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Diagnostics of bearings in presence of strong operating conditions non-stationarity—A procedure of load-dependent features processing with application to wind turbine bearings

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ABSTRACT

Condition monitoring of bearings used in Wind Turbines (WT) is an important issue. In general, bearings diagnostics is a well recognized field of research; however, it is not the case for machines operating under non-stationary load. In the case of varying load/speed, vibration signal generated by rolling element bearings is affected by operation factors, and makes the diagnosis relatively difficult. These difficulties come from the variation of vibration-based diagnostic features caused mostly by load/speed variation (operation factors), low energy of sought-after features, and low signal-to-noise levels. Analysis of the signal from the main bearing is even more difficult due to a very low rotational speed of the main shaft. In the paper, a novel diagnostic approach is proposed for bearings used in wind turbines. As an input data we use parameters obtained from commercial diagnostic system (peak-to-peak and root mean square (RMS) of vibration acceleration, and generator power that is related to the operating conditions). The received data cover the period of several months.

The method presented in the paper was triggered by two case studies, which will be presented here: first when the bearing has been replaced due to its failure and the new one has been installed, second when bearing in good condition has significantly changed its condition. Due to serious variability of the mentioned data, a decision making process on the condition of bearings is difficult. Application of classical statistical pattern recognition techniques for “bad condition” and “good condition” data is not sufficient because the probability distribution/density functions (pdf) of features overlap each other (for example probability distribution/density function of peak-to-peak feature for bad and good conditions). It was found that these data are strongly dependent on operating condition (generator power) variation, and there is a need to remove such dependency by suitable data presentation. To achieve it, load susceptibility characteristics (LSCh) presenting as feature – operating condition space has been used. Presented approach is based on an idea proposed earlier for planetary gearboxes, i.e. to analyse data for bad/good conditions in two dimensional space, feature – load/rotation speed. Here it has been proven experimentally for the first time that there are two types of susceptibility characteristics related to the type of a fault.

The novelty of the paper also comes from an extension of previous study that is statistical processing of data (linear regression analysis) in moving window in the long time

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of a turbine operation is used for feature extraction. It is proposed here to use novel features for long term monitoring. It will be shown that parameters of regression analysis can be used as unvarying, and fault sensitive features for decision making.

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 relatively significant variability. Good example of such machinery might be wind turbines. They become widely used for the electric power generation and they are also frequently considered as an interesting object from condition monitoring perspective [1–7].

Most of diagnostics efforts are focused on rolling element bearings [8–14] and gearboxes [15–21] damage detection. In general, gears and bearings diagnostics is well recognized field; however, it is not the case for machines working under non-stationary load. In the case of varying operational conditions, a vibration signal is often relatively difficult to analyse due to influence of speed/load variation on vibration signal [19,32]. Estimation of operational conditions and their influence on raw vibration signals has been a subject of number of studies [22–25]. Majority of difficulties in vibration-based condition monitoring come from the variation of diagnostic features caused mostly by load/speed changes, low energy of sought – after features and high noise levels [26–37]. Time varying operating conditions, in the case of wind turbines, are related to non-stationary wind behavior (wind power) [5,22–24] that plays an important role and might be understood as the time varying excitation of the system.

In this paper a novel diagnostic approach is proposed for bearings used in the machinery operating under non-stationary operational conditions. The paper extends previous study done for planetary gearbox diagnosis [30]. In Ref. [30] it has been shown that the *load susceptibility characteristics* (LSCh) of monitored machinery can be approximated by linear regression model. Research results introduced in this paper show that linear regression parameters calculated for subsequent short-time data segments can be presented as long term time series. It is shown that such parameters (results of regression analysis for data segment) are relatively unvarying; however, fault sensitive, which makes them very efficient as fault indicators. The 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. It is the authors' belief that proposed approach will simplify decision making process by presenting fault indicators in simple and comprehensible way.

The idea of novel approach is provided by analysis of two case studies presented in the paper. First one discusses rolling element bearing degradation process development. Second one examines data obtained during operation of damaged bearing and after its replacement.

In order to provide diagnostic decision, two kinds of information (measurements) have been acquired: namely peak-to-peak and RMS of vibration acceleration and generator power that is related to the operating conditions. The received data cover the period of several months. These data come from a commercial diagnostic system. (It should be underlined here, that our intent was to use the available data from existing monitoring systems. We were not able to process raw vibration to obtain other, maybe more sensitive features).

Due to serious variability of the mentioned data, a decision making regarding the condition of bearings is difficult. Application of classical statistical pattern recognition techniques for “bad condition” and “good condition” data is not sufficient because the probability distribution/density functions (pdfs) of features overlap each other (for example, pdfs of peak-to-peak feature for bad and good conditions).

It was found that these data are strongly dependent on the operating condition (generator power) variation and there is a need to remove such dependency by a suitable data presentation. To achieve it, the *load susceptibility characteristics* (LSCh) presenting as *feature – operating condition space* has been used.

2. Bearings diagnostics – a brief review

It should be clarified that, in general, one may easily find several interesting papers regarding bearing diagnostics using envelope analysis [8], wavelets [9], adaptive filters [10,11], exploiting cyclostationarity of vibration [12,13], and many others [14].

Wind turbine is an example of machinery operating under varying operational conditions and – as it was shown – the damage detection of bearings in such condition is relatively challenging [3–5]. Some of state of the art works try to discuss/compare/evaluate existing algorithms [2,4]. Several examples of successful applications of vibration-based condition monitoring are discussed in Refs. [5–7], where techniques based on advanced signal processing (spectral kurtosis, wavelet), data compression and analysis using SVD, etc., were used. As it was mentioned, external, environmental issues are also important, because they affect operation of wind turbine [1,3,5]. However, idea presented in the paper was to use diagnostic data provided by the online monitoring system, not raw vibration signals. In order to use raw vibration signals one needs to build advanced feature extracting module in online version that would be rather expensive. For offline processing, it is not