Journal of Sound and Vibration 425 (2018) 208–220

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

A novel rail defect detection method based on undecimated lifting wavelet packet transform and Shannon entropy-improved adaptive line enhancer

Qiushi Hao [a], Xin Zhang [a,*], Yan Wang [a], Yi Shen [a], Viliam Makis [b]

[a] *Department of Control Science and Engineering, Harbin Institute of Technology, 150001, PR China*
[b] *Department of Mechanical and Industrial Engineering, University of Toronto, M5S 3G8, Canada*

ARTICLE INFO

Article history:
Received 16 November 2017
Received in revised form 26 February 2018
Accepted 5 April 2018

Handling Editor: K. Shin

Keywords:
High speed
Rail defect detection
Undecimated lifting wavelet packet transform
Adaptive line enhancer
Shannon entropy

ABSTRACT

Acoustic emission (AE) technology is sensitive to subliminal rail defects, however strong wheel-rail contact rolling noise under high-speed condition has gravely impeded detecting of rail defects using traditional denoising methods. In this context, the paper develops an adaptive detection method for rail cracks, which combines multiresolution analysis with an improved adaptive line enhancer (ALE). To obtain elaborate multiresolution information of transient crack signals with low computational cost, lifting scheme-based undecimated wavelet packet transform is adopted. In order to feature the impulsive property of crack signals, a Shannon entropy-improved ALE is proposed as a signal enhancing approach, where Shannon entropy is introduced to improve the cost function. Then a rail defect detection plan based on the proposed method for high-speed condition is put forward. From theoretical analysis and experimental verification, it is demonstrated that the proposed method has superior performance in enhancing the rail defect AE signal and reducing the strong background noise, offering an effective multiresolution approach for rail defect detection under high-speed and strong-noise condition.

1. Introduction

Nowadays, under rapid development of high-speed railway, Acoustic Emission (AE) technology stands out as a dynamic passive non-destructive fault detection method, owing to its ability to reflect subliminal activities in rails, such as interior fatigue cracks and surface abrasions. Its feasibility for rail defect detection has been proved in laboratory and field by authors [1]: invented a rail-track and presented an experimental study on the applicability of AE for defect diagnosis. It was also found that the AE technique can be a non-destructive testing tool of rails under operation [2]. Additionally, possibilities of AE testing of rails on a bridge were investigated in Ref. [3]. [4] presented a laboratory study on the interaction of wheel-trail contact using AE in wheel/rail defect detection. Moreover, field experiments were conducted on real rail and wheels, which validated the diagnostic potential of AE technique [5].

Affected by the inevitable background noise derived from wheel-rail contact rolling, AE detection has a big problem of identifying the valid signal. In high-speed condition, rail defects are mainly caused by fatigue crack expansions, while the

* Corresponding author.
E-mail addresses: hqs1991@163.com (Q. Hao), zhangxin7030@gmail.com (X. Zhang), wyabc@hit.edu.cn (Y. Wang), shen@hit.edu.cn (Y. Shen), makis@mie.utoronto.ca (V. Makis).

https://doi.org/10.1016/j.jsv.2018.04.003
0022-460X/

strong contact rolling noise is motivated by rail surface abrasion with different energy distribution compared to the former in frequency domain [6]. Thus, among the investigated denoising method such as Empirical Mode Decomposition (EMD) [7], Independent Component Analysis (ICA) [8], Principal Component Analysis (PCA) [9], high order statistics-based denoising [10], etc, wavelet transform-based multiresolution analysis has achieved the best performance and has been widely applied due to its excellent time-frequency localizing property [11–13]. However, traditional wavelet denoising methods such as threshold denoising and modulus maximum denoising are not enough for strong noise situation. In this case [14], proposed a rail defect detection method based on the wavelet transform in which Shannon entropy of the coefficients varying with a time window was calculated to detect the rail defect. By taking advantage of the Shannon entropy-related feature and careful selecting of the time window, this approach is capable of detecting the defects under 124 km/h. Whereas, this method is highly dependent on the time window, and can only detect the occurrence of the rail defect while the time series containing more information for further analysis of the defect cannot be obtained. In order to address these issues, multiresolution analysis is combined with an adaptive denoising method in this paper. Here, not only the strong contact rolling noise is reduced, also the weak rail defect signal is enhanced.

In our case, the main components of contact rolling noise are low-frequency. However, AE signals of cracks have wider distributions, which are composed by both low-frequency components and high-frequency counterparts [6]. In order to reduce the impact of the overlap, it is favorable to have a finer division of the frequency axis. Since Wavelet Packet Transform (WPT) [15,16] inherits all the merits of wavelet transform and further decomposes the detail coefficients, it is better than wavelet transform in this context. Moreover, the magnitude of contact rolling noise will rise along with the increasing speed. The strong noise in high-speed condition cannot be easily removed. Wavelet transform and WPT have a downsampling step that halves the length of coefficients by each decomposition. In this case, denoising of the decomposed wavelet coefficients is difficult to meet high accuracy demand with large sparsity. In order to overcome the sparsity problem in multi-decomposition, Undecimated Wavelet Transform (UWT) removes the downsampling step in the transform and keeps the size of each group of coefficients as large as that of the original signal [17]. Therefore, Undecimated Wavelet Packet Transform (UWPT) is favorable for our problem, where denoising on the undecimated wavelet coefficients is more elaborate with higher effectiveness. Furthermore, to deal with the increased calculation amount of UWPT, lifting scheme is introduced, which has equivalent performance while halves the computational complexity. By now, lifting scheme-based UWPT has been tested on gearbox fault diagnosis [18], gasoline engine valve trains monitoring [19], and bearing fault detection [20], where it shows good performance in vibration fault signal detection. Therefore, in the present work, for multiresolution analysis of rail defect AE signals, UWPT is conducted by lifting scheme for elaborate denoising.

Aiming to adjust the transform to the signal of interest, the idea of adaptation has been introduced into wavelet transform for many years. Within adaptive filtering structure, Adaptive Line Enhancer (ALE) has benefits of enhancing specific signal and reducing broadband random noise without help of their prior knowledge [21]. Regarding the stochastic AE signals of rail defects and the speed dependent contact rolling noise in our research, ALE stands out as a suitable defect detection method. However, in the case of traditional ALE, the updating process of adaptive weight parameters merely relies on a convergence criterion constituted by the error, leaving intrinsic information of the wanted signal wasted. Researches have been done to improve this situation. A feedback ALE is proposed in Ref. [22], which takes advantage of the output and provides equivalent performance with shorter adaptive filter length. In paper [23], the singularity of the desired signal is featured by implanting a Singular Spectrum Analysis (SSA) into a traditional structure of ALE. Moreover, mutual information is utilized to constitute a frequency-dependent step size in ALE for harmonic noise reduction [24]. In our case, with respect to the impulsive property of a rail crack signal, Shannon entropy of the signal is taken advantage of. Considering the fact that large value of Shannon entropy represents high disorder of the signal, Shannon entropy of contact rolling noise is bigger than that of the crack signals. Therefore, a Shannon entropy-improved ALE method for lifting-based UWPT coefficients denoising is proposed as a rail defect detection method under high-speed condition.

The rest of this paper is organized as follows. Section 2 reviews the basic theory of lifting scheme-based UWPT, and then the Shannon entropy-improved ALE denoising method is proposed. Theoretical analysis and derivation of the adaptive update equation of weight parameters are presented as well. Afterward, a corresponding rail defect detection plan is proposed. Section 3 gives a brief introduction of the experiments from which the contact rolling noise and rail defect AE signals are acquired. In Section 4, the proposed method is analyzed and validated comparatively. Finally, conclusions are drawn in Section 5.

2. Denoising method based on undecimated lifting wavelet packet transform and Shannon entropy-improved ALE

2.1. Undecimated lifting wavelet packet transform

Fig. 1 gives an example of a wavelet packet decomposition tree with 3 levels, where $\mathbf{H}(z)$ and $\mathbf{G}(z)$ are the low-pass filter and high-pass filter in Mallat algorithm, $W_{j,k}(j = 0, 1, 2, 3, k = 0, 2, ..., 2^j - 1)$ represent the transform coefficients of node (j,k), N is the length of the signal, and f is the frequency axis. Through multiscale decomposition, the energy of each wavelet packet plays an important role in signal analysis, which will reveal participation of that packet in the combination of the original signal. In other words, these energy features can reflect unique characteristics of the original signal in frequency domain. The finer the frequency is divided, the more elaborate the energy distribution will be.