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Advanced bearing diagnostics: A comparative study of two powerful approaches

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ABSTRACT

The last decade has witnessed spectacular advances in vibration-based fault detection of rotating machines and, in particular, rolling element bearings. Nowadays, the related state of the art can be considered mature thanks to a set of powerful signal processing techniques able to denoise and process the vibration signal to detect fault symptoms. Among these techniques, two emerging approaches have specifically captured the interest of the scientific community thanks to their efficiency and robustness. They have also been recommended in the bearing diagnostic tutorial written by professors R. B. Randall & J. Antoni, published in MSSP in 2011. The first approach consists of pre-processing the random part of the vibration signal (after removal of deterministic components) through the minimum entropy deconvolution (MED) method, followed by the spectral kurtosis (SK), before analyzing the spectrum of the signal envelope. The MED enhances the signal impulsivity by deconvolving the system transfer function through an optimization approach that maximizes the kurtosis of the filter output. Then, the SK is applied to conceive the optimal filter that promotes the most informative spectral band before computing the (squared) envelope spectrum. The second approach is based on a cyclostationary modeling of the bearing signal. It applies a bi-variable map— called the spectral coherence— of (i) the cyclic frequency, which describes the cyclic content of modulations, and (ii) the spectral frequency which describes the spectral content of the carrier. When applied to the random part of the signal, this quantity is able to detail the signal in this plane according to the signal-to-noise ratio, thus allowing weak fault components to appear in the distribution. This paper investigates and compares these two approaches on real bearing vibration datasets including run-to-failure tests. The study also addresses the extension of these approaches to the non-stationary operating regime.

Abbreviations: REB, rolling element bearing; SES, squared envelope spectrum; SK, spectral kurtosis; STFT, short-time Fourier transform; MED, minimum entropy deconvolution; CS, cyclostationary; SC, spectral correlation; SCoh, spectral coherence, IES, improved envelope spectrum; ACP, averaged cyclic periodogram; FFT, fast Fourier transform; SNR, signal-to-noise ratio; NES, normalized envelope spectrum.

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1. Introduction

Rolling element bearings (REBs) are perhaps the most widely used elements in rotors. Because of their fragility, REB are likely to be exposed to sudden failures causing system outage. Therefore, in recent decades there has been increasing interest in developing appropriate techniques for signal denoising and incipient fault detection [1]. Due to their non-invasive nature and their high reactivity to incipient faults, the development of vibration-based techniques has spiked the interest of the scientific community.

In this context, envelope analysis has long been recognized as a powerful REB diagnosis technique. Typically, it consists of a bandpass filtering step in a frequency band wherein the impulsive response is amplified, followed by a demodulation that extracts the signal envelope. The spectrum of the envelope reveals the desired diagnostic information, including the repetition frequency of the fault as well as possible modulations. It has been shown in Ref. [2] that it is preferable to use the squared envelope instead of the envelope as the latter is likely to introduce other spurious components in the envelope spectrum. Since that time, the envelope spectrum was replaced by the squared envelope spectrum (SES) which has become the benchmark technique for bearing diagnostics. In some publications, e.g. [3], the SES is defined as the power spectrum of the squared envelope, rather than the amplitude of its direct Fourier transform, but the key point is the use of the squared envelope rather than of the envelope itself. (It can be appreciated that the squaring operation in the time domain tends to enhance modulation effects and thus sidebands in the corresponding spectrum, while squaring the spectral amplitudes tends to deemphasize already-weak sidebands and higher harmonics of the fault frequency, and so this second squaring operation is usually disadvantageous for basic diagnostic applications, but it does give advantages with respect to statistical analysis [3] and allows for operations such as mean-square averaging to be conducted.)

Later on, efforts were directed on how to choose the most suitable band for demodulation. This was originally estimated either through hammer tap testing by finding the bearing housing resonances or by monitoring the evolution of the (dB-) spectrum given a healthy reference signal. In this context, the theoretical foundations of the spectral kurtosis (SK) have been proposed by Antoni in Ref. [4], providing a way of identifying the best demodulation band from the signal and without the need of a reference. Being based on a statistical approach, the SK provides a way to determine which frequency bands are informative according to their impulsivity. It can actually be seen as the kurtosis of the signal bandpass filtered with a filterbank covering its frequency content. In a companion paper, Antoni & Randall addressed the application of the SK in vibration-based condition monitoring of rotating machines in Ref. [5], providing a robust way of detecting incipient faults and offering a way of designing optimal filters to promote the mechanical signature of faults. In this framework, they introduced the concept of *kurtogram* in Ref. [6] which computes the SK for all possible values of the short-time Fourier transform (STFT) window size involved in the SK calculation (i.e. frequency resolutions). Yet, the kurtogram turns out to be impractical owing to its very high computational complexity. As a solution, Antoni has proposed a fast computation algorithm of the kurtogram, accordingly called the *fast kurtogram*, which uses a multirate filterbank to cope with the computational complexity of the kurtogram. The success of the SK was not confined to bearing diagnostics as its use has spread to numerous mechanical applications; interested readers may find a related review in Ref. [7]. Despite its relevance in machine signal analysis, the SK has proven ineffective in some applications; for instance, when the correlation length of the impulse response is longer than the defect period. This significantly reduces the signal impulsivity and jeopardizes the effectiveness of the SK. A typical example is a faulty bearing signal in high speed applications wherein the repetition rate of the fault impacts may be shorter than the transient damping time.

Interestingly, a solution has been proposed in Ref. [8] to preprocess the signal before applying the SK by means of the “minimum entropy deconvolution” (MED) . The latter is based on finding the optimal inverse filter which compensates the transfer function of the transmission path, with the aim of separating the impulse responses in the measured signal. In fact, owing to its remarkable performance, the MED has been applied alone in many mechanical applications [9–12]. The combination of the MED with the SK has proven very effective for incipient fault detection in bearings and, since then, has become a leading procedure in vibration-based machine diagnostics [13,1,14,15].

Another interesting approach for bearing diagnosis is based on the cyclostationary (CS) theory. This goes back to Refs. [16,17] wherein bearing vibrations were shown to be fairly approximated as CS signals. In details, it has been shown that the vibrational component generated by a faulty bearing is random in nature and has symptomatic properties that can be explored by means of (second-order) CS descriptors such as the *spectral correlation* (SC), the *spectral coherence* (SCoh), the *integrated cyclic coherence* and others [18–20]. These techniques have also proven efficient and their use continues to grow [21,22,23,59,24]. Recently, it has been shown in Refs. [25,26] that an enhanced version of the SES may be obtained by integrating the (squared-) magnitude of the SCoh over the spectral frequency variable (widely denoted by f and expressing the *carrier* of a CS signal, as opposed to the cyclic frequency α which describes its modulations). This will be referred to in the present paper as the *improved envelope spectrum* (IES). An important point to consider when dealing with CS tools is the choice of the SC estimator from which the SCoh and the IES are determined. Actually, the high computational cost has so far hindered the use of CS tools in machine diagnostics. Until now, the *averaged cyclic periodogram* (ACP) [27,18] has been the most popular estimator of the SC in engineering applications as it satisfies an acceptable computational cost principally powered by the fast Fourier transform (FFT) algorithm involved in its calculation. The ACP algorithm consists of the calculation of a (cross-) averaged spectrum (i.e. the Welch estimator) for each scanned cyclic frequency. Very recently, Antoni et al. have proposed in Ref. [25] a new estimator of the SC, called the “fast-SC”, based on the STFT. As stated in the same