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Optimal filtering of gear signals for early damage detection based on the spectral kurtosis

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ABSTRACT

In this paper, we propose a methodology for the enhancement of small transients in gear vibration signals in order to detect local tooth faults, such as pitting, at an early stage of damage. We propose to apply the optimal denoising (Wiener) filter based on the spectral kurtosis (SK). The originality is to estimate and apply this filter to the gear residual signal, as classically obtained after removing the mesh harmonics from the time synchronous average (TSA). This presents several advantages over the direct estimation from the raw vibration signal: improved signal/noise ratio, reduced interferences from other stages of the gearbox and easier detection of excited structural resonance(s) within the range of the mesh harmonic components. From the SK-based filtered residual signal, called *SK-residual*, we define the local power as the smoothed squared envelope, which reflects both the energy and the degree of non-stationarity of the fault-induced transients. The methodology is then applied to an industrial case and shows the possibility of detection of relatively small tooth surface pitting (less than 10%) in a two-stage helical reduction gearbox. The adjustment of the resolution for the SK estimation appears to be optimal when the length of the analysis window is approximately matched with the mesh period of the gear. The proposed approach is also compared to an inverse filtering (blind deconvolution) approach. However, the latter turns out to be more unstable and sensitive to noise and shows a lower degree of separation, quantified by the Fisher criterion, between the estimated diagnostic features in the pitted and unpitted cases. Thus, the proposed optimal filtering methodology based on the SK appears to be well adapted for the early detection of local tooth damage in gears.

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1. Introduction

The problem of local fault detection in gears from vibration analysis has been widely studied in the literature. Many different techniques have been proposed including: amplitude and phase demodulation [1], cepstrum analysis [2,3], adaptive filtering [4,5], use of a model [6,7], inverse filtering [8,9], time–frequency (TF) analysis [10–14] or time-scale analysis [15–17].

The proposed techniques so far have been mostly applied to the detection of relatively advanced and severe faults in gears, such as tooth cracks. Few works report the analysis of incipient tooth surface wear such as *pitting*. On the other hand, there is now a growing demand from the industrial sector to detect local faults at a very early stage of damage, e.g. less than 10% or 5% pitting of the tooth surface.

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Most of the gear fault detection techniques are based upon the so-called *residual signal* as classically obtained after removing the mesh harmonic components from the time synchronous average (TSA) of the gear [18,19]. In case of incipient damage, however, the fault signature may be masked in the residual signal among some interfering components, such as: apparently random patterns due to normal variations in tooth profile and pitch [19], a slow modulation of the meshing vibration which may be induced by a shaft unbalance, ghost components [2], or even some residual noise that may be left in the TSA signal. In that case the residual signal may be advantageously analysed in the TF domain. Some efforts have been made in order to derive useful diagnostic features from the observed TF patterns in the purpose of automatic fault detection [13,14]. However, the automated analysis of TF maps remains a delicate task to perform for the condition monitoring of the system.

Pitting like other local gear fault are known to produce vibration impacts which in turn excite the structural resonance(s) in the system. Wang [20] proposed to apply the *resonance demodulation* technique which was based on envelope analysis of the residual signal after band-pass filtering within an excited resonance. However, the identification of the resonance bandwidth was based on spectral analysis of the residual signal but no solution was given in order to adaptively detect the(se) resonance(s) and select the band-pass filter.

The problem of local fault detection in gears can be related to the more general problem of *transient detection* in a signal. In that purpose, a detection technique has been recently proposed based on the *spectral kurtosis* (SK) [21]. The SK is a tool sensitive to non-stationary patterns in a signal and that can indicate at which frequencies those patterns occur. Furthermore, the SK can be used to design *detection filters* that adaptively extract the fault signal from the noisy background. This technique has been successfully applied to the case of bearing fault detection [22,25].

In this paper we propose to use the SK for the enhancement of incipient damage in gears and we discuss the best way to estimate and apply the SK-based optimal denoising filter (*Wiener* filter) to gear signals. Particularly, we show that the use of the residual signal presents some advantages over the raw vibration signal. Thus, in that sense this method provides a solution for the identification of the excited structural resonance(s) in [20].

The paper is organised as follows. In Section 2 we first briefly recall the definition and some useful properties of the SK. In Section 3 we propose to estimate and to apply the optimal denoising filter based on the SK to the gear residual signal. A methodology is then proposed for the estimation of the SK-based filtered residual signal (the *SK-residual*) as well as of its smoothed squared envelope (the local power) which provides a useful energy-based feature for the detection of local tooth faults. The technique is then applied in Section 4 to the case of fault detection on a multiple *natural-like* pitted wheel in an two-stage helical reduction gearbox operating on a industrial site. The adjustment of the frequency resolution for the SK estimation and the use of different variants of the residual signal are discussed. The proposed SK-based filtering method is shown to dramatically enhance the small transients induced by the pitting faults, thus allowing the fault detection at an early stage (i.e. less than 10% pitting on an helical gear). Finally, the method is compared to an inverse filtering (blind deconvolution) approach. However, this latter method turns out to be more sensitive to noise and interferences and consequently its diagnostic potential, quantified by the value of the Fisher criterion, is lower than with the proposed optimal filtering approach.

2. The spectral kurtosis (SK): recall of definition and properties

In this section we briefly recall the definition of the SK and the properties which will be used subsequently.

2.1. Definition of the SK

The SK of a signal $x(t)$ is defined as the normalised fourth-order spectral moment [21]:

$$K_x(f) = \frac{S_{4,x}(f)}{S_{2,x}(f)^2} - 2 \quad \text{with } S_{n,x}(f) = \langle |X(t,f)|^n \rangle \tag{1}$$

where $\langle\cdot\rangle$ stands for the time averaging operator and $X(t,f)$ represents the *complex envelope* of signal $x(t)$. $X(t,f)$ may be estimated by the short time Fourier transform (STFT):

$$X(t,f) = \sum_{n=t}^{t+N_w-1} h(n-t)x(n)e^{-j2\pi fn} \tag{2}$$

where $h(t)$ is the analysis window with length N_w.

The SK was interpreted in [21] as the relative *temporal-variance* of the TF energy distribution $|X(t,f)|^2$ of the signal at each frequency f. Thus, the SK can be used as a *frequency dependent measure of the non-stationarity* of the signal. It was shown to be sensitive to small non-stationarity events (transients) in a signal and to indicate at which frequencies those events occur [22,23].

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