in Figure 4 it selected a band in the vicinity of 20 kHz, for both the constant and variable speed cases, and this did not reveal the anticipated outer race fault frequencies.

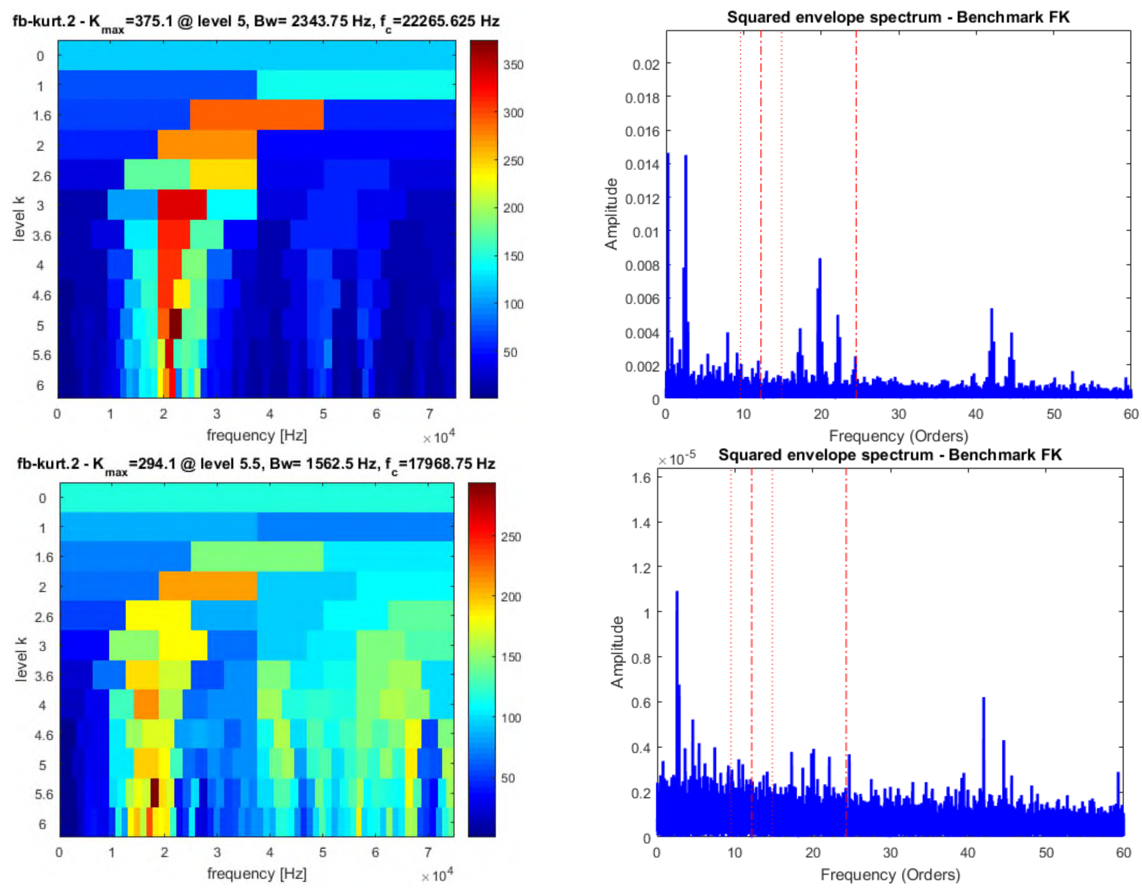

Fig. 4: Results using fast kurtogram for band selection. Left: fast kurtogram; right: SES (cursors at BPOO; expected sidebands shown); top: constant speed; bottom: variable speed

2.2.1 Targeted cyclostationary indicator

A new targeted indicator is proposed, based on maximising second order cyclostationarity at one of the bearing fault frequencies, using the indicator ICS2 [12]. This has the downside that a separate calculation needs to be made for each potential fault frequency, but in general these are known. A new visual tool, the 'ICSgram', was created based on the fast kurtogram, in the sense that it uses the same (frequency/frequency resolution) plane and 1/3-binary tree structure, but rather than kurtosis it plots the values of ICS2 at a pre-specified cyclic frequency. This allows for demodulation of the band that maximises cyclostationarity at the chosen fault frequency. The determination of ICS2 necessarily involves calculations in the angle domain, but for the reasons previously discussed the bandpass filtering and demodulation is performed on the time signal. Here the conventional squared envelope spectrum (SES) is employed, because its interpretation is widely understood and it allows for the observation of additional features (e.g., modulation patterns, number of fault frequency harmonics, etc.).

In [12], the ICS2 indicator was calculated using the square of the signal as a proxy for the squared envelope, but here the squared envelope (angle domain) is used directly:

$$\mathrm{SE}_x(\theta) = x^2(\theta) + \tilde{x}^2(\theta) \quad \text{and} \quad \mathrm{SES}_x(f_\theta) = \left|\mathrm{DFT}\left\{\mathrm{SE}_x(\theta)\right\}\right| \tag{1}$$

where $\tilde{x}$ is the Hilbert transform of signal x, θ refers to rotation angle, DFT represents the discrete Fourier transform, and f_θ refers to frequency in orders. ICS2 is defined as:

$$\mathrm{ICS2}_{x,\alpha} = \frac{\sum_{m=1}^{M}\left[\mathrm{SES}_x(f_\theta)\Big|_{f_\theta=m\alpha}\right]^2}{\left[\mathrm{SES}_x(0)\right]^2} = \frac{\sum_{m=1}^{M}\left[\mathrm{SES}_x(f_\theta)\Big|_{f_\theta=m\alpha}\right]^2}{\left[2\times \mathrm{MS}_x\right]^2} \tag{2}$$

where α is the cyclic frequency (pre-set to an expected fault frequency), MS_x refers to the mean-square value of the signal x, and M is the number of fault frequency harmonics considered. Note that unlike with gears or other deterministic modulating functions, the presence of random slip in bearings means the fault frequency (order) is not known exactly. This means that a tolerance around α must be built into the calculation of ICS2, so the bandwidth of the search area for potential fault-related components increases in proportion with harmonic number m. Thus, the more fault frequency harmonics considered, the greater the chance of contamination from extraneous components. For this reason, it was decided here to restrict the calculation to the first two harmonics of BPOO (i.e., M = 2 in Eqn. 2).

3 Results with ICS2 indicator

Fig. 5 shows the results obtained using the 'ICSgram' for targeted band selection. To achieve this, α in Eqn. 2 was set to BPOO (actually slightly lower due to slip). The ICSgrams look quite different to the kurtograms of Fig. 4, with a narrow band near 50 kHz selected in both cases. The SES of the constant speed case gives a very clear diagnosis, with sidebands indicating the expected modulation frequency at the relative speed of the planet and planet carrier, which is the rate at which the outer ring passes through the load zone. The variable speed SES is less clear, but still gives an acceptable diagnosis, especially with the presence of sidebands. The fact that the BPOO component and sidebands are still very localised indicates that the distortion of the pulse length by order tracking has not smeared the repetition frequency.

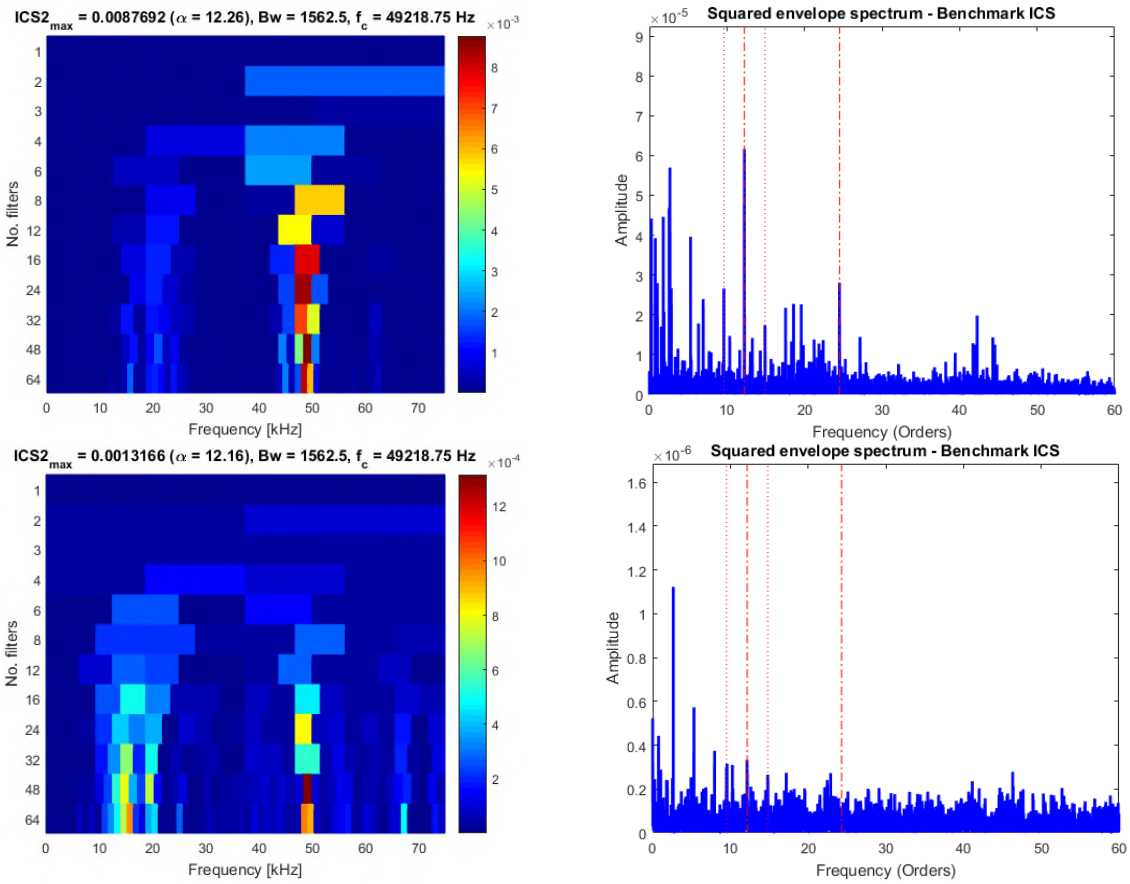

Fig. 5: Results using CS properties for band selection. Left: ICSgram; right: SES (cursors at BPOO; expected sidebands shown); top: constant speed; bottom: variable speed

4 Discussion

The results in the preceding sections suggest that a targeted diagnostic approach is required in this challenging application, where the fault symptoms are apparent only in a relatively weak, narrowband, high frequency resonance. Retrospective inspections of the fast kurtograms do not suggest a fault around the frequency band that was found to carry the fault-related information, perhaps suggesting a gentle modulation rather than a series of sharp pulses. This is reinforced by the SES of the constant speed case (Fig. 5, top-right), which, though clear, contains only two clear harmonics of BPOO. It does seem that in this case careful (time domain) band selection was absolutely essential to achieving a successful diagnosis. It is therefore unlikely that diagnostic approaches based on cepstral editing (either whitening [13, 14] or liftering to retain resonances [15]), which are usually based on full bandwidth analysis, would yield successful diagnoses, although such techniques could perhaps be implemented as a pre-processing step prior to bandpass filtering.

5 Conclusion

This paper studied the challenging case of planet bearing diagnostics in variable speed operation, and concludes with the following points:

1. Faulty bearings operating under variable speed produce cyclo-non-stationary signals, which must be treated jointly in the time/angle (or frequency/order) domains.

2. This can be incorporated into conventional bearing diagnostic algorithms, but requires frequent (reverse) order tracking to ensure the right domain is used for the various processing steps. Bandpass filtering, for example, should be performed in the time domain to preserve the nature of the excited resonances, at least with respect to carrier frequency band.

3. In the proposed method in Fig. 1, the (squared) enveloping is done in the time domain, giving uniform length pulses with variable spacing. The subsequent order tracking to the order domain will distort the length of the individual pulses but should have minimal effect on the envelope spectrum as the repetition and modulating frequencies will be correct. Note that the length of the envelope pulses would be unaffected by generating the envelope after the order tracking.

4. In challenging diagnostic environments, a targeted (rather than blind) approach may be required to uncover bearing faults. The (blind) fast kurtogram was not successful here even at constant speed, but a diagnosis was achieved by selecting a band that maximised second-order cyclostationarity at the bearing fault frequency.

5. The bearing fault was only apparent in a relatively weak, narrowband, high frequency (50 kHz) resonance, suggesting full bandwidth approaches would not be suitable in this application.

6. It would be desirable to compare these results with the methods of Refs. [6, 7], and this is planned in the near future.

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