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Integrated modulation intensity distribution as a practical tool for condition monitoring

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ABSTRACT

Modulations present in vibration signals generated by rotating machinery might carry a lot of useful information about objects' technical condition. It has been proven that both gearboxes and rolling element bearing (REB) faults manifest themselves as modulations. The paper describes a technique for detection of modulations in vibroacoustic signals, called modulation intensity distribution (MID), which is a function that combines multiple spectral correlation densities in one way or another, depending on the application. Additionally, the paper describes a functional obtained by integrating an MID (denoted by IMID) that has the advantage of being a function of only one frequency variable instead of two. The paper investigates the utility of the MID as an indicator for detection of the presence of rolling element bearing faults in high noise environments. For the purpose of testing, a wind turbine that suffered both advanced gearbox fault and early stage of bearing fault was chosen. Additionally, the paper undertakes the problem of application of the proposed tool in an industrial condition-monitoring system. In order to show the behavior of cyclic components generated by the turbine under study over a long period of time, the set of MIDs integrated over full range of potential carrier signals was presented as a cascade plot.

1. Introduction

In recent years, a growing demand for vibrodiagnostic data analysis has arisen in many industries. This demand compels researchers to develop signal processing techniques suitable for analysis of signals generated by more complex machinery, frequently exposed to significant influence of noise [1].

Nowadays, cyclostationarity analysis is one of the most promising approaches for rotor machinery vibration analysis [2]. The variety of cyclostationarity-based methods of identification [3] and separation [4,5] of signal components enables one to obtain much useful information about signals' cyclic components. An important feature of cyclostationarity analysis is its ability to reveal amplitude modulations that are present in vibration signals [6,7]. Modulations of various signal components can often serve as valuable indications of fault occurrence [8]. It has been proven that both gearboxes and rolling element bearing (REB) faults manifest themselves as modulations. For rolling element bearings, systems' natural (resonance) frequencies are periodically excited with the fault characteristic frequency [9]. For gearboxes, gear-mesh frequency is modulated by components of rotation frequency of both input and output shafts [10] and in the case of advanced fault occurrence, additional excitations of natural frequencies by both shafts speed-related components might be present [11]. Usually, when kinematics of machinery under study is known, faults characteristic frequencies are known as well. However, in practice, exact values of systems' natural frequencies remain unknown. Spectral characteristic of mechanical objects' resonances depends on its dimensions and material properties. Additionally, transfer path between excitation source (e.g. faulty bearing) and the vibration sensor will have impact on spectral characteristic of observed modulated signal [12]. In general, any types of impacts related to the operation of the machinery will serve as a source of signals that excite natural frequencies. For industrial machinery, typical examples of such sources might be: operating pistons [1,13], machining process [14], rotor blades abrasion [15], etc. Therefore, when kinematics of observed machinery is relatively complex, vibration signal might contain various natural frequencies excited by different sources. This fact leads to the conclusion that, especially for mechanical vibration, it might be useful to represent the signal as a function of two frequencies – modulated signal frequency f and modulating signal frequency (usually denotes as cyclic frequency α). A useful cyclostationarity analysis tool for such representation is the cyclic spectrum

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or spectral correlation density or its conjugate version [3,6,16]. Listed tools return overall information of how various modulations are distributed in the signal and might serve as a valuable information about observed objects' technical condition including both: mechanism operation and structural health [3]. However, results presented as three-dimensional plots make their interpretation relatively complicated, especially for automated industrial condition-monitoring systems.

In this paper, authors present the concept of a modulation intensity distribution (MID) as a signal processing tool that is convenient and effective for amplitude modulations detection in a vibration signal based on its cyclostationarity properties [17]. Ideas introduced in Ref.17 are extended here, providing analytical link between MID and spectral correlation density using traditional mathematical description [18]. It is shown that MID returns similar information as the spectral correlation density while being more immune to the presence of noise. Additionally, this paper investigates what the authors call the integrated MID (denoted as IMID [17]). Then, throughout the paper it is proven that IMID is the optimal method for detection of second order cyclostationary components in vibration signals with respect to maximum likelihood ratio test. Theoretical investigation included in the article illustrates the foundation for practical application of IMID to industrial condition-monitoring systems designed to supervise the machinery of relatively complex kinematics (e.g. wind turbines).

Large demand for application for condition monitoring systems has recently grown in the field of wind energy production. Wind turbines present one of the most challenging objects for vibration monitoring [5]. Additionally, relatively difficult access to the turbine and varying weather conditions require increased reliability of industrial condition-monitoring systems designated for wind turbines. Due to the substantial load variations caused by the variable wind, most turbines are exposed to the risk of accelerated development of mechanical faults. Moreover, limited access to the turbine due to weather conditions frequently prevents execution of required repairs.

Since the kinematics of the wind turbine is relatively complicated [5,19,20] and the risk of fault occurrence is significant, vibrodiagnostic tools implemented in industrial condition-monitoring systems should be selective and sensitive in order to return indicators that concerns technical conditions of each part of mechanical chain separately [21]. Due to relatively high costs of wind turbine maintenance and substantial financial losses caused by unscheduled downtimes, it is of utmost importance to detect potential fault occurrence as early as possible [22].

The paper is organized as follows. Section 2 introduces the MID technique together with an interpretation of its results. Section 3 introduces IMID and provides a theoretical justification for the use of spectral correlation for calculation of MID, including identification of a link between IMID and low signal-to-noise ratio (SNR) maximum likelihood synchronizers. After that, it presents a theoretical investigation of the possibility of implementation IMID within actual vibration-based condition-monitoring systems: the model of the second order poly-cyclostationary signal is presented and the results of two implementations of MID and IMID are compared. Next, results are discussed in terms of practical application for complex-machinery vibroacoustical-signal analysis. Section 4 gives a general specification of the wind turbine selected for the case study. Section 5 includes a description of the technical condition of the turbine under study and then presents the vibration signal generated by the turbine with a significantly damaged gearbox. Finally, the paper presents the results of the application of the MID and discusses the utility of MID and IMID for analysis of vibration signals generated by wind turbines.

2. Modulation intensity distribution

2.1. Principles of the method

Modulation intensity distribution is a general technique for detection and identification of modulations present in a signal. MID was originally designed for gearboxes and rolling element bearings diagnostics purposes; therefore, it is focused on detection of amplitude modulations that manifests themselves as symmetrically spaced spectral sidebands. It allows to present values of indicator of modulations on a bi-frequency plane of carrier signal frequency f and modulating signal frequency α. Several statistical operations exists that might be used to define the indicator of presence of modulations; therefore, the proposed method might be customized in order to emphasize selected properties of different signals under study. This paper focuses on two particular methods of detection of modulations based on cyclostationary properties of mechanical signals. Namely: spectral correlation and spectral coherence. More comprehensive study on types of modulations that might serve as fault indicators together with exhaustive description of MID with its capabilities and limitations can be found in Ref. [17].

In order to explain principles of MID let us consider a simple signal consisting of a sine-wave of frequency f amplitude-modulated by several sine components with frequencies corresponding to multiples of α and amplitudes equal to $A_{1\ldots m}$:

$$x(t) = \sin(2\pi ft)[1 + A_1\sin(2\pi\alpha t) + A_2\sin(2\pi 2\alpha t) + \cdots + A_m\sin(2\pi n\alpha t)], \quad \text{for } n = \{1,2,\ldots,N\} \quad \text{and } m = \{1,2,\ldots,M\}. \quad (1)$$

The spectrum of the above signal consists of a spectral line located at frequency f, representing carrier signal, together with spectral lines symmetrically located from center frequency f by cyclic frequency α and its subsequent multiples, representing the modulating signal (see Fig. 1).

The core of MID is to make use of a sideband filter that allows extracting potential carrier signal together with corresponding modulating signals. The idea of the sideband filter is illustrated in Fig. 1.

A time signal filtered in this way contains (in the idealized case) only the specified component with no additional signals and with highly reduced noise level. It can be then understood as a set of three elements:

$$x_i = x_{\Delta f}(t, f - i\alpha) \quad \text{for } i = \{-1, 0, 1\}, \quad (2)$$

where $x_{\Delta f}(t,f)$ stands for the filtered version of $x(t)$ in a narrow frequency-band $[f - \Delta f/2;\ f + \Delta f/2]$. The output of the presented filter might be then used for calculating the relation between three spectral components spaced apart by frequency α, which might be used

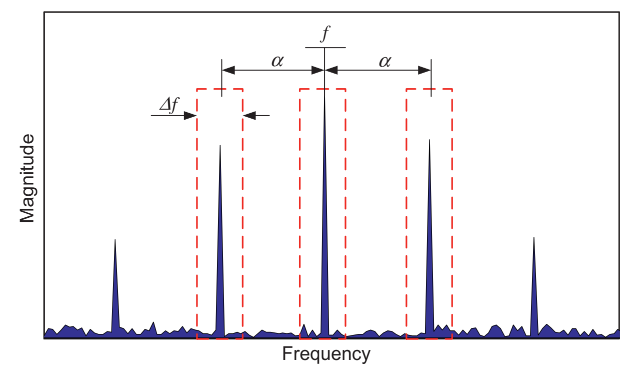

Fig. 1. The concept of a sideband filter.