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A new performance evaluation scheme for jet engine vibration signal denoising

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ABSTRACT

Denoising of a cargo-plane jet engine compressor vibration signal is investigated in this article. Discrete wavelet transform and two families of *Donoho–Johnston* and *parameter method* thresholding, are applied to vibration signal. Eighty four combinations of wavelet thresholding and mother wavelet are evaluated. A new performance evaluation scheme for optimal selection of mother wavelet and thresholding method combination is proposed in this paper, which is make a trade off between four performance criteria of signal to noise ratio, percentage root mean square difference, Cross-correlation, and mean square error. *Dmeyer* mother wavelet (dmey) combined with *Rigorous SURE* thresholding has the maximum trade off value and was selected as the most appropriate combination for denoising of the signal. It was shown that inappropriate combination leads to data losing. Also higher performance of proposed trade off with respect to other criteria was proven graphically.

1. Introduction

It is obvious that there is no signal without noise in the real world data. *Intrinsic noises* such as white noise, shot noise and diffusion noise, and *extrinsic noises* such as environmental perturbations and crosstalk noises, are two inevitable sources of noise [1]. So, denoising is a basic and principal step in signal processing. But when the early and novel faults are probed in a signal, removing the noise is a more serious and sensitive job. Some of the faults and abnormal operations in the machines, in the early stages of growth, are indicated by weak and low amplitude in time history of machine vibration signal which is maybe suspected noise or vice versa. But in general, when the processing signal is similar to noise fluctuations, the noise is more significant. In other words, the lower ratio of signal to noise is more influenced against noise.

Monitoring of high integrity systems such as jet engine compressors that usually rotate at high speeds and heavy loads is necessary. Because of rolling bearings, vibration condition monitoring is the best solution of monitoring in these devices. But recorded signals are usually affected by various noises. Such a raw signal must be cleaned primarily for the next processes.

Wavelet transform provides an advanced denoising tool which is based on thresholding. Choosing an appropriate threshold is the main question in many threshold selection procedures. The result of a small threshold may be close to the input signal in a least squares sense, whereas this result may still be too noisy. A large threshold leads to sparse representation by setting to zero the wavelet coefficients [2] that is not desirable for detection of incipient faults in machines.

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For the first time, Donoho and Johnston developed *wavelet shrinkage* which is a denoising method by thresholding in wavelet domain [3]. In their approach, thresholding can be applied by either implementation of hard or soft. Finally Donoho et al. developed a family of thresholding methods includes *Sqtwolog, Heursure, SURE and Minimax* [4–7]. Parameter methods were developed by Birgé-Massart which includes penalized method [4]. Angelini and Vidakovic [8] proposed a method for wavelet filtering of noisy signals when prior information about the energy of the signal is available. This method is suited when signal to noise ratio is low. Luo and Zhang [9] were discussed wavelet denoising, noise estimation methods, hard and soft thresholding, and fixed or level-dependent thresholding methods.

Performance comparison of various thresholding methods have been presented in many publications [10–12]. In some of them, thresholding methods are applied to biological signals such as electrocardiogram (ECG) and electroencephalogram (EEG) signals. Karthikeyan et al. [13] applied four thresholding methods of Universal, Heursure, SURE and Minimax, combined with three mother wavelets of "db4", "coif5" and "sym7" on ECG signals. Four different performance criteria such as, Signal to Interference Ratio (SIR), noise power, Percentage Root Mean Square Difference (PRD), and periodogram of Power Spectral Density (PSD), were considered to select the appropriate wavelet function and thresholding rule for efficient noise removal methods. No additive noise was considered for signal and mother wavelet of coif5 combined with SURE thresholding method was recognized for the real ECG signal. Al-Qazzaz et al. [14] applied forty five mother wavelets combined with four thresholding methods of Sqtwolog, Rigrsure, Heursure and Minimax to a real EEG signal. The noise was considered as an unknown (there was no additive noise) and four evaluating criteria which include Signal to Noise Ratio (SNR), Peak Signal to Noise Ratio (PSNR), Mean Square Error (MSE) and cross correlation method (xcorr). In some articles an additive known noise such as white Gaussian noise was added to a real or simulated signal, and performance analysis of thresholding methods were investigated [15–18]. Kabir and Shahnaz [18] combined Empirical Mode Decomposition (EMD) and Discrete Wavelet Transform (DWT) for ECG signal denoising. They used three standard metrics namely SNR, MSE and PRD for performance analysis.

There are a few publications in the field of jet engine vibration signal denoising. Feng et al. [19] studied denoising problem of acoustic emission signal of a pump bearing, by using DWT thresholding methods. Two families of Donoho-Johnston methods and parameter methods were compared in terms of performance. Chao and Shanxue [20] studied the denoising problem of actual pressure signal of the oil pipeline leakage. They used DWT and four thresholding methods of Donoho-Johnston family. The performance of the methods was compared by means of graphic and standard deviation where Sqtwolog method was selected. Wang and Jiang [21] used an adaptive wavelet denoising method to reduce noise of the vibration signal of a jet engine for the purpose of fault detection and diagnosis. Cui et al. [22] studied the wavelet noise reduction methods on vibration signals of an aircraft rolling bearings. Performance of the method demonstrated graphically. Bailing et al. [23] studied the wavelet-based applications in denoising of aero-engine signals which include the inlet dynamic pressure signal, the engine vibration signal, the compressor signal, the transitional signal, the engine vane ultrasonic testing-signal, the lubricating oil testing-signal, etc. Mercorelli [24] proposed a noise removal algorithm which uses wavelet packets for use in the online, instantaneous detection of changing harmonic signals. He did not use classical thresholding techniques in his proposed cleaning method. Some studies have used other methods than wavelet and its applications for denoising of jet engine signals [25–27].

The main goal in this article is selection of an appropriate combination of mother wavelet and thresholding rule for denoising of vibration signal of a jet engine compressor; which was not presented in none of the literatures above. DWT and wavelet packet decomposition are two

DWT and wavelet packet decomposition (WPD) [28] are two transforms which are used widely in denoising procedures. As the discrete wavelet transform (DWT) and its applications are well known for the most of authors and researchers, it is not presented in this article. This subject was studied in [29–32] in detail.

2. Problem formulation

The common form of a denoising problem is as follows:

$$s_i = f(t_i) + \Lambda e_i \quad i = 1 \ldots n \tag{1}$$

where s_i are the noisy data, f_i are the original (clean) signal, e_i are *iid N(0,1)*, and Λ is the noise level that may be known or unknown. It was mentioned above that in some of the papers the Gaussian white noise was added to an original clean given signal and attempted to remove the noise and recover the original signal by applying their denoising methods. Actually original signal (s_i) and the noise (σe_i) have been considered as known, on these types of papers. But in the real and practical conditions, neither the original signal nor the noise is defined and known. Removing the noise from the real signal with small error is the purpose of denoising.

Applying the wavelet transform to (1), leads to the following relation:

$$s_{jk} = c_{jk} + \Lambda \tilde{e}_{jk} \tag{2}$$

where s_{jk} is the wavelet coefficients of y_i, c_{jk} is the wavelet coefficients of f_i and $\tilde{e}_{jk}$ is the wavelet coefficients of e_i, where, j denotes the decomposition level and k is the index of the coefficient in this level. As the analysis of the signal in the wavelet domain has some advantages; recovering the f in (1) has been replaced with recovering the c_{jk} in (2) [33]. Removing the