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Study of pre-processing model of coal-mine hoist wire-rope fatigue damage signal

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ABSTRACT

In this paper, we propose a pre-processing method for the detection of wire-rope signals. This is necessary because of the lack of processing methods that are currently employed. First, we investigated the one-dimensional discrete morphological and wavelet transform. Then, we developed a pre-processing model that is based on the morphological wavelet-filtering algorithm. We then proposed a modified morphology filtering algorithm. We also designed an experiment platform for wire-rope detection. Eight levels of localized flaws (LFs) and damage were formed in the wire-rope specimen. We performed a series of experimental studies, and the results show that the proposed method can effectively filter the drift signal. The signal-to-noise ratio of the new filtering algorithm was over 26 dB. The signal-to-noise ratio of the existing method is less than 15 dB, and the noise-signal ratio of the new filtering algorithm has improved by 73%. Based on our results, the filtering effect of the proposed method is better than that of the present method. This study has great significance and practical value in engineering applications.

1. Introduction

Wire rope is widely used in China's coal mining industry because of its advantages, which include good elasticity, strength, and light weight. In addition, it is a key component in the hoisting of equipment in the main and auxiliary shafts of a coal mine. However, a wire rope that has been subjected to long-term bending over a sheave will result in cut wires, wear, and corrosion. Wire-rope failures are often associated with fatigue damage. If there is a failure in the coal-mine hoist wire rope, significant damage may result. In order to prevent such accidents, many local and international experts and scholars have proposed different automatic-detection methods for wire-rope damage, and the electromagnetic testing method is considered to be the most reliable. However, current detection methods based on electromagnetic testing are still inadequate, and function only as supplementary methods for artificial visual examination. Therefore, the testing of coal-mine hoist wire ropes is still considered to be a difficult problem globally, and the absence of accurate and reliable pre-processing methods for online detection of wire-rope signals is believed to be one of the main reasons.

At present, wavelet transform is a wire-rope detection signal pre-processing method that is widely used, and it has good performance results. Jing et al. used this method to combine the soft and hard thresholds. They constructed a scale-effect threshold function to quantify the wavelet coefficients in different decomposition scales. In addition, the high-frequency signal noise is filtered by this method [1]. Zhang and Lu et al. use dyadic wavelet-transform technology to decompose and reconstruct the broken wire signals of the wire rope, reducing the high frequency interference signal [2,3]. Zhou et al. use the multi-resolution analysis characteristic of the wavelet transform to filter the high-frequency noise of the damage signal and the wire-rope strand interference signal [4]. Xia et al. used the method of multi-wavelet threshold function to filter the signal noise and to preserve a small singularity signal based on the wavelet threshold de-noising method studied by Donoho [5,6].

The wavelet transform method is used to extract singularity damage signals and to filter interference signals by the local analysis of temporal and spatial frequency. This method enables a better detection of the wire rope in a static state. During the detection of the coal-mine hoist wire rope, the shaking of the wire rope will be affected by its operating speed and tension. Further, the detection signal can vary as a result of the shaking. The wavelet-transform method is not sensitive to the low-frequency drift signal, which changes with velocity, and requires extensive calculations. As a result, the low-frequency drift noise signal often cannot be filtered in time. This affects the subsequent quantitative identification of the signal, which results in an identification error.

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It is therefore necessary to improve the existing signal-filtering method based on wavelet transformation.

Morphological filtering is a new nonlinear filtering method that was recently developed based on mathematical morphology. It uses the opening-closing and closing-opening operations, which consist of the weighted combination of different-sized structural elements, to effectively filter the drift and noise in the signal under the condition where there is no blurring between the global and local features of the signal. This method has the advantages that include a good filtering effect, fewer computations, and fast speed. Presently, the morphological filtering method has been applied in two-dimensional (2D) image signal processing and one-dimensional (1D) biomedical signal correction. The application of morphological filtering to the online detection of wire-rope signals has been somewhat limited, and few related studies have been performed. In this study, we combined the morphological filter and wavelet transformation method, and used the morphological wavelet transform method to process the online detection signal of wire ropes. This study has important theoretical and practical significance as it is expected to improve the automatic detection technology employed with coal-mine hoist wire rope, and will ensure the safe usage of coal-mine wire ropes.

2. Discrete morphological transform

The wire-rope detection signal can be expressed as a 1D discrete gray signal based on the sampling distance. The basis of the structure of the digital morphological filter is a discrete morphological transformation. Therefore, in this paper, we focus only on the 1D discrete gray morphological transformation, which mainly includes expansion, corrosion, and open and close operation.

Assume that the sampling signal $f(m)$ is a discrete function. The domain of the function is $F=\{0,1,2,\ldots,M-1\}$. The structural element $g(m)$ is another discrete function, and its domain is $G=\{0,1,2\ldots,N-1\}$. $g(m)$ is a limited subset of F, $N<M$, and the four basic forms of $f(m)$ with respect to $g(m)$ are defined as follows [7,8].

The expansion and corrosion operation of $f(m)$ with respect to $g(m)$ are respectively:

$$(f\oplus g)(m)=\max\{f(m-n)+g(n)\}$$
$$n=0,1,2,\ldots,N-1$$
$$m=N-1,N,N+1,\ldots,M-1 \tag{1}$$

$$(f\Theta g)(m)=\min\{f(m+n)-g(n)\}$$
$$\begin{aligned}&n=0,1,2,\ldots,N-1\\&m=0,1,2,\ldots,N-M\end{aligned} \tag{2}$$

The open and close operations of $f(m)$ with respect to $g(m)$ are respectively:

$$(f\circ g)(m)=[(f\Theta g^{*})\oplus g](m) \tag{3}$$

$$(f\cdot g)(m)=[(f\oplus g^{*})\Theta g](m) \tag{4}$$

where g^{*} is the origin symmetric function of g.

According to formulas (1) and (2), the expansion and corrosion operations are equivalent to the inhibition of the signal peak and valley values, respectively. The specific width pulse in the signal is filtered out. Again, according to formulas (3) and (4), the discrete morphological opening and closing operation is composed of expansion and corrosion operations in a specific manner. Therefore, the morphological opening and closing operation smoothes the signal based on the basic expansion and corrosion operation. The morphological opening and closing operations comprise a very simple morphological filter. The filtering effect is mainly decided by the specific combination form of the opening and closing operation as well as the structural element of the operation. Under normal circumstances, if the width of the structural element in the operation is W, pulse signals with width less than W will be filtered out through the opening and closing operation.

3. Wavelet transform

Traditional signal theory is established based on Fourier analysis. The wire-rope detection signal is a non-stationary signal in the spatial domain. Information about broken wires is considered to be a singularity of the detection signal. As a type of global change, the Fourier transform has some limitations. Wavelet transform is one of the most popular candidates for time–frequency transformations, as it can focus on any signal detail and solve the difficult problem associated with the Fourier transform.

Assume that $f(x)$ is a function of the square integrable functions. That is: $f(x)\in L^{2}(R)$. Then, the wavelet transform of $f(x)$ is defined as [9]:

$$\begin{aligned}W_f(a,b)&=\langle f,\psi_{a,b}(x)\rangle=\int_{-\infty}^{+\infty}f(x)\psi_{a,b}(x)dx\\&=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}f(x)\psi\left(\frac{x-b}{a}\right)dx\end{aligned} \tag{5}$$

where a and b are the scaling and time shift factors, respectively, and $\psi_{a,b}(x)$ is a sequence of wavelet functions.

The wire-rope detection signal is a 1D discrete signal. Therefore, in the numerical calculation, the scaling and time-shift factors of the wavelet transform need to be separated. The discrete method is shown below:

Let the scaling factor $a=a_0^m$, $b=ka_0^nb_0$, where $a_0>1, b\neq 0$, and m and n are integers. Then, the wavelet function is:

$$h_{m,n}(x)=\frac{1}{\sqrt{a_0^m}}h\left(\frac{1}{a_0^m}x-nb\right) \tag{6}$$

Let $h_{m,n}(x)$ constitute the standard orthogonal basis under the appropriate choice of h, a_0, and b_0.

4. Pre-processing model of wire-rope fatigue damage signal

In order to effectively filter the damage interference signal of a wire rope, and to achieve the online detection of a coal-mine hoist wire rope, in this study we designed a pre-process model of wire-rope damage signals. The processing model is shown in Fig. 1,

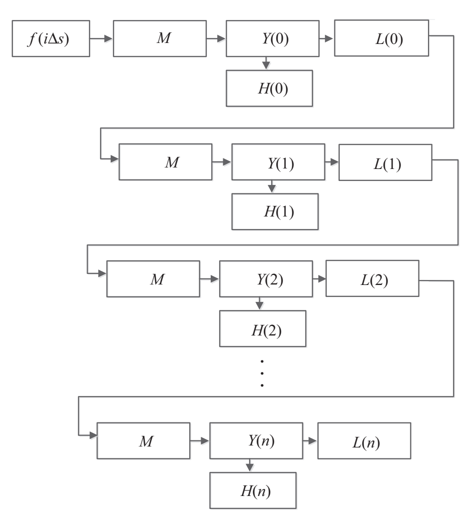

Fig. 1. Wire-rope fatigue damage signal processing model.