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Vibration diagnosis of a gearbox by wavelet bicoherence technology

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Gearboxes are critical elements of mechanical systems that are widely used in aerospace, energy generation, land and naval applications. The early detection of changes in the technical condition of this equipment is of great importance for the optimisation of maintenance costs. Vibration signal components resulting from the presence of the developing faults of meshing gears contain the information that, once extracted from the signal, may allow for a reliable estimation of the technical condition of the meshing gears. Wavelet bicoherence (WB)-based technology has been used to obtain the signal feature characterising the phase relationship between the signal components generated by gear faults in the selected frequency bandwidths. In previous research, WB has been successfully applied to the detection of artificially-created gearbox faults. This paper will present the application of WB in the detection of naturally-developing gear faults.

1. Introduction

Local gear faults produce short-duration non-stationary impacts, which excite the broad frequency band vibrations. The transient nature of these events means that conventional FFT-based signal processing methods are frequently insufficient. As the vibration signals generated by gear faults may exhibit a phase coupling between particular frequency components, high-order spectra have been successfully used to extract information concerning this fault-related vibration signal feature[1]. Due to the dependency of high-order spectra on signal component amplitudes, methods based on normalised high-order spectra such as, for example, bicoherence (normalised bispectrum) have been proposed[2].

The transient non-stationary character of vibration generated by gear faults, which makes them difficult to capture with FFT-based methods, makes the wavelet transform, which preserves the temporal information, a particularly useful tool that has been successfully used for vibration transient detection[3-9].

To benefit from the advantages of both approaches, that is the sensitivity to phase coupling between particular frequency components of high-order spectra and high time-frequency resolution of wavelet transform, Gelman has proposed the use of wavelet bicoherence (WB) for gear damage detection[9]. WB applicability to gear damage detection has been proven by subjecting it to the examination signals recorded for brand new undamaged gears and the same gears with multiple 'natural-like' created faults that simulate pitting.

Current research has proven the applicability of the WB through successful observation of naturally-developing pitting of the gear teeth surfaces, which has not been done so far with this method.

2. Application of wavelet bicoherence for observation of tooth micro-pitting development

2.1 The wavelet bicoherence and wavelet bicoherence feature

The locally-averaged WB has been proposed by von Milligan *et al*[10] in the domain of turbulence analysis. To adapt the capabilities of WB to non-stationary signals, Combet and Gelman proposed instantaneous WB and the locally-averaged WB with a local time averaging interval $\langle \ldots \rangle_T$ short enough to capture the temporal phase coupling between particular vibration signal components originating from the damaged gearbox meshing. The local time averaging interval $\langle \ldots \rangle_T$ length has been shortened down to the meshing period T_m, thanks to which localisation of the gear faults is possible[9]. The locally-averaged WB is given by:

$$b_{W,T}(f_1,f_2,t)=\frac{E\left\{\left\langle W_\psi(f_1,t)W_\psi(f_2,t)W_\psi^*(f,t)\right\rangle_T\right\}}{\sqrt{E\left\{\left\langle \left|W_\psi(f_1,t)W_\psi(f_2,t)\right|^2\right\rangle_T\right\}E\left\{\left\langle \left|W_\psi^*(f,t)\right|^2\right\rangle_T\right\}}} \quad \ldots (1)$$

where the frequencies f_1, f_2 and f fulfil the condition $f_1 + f_2 = f$, $\langle \ldots \rangle_T$ is the local time averaging operator, E is the ensemble averaging operator and W_ψ is the continuous wavelet transform of signal $x(t)$ given by:

$$W_\psi(a,t)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}x(t')\psi^*\left(\frac{t'-t}{a}\right)dt' \quad \ldots\ldots (2)$$

where a and t are scale and time shift variables, * is the operator of complex conjugation and ψ denotes the complex Morlet wavelet expressed with:

$$\psi(t')=\frac{1}{\sqrt{\pi f_b}}\left(e^{-i2\pi f_c t'}-e^{-f_b(\pi f_c)^2}\right)e^{-t'^2/f_b} \quad \ldots\ldots (3)$$

where f_c is the central frequency of the mother wavelet and f_b is the bandwidth parameter characterising the half-power bandwidth in the frequency domain, defining the balance between the time and frequency resolution of the wavelet transform. The equivalent of f_b in the time domain is t_B[10]. The product $t_B f_c$ corresponds to the

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number of oscillations of the Morlet wavelet within its half-power time-width.

To achieve optimal effectiveness of the detection of transients caused by a tooth fault, the width of the wavelet should match the length of these transients. Therefore, the $t_B f_c$ product defining the length of the wavelet should be set for every scale $a = f_c / f$ (f is a Morlet wavelet frequency) in the way that the time-width $at_B = t_B f_c / f$ of the analysing wavelet matches the meshing period T_m[8,9,10].

As the WB is dependent on two frequencies and time, it is difficult to visualise its results[11,12]. Therefore, the integrated WB (IWBC) modulus has been proposed as the WB feature given by:

$$I_{b_W}(t) = \frac{1}{B_1 B_2} \int_B \int_B \left| b_W(f_1, f_2, t) \right| df_1 df_2 \quad (4)$$

2.2 Test-rig and experimental set-up

Vibration measurements have been carried out on a 91.5 mm back-to-back test-rig at the Design Unit – Gear Research Centre of the University of Newcastle. The test-rig consisted of two identical gearboxes, A and B, featuring the same canter distance and ratio (16 teeth pinion, 24 teeth wheel). Gearboxes were connected with torsionally-compliant shafts. A servo-hydraulic torque actuator interposed between the gearboxes allowed for precise control and adjustment of the loading torque while running.

Gearbox A was the one on which the vibration signal was recorded in the axial direction together with a tacho signal. All signals were recorded with a 40 kHz sampling rate and anti-aliasing filters were applied. Because of the amplitude-frequency characteristics of the accelerometer, an active low-pass filter cut-off frequency was set to 13.5 kHz.

During the test, gears performed over 50 million cycles, *ie* shaft revolutions at a loading torque of 500 ±5 Nm with a pinion speed of 3000 r/min. After each 10 million cycles, the experiment was stopped and the gears were examined, so the progress of the developing micro-pitting could be evaluated. After each break in the test the gears were reinstalled in the test-rig in exactly the same position so the development of damage on every gear tooth could be tracked. Figure 2 shows the estimation of the micro-pitting progress on the selected pinion teeth that had worn out the most during the experiment.

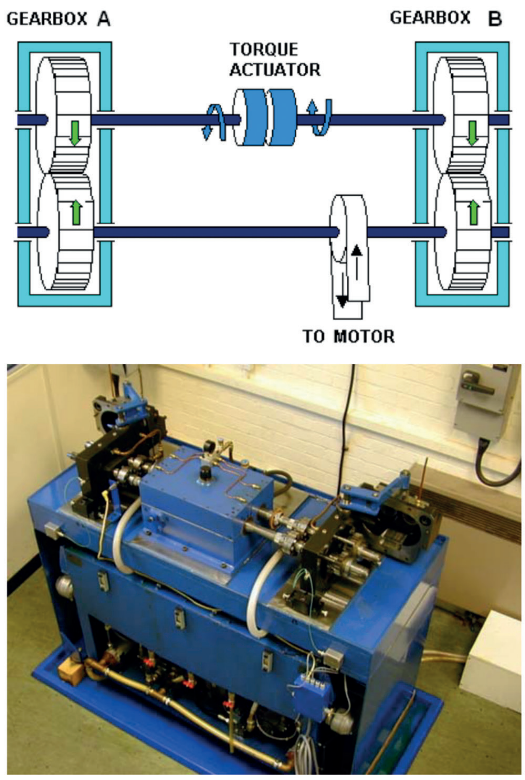

Figure 1. Schematic and picture of the gearbox test-rig

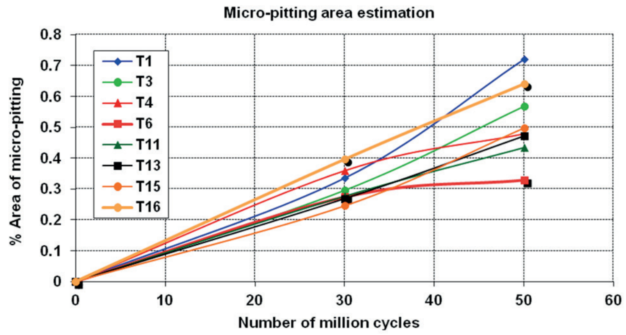

Figure 2. Estimation of progressing micro-pitting on selected teeth of a pinion (T1 – tooth one (...) T16 – tooth 16)

2.3 Estimation of the diagnostic WB feature

2.3.1 Angular signal resampling

As the progress of micro-pitting on the pinion was the object of investigation, the vibration signal captured on a gearbox has been subjected to time synchronous averaging (TSA), extracting from the signal all frequencies related to the pinion. Therefore, the period of TSA was the period of one pinion revolution. Due to slight fluctuation of the pinion rotational speed, while estimating the TSA signal sections corresponding to the pinion, one full 360° revolution has been upsampled to an equal number of samples and then averaged.

2.3.2 Classical residual signal

The gear faults create low-energy impacts that hardly affect the levels of mesh harmonics and they are therefore not clearly visible in the TSA signal. Common practice is to subtract mesh harmonics from the TSA signal and in that way reduce it to a classical residual signal, which is subjected to further signal processing. Classical residual signal $r(t)$ has been obtained by subtracting the averaged tooth meshing vibration signal from the TSA signal in accordance with:

$$r(t) = m(t) - \frac{1}{N_t} \sum_{k=0}^{N_t - 1} m(t - kT_m) \quad (5)$$

where $m(t)$ is a TSA signal, T_m is the mesh period and N_t is the number of teeth[13].

2.3.3 Wavelet transform calculation

WB calculation requires a choice of an optimal wavelet transform parameter f_c, the central frequency of the mother wavelet, and in this case the right wavelet time-width at_B parameter (Section 2.1). In the case of these research parameters, f_c = 5 rad/s and $at_B \approx T_m$, so 1/16 of the period of pinion rotation has been chosen. Wavelet scalograms obtained with these wavelet transform parameters for the gearbox at the beginning of the experiment and after 40 million and 50 million cycles has been shown below.

2.3.4 Wavelet bicoherence and the wavelet bicoherence feature

To allow precise localisation of the gear fault, the set-up of the local averaging $\langle \ldots \rangle_T$ is a key factor as it defines the time/angle resolution of the WB results. In this research, the local averaging was carried

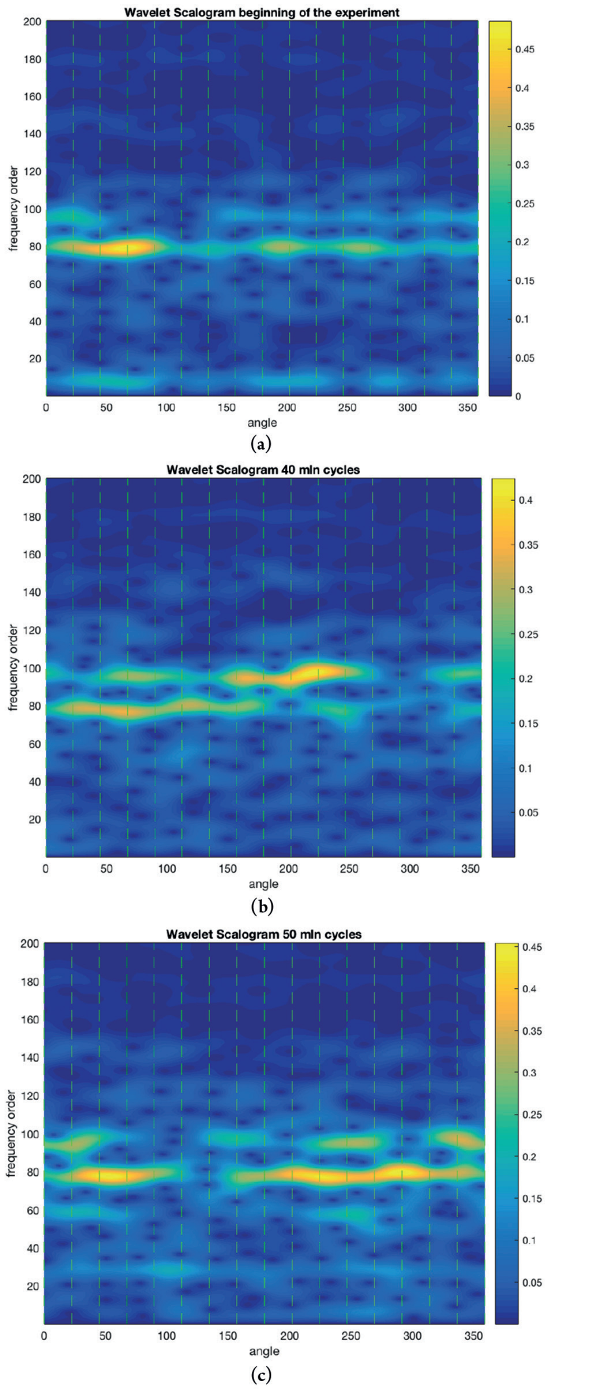

Figure 3. Wavelet scalograms recorded at: (a) the beginning of the experiment; (b) after 40 million cycles; (c) after 50 million cycles

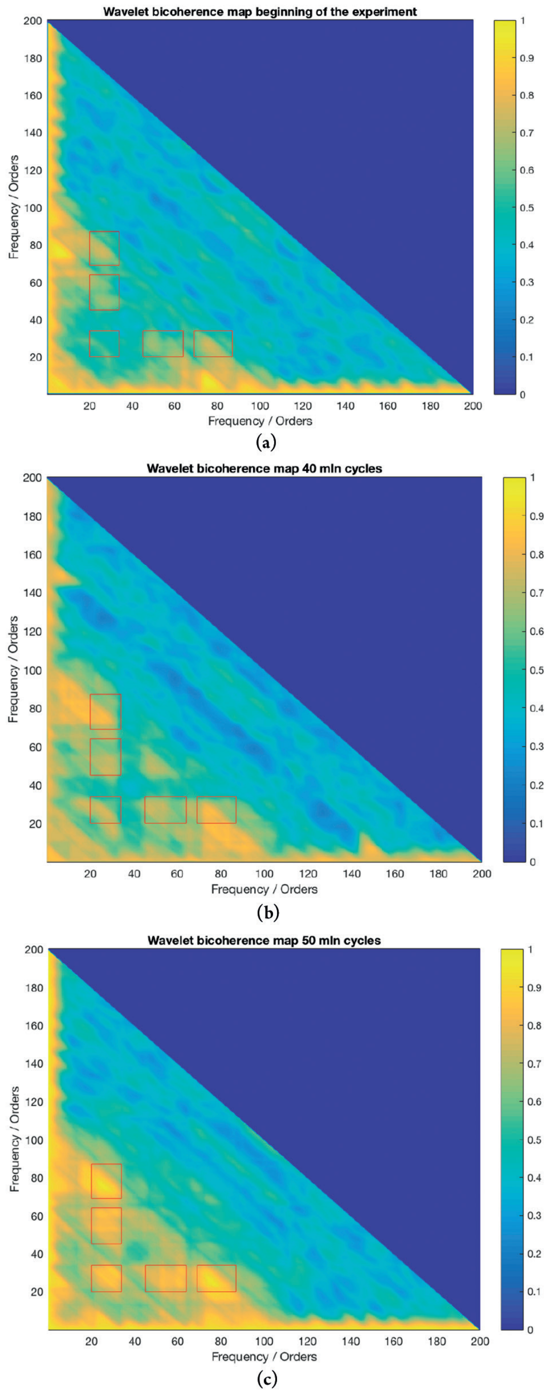

Figure 4. WB maps showing the frequency bands reacting the most to gearbox fault development: (a) at the beginning of the experiment; (b) after 40 million cycles; (c) after 50 million cycles

out using five consecutive samples, which determined the angle resolution of 1.76°. Figure 4 shows the WB maps estimated for the gearbox at the beginning of the experiment and after 40 million and 50 million cycles. The red squares mark the frequency ranges chosen for integrated WB modulus calculation in order to obtain the integrated WB (IWBC) feature.

Evaluation of the WB maps allows for selection of the relevant frequency bands, but it does not allow for fault localisation as they present the modulus of the complex WB integrated over time. The integrated WB (IWBC) modulus calculated for selected frequency bands indicates the exact gear angular position of the pinion at which phase-coupled signal components appear. Figure 5 shows the values of the integrated WB feature for 30 consecutive WB realisations, performed on a signal recorded at different stages of gearbox wear-out.

2.3.5 Fisher criterion

In order to verify the diagnostic capabilities of the WB technology and the sensitivity of the WB feature to the changes in the vibration signal generated by the degrading gearbox, the Fisher criterion (FC) was used. The FC was calculated using values of the integrated WB (IWBC) feature obtained from the vibration signal recorded at the beginning of the experiment (no defect) and the vibration signal recorded after 40 million and 50 million cycles (with defect). The FC estimation has been carried out for every angular position of the

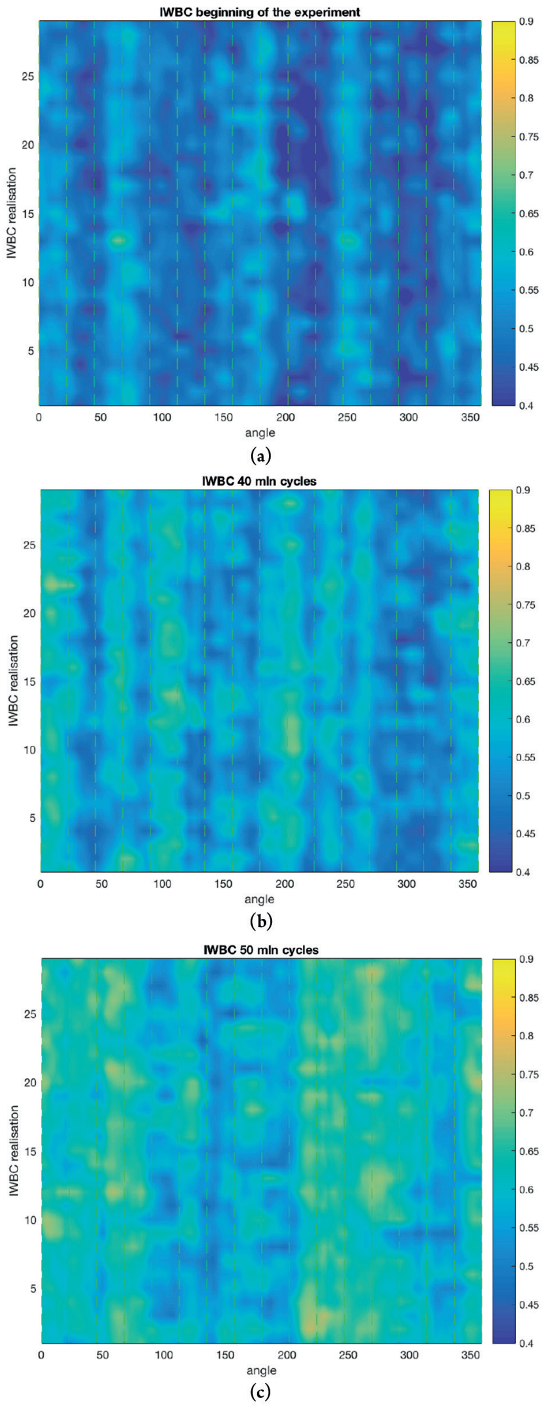

Figure 5. 30 consecutive realisations of the WB feature (IWBC) for the gearbox at: (a) the beginning of the experiment; (b) after 40 million cycles; (c) after 50 million cycles. Vertical lines mark the approximate angular position of the pinion teeth

shaft by using the following formula:

$$FC(\theta)=\frac{\left(\mu_D(\theta)-\mu_{ND}(\theta)\right)^2}{\sigma_D^2(\theta)+\sigma_{ND}^2(\theta)} \quad (6)$$

where μ and σ are, respectively, the mean value and the standard deviation of the integrated WB feature calculated for each angle θ over all WB realisations. Subscripts D and ND denote defect (after 40 million cycles or 50 million cycles) and no-defect gearbox conditions. Increased values of the Fisher criterion indicate the angular positions of the teeth that generated the signal consisting of

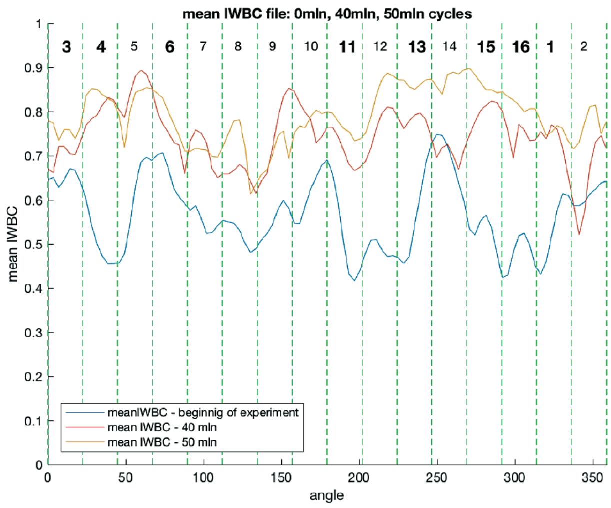

Figure 6. Averaged 30 consecutive realisations of the WB feature for the gearbox at the beginning of the experiment and after 40 million and 50 million cycles

frequency components between which the phase coupling detected by WB has changed the most during the research.

The results obtained by the WB technology for signals recorded at the beginning of the experiment (no pitting), after 40 million cycles (0.3%-0.5% relative pitting) and after 50 million cycles (0.3%-0.7% relative pitting) allowed for the detection and localisation of damaged teeth. Figure 7 shows the values of the Fisher criterion after 40 million and after 50 million cycles obtained for damaged teeth 1, 15 and 16.

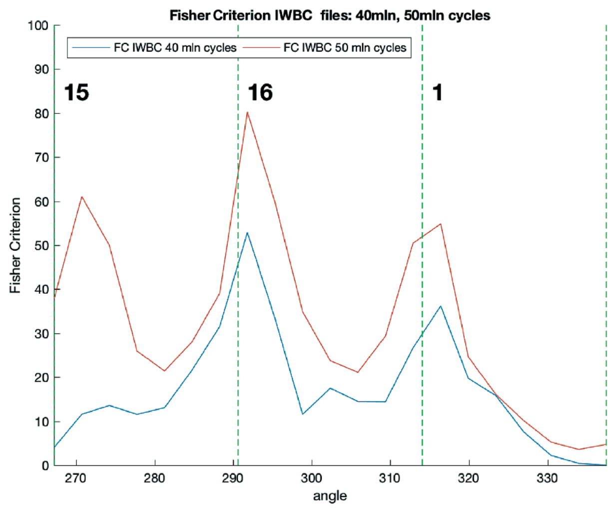

Figure 7. FC calculated for gearbox after 40 million and 50 million cycles. Vertical lines and numbers mark the approximate position of particular teeth. The numbers in squares indicate the teeth in which the pitting was measured (Figure 2)

3. Conclusions

Wavelet bicoherence technology has already been applied to rolling element bearing and gearbox condition monitoring[8,11,12]. Nevertheless, in these cases, the vibration signals were generated by no-defect and damaged objects (gears/bearings) in which faults had been artificially implemented.

This paper presents the results of research in which the WB technology has been used to diagnose initial micro-pitting that has developed naturally during the gearbox endurance test. The results obtained confirmed the diagnostic capabilities of the WB technology for the early detection of natural gearbox damage and the characterisation of damage propagation.

4. References

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