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Blind equalization using combined skewness–kurtosis criterion for gearbox vibration enhancement

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ABSTRACT

In this paper a method for vibration signal enhancement is presented. It incorporates an idea that the signal acquired on the machine housing is a convolution of an informative signal (cyclic pulse train) with an impulse response of the system. The impulse response corresponds to a transmission path through which the informative signal propagates. The informative signal is a signal that contains information about a local damage. The classical method that estimates the impulse response of the system is called minimum entropy deconvolution (MED) and it aims to maximize kurtosis of the deconvolved signal, i.e. kurtosis of the informative signal estimate. Recently, skewness-based deconvolution (equalization) has been proposed as an alternative method for damage detection in rotating machines. In this paper we incorporate an alternative criterion which combines advantages of both of the previously used deconvolution criteria. Kurtosis is a widely-used tool for impulsiveness detection even if they are hidden in the signal, although favouring single-spike signals is a disadvantage of kurtosis. On the other hand, skewness is more robust, since it incorporates statistical moment one order lower than kurtosis. However, signals related to local damage are not always asymmetric, thus skewness is not a suitable criterion for their extraction. Thus, it is worth to combine both kurtosis and skewness in a single deconvolution criterion. We compare properties of two previously used criteria (kurtosis and skewness) with the novel one which is based on the Jarque–Bera statistic using a simulation study. An experimental validation on a real vibration signal (two-stage gearbox from an open-pit mine) is performed as well.

1. Introduction

The origin of blind deconvolution algorithms driven by a measure of impulsivity is in 1978, when R.A. Wiggins developed the minimum entropy deconvolution (MED) for enhancement of seismic reflection data [1]. The method is based on searching for a linear time-invariant filter which maximizes kurtosis (normalized fourth-order statistic) of the filtered signal. Through the last decades MED has found widespread application in many areas, including machine diagnostics [2–9]. In [2] the Authors applied MED to detect localized faults in gears. Such application of MED is motivated by the fact that the faulty gear emits an impulsive signal which is often masked by other sources. MED makes the impulsive signal visible in the time domain. Moreover, MED has been validated as a useful method not only in detection of such signal, but also in advanced gear tooth localized faults diagnosis – it allows to differentiate between a spall and a crack [3]. In [4] the

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Authors exploited MED in fault detection in rolling element bearings and guided the user to select optimum parameters for the MED filter.

The fundamental work of R.A. Wiggins has been generalized by several authors. Instead of the kurtosis one can apply other criteria of impulsivity. In [10] C.A. Cabrelli proposed a non-iterative algorithm for searching a linear filter that maximizes the D-norm, i.e. maximum absolute value of the filtered signal normalized by its Euclidean norm. An improvement of Carbelli's method that provides the same results and reduces computational time is presented in [11]. One can also benefit from generalization of the D-norm, i.e. higher order D-norms. This approach is described in [12] where the Authors analyze simulated seismic signals. Such norms might be useful in applications where an isolated impulse is expected as the excitation signal. Thus, effectiveness of this method in the field of rotating machinery diagnostics might be limited, because a set of impulses is expected in the case of damage – not only a single spike. Also, the original Wiggins' moment-based method has been extended. In [13], W. Gray analyzed normalized moments of orders other than the fourth, i.e. moments of k-th order, where $k > 2$. This generalization has been analyzed also in [12,14]. It is worth mentioning that one of these norms, namely skewness, demonstrate ability of indicating asymmetric signals which occur in certain types of damage in rotating machines [15]. In [16] the Authors provide generalization of the original minimum entropy deconvolution by incorporating so called "entropy function". In [17] the Authors introduce a method called "maximum correlated kurtosis deconvolution" (MCKD) which is desired to find a periodic series of impulses as the deconvolved signal. Another blind deconvolution method is presented in [18], where the authors propose a deconvolution norm beneficial in damage detection in planetary gearbox.

In this paper we provide another generalization of the Wiggins-type blind deconvolution algorithm. Since the previously investigated norms might be treated as measures of non-Gaussianity of the deconvolved signal, we present how the original algorithm presented in [1] might be generalized using a measure of non-Gaussianity, namely the Jarque–Bera (JB) statistic [19]. The use of this measure is motivated by several reasons. Firstly, the Jarque–Bera statistic has been recently successfully applied in rotating machinery diagnostics as an impulsivity measure that substituted the kurtosis (for some cases) in the spectral kurtosis approach [20,21]. The second reason is related to the fact that the Jarque–Bera statistic combines squares of both skewness and kurtosis. Thus, it might share kurtosis' ability of impulses detection in noisy background and skewness' properties, i.e. ability to track assymetry in the distribution of a signal and low propensity to indicate a single spike. We compare the proposed criterion with both classical MED (driven by kurtosis) and the blind deconvolution driven by skewness.

Three data sets are used in order to investigate the performance of blind equalizers. The first two are simulated signals that follow the linear time-invariant model with additive noise and noisy pulse train as excitation. One of these signals contains relatively low background noise. Moreover, variability of amplitudes of the informative signal impulses is relatively high. Thus, it could be a challenging signal for the classical MED. The second one is characterized by relatively high level of background noise. Thus, it might verify how each deconvolution criterion deals with informative signal barely visible in bot time and time–frequency domain. The third data set consists of an industrial vibration signal. Such signals are often difficult to process, especially when the related mechanical system is complex, operates in non-stationary conditions and the environment influences the measurements. For instance, measurements of instantaneous shaft's angular speed for engine diagnostics might be affected by the marine environment [22] or other types of interferences might occur during recording of the signal [23]. Non-stationary conditions might be a reason to introduce specific algorithms based on e.g. adaptive filters or time-varying models [24–26]. In general, processing of a vibration signal is only an example of challenges in industrial maintenance [27]. Thus, development of new, more robust tools for damage detection is a crucial problem in industrial data processing.

2. Methodology

Consider an input signal $\varepsilon, n = 1, \ldots, N$ (raw vibration signal). The classical version of the minimum entropy deconvolution is based on searching for coefficients $f_l, l = 1, \ldots, L$ of a filter which maximizes the following objective function of the filter's output y_n [1]:

$$O_4(f[l]) = \frac{\sum_{n=1}^{N} y^4[n]}{\left[\sum_{n=1}^{N} y^2[n]\right]^2}, \tag{1}$$

where $y_n = \sum_{l=1}^{L} f[l]\varepsilon[n-l]$. Optimal coefficients of the filter are calculated by solving

$$\frac{\partial(O_4(f[l]))}{\partial(f[l])} = 0. \tag{2}$$

Since $\frac{\partial y[n]}{\partial f[l]} = \varepsilon[n-l]$, Eq. (2) can be rewritten as:

$$\frac{\sum_{n=1}^{N} y^2[n]}{\sum_{n=1}^{N} y^4[n]} \sum_{n=1}^{N} y^3[n]\varepsilon[n-l] = \sum_{p=1}^{L} f[p] \sum_{n=1}^{N} \varepsilon[n-p]\varepsilon[n-l]. \tag{3}$$

Denoting the left side of Eq. (3) as b (cross correlation of the input and the output cubed) and the right side of Eq. (3) as multiplication of the vector f and the Toeplitz autocorrelation matrix A, Eq. (3) can be expressed as $b = fA$ (matrix form of Eq. (3)). This system might be solved iteratively. A clear description of the iterative procedure might be found in [1,2]. In the literature one can find many different criteria that define the moment to stop iterations. For instance, the iterative procedure might be stopped while a minimum change in objective function of the filter's output is reached [17], while correlation coefficient between outputs related to two following iterations is close enough to 1 [12] or while difference between filter coefficients related to two following iterations is