Przegląd i analiza istniejących metod diagnostyki maszyn pracujących w zmiennych warunkach eksploatacyjnych

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Dokument zawiera przegląd uznanych rozwiązań dotyczących problematyki, jak również najnowszych metod opublikowanych w uznanych czasopismach o zasięgu międzynarodowym. W dokumencie zdefiniowano problem zmiennych warunków eksploatacyjnych, przedstawiono metody obróbki wstępnej sygnału oraz analizę istniejących metod przetwarzania skorelowanych sygnałów drgań.

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1 Introduction

Vibration-based condition monitoring is nowadays widely used in many branches of the industry. Rapidly growing field of potential applications of condition monitoring systems results in development of more advanced data processing methods suitable for more complex machinery frequently operating under conditions of significant variability. Examples of such machinery, where a strong current focus is observed are wind turbines, underground machinery mining machinery etc. Either directly or serving as a middleman, these machines become widely used for the electric power generation and they are also frequently considered as an interesting object from condition monitoring perspective [1]-[7].

Within analysis of vibration and acoustic signals from such machinery, most of diagnostics efforts are focused on rolling element bearings (REB) [8]-[14] and gearbox [15]-[21] damage detection. In general, gears and bearings diagnostics is a well-recognized field; however, it is not the case for machines working under non-stationary conditions, especially rapidly and relatively largely changing load. In the case of varying operational conditions, a vibration signal is often relatively difficult to analyse due to influence of speed and load variation within the vibration signal time record [19]. In consequence, during last decade, the concept of mandatory estimation of operational conditions and their influence on raw vibration signals was a subject of number of studies [22]-[25]. From these works it might be concluded that majority of difficulties in vibration-based condition monitoring comes from the variation of diagnostic features caused mostly by load and speed changes, low energy of sought-after features, as well as high noise levels [26]-[39]. Nevertheless, within the analysis of rotating machinery working under such conditions, the fundamental hypothesis is that the non-stationary behaviour of the object reflected in non-stationary data comes from inevitable time-varying conditions, like changing wind or fossil and ore contents [5]-[29]; thus, it needs to be understood as a time-varying excitation of the system rather than defined transient responses described by parametric prediction models.

The aforementioned assumption leads to a novel path of signal processing, which is free from the assumption of constant speed and load leading to more realistic scenarios. For instance, in practice nearly all of bearings experience some speed and load variations, like vehicle bearings, wind turbine bearings or mining excavator bearings. It is currently widely accepted that under variable speed conditions, the repetition frequencies of impulses also vary with time and hence the corresponding envelope signals are non-stationary in nature [38]. Consequently, direct application of methods processing signals in frequency domain leads to spectral smearing effects resulting in final false alarms or alert overlook. It is important to point out that in recent years, the majority of papers describing processing of vibration signals coming from machinery working under non-stationary was oriented towards order tracking, as a mainstream technique for minimizing the smearing effects [38]. In addition, order tracking (also called "resampling") could be combined with time synchronous averaging (TSA) to remove the background noise and non-concerned signal components generated by shaft-related components, e.g. gear meshing frequency and its harmonics [39]. Nevertheless, this approach is burdened with mandatory speed sensor (often very expensive encoders) and limited permissible speed fluctuation.

The main goal of this project is to develop a set of novel diagnostic techniques for diagnostics of rotating machinery operating under non-stationary operational conditions, with the emphasis on data associated with extreme process changes encountered in practice. The project extends previous studies undertaken by the authors, as well as studies of other researchers described in this report and listed in references. The purpose of this research task is to select, among existing methods, ones that could be suitable for further development in order to reach the goal of this project. Therefore, before going through the state-of-the-art in vibration based condition-monitoring techniques, basic principles of the undertaken, previously defined by the authors will be presented in the following subsection [5, 22 -24].

1.1 Formulation of the problem

It has been proven that operational conditions of machinery can be strongly reflected within vibration signals generated during its operation. Based on the previous work of the authors the influence of varying operational conditions to vibration analysis will be presented on the example of wind turbine [5]. Wind turbines are industrial objects of relatively complex kinematics, operating under varying conditions and in rather harsh environment. These factors make vibration analysis comparatively difficult due to the complexity of measured signals and the significant influence of noise.

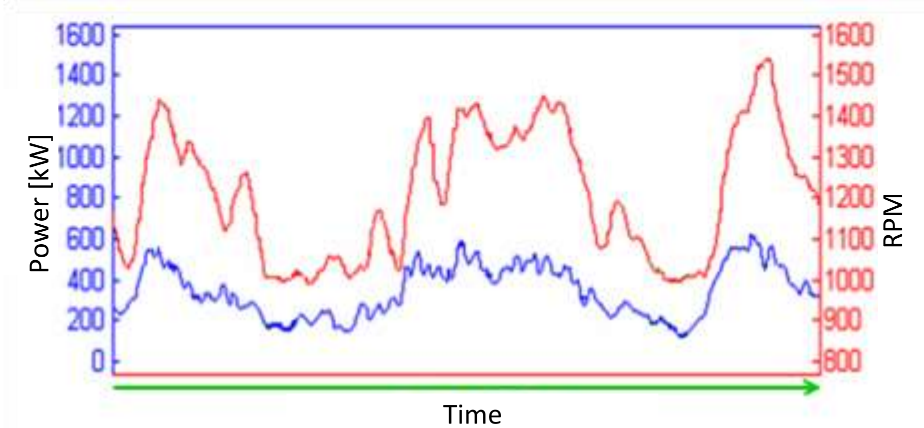

Figure 1. Variation of generator rotational speed and output power during 15 minutes

Quick changes of the operational conditions are an important feature of wind turbines measurements. The example of such changes is presented in the figure 1 during 15 minutes, the generator output power varies between 200 and 600 kW. Such changes have significant influence on vibration signal and can blur the changes caused by a malfunction. Speed fluctuation and variation in the system causes “smearing” of the discrete frequencies (components) in the spectrum, meaning that these frequencies will no longer be seen and detected as discrete lines (sine/cosine signals with power concentrated in one line), but rather as a frequency band around the mean speed, where energy extends across a number of frequency bins. Such effect may cause significant disadvantages in the functionality of vibration-based condition monitoring systems. In particular the signal processing techniques developed to analyze signals at a constant speed in bearings and gears will fail.

At this point, the reader should note that not only the frequency of the component related to rotational frequency will change due to variable operational conditions, but also their energy will depend on the speed. Results of synchronous averaging of selected cycle might be understood as a mean instantaneous energy of the component of interest. Such property may lead to the wrong judgments about the dynamic condition of monitored object due to large dissimilarities in the energy of the cycles.

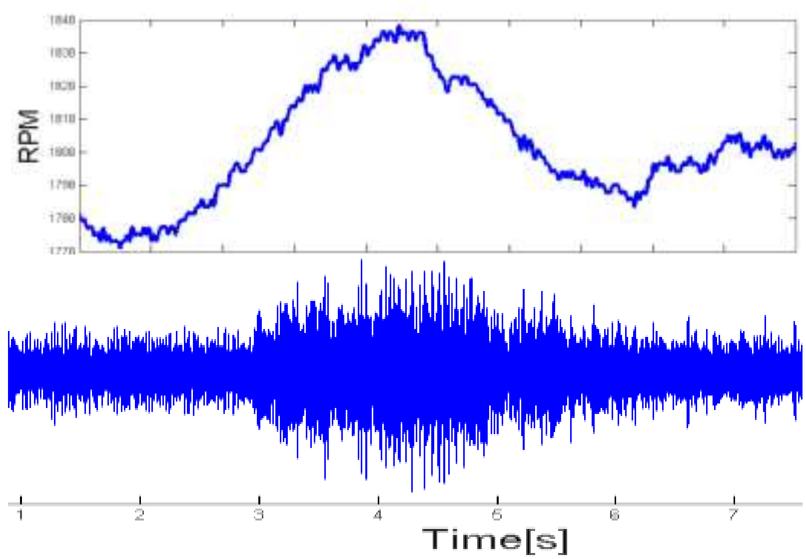

Figure 2. Speed profile of the wind turbine (top) and corresponding vibration signal (bottom).

As shown in figure 2, instantaneous amplitude (or envelope) of measured vibration signal is strongly related to the instantaneous value of rotational speed. Unfortunately, majority of existing and commonly used methods base on averaging and neglect the information contained in instantaneous phase. As it was shown by the previous research of the authors instantaneous values of amplitude changes related to operational conditions can be valuable source of information [48, 51]. More detailed review on existing methods in vibration-based condition monitoring will be presented later in this report.

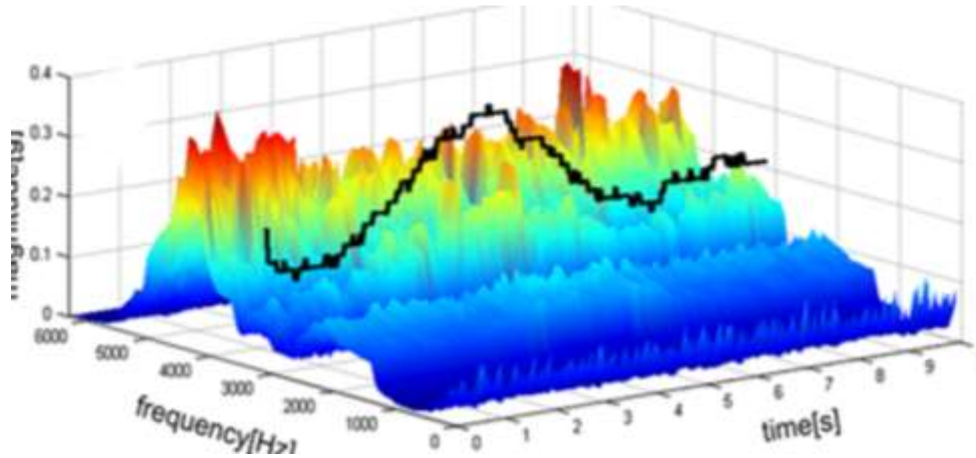

Figure 3. Variation of instantaneous amplitude of bearing fault-related component presented with respect to rotational speed (black profile) on time-frequency scale [51].

As it was shown on the example of a wind turbine, operational conditions of the machinery might change significantly and it can have its influence on measured vibration signals. It has been said that it can affect the results of spectral analysis. However, based on recent work of the authors [48] as well as the other leading research group in this subject [29 - 31] it has been shown that load as well as rotational speed seriously affects vibration-based diagnostic features. Ref. 48 gives brief preliminary results presenting the influence of both; speed and load on vibration-based features, namely: peak-to-peak and RMS. Exemplary results might be seen in the figure 4. Further investigation of this property is one of the subject of following project. Preliminary results illustrating influence of load (or as in the case of wind turbines) generated power and rotational speed (RPM) on vibration-based features are shown in figure 4.

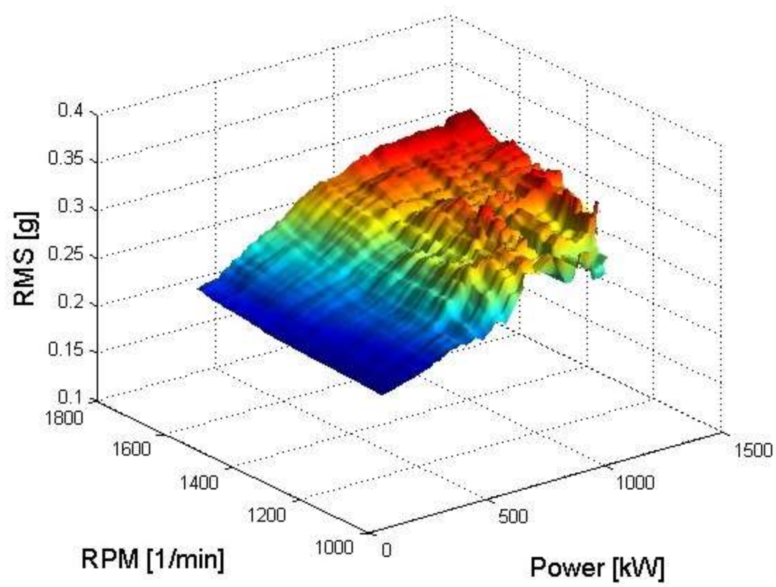

Figure 4. Diagram illustrating RMS of vibration signal as a function of RPM and generated power.

The purpose of presented examples is to highlight the problem of vibration-based condition monitoring of machinery operating under varying regime. As it will be presented later in this report, there are some existing methods adopted to those conditions. However, existing methods either take under consideration only selected factors or can be applied for limited variability of operational conditions. It is the authors opinion that nowadays there is no general approach that could exhaustively describe behavior of vibration signals generated by machinery operating with varying speed and load but with virtually unlimited range of variation.

2 State-of-the Art

Latest literature shows a rapid development of methods for advanced processing of data, which was not available hitherto. These methods include:

- instantaneous power spectrum analysis [5], [23]-[25],

- signal decomposition techniques [42],

- handling high speed variability [29], [43],

- load variability-based deduction [20], [32], [35], [43], [45],

- time-frequency and bi-spectral analysis [6], [45],

- machine element oriented signal processing [46],[47],

- analysis of dependence of signal characteristic features on variability of operational parameters [48], [49], and [50].

Sections 2.1-2.6 describe each approach in details. The studied papers include publications in peer-reviewed journals like *Mechanical Systems and Signal Processing*, *Measurement*, *Renewable Energy*, *Sensors*, *Journal of Sound and Vibration*, *European Journal of Mechanics*, *IEEE Transactions on Signal Processing*, as well as conference papers and engineering white papers.

Section 3 presents set of diagnostic methods dedicated for rotor machinery operating under varying regime developed by the authors of this project. Presented methods will then be used as a starting point for reaching the goal of this research project.

2.1 Instantaneous power spectrum analysis and signal decomposition

First group of reviewed papers deal with the analysis of variable frequency ingredients of vibration signals recorded from machinery under study. In [41], the authors combine instantaneous power spectrum (IPS) and genetic programming for extracting feature frequencies of each machine state for measured vibration signals for distinguishing faults by relative crossing information. Genetic programming can sensitively reflect the characteristics of signals for precise diagnosis. The concept of IPS is further developed by report's co-authors in [5], where the method called averaged instantaneous power spectrum (AIPS) is introduced as a time-frequency representation of selected cyclic components as it provides supplementary information about the character of component of interest via reduction of influence of speed variation and separation of spectral information. Moreover, in [42], the authors propose a local mean decomposition technique as a new iterative approach to demodulate amplitude and frequency modulated signals for obtaining instantaneous frequencies in wind turbine condition monitoring and fault diagnosis.

2.2 High speed variability

Second group of papers deals with handling high speed variability. This phenomena are especially detrimental to signal analysis where signal order tracking is to be performed. For machinery under investigation, such variability is not only characteristic during machine run-ups and run-downs, but is inevitable during nominal operation. Figure 1 illustrates a real machine data, which might not be processed using classical frequency-domain techniques.

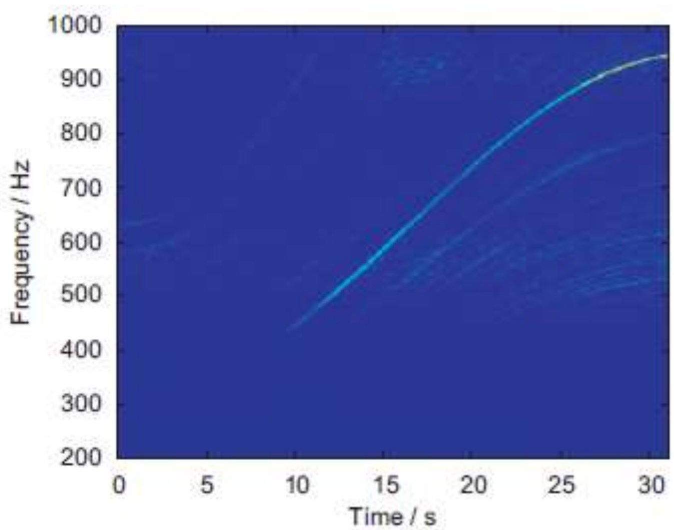

Figure 1. Exemplary real data experiencing extreme speed variation

In [41], the authors present development of angular resampling algorithm for applying in conditions of high speed variability and the results obtained when applied to simulated signals, bearings diagnostic test-beds and wind turbines. As illustrated in the case-study part, the results improve the accuracy of similar resampling offered in the bibliography. In [29], the presented study deals with variable speed by segmentation of vibration response into speed bins with small range of speed. The mean and covariance matrices for the feature vectors in each speed bin are computed in order to derive a statistical novelty boundary for that bin. Each component of these statistical parameters can then be interpolated or regressed in order to derive boundaries for speed segments where no training data is available. A comparison included in the paper shows high degree of separation between data from healthy and faulted states-providing exceptional classification error.

2.3 Load variability-based deduction

The third group of papers field of interest is related to deduction based on analysis of load-variability as a major factor in the process of vibration data analysis and diagnostics. In [43], the authors deal with detection of unbalance and misalignment under wide range of working conditions of speed and load (similar to wind turbines). In the paper, the authors examine variables for their sensibility to failure using developed statistical diagnosis algorithm based on the significance level of the modeled fault. In another approach illustrated in [33], the researchers focus directly on diagnostics of planetary gearboxes under non-stationary operating conditions, pointing out suppressing influence of load characteristics vs. speed variability. Authors claim that energy-based features are sensitive to load conditions, which constitutes a major obstacle in significant machine fault diagnosis. The paper suggests a novel way for condition monitoring of planetary gearboxes based on multivariate statistics. The emphasis is put on the algebraic and geometric interpretations of the Principal Component Analysis (PCA). In the second approach within the same work, the Canonical Discriminant Analysis (CDA) method is proposed for the first time in such context. Throughout the paper, the PCA is used for data reduction; however, the authors neglect the analysis of the geometry after projection. In other works, similar group of co-authors [42] illustrates monitoring of planetary gearboxes of bucket wheel excavators, and finds that identification of the varying external load is crucial to the evaluation of the planetary gearbox conditions.

From the research, it is concluded that a proper consideration of factors influencing the vibration diagnostic signal together with the proper signal analysis methods leads to the proper choice of condition criteria for planetary gearboxes in analyzed machinery.

In the same year, these authors published a formalization of the load dependence characteristics, and named it “load susceptibility characteristics” (LSCh) [30]. The work shows that LSCh of monitored machinery could be approximated by linear regression model, as illustrated in Figure 2. Research results introduced in this paper show that linear regression parameters calculated for subsequent short-time data segments could be presented as long term time series. It is also shown that such parameters (results of regression analysis for data segment) are relatively unvarying; however, fault sensitive, which makes them relatively efficient fault indicators. The undisputable novelty presented in this paper is the concept of replacing traditional vibration-based features (peak-to-peak, RMS, etc.) with regression parameters for practical long-term condition monitoring.

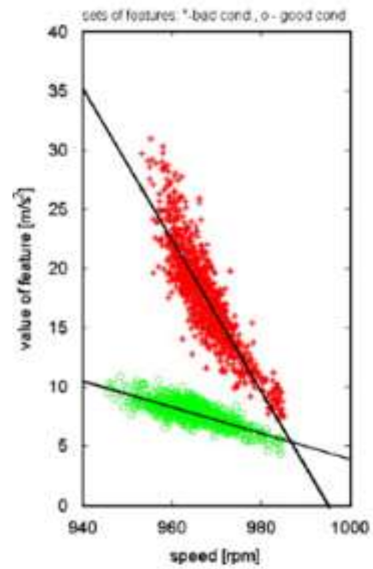

Figure 2. Distribution of characteristic features for damaged (stars) and healthy (circles) condition as function of instantaneous speed

It is the authors' belief that proposed approach could simplify decision-making process by presentation of fault indicators in simple and comprehensible way. The idea of novel approach is provided by analysis of two real case studies presented in [30].

The first case study discusses a REB degradation process development, while the second examines data obtained during operation of damaged bearing and after its replacement. In order to provide diagnostic decision, two kind of information (measurements) have been acquired, namely peak-to-peak and RMS of vibration acceleration and generator power, which is related to the operating conditions. The paper describes how serious variability of the mentioned data causes the decision making regarding the condition of bearings to be difficult.

Moreover, authors try to show that application of classical statistical pattern recognition for data bad condition and good condition is not sufficient because the probability distribution/density functions (PDFs) of features overlap each other (for instance, PDFs of peak-to-peak feature for bad and good conditions). The authors conclude with a statement that that this data sets are strongly dependent on the operating condition (generator power) variation and point out a need to remove such dependency by a suitable data presentation. Consequently, the introduces LSCh technique is just a proposition of the solution of the problem. Since this concept have not been proven to be successful on other sets of data, including other machinery), we believe the techniques developed within realization of the project might fill this gap in state-of-the art of processing of vibration signals.

Furthermore, paper [43], proposes utilization of the feature-power dependency, which might change in a different way, depending on the fault occurred in the machine. The attempt of generalization of such feature dependency is demonstrated. In the presented scheme, each segment is processed using feature-load space concept, i.e. analyse data as function of power in kW, and estimated with regression parameters: “a” and “b” from linear regression (feature = a · power + b), as illustrated in Figure 3.

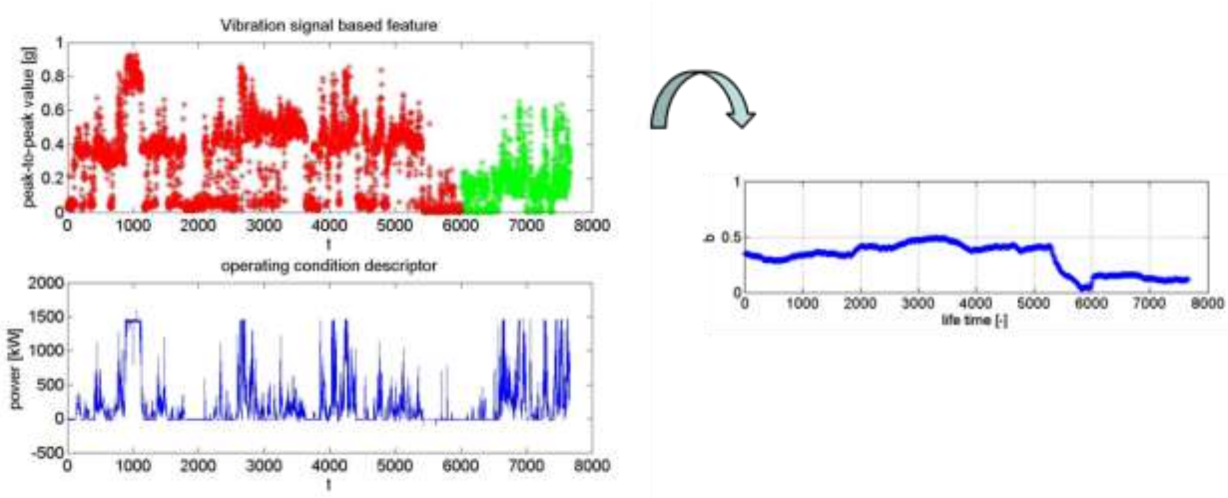

Figure 3. Exemplary of generalization of signal’s characteristic feature with respect to rotating machinery power [43]

The authors show that the and “b” parameter will change indicating the damage type, but this is just a single case-study insufficient for general acceptance. Nevertheless, the proposed novel diagnostic parameters are load independent, which is a fundamental difference in comparison with vibration-based features delivered by the diagnostic system in presence of time varying load conditions. It appears that the proposed approach might significantly improve the functionality of industrial condition monitoring systems. Due to the independence of operational conditions both, automatic alarm threshold level estimation and technical condition decision making procedures might be more efficient.

2.4 Two dimensional functions analysis

The next group of signal processing techniques includes time-frequency together with bispectral methods. Former methods try to resolve the uncertainty problem relating time and frequency representation. The general idea of the problem is illustrated in Figure 4.