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Automatic gear and bearing fault localization using vibration and acoustic signals

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ABSTRACT

The vibration and the acoustic responses from a rotary system in a given situation are not identical. The commencement of signal bursts in presence of defect has been investigated to design a robust system of filters, which can perform adequately for both the class of signals captured from geared and bearing systems for a wide range of faults. The proposed system of filters has several stages of signal processing such as denoising, time–frequency analysis, extraction of smooth envelope signal (SES) followed by a robust peak detection technique. First, the strength of wavelet packet transform (WPT) has been exploited along with a proposed algorithm to identify the denoised signal for further processing. In the second stage, the SES has been generated by integrating the enhanced spectrogram coefficients in time domain. The corresponding enhanced time–frequency spectrogram has been generated by adopting complex Morlet wavelet transform (CMWT) followed by a thresholding routine. As the objective is to localize faults in time domain signals, in the last stage, a robust peak detection technique has been integrated in the proposed system of filters. In all the aforementioned stages of filter design a two stage validation process has been followed. This involves a performance analysis with a synthetic signal followed by an experimental investigation. The strength of a strong signal preconditioning, which helps in identifying an appropriate mother wavelet function for different systems and for a wide range of faults, has been highlighted.

1. Introduction

Acoustic and vibration based condition monitoring practices has been drawing the attentions of many researchers from last three decades. For a qualitative judgment, acquisition of clean responses from a system is desired, which is quite promising in industrial working environment. The possibility of getting corrupted is more in acoustic signals compared to vibration responses. Hence, establishing a single robust signal processing technique which performs adequately for both the class of signals from different systems to localize a wide range of faults is still a challenge for investigators. In the present work, a robust system of filters has been proposed for the purpose.

From literature, one can find numerous signal processing techniques which have been implemented on acoustic or vibration responses from a geared or bearing systems for fault identification or localization or severity measurement [1–5]. Recently, acoustic signal processing techniques have been widely used for condition monitoring of diesel engines [6–10]. However, the requirement of a robust denoising technique is desired for the signal particularly where the noise level dominates the defect signatures due to defect severity, presence of multiple faults, or presence of additional noise sources. Retaining the defect signatures during the denoising process is somewhat a challenging task [11–13].

In the domain of acoustic and vibration based condition monitoring of rotary systems, variety of wavelet transforms have been investigated [14–17]. More appropriate results can only be obtained with selection of appropriate wavelet function, which resembles to the defect signature [18,19]. From the literature, one can notice that the defect signatures are dependent on type of faults, systems and signals. Now, the question is to identify a mother wavelet which will perform adequately for both the acoustic and the vibration responses [20,21]. However, this is nearly impossible to achieve as the defect signatures are highly fault, system and response type dependent. Then, the only option is to develop a robust signal preconditioning technique [22–24,5]. In that case, the complexity persists in retaining the defect signatures in acoustic and vibration responses for different systems, adequately.

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The enveloping technique is also widely adapted in acoustic and vibration based condition monitoring. Apart from Hilbert transform various methods have been deployed for generating envelope signals [15,25,7,26,27]. The envelope spectrum enhances the capability of investigators in fault identification practice such as detecting the periodicity and presence of multiple defects. However, the desired envelope signal can only be extracted from a clean signal or signal with lower level of noise interference. In order to achieve a smooth envelope signal (SES) for both the classes of signals from different systems such as geared or bearing system, a robust signal pre-conditioning followed by a signal processing technique is desired.

Summarizing, a significant scope has been observed in designing a system of filters, which can perform adequately for acoustic and vibration responses of different rotary systems for a wide variety of defects. The requirement of a robust signal pre-conditioner has been noticed to improve the quality of the captured signals. Moreover, the necessity of generating a smooth envelope, having potential to retain the defect signatures, has been recognized. In addition to this, the prerequisite of a robust peak detection technique, which enables the investigators to identify multiple defects and their periodicity, has been perceived.

The intention of this work is to ascertain a robust signal processing technique, which can handle the acoustic and vibration signals captured from any geared and bearing systems for identifying and localizing various degree of faults. The present article aims to develop a system of filters which require negligible intervention from the investigators. The proposed system of filters has a strong signal preconditioning stage which eventually calls for an appropriate mother wavelet for successive processing. After this present section of introduction, Section 2 explains theoretical basis of the proposed system of filters. Section 3 evaluates the performance of the proposed filtering system using a synthetic signal. The experimental details have been briefed in Section 4. In Section 5, the proposed system of filters has been implemented on experimentally captured acoustic and vibration signals. The last section concludes some important observations of the present exercise.

2. Proposed system of filters

The proposed filtering technique, which aims at unifying the approach for both the acoustic and vibration signals, consists of three signal processing stages. The first stage exploits the strength of the wavelet packet transform (WPT) to improve the signal to noise ratio (SNR) of the raw acoustic and vibration signals. An algorithm has been designed to identify the optimal decomposed signal, based on statistical parameters of the decomposed signals. The signal, thereafter, has been treated as the denoised signal in subsequent analysis. In the second stage, the smoothed envelope signal (SES) has been generated using complex Morlet wavelet transform (CMWT) followed by a thresholding technique to remove the unwanted transformed wavelet coefficients. In the final stage, a robust peak detection algorithm has been implemented to localize the peaks. These three stages have been explained in detail in the coming sections.

2.1. Signal denoising

The first step of the filtering system decomposes the signal using WPT. In principle, WPT is quite similar to discrete wavelet transform (DWT) for low frequency region [28–31,19]. The transformation can be achieved by implementing a pair of low-pass ($h(k)$) and high-pass ($g(k) = (-1)^k h(1-k)$) wavelet filters, also known as quadrature mirror filters (QMF). These quadrature mirror filters are constructed using user defined wavelet function $\psi(t)$ and its corresponding scaling function $phi(t)$. Mathematically, these can be expressed as:

$$\phi(t) = \sqrt{2}\sum_k h(k)\phi(2t-k) \quad (1)$$

$$\psi(t) = \sqrt{2}\sum_k g(k)\phi(2t-k) \quad (2)$$

$$\text{where } \sum_m h(k) = \sqrt{2}, \text{ and, } \sum_m g(k) = 0 \quad (3)$$

Employing the above wavelet filters, a signal can be decomposed to generate a set of low and high frequency components, denoted as $a_{j,k}$ and $d_{j,k}$, respectively.

$$a_{j,k} = \sum_m h(2k-m)a_{j-1,m} \quad (4)$$

$$d_{j,k} = \sum_m g(2k-m)a_{j-1,m} \quad (5)$$

In the above equations, j represents the level of decomposition. The "approximation", $a_{j,k}$, and the "detail", $d_{j,k}$, coefficients for wavelet scale 2^j can be obtained by convolving the approximation coefficients at the previous level $(j-1)$ with the low-pass and high-pass filter coefficients, correspondingly. Subsequently, the detail coefficients can be decomposed to a desired level j. In order to achieve this, the above equations can be unified as:

$$U_{2n}(t) = \sqrt{2}\sum_k h(k)u_n(2t-k) \quad (6)$$

$$U_{2n+1}(t) = \sqrt{2}\sum_k g(k)u_n(2t-k), \quad (7)$$

where $U_0(t) = \phi(t)$ and $U_1(t) = \psi(t)$. The desired decomposed signals can be achieved by the following expressions.

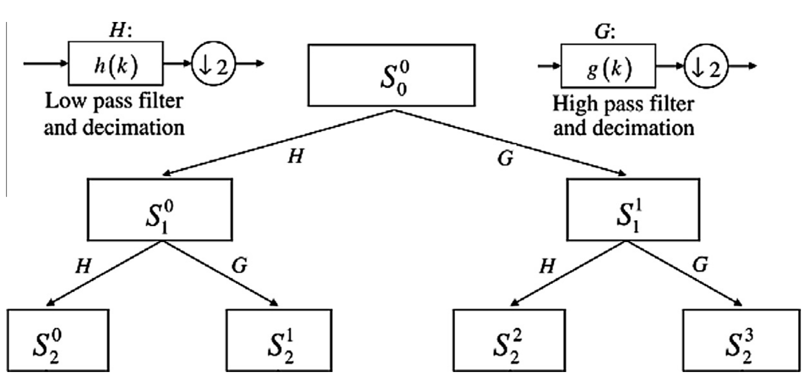

Fig. 1. Decomposition of wavelet packet transform (WPT).