Diagnostic approaches for epicyclic gearboxes condition monitoring

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Abstract

Since epicyclic gearboxes are broadly employed in mining and wind turbine industry, they are frequently subjected to highly non-stationary operation conditions, with harsh changes of load and input speed. Therefore, epicyclic gearbox diagnostic methods should cover for at least three requirements: - Ability to work under rapidly changing speed and loading conditions, - Ability to work in conditions of low angular speed, - Ability to encompass and identify any faulty component of a gearbox. The most commonly used approach to epicyclic gearbox monitoring is based on acquisition of vibration signatures, due to low equipment cost and typically straightforward data acquisition procedures. Unfortunately, most of vibration signal processing and interpretation algorithms do not fulfill requirements enumerated above. This paper identifies and explains some challenges related to monitoring of epicyclic gear trains and provides concepts and solutions that are used to solve them. Capabilities and limitations of popular methods are addressed. Selected damage detection and identification methods including novelty detection approach and 2D representations of vibration signals are illustrated on the basis of data acquired on industrial gearboxes mounted on wind turbines.

Keywords: Condition monitoring, Vibration analysis, Vibration diagnostics, Epicyclic gearbox, Signal processing, Variable operational conditions

1. INTRODUCTION

Epicyclic gearboxes (EGs) are widely used in industry, because of good value-to-weight ratio, concentricity of shafts and multiple configurations of the input and output. Failure of such gearbox is expensive not only because of gearbox cost itself, but also because of production loss and difficult replacement procedures. Due to area of implementation, EGs usually work under variable speed and loading conditions, which makes diagnostic procedures especially challenging.

This paper presents organization of diagnostic algorithms used in diagnostic of epicyclic gearboxes with respect to required data and signal processing approaches. Strengths and limitations of particular solutions are presented. Experimental outcomes of selected algorithms are provided within the paper using data acquired on industrial gearboxes.

The organization of this paper is as follows: diagnostic pathways with respect to required data are presented in section 2, section 3 introduces challenges related to epicyclic gearbox
monitoring and provides limitations of existing signal-processing methods; section 4 presents selected results of industrial gearbox monitoring with use of novelty detection and ICPCP map approaches. Finally, section 5 summarizes and concludes the paper.

2. DIAGNOSTIC PATHWAYS

A number of approaches for technical state of the rotary machinery assessment in general and epicyclic gearboxes in particular exist. These solutions can be divided with respect to required data, complexity of diagnostic system, as well as with respect to phenomena that arise as indications of particular damages, which can be extracted by specialized signal processing algorithms. The former classification is dealt with in this section. The latter is briefly commented on in section 3.

2.1. Norm-based diagnostics

The simplest of approaches require usage of one diagnostic feature calculated from vibration signal and then comparison of its value with proper norm. This diagnostic path is depicted in fig. 1. Its main advantage lies in lack of required data other than signals registered for the purpose of state assessment, which renders this method to be of use even if no a-priori knowledge of given machine is available. Its main disadvantage, on the other hand, is its low sensitivity to damage. Although the latest ISO 10816-21 gives values for both, the permissible velocity and acceleration, it still recommends frequency-domain ranges for monitoring, namely 0,1-10 Hz and 10-2000 Hz.

Figure 1: Norm-based diagnostic pathway.

As proven by numerous case studies, such fault detection is reliable only at severe level of damage, while the industrial interest is at early fault detection, for which precise identification of EG components on resampled signal is expected.

2.2. Trend analysis and threshold-based diagnostics

This most commonly used diagnostic method requires observation of machine’s state over extended period of time. Then, particular features, including wideband, narrowband, and combined rational estimators calculated from vibration signal are plotted against time thus allowing analyses of their trends. The path is depicted in fig. 2.
Historically, such trends include wideband estimators (PP, RMS, VRMS, crest, kurtosis) and narrowband estimators (GMF, Planet Pass Frequency, REB characteristic frequencies). In recent years, some combinations of features based either on pulse response counters or sideband energy ratio have been introduced as well.

2.3. Novelty detection

Multiple diagnostic features have been regarded as metrics sensitive to damage in rotary machinery. When analysed one-by-one they usually serve in trend analysis (See sec. 2.2). However, there is also an approach, recognized under the name of novelty detection that allows detection of damage by assessment of feature distribution in multidimensional feature space [1,2]. In this case set of features calculated from vibration signal in given measurement is treated as point in this space. Then, based on signals acquired in initial stage of monitoring, a normal range of features can be calculated. If new measurements exceed this range, they are treated as premises of damage. The main disadvantage of the method lies in necessity to track large number of parameters from the beginning of device’s operation. The scheme of diagnostic path is depicted in fig. 3.

2.4. Supervised data classification

Since the novelty detection algorithms return only information whether the measurement is similar to previously acquired data, damage identification has to be performed using different approach. This is possible using supervised data classifiers which are trained on so called database of events that include data gathered for different states of similar machines [3, 4]. After such training, classifiers are able to detect and identify particular damage. The main drawback of this approach lies in required training data – which should cover all possible damage scenarios. Such database is costly and at times impossible to acquire thus
significantly limiting usage of this method. Signal flow in this approach is depicted in fig. 4.

**Figure 4: Supervised classifier for identification of faults in gearboxes**

### 3. LIMITATIONS OF EXISTING SIGNAL PROCESSING METHODS

According to majority of researchers that published papers on vibrodiagnostics, signal processing methods can be divided into several major categories, including time, frequency, time-frequency and others [5, 6, 7, 8]. Existing methods’ organization is depicted in fig. 5. However, way of operation of epicyclic gearboxes renders application of these methods to be challenging. Rapid changed of speed and load that are inherent for e.g. wind-turbine or mining gearboxes cause fourier-based spectra to be blurred. Shortening of the time window to cover for speed changes reduces resolution of the result. These problems can be compensated by resampling algorithms but only for precise speed reference and slow changes of angular speed. Time-domain methods are also of limited use because loading changes affect time-domain-based signal statistics and significantly influence time-synchronous-averaging of acquired signals. This latter method is also affected by instantaneous configuration of gearbox, which is hard to track. More advanced methods were proposed but, according to several authors [6, 8] were either not sufficiently tested, based on too many assumptions or devoted to monitoring of specific components only.

**Figure 5: Domains of operation of existing vibration-based diagnostic methods**
Several of methods are, however, regarded as potentially effective. These include application of spectral kurtosis (e.g. [9]), load susceptibility (e.g. [10]), novelty-detection-based approaches (e.g. [11]) or analyses of 2D signal representations other than time-frequency map (e.g. [12]). Selected results of the two latter methods are given in next section.

4. POSSIBLE SOLUTIONS TO THE PROBLEM

4.1. ICPCP map

ICPCP (from instantaneous circular pitch cyclic power) is based on the calculation of instantaneous energy of a vibration signal for consecutive circular pitches, and it aims in detection of abnormal phenomena of some meshes comparing to remaining ones. The method requires one pulse per one shaft revolution as a reference speed signal, which is used for resampling process. The resampling process is similar in assuring divisibility of larger signal fragments by selected number of teeth. In this way, the length of final fragments corresponds to time between circular pitches of successive teeth pairs.

As illustrated in fig. 6, the resampled signal is divided into fragments corresponding to consecutive n carrier revolutions. The K number of samples corresponding to a single carrier revolution is calculated directly as the total number of samples M in the entire resampled signal divided by the number of carrier revolutions n. In the next step, each signal fragment of length K is divided into fragments corresponding to consecutive ring gear teeth. The length L of each new fragment is calculated analogously as the K number of samples per a single carrier revolution divided by the number of teeth on the ring gear Zr. The calculated signal fragments are arranged in a matrix form, where each cell contains a signal’s fragment corresponding (in the angle domain) to a single circular pitch of a ring gear in a particular carrier revolution. For every cell containing a single smallest calculated fragment, signal energy is calculated as a sum of values, e.g. RMS. Generally, the ICPCP is unique in a sense that it enables visualization of multi-stage modulation processes, which are characteristic for
planetary gearboxes experiencing planets’ faults, and which are imperceptible otherwise. Worth mentioning, the method is at early stage of development, and requires many tests to provide reliable conclusions from the map.

For the purpose of method's illustration authors used vibration signal acquired on three stage wind-turbine gearbox composed of a planetary gearbox and two parallel gearboxes of total ratio 1:103.898. Planetary gearbox contained three planets. Vibration signal was acquired on the main bearing of the planetary gearbox stage, whereas speed sensor was located on the output shaft of the gearbox. Speed signal was used for resampling of the time domain signal to the angle domain signal. The scheme of EG used for data acquisition is depicted in fig. 7.

![Fig 7 - A scheme of the epicyclic stage of the gearbox used for data acquisition](image)

Acquired signal was sampled at 25kHz, total acquisition time was 120s, which in total gave 3 000 000 samples. During the acquisition time transient phenomena were of special interest. That is why at first machine was run up from zero to maximal speed, followed by run down from maximal speed to zero. Varying speed and huge ratio (1:103.898) were the reasons why only 32 revolutions of input shaft were caught. This signal was used to calculate ICPCP map, which is depicted in fig. 8.

Instantaneous cyclic power for each tooth at given revolution can be seen here. Amplitude modulation phenomena could be observed for particular groups of teeth, i.e. modulations could be observed in vicinities of teeth 20, 55, and 90.
4.2. Novelty detection approach

Acquisition of vibration signals for a gearbox in intact state is a relatively easy task. Such data can be used to calculate several features and then preserve their distribution for the purpose of new data assessment. For the purpose of method's illustration authors have performed a simple experiment aimed at detection of imbalance in rotary machinery. Procedure described in sec. 2.3. was used to evaluate the state of the test rig depicted in fig. 9.
The test signals were collected from a test rig equipped with a 0.75 kW motor and 0.75 kW braking motor that introduced the load to the system, parallel gearbox with ratio 2.91, and two spherical rolling element bearings type YAR204-2F. The data was collected with sampling frequency 25 kHz and VIS-311B accelerometers with 15 kHz range. The motor and the braking unit were controlled by external software synchronized with the data collecting application. During this session, the torque was in range from 0 Nm to 20 Nm, and the speed was up to 300 rpm. Two experiments were performed: for intact and imbalanced state. The imbalance was introduced by attaching a mass to one of disks marked in fig. 9.

Data acquired in the first experiment were randomly divided into training subset that was used to build database of features for novelty detection algorithm and evaluation subset for assessment of false error rate, respectively. Features calculated from data acquired in the second experiment were fed to the trained novelty detector to assess its performance in detection of imbalance.

Authors have used four features: RMS, vRMS, rotations per minute, and peak-to-peak value of signal. These features were used to build classification rules based on nearest-neighbour-approach: for each data point its closest neighbor in training database is found. Euclidean distance to this neighbor is compared with the threshold, which is set as median of euclidean inter-sample distance in training database plus three times its standard deviation. It is derived from an assumption that distribution of data is normal. In that case such threshold would allow for 99.9% efficiency in classification of non-novel data.

Results for both cases are presented in fig. 10. It is seen, that novelty score is below threshold for all samples in testing database. On the other hand, detection threshold is clearly exceeded for most of the samples in novel data. The novel samples for which detection threshold was not exceeded were acquired under low speed conditions. That is consistent with expectations, as imbalance manifest itself in signals only when the speed is sufficiently high: centrifugal force is a square of angular speed.
5. SUMMARY AND CONCLUSIONS

The article identified major challenges related to epicyclic gearboxes monitoring. Two particular solutions to the problem have been proposed: novelty detection and ICPCP map. The former approach distinguishes normal patterns in features calculated from vibration signals from novel ones, which are treated as premises of damage. The latter allows for easy interpretation of complicated vibration signal by resampling it and plotting as a 2D map of energy related to meshing of particular teeth. Both approaches have potential to diagnose damage in practical conditions, however, their efficiency is yet to be tested.

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REFERENCES


