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A time–frequency analysis approach for condition monitoring of a wind turbine gearbox under varying load conditions

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ABSTRACT

This paper deals with the condition monitoring of wind turbine gearboxes under varying operating conditions. Generally, gearbox systems include nonlinearities so a simplified nonlinear gear model is developed, on which the time–frequency analysis method proposed is first applied for the easiest understanding of the challenges faced. The effect of varying loads is examined in the simulations and later on in real wind turbine gearbox experimental data. The Empirical Mode Decomposition (EMD) method is used to decompose the vibration signals into meaningful signal components associated with specific frequency bands of the signal. The mode mixing problem of the EMD is examined in the simulation part and the results in that part of the paper suggest that further research might be of interest in condition monitoring terms. For the amplitude–frequency demodulation of the signal components produced, the Hilbert Transform (HT) is used as a standard method. In addition, the Teager–Kaiser energy operator (TKEO), combined with an energy separation algorithm, is a recent alternative method, the performance of which is tested in the paper too. The results show that the TKEO approach is a promising alternative to the HT, since it can improve the estimation of the instantaneous spectral characteristics of the vibration data under certain conditions.

1. Introduction

Statistics show that the most frequent damages observed in wind turbine systems are in the electrical control components, the blades, the main bearing and the gearboxes and that the most responsible component for downtime is the gearbox [1]. This means that condition monitoring of wind turbine gearboxes is a necessary practice. Vibration analysis is a commonly used approach for condition monitoring, and is based on the idea that the rotating machinery has a specific vibration signature for their standard condition that changes with the development of damage. Vibration based condition monitoring should be a relatively easy task for gearboxes operating under steady conditions, as offered in laboratory environments. Unfortunately, working wind turbine gearboxes have a vibration signature that is also affected by the environmental conditions (temperature variations, wind turbulence) and time varying loads under which they operate. The

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load variations of wind turbine gearboxes are far from smooth and are usually nondeterministic, and since vibration signals tend to change with speed and load of the gearbox, varying loads (and/or speeds) might not necessarily generate stationary signals. In this case, false alarms could be created in the signals and damage features might be influenced by the variations. This makes condition monitoring of wind turbine gearboxes a difficult matter, since the signal processing that is required in this case should overcome the problem of nonstationary influences in the signals not related to damage.

In general, condition monitoring methods do not differ from other damage detection methods apart from the fact that one knows *a priori* about the frequency bands related to damage, for the gears, bearings and other components. A review of methods used for damage detection is given in Ref. [2]. In the early studies, some of the conventional techniques used for condition monitoring were the probability distribution characteristics of the vibration such as the skewness and kurtosis [3], the Fourier spectrum and modulation sidebands [4,5] and Cepstrum analysis [6]. These methods have been widely used for condition monitoring and were proved to work well under certain conditions, such as steady loading of the gearboxes. Unfortunately, in the majority of cases, gearbox signals have spectral characteristics that vary with time. This variation with time cannot be obtained using the Fourier transform as this transform simply expands a signal as a linear combination of single frequencies that exist over all time. This drawback was the motivation for greater attention to time–frequency analysis methods such as the Wigner–Ville distribution [7], wavelet analysis [8] and cyclostationary analysis [9]. Wavelet analysis is probably the most popular technique [10], but has the drawback that the basis functions of the decompositions are fixed and do not necessarily match the varying nature of the signals. Relatively recently, the Empirical Mode Decomposition (EMD) method was also proposed [11]. Since then, attention was placed on applying the EMD in the damage detection field [12,13]. This technique decomposes the signal into a number of meaningful signal components, representing simple oscillatory modes matched to the specific data. This is one of the basic advantages of the EMD when compared to other time–frequency methods. After decomposing the vibration signal, the instantaneous frequency and amplitude of each component can be estimated, most commonly by applying the Hilbert Transform (HT). An alternative approach in order to obtain the instantaneous characteristics of the decomposed vibration signals is to use an energy tracking operator to estimate the energy of the signal, as developed by Teager [14,15] but first introduced by Kaiser [16,17], and then use an energy separation algorithm for the estimation of the amplitude envelope and instantaneous frequency of each signal component produced by the EMD method. This method promises high resolution and low computational power. That is why some primary studies occurred in the literature [18–20] associated with the application of this energy operator in machinery fault diagnosis. Ref. [20] focuses on the application of this operator to the fault diagnosis of wind turbine planetary gearboxes, where the challenge was the planetary gearbox signals' spectral complexity under steady load conditions. What the current study aims for is to show how the challenges of load variations of wind turbine gearbox vibration signals can be overcome using a time–frequency approach, in this case the EMD method in combination with the TKEO and an energy separation algorithm. The experimental datasets used in this paper are obtained from a real wind turbine gearbox in operation, as opposed to many other studies. In addition, only few previous studies go beyond the application of new time–frequency methods in condition monitoring and examine the effects of time varying loads in the gearbox vibration signals when trying to do condition monitoring [21–24]. In these references the use of the signal RMS value, or the arithmetic sum of the amplitudes of the spectral gearmesh components as well as the use of the short-time Fourier transform and the Wigner–Ville distribution is applied.

It is difficult to state all the advantages and disadvantages of the EMD method and other filter bank methods, such as the short time Fourier Transform (STFT) or the wavelets mainly because of their different theoretical background. It is also reasonable to claim that for different situations different methods might work better than the others. The wavelet transform and the STFT are similar in a mathematical sense, both methods decompose the signal to be analysed by convolving it with a predefined "basis", e.g. the mother wavelet for the case of the wavelet transform. It might be easier to compare these two methods in that sense, although this is beyond the purpose of the current paper, since it is the EMD method that the authors are currently examining. Considering the case of the wavelet transform the choice of mother wavelets might influence the results of the analysis. Also assumption of stationarity during a time-span of the mother wavelet (or window for the STFT) might inhibit the estimation of the subtle changes in the frequencies. On the contrary, the EMD method is not exactly equivalent on its own to the previously mentioned methods. The procedure of the decomposition, not mathematically proven yet, is based on the adaptation to the geometric characteristics of the signal, without leaving the time-domain. The method decomposes the signal by using information related to the local characteristics for each time-scale of the signal. Being an adaptive method, it represents better the mechanisms hidden in the data, no pre-defined basis function or mother wavelet is needed during the process since the decomposition is completely data-driven. The adaptivity is therefore one major advantage of the method and also in some cases its ability to better estimate subtle changes in the signal, due to the fact that one does not use any kind of window function in the process and does not need to assume stationarity for any time-span of the signal. As for the case of every method of course, the EMD has some limitations too. The most known ones are the end effect and the mode mixing problems that will be described in more detail in the next sections of the paper.

The structure of the paper is going to be the following: in Section 2 the gear model used in the simulation part of the work will be thoroughly described, as well as the type of loads and the kind of fault introduced to the model. The purpose of the simulation is basically to test how the time frequency analysis method proposed corresponds to the simulated signals in order to have an initial idea of the kind of damage features one should expect in the real wind turbine data. In addition, the effect of load variation in the signals will be examined in this simulation environment, which is more controlled and easier to understand. In Section 3 the experimental datasets from the wind turbine gearbox vibration data will be presented. The