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GEARBOX CONDITION MONITORING UNDER VARIABLE OPERATIONAL CONDITIONS

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ABSTRACT

The gearbox vibration spectrum is complicated and overloaded with artefacts, making it difficult for the eye to register a change due to a fault. In order to overcome this difficulty, this paper presents a gearbox condition indicator, which can be trended. The gearbox condition indicator is based on the summation of the sideband levels around the first three harmonics of the gear mesh frequency. The sensitivity of the proposed gearbox condition indicator to damage is investigated using seeded improper backlash under a range of operational conditions.

KEYWORDS : *backlash, condition indicator, variable load, variable speed, frequency analysis*

INTRODUCTION

The signal processing techniques used in the analysis of gear vibration under variable operating conditions can be grouped into four categories:

- Statistical modelling and analysis – Autoregressive Modelling [1, 2, 3, 4] and other statistical approaches [5, 6, 7, 8, 9],
- Signal separation methods - Deterministic/Random signal separation methods – Order tracking and Time Synchronous Averaging [10, 11, 12] to deal with fluctuating speed and decomposition methods – Empirical Mode Decomposition [13] and Local Mean Decomposition [14],
- Time-frequency analysis – Wavelets [15, 16] and Instantaneous Power Spectrum [17],
- Fourier analysis [18, 19].

- **Statistical modelling and analysis:**

The authors suggest a time-varying autoregressive–moving-average (ARMA) model in [1, 2] in order to detect the developing deterioration of gears under variable speed and load. The parameters of the model were chosen by using the Satterthwaite t-test [1]. Additionally in [2] the Kolmogorov-Smirnov goodness-of-fit test was applied in order to detect faulty gear conditions. In [3] the gear motion residual signal is incorporated within a time-varying autoregressive model applying a noise-adaptive Kalman filter. Further, the percentage of the outliers which exceed three standard deviations is used as a measure to assess the state of the gears. The authors develop the adaptive time series model based on Bayesian model selection in [4] to filter out the components which represent only the variability of the operational conditions and obtain a residual signal which will only change if a fault is progressing.

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McBain and Timusk [5] suggest a statistical parameterisation method to account for the effects of variability in the rotational speed. The vibration signal is divided into several segments with constant operating conditions. The mean and the covariance matrix for each speed bin are established in order to enable better discrimination between healthy and damaged gear states. In [6], a statistical model of loading is presented, which is subsequently used as a corrective factor for calculating crack propagation speed. In [7], the authors suggest a statistical model of dependences of the vibration on load, speed and fault. Based on statistical significance analysis, the most sensitive to fault variables are selected. The significance level of the modelled fault parameter is monitored as an indicator of a developing fault.

In [8], Bartelmus and Zimroz investigated the factors which influence the vibrations generated by a planetary gearbox. Based on that research the same authors suggest a new feature for condition monitoring of planetary gearboxes in [9], taking advantage of the fact that a gearbox in bad condition is more likely to be influenced by load variation. The dependency between the diagnostic feature and the instantaneous speed is modelled through a regression equation. The authors demonstrate that the slope of the line is different in the case of a healthy gearbox and in the case of a damaged gearbox, and therefore it can be used as a single damage indicator.

- **Signal separation methods:**

The conventional vibration analysis tools of deterministic/random signal separation like order tracking and time synchronous averaging [10] have been successfully applied for variable speed operational conditions. Randall [11] points out that the mechanical transmission path distorts both the amplitude and phase, which is additionally complicated by the variability in time. This phenomenon reduces the effectiveness of the traditional tachometer-based order tracking, compromising the results of a discrete-random separation performed by synchronous averaging. Several methods are suggested in [10] including the new approach presented in [12 for resolving the influence that the transmission path phase has on synchronous averaging.

Two decomposition methods are applied in [13, 14], including Empirical Mode Decomposition (EMD) and Local Mean Decomposition (LMD) respectively. In [13], the authors suggest instantaneous dimensionless frequency normalisation which is the ratio between the instantaneous frequencies of Intrinsic Mode Functions (IMF), which were obtained by EMD using Huang Hilbert transform (HHT) and shaft rotating speed. The authors demonstrate its applicability for worn and broken tooth and gear unbalance. Another representative of the group of signal decomposition methods is LMD [14]. LMD was applied in order to obtain the instantaneous time frequency spectrum, which was used to derive the marginal spectrum. The authors suggested a new parameter called energy dispersion ratio, which is the ratio between the energy in the frequency band of interest and the total energy, for evaluating the state of the gears.

- **Time-frequency analysis:**

In [15] a fault growth parameter based on the amplitude of complex Morlet continuous wavelet transform is suggested. The residual signal is adopted as as source data, as it is less sensitive to variations in operational conditions. The authors in [16] use wavelet transform coefficients to calculate the envelope probability distribution function. The Rényi entropy and Jensen–Rényi divergence of the envelope Probability Distribution Function (PDF) are used as a load and speed fluctuation invariant indicator for fault detection in gears. The technique is based on the fact that envelope PDF shape depends on the number of sinusoidal components from which the vibration signal is comprised. In [17] the authors suggest using another time-frequency distribution called instantaneous power spectrum which they demonstrate to be applicable to detection of local faults under variable load conditions.

- **Fourier analysis:**

Although the frequency domain methods have limited applicability for nonlinear systems and for non-stationary signals, Barszcz and Randall demonstrates in [18] that spectral kurtosis is applicable for detecting a tooth crack. The authors also show that in this case the Time Synchronous Averaging failed to detect the onset of gear health deterioration. Other examples are the Sideband Algorithm suggested in [19], including Amplitude of Sidebands of Vibration Response [20], Amplitude of Sidebands [20], which are based on extracting features indicative for developing a fault from the spectrum and adding them together. All of the indicators are variations of Sideband level factor and Sideband index suggested by Stewart et al. in [21].

Several condition indicators based on statistical modelling and analysis, signal separation methods and time-frequency analysis are suggested, e.g. fault growth parameter [1, 9] and energy dispersion ratio [17]. Nevertheless the demonstrated successful detection of faults using those parameters, frequency domain analysis is still the most widely used signal processing technique in industry.

A new Gearbox Condition Indicator, based on features extracted from the spectrum is suggested in the present paper. The indicator is a summation of ten sideband levels around the first three harmonics of Gear Mesh Frequency (GMF) as most of the gearbox faults are manifested within them [23]. The GMF and its harmonics are not reliable indicators of a developing fault as it is stated in [23]. The aim of the present paper is to investigate the sensitivity of the Gearbox Condition Indicator to damage under variable operational conditions which extend over a wide range of operational conditions.

1 Gearbox Condition Indicator

Gear faults can be divided into two groups: local faults such as tooth cracks and spalls and distributed faults such as shaft unbalance, gear misalignment and gear eccentricity [22]. Generally, distributed faults will generate sidebands and harmonics that have high level amplitudes close to GMF. On the other hand, the local faults will produce a flat sideband spectrum with low level amplitudes. Nevertheless there are differences in the vibration signatures within the frequency domain produced by the local and distributed faults; most of these types of faults manifest themselves in increased levels of the sideband amplitudes. Apart from the increase in the sideband amplitude levels, some faults can also increase the amplitude of GMF and its harmonics [23]. Based on these characteristic features, several organisations have developed condition indicators - Sideband Power Factor, Amplitude of Sidebands, Amplitudes of Gearmesh Frequencies and dimensionless Amplitude of Sidebands.

A gearbox health condition indicator called Sideband Power Factor is suggested in [19]. It is defined as the sum of the Power Spectral Density amplitudes of the second harmonic of gear mesh frequency and its neighbouring 10 sidebands. Amplitude of Sidebands, Amplitudes of Gearmesh Frequencies and dimensionless Amplitude of Sidebands are proposed in [21]. The Amplitude of Sidebands sums all the sidebands levels around all harmonics of GMF. The Amplitudes of Gearmesh Frequencies indicator is a sum of the amplitudes of GMF and its total harmonics in the vibration signal spectrum. The ratio between these represents the dimensionless Amplitude of Sidebands.

The spectrum of a gearbox is complicated and it is difficult to see if any change happens. Therefore a single indicator, which can be trended is needed. Motivated by this necessity, we developed a new indicator, which is based only on the magnitude levels of the sidebands extracted from the frequency spectrum. The Gearbox Condition Indicator (GCI) can be described by the following equation:

$$GCI = \sum_{i}^{5} SB_{1,i} + \sum_{i}^{5} SB_{1,-i} + \sum_{i}^{5} SB_{2,i} + \sum_{i}^{5} SB_{2,-i} + \sum_{i}^{5} SB_{3,i} + \sum_{i}^{5} SB_{3,-i} \cdot \quad (1)$$

where GCI is the gearbox condition indicator, and $SB_{1,-i}$, $SB_{1,i}$, $SB_{2,-i}$, $SB_{2,i}$, $SB_{3,-i}$, $SB_{3,I}$ are the sidebands on the left and right around first, second and third harmonic of the gear mesh frequency respectively. The level of the amplitude of GMF or its harmonics is not included because as mentioned in [23], they are not a reliable indicator for developing fault. Further the GCI was investigated to see if it is sensitive to damage and invariant to variations in operational conditions. An improper backlash was used as a seeded fault for two reasons: firstly, improper backlash is a common fault and secondly backlash introduces nonlinearity into the system.

2 EXPERIMENTAL SETUP

The amount of clearance between mating gear teeth is called backlash [24]. Backlash is essential for preventing the jamming of the teeth and for lubrication purposes, or to accommodate manufacturing errors and tooth deflections [24]. However, excessive or less than appropriate backlash is undesirable, as it introduces looseness into the system, or causes interference between the teeth. This kind of backlash is called improper backlash [23].

The experimental Gear Test Rig, which has the ability to reproduce improper backlash is shown in Figure 1. The Gear Test Rig comprises of an electronic brushless servomotor with nominal torque 5.5 Nm. The motor excites the gear, which in turn interacts with a second driven gear. The servomotor which provides loading is identical to the servomotor that drives the gears.

The gears are spur gears and both have 18 teeth. In order to vary the degree of backlash the driven gear is split into two separate discs so that the teeth of one of the discs may be moved relative to the teeth on the other. An exploded view of this gear is shown in Figure 2a. The movable disc may be rotated on the boss of the disc which is locked to the shaft. The movable disc may then be clamped to the locked disc using four bolts.

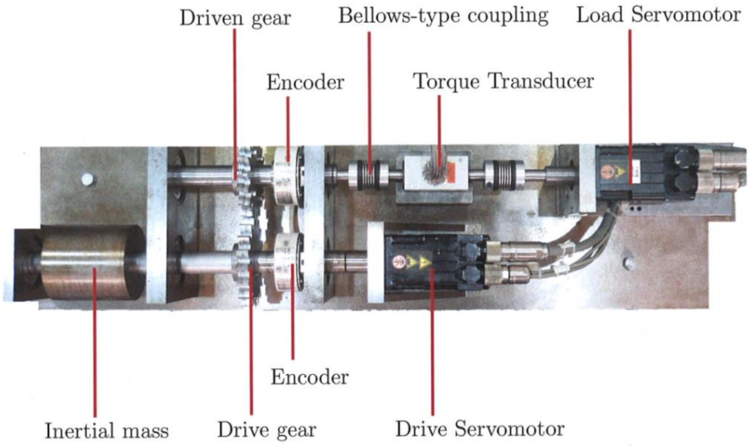


Figure 1: Gear Test Rig

By varying the effective tooth width of the driven gear, the degree of improper backlash may be varied. The fully assembled variable backlash gear is shown in Figure 2b. Through control of the drive and load servomotors, various speeds and torques can be applied.

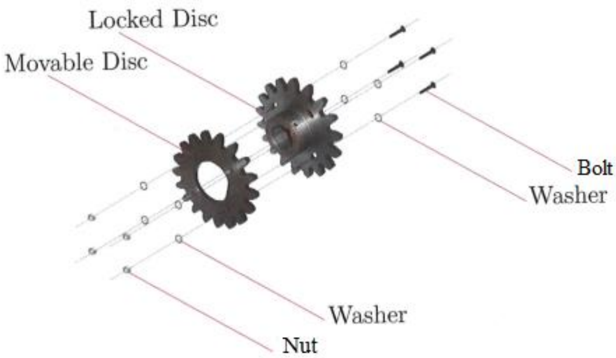


Figure 2a: An exploded view of the gear Figure 2b: The assembled variable backlash gear

3 DATA ACQUISITION

The Gear Test Rig (Figure 3) was instrumented with seven high performance compact 100mV/g shear mode accelerometers model BI-5113A with 80g peak dynamic range. Initially, 9 possible positions of the accelerometers were investigated with running gears at constant speed – 4 horizontal, 4 vertical and 1 axial. The redundancy in the channels was analysed based on correlation, and a decision was made to use only 7 accelerometers instead of 9. The speed was measured using Helitune Optical Pick Up P/No. 386020 with sensing speed range between 3 and 50,000 RPM and sensing distance between 20 and 1000 mm. Torque was measured using a HBM T20WN torque transducer, which has a nominal torque of 5 Nm and a resolution of 0.0049 Nm.

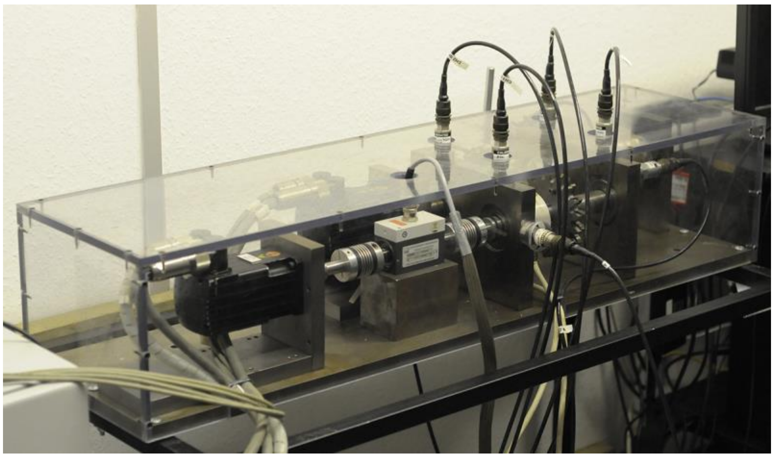


Figure 3: Instrumented Gear Test Rig

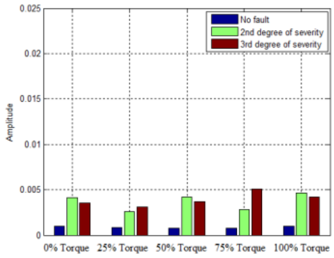
The vibration and speed data was collected and processed using the Beran PlantProtech 720 Advanced Plant Monitor (Figure 4), which has sixteen channels for vibration and process data and four speed inputs. The Beran PlantProtech 720 Advanced Plant Monitor can operate stand-alone, with all data acquisition storage performed internally; thus time domain data was downloaded via the USB port for import into MATLAB™ for further processing.

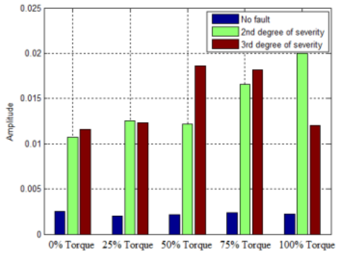
Figure 4: PlantProtech 720 Advanced Plant Monitor

The frequency band which was captured was 1250 Hz with 4000 lines and the sampling frequency was 3200 Hz.

4 DATA ANALYSIS

In order to establish both the sensitivity and robustness of the Gearbox Condition Indicator, 45 tests were conducted over a wide range of speeds and torques, representing a combination of 5 running speeds, 5 torques and 3 degrees of severity of backlash. The speed was adjusted respectively at 1, 2 and 3 Hz. The speed was stabilised at ±3%. The torque was harmonically varying and the average of the torque was set at 0%, 25%, 50%, 75% and 100% of the nominal torque respectively, with the average amplitude being maintained within ±5%. The tests were conducted for 3 degrees of severity of backlash. Between 10 and 15 datasets were taken for each combination of speed, torque and backlash severity. The results are depicted in Figure 5a, 5b, 5c and 6.





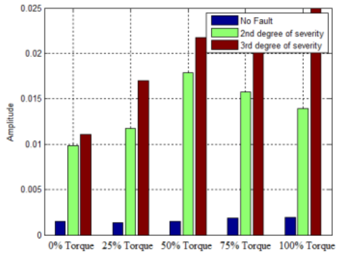


Figure 5a: GCI at speed 1Hz Figure 5b: GCI at speed 2Hz Figure 5c: GCI at speed 3Hz

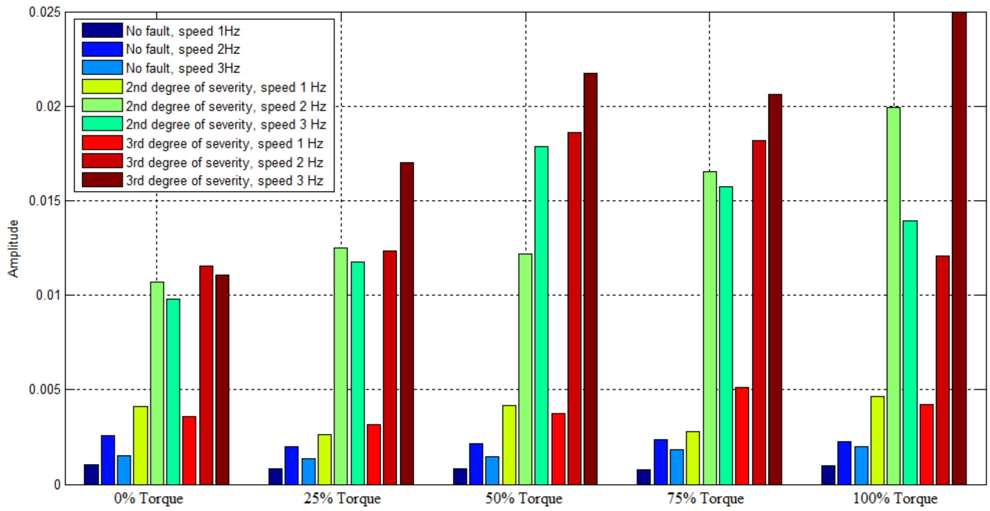


Figure 6: Gearbox Condition Indicator for various speeds and loads

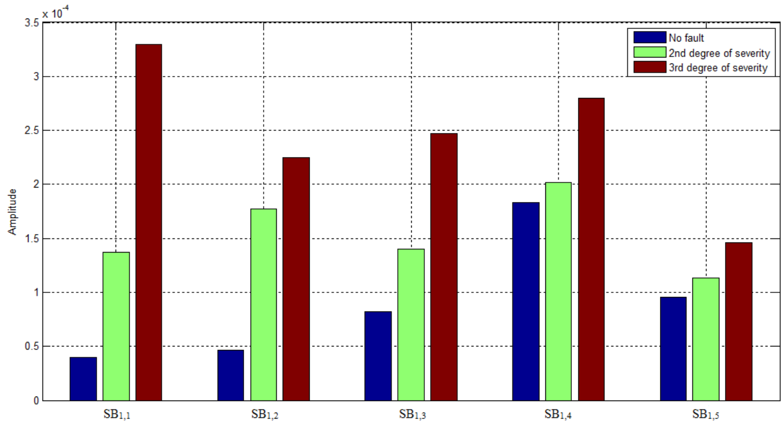


Figure 7: Sidebands levels around GMF

As is seen in Figure 6 the GCI is able to discriminate between proper and improper backlash. The first five sidebands around the first three harmonics were included in the GCI unlike the condition indicator suggested in [19]. Looking at the sidebands levels for this particular gear we found that the sidebands around other than second harmonics of GMF are sensitive to damage too as can be seen from Figure 7 where the sidebands on the right hand side of the GMF are exemplified. Only the sidebands around the first three harmonics of GMF are chosen as most of the faults manifest themselves through excitation of the sidebands around those particular harmonics of GMF [23]. It would be difficult to include sidebands around higher harmonics of GMF as this would mean extending the bandwidth and loosing resolution. However, further investigation is needed in order to establish whether there are spectral features sensitive only to damage and invariant with respect to the operational conditions. As the data is two-dimensional, a method suitable to summarise this kind of data would be needed.

It can also be seen from Figure 6 that the GCI is unable to discriminate between the 2nd degree and 3rd degree severity of improper backlash, and is sensitive to both variations in speed and in load. Further investigation is required in order to determine whether the GCI can be modified to reduce sensitivity to variations in speed and/or load. One possible solution is blind source extraction in order to filter out the influence of the operational conditions. Further investigation is also required to determine whether the GCI can be modified to enable discrimination between backlash severities so that fault progression may be monitored.

CONCLUSION

In this paper a Gearbox Condition Indicator was investigated in order to determine its sensitivity to backlash under variable operational conditions. It was demonstrated that the Gearbox Condition Indicator is able to discriminate between proper and improper backlash conditions. However, it cannot be used to follow the progression of the fault and is sensitive to variations in operational conditions. Further investigation is required in order to improve the ability of the GCI to follow fault progression and reduce sensitivity to operational conditions.

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