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Adaptive noise cancelling and time–frequency techniques for rail surface defect detection

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ABSTRACT

Adaptive noise cancelling (ANC) is a technique which is very effective to remove additive noises from the contaminated signals. It has been widely used in the fields of telecommunication, radar and sonar signal processing. However it was seldom used for the surveillance and diagnosis of mechanical systems before late of 1990s. As a promising technique it has gradually been exploited for the purpose of condition monitoring and fault diagnosis. Time–frequency analysis is another useful tool for condition monitoring and fault diagnosis purpose as time–frequency analysis can keep both time and frequency information simultaneously. This paper presents an ANC and time–frequency application for railway wheel flat and rail surface defect detection. The experimental results from a scaled roller test rig show that this approach can significantly reduce unwanted interferences and extract the weak signals from strong background noises. The combination of ANC and time–frequency analysis may provide us one of useful tools for condition monitoring and fault diagnosis of railway vehicles.

1. Introduction

The interest in the ability to monitor system structure integrity and detect damage at the earliest possible stage is persistent throughout the civil, mechanical and aerospace engineering communities. Due to the fact that many such systems are complex, dynamic and time-varying, the necessary signal pre-processing and analysis techniques are required in order to extract useful information from raw signals. The signal pre-processing methods are to condition the raw signals and make every effort to eliminate the unwanted noise from the raw signals while signal analysis techniques are to extract signal features from the conditioned raw signals. One of the well-known techniques in communication area for raw signal pre-processing is adaptive noise cancellation (ANC). ANC is a technique which is very useful to remove additive noises from the contaminated raw signals. It was firstly reported in 1975 that ANC was successfully applied to subtract a pregnant woman's heart rate interference from the very weak foetus heart rate monitoring [1]. Then this technique was widely used in telecommunication, radar and sonar signal processing because of its good performance in applications of noise reduction. The results from experiments of speech enhancement and speech recognition are especially encouraging [2,3]. After the late 1990s, ANC has also found its application in the area of condition monitoring and fault diagnosis [4–6].

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The signal analysis techniques for condition monitoring can be classified into time-domain analysis, frequency-domain analysis, and joint time–frequency domain analysis. The time-domain analysis methods are to identify the quantities of a signal related to its time behaviour such as the maximum amplitude, root mean square (rms) value, kurtosis and crest factor of a signal, while the frequency-domain analysis methods are to analyse the contents of a signal related to its frequency behaviour, like power spectrum, cepstrum and higher-order spectrum of a signal [7–11]. Since machinery operating in non-stationary mode generates a signature which at each instant of time has a distinct frequency, it is desirable to use time–frequency analysis technique to see how frequency changes with time. Time–frequency analysis techniques had found limited use in the past, except for the last two decades, primarily due to their very high computational complexity and the lack of adequate computing resources of the time. However the fast advances of computers in the last 10 years and the outstanding potential of new time–frequency method like wavelet transform has made them recently a very active area of research [12–16].

Rail and wheel faults like rail surface crack, squats, corrugation, and wheel flat can cause large dynamic contact forces at the wheel–rail interface and lead to fast deterioration of the track. Early detection of such defects is very important for timely maintenance. Extensive theoretical and experimental works have been carried out to investigate what is the best way to identify rail and wheel faults. Jun et al. [17] suggested a method of estimating irregularities in railway tracks using acceleration data measured from high-speed trains. A mixed filtering approach was proposed for stable displacement estimation and waveband classification of the irregularities in the measured acceleration. Kawasaki and Youcef-Toumi [18] presented a method based on the car-body acceleration for track condition monitoring. But the car-body acceleration is highly dependent on the primary and the secondary suspension, so the effect of the track irregularities is difficult to extract from such data. Marija and Zili et al. [19] attempted to determine a quantitative relationship between the characteristics of the accelerations and the track defects, axle box acceleration at a squat. The dynamic contact was simulated through finite element modelling. Belotti et al. [20] presented a method of wheel flat detection using a wavelet transform method. In their study, a series of accelerometers were put under the rail bed to detect the impact force caused by a wheel flat and the signals were analysed based on the wavelet property of variable time–frequency resolution.

This paper made an attempt to use the ANC technique as signal pre-processing in order to increase the signal-to-noise ratio of a signal and also to use time–frequency analysis techniques for time-varying impact excitation caused by rail and wheel surface defects. The paper is presented as follows. Section 2 introduces the basic concepts for ANC and four time–frequency analysis techniques (Short-Time-Fourier-Transform, Wigner–Ville-Transform, Choi-Williams-Transform and Wavelet Transform). In Section 3 the experimental test rig is described. Experimental results and discussion are shown in Section 4. Finally conclusions are given in Section 5.

2. ANC and time–frequency analysis theories

2.1. Adaptive noise cancelling technique

The principal of ANC is that it makes use of an auxiliary or reference input derived from one or more sensors located in points in the noise or unwanted signal field where the concerned signal is weak. The input is filtered and subtracted from a primary input containing both signal and noise. Because the filtering and subtraction are controlled by an appropriate adaptive process, noise reduction can be accomplished with little distorting the signal or increasing the output noise level. Fig. 1 presents the basic philosophy of ANC. It can be seen that the primary input is a combination of the signal source $\boldsymbol{s}$ and the noise source $\boldsymbol{n}$. The auxiliary input is the noise source $\boldsymbol{n_1}$ which is correlated with the primary input noise source $\boldsymbol{n}$ and is filtered to produce an estimation of the noise source $\hat{\boldsymbol{n}}$. The system output $\hat{\boldsymbol{s}}$ is the source estimation which is the signal $\boldsymbol{s}$ plus noise source $\boldsymbol{n}$, and then minus the estimation of noise source $\hat{\boldsymbol{n}}$ with the adaptive filter. If $\boldsymbol{n}$ and $\hat{n}$ are close enough, a better estimation of signal source $\hat{s}$ can be obtained. However there are some conditions attached for this method. The first condition is that the signal source $\boldsymbol{s}$ is uncorrelated with noise signal $\boldsymbol{n}$ and $\boldsymbol{n_1}$. The second condition is that in order to produce the best estimation of the signal source the ANC system output $\boldsymbol{e}$ has to be minimized in term of least means square of power as follows [21]:

$$\boldsymbol{e} = \hat{\boldsymbol{s}} = (\boldsymbol{s}+\boldsymbol{n}) - \hat{\boldsymbol{n}} \tag{1}$$

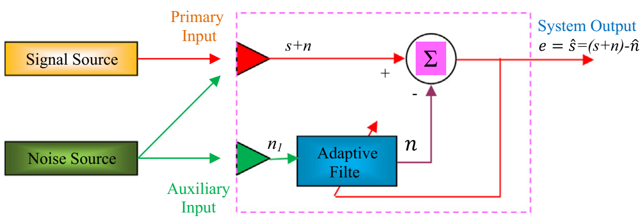

Fig. 1. The adaptive noise cancelling concept.