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Singularity Detection of Magnetic Memory Signal of Steel-Cord Conveyor Belt

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Abstract

Metal magnetic memory technology was an important method for detecting the steel-cord conveyor belt early fault, characteristics of magnetic memory signal extraction is critical for judging of the conveyor belt failure. Generally using of magnetic memory signal maximum gradient value can quickly judge the stress concentration zone, but the magnetic memory signal is susceptible to effected by environmental and noise; In view of the weak and non-stationary characteristics of magnetic memory signal, this paper has proposed the singularity detection method based on wavelet transform modulus maximum for metal magnetic memory signal, the method could exactly judged the stress concentration zone of joints and located the fault points of the steel-cord belt, the characteristic gradient of magnetic memory signal and the Lipschitz exponent were extracted. The result of simulation indicated the technology was effectively for judging the stress concentration zone and fault point.

Keywords*: steel-cord conveyor belt, metal magnetic memory, wavelet transform, stress concentration zone, singularity detection*

1. Introduction

The steel cord conveyor belt is an adhesive tape embedded wire rope, because of its great tensile strength it is often used in long-distance, large capacity, big dip angle mines, docks, power and other departments. A long distance steel cord conveyor belt is connected with a few or dozens of adhesive tape with a special optimum technology, the strength of the joints in the process of long-term use is difficult to achieve the required retention, and therefore the joints become lowest tensile strength and the weakest link in the whole tape [1-2]. During operation the joints of steel cord conveyor belt suddenly happen twitching and fracture, ranging from loss of production to heavy casualties. Judging from the exiting steel cord convey belt breaking accidents in coal enterprises, mainly caused by fracture, twitching, broken wire and corrosion of steel cord belt vulcanized tape joints. Therefore, how to predict the bad situation of joints and the entire of steel cord conveyor belt in advance has become a top priority for the safe transportation of steel cord conveyor belt [3].

At present, the fault detection methods of steel cord conveyor belt joints are manual inspecting, magnetic flux leakage testing, X-ray inspection, as well as the latest development of metal magnetic memory testing method [4]. Manual inspection can only check those obvious cracks and broken wires in the static situation; The magnetic flux leakage detection [5] only can detect the defects of steel cord surface and near surface, and cannot check the internal early damage; X-ray detection [6] is production workers in the still conveyor use a portable X-ray machine to detect the conveyor belt damage with fixed-point detection, which can be more intuitive to see the joints rope substantial twitching and fracture; but it is not easy to see the steel cord corrosion and small amplitude broken wires and twitching situation, which will leave great risks to the safe operation of the conveyor belt. The metal magnetic memory testing [7] is a new method, which can accurately detect the dangerous parts characterized with stress concentration zone of the steel cord conveyor belt, metal magnetic memory technology is the one of effective non-destructive testing methods which can detect the early fault of metal parts.

Generally the stress concentration zone of the conveyor belt can be determined through the gradient maxima of magnetic memory signal, however, the gradient is quite sensitive to the

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noise, it is difficult to extract the gradient characteristic quantities in a complex environment [8-11]. If there are twitching and fracture taking place at the steel cord conveyor belt joint, the magnetic memory signals of the stress concentration zone will be abruptly changed. Fourier Transform can only determine the whole singularity of the signal, and is difficult to locate the spatial location and ensure distribution of the singular points. Using good time-frequency domain localization properties of wavelet transform can effectively analyze the signal singularity, Therefore by comparison, in this paper we adopt wavelet singularity detection technology to analyze the metal magnetic memory signal of steel cord conveyor belt, to judge the local stress concentration zone of steel cord conveyor belt, and through the wavelet transform modulus maxima method to detect the singular points of the magnetic memory signal of steel core, it also can quantitatively determine the value of the singularity based on Lipschitz exponent calculated. Thus, the method can accurately diagnose the twitching and fracture location of steel cord belt joint.

2. Principle of Metal Magnetic Memory Testing

The steel cord conveyor belt during work period, by the combined effect of the natural geomagnetic field and cyclic loading, the magnetic domain organization directed and irreversible re-orientation of the magnetostriction effect will be produced of the stress concentration zone at internal steel cord joints, this irreversible changes of the magnetic state will be retained without the work load, resulting in stress deformation concentration zone to form a maximum self-leakage magnetic field Hp, the tangential component Hp(x) of self-magnetic flux leakage reaches to maximum and normal component Hp(y) passes through zero in the maximum stress concentration zone (see Figure 1). The method of determine steel cord belt stress concentration zone is: find out the region where the normal component of self-leakage magnetic field on the surface of steel core strongly changes in the line of zero, and calculate the component gradient value K, the gradient value is numerically equal to the modulus difference of the maximum value and the minimum value of magnetic field strength than the distance between two points. In short, the metal magnetic memory testing method can accurately detect the defect parts characterized by the stress concentration zone in the steel cord belt, which can further determine the occurrence of twitching and fracture region in the steel cord belt joint [12-16].

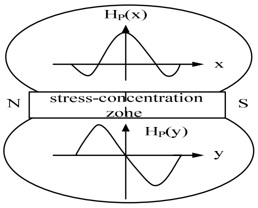

Figure 1. Principles of Metal Magnetic Memory Testing

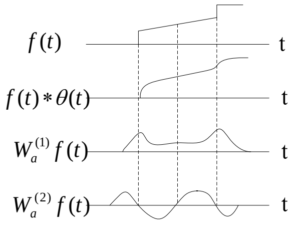

Figure 2. The relationship between signal mutations and wavelet modulus maxima

3. Wavelet Transform and Singularity Exponent of Signal

Singular signals are usually divided into two types: one is the edge mutation, which is equivalent to a step signal superimposed at mutations moment; the other is the peak mutations, corresponding to a shock signal superimposed at mutation moment. The singularity of steel cord magnetic memory signal to be analyzed in this article belongs to the first type. The singularity analysis of magnetic memory signals included locate the singular points and determine the value of the singularity two aspects. In the process of steel cord belt failure detection, leakage magnetic field will generate mutations of signal, joints signal mutation points is singular points of the signal, in mathematics, the Lipschitz exponent is used to quantitatively describe the singularity of the signal [17].

Suppose signal f(t), n is an integer of no negative, and $n \le \alpha < n+1$ if there is a constant $K>0$, one n number multinomial $f(t_0)$, signal f(t) nearby t_0 have:

$$\left|f(t)-f(t_0)\right| \le K\left|t-t_0\right|^{\alpha} \qquad \forall t \tag{1}$$

So call Lipschitz exponent of signal f(t) at t_0 α. Where $f(t_0)$ is f(t) the Taylor series within an area t_0.The signal singularity characterized by Lipschitz exponent α, the greater α the signal more smooth, the smaller α the greater singularity. If the signal has singularity at a point, then it can get wavelet transform modulus maxima at the point. Thus the signal singularity can be detected by wavelet transform coefficient modulus maxima.

3.1. Positioning of Signal Singular Point

Grossmann [18] had discussed how to use the time-frequency localization of wavelet transform features to local the singular position of detection signal. Suppose θ(t) is a low-pass smoothing function, and has the second derivative, and define

$$\psi^{(1)}(t)=\frac{d\theta(t)}{dt},\ \psi^{(2)}(t)=\frac{d^2\theta(t)}{dt^2}$$

Ψ(1)(t), Ψ(2)(t) meet with wavelet admissible condition, and can be used as mother wavelet. If θα (t) = (1/a)θ(t/a), then θα(t) is θ(t) extension at scale a. The wavelet transform of signal f(t) corresponding to mother wavelet Ψ(1)(t) at scale a as:

$$\begin{aligned} W_s^{(1)} f(t) &= f(t) * \psi_a^{(1)}(t) = f(t) * \left[a\frac{d\theta_a(t)}{dt}\right] \\ &= a\frac{d}{dt}\left(f(t) * \theta_a(t)\right) \end{aligned} \tag{2}$$

$$\begin{aligned} W_s^{(2)} f(t) &= f * \psi_a^{(2)}(t) = f(t) * \left[a^2\frac{d^2\theta_a(t)}{dt^2}\right] \\ &= a^2\frac{d^2}{dt^2}\left(f(t) * \theta_a(t)\right) \end{aligned} \tag{3}$$

From the above equation, f(t)*θ(t) play role of smoothing f(t), corresponding to the different scale factor α, The wavelet transform Wa(1)f(t)、Wa(2)f(t) are the first-order derivative and the second derivative of function f(t) after take smooth, the relationship among function f(t)、f(t)*θ(t)、Wa(1)f(t) and Wa(2) f(t) in Figure 2.

Figure 2 above shows that the singular point of signal f(t), by way of wavelet transform, correspond to the inflection points of f(t)*θ(t), correspond to the extreme value points of Wa(1) f(t), correspond to the acrossing zero points of Wa(2)f(t). Thus, if regarded the wavelet function as the first derivative of a smooth function, the wavelet transform modulus maxima points correspond to the mutation points or edge of the signal; if regarded wavelet transform as the second derivative of a smooth function, the mutation points or edge correspond to the crossing zero point of the signal wavelet transform coefficients. Therefore, making use of wavelet transform modulus maxima to detect the signal mutation points has significant advantages.

3.2. Judgment of the Extent of Signal Singularity

The above shows how to locate the singular points, and the following describes how to determine the extent of singularity. Mallat [19-20] gives the relationship between the performance of the wavelet transform modulus maxima multi-scale and Lipschitz exponent. Let f(t) be a compactly supported wavelet with n vanishing moments and n order continuously differentiable, there is A>0, if the wavelet transform of f(t) satisfy:

$$\left|W_f(s,t)\right| \le As^{\alpha} \tag{4}$$

Give the logarithmic on the both sides at the same time, namely:

$$\log\left|W_f(s,t)\right| \le \log A + \log s^{\alpha} \tag{5}$$

In the dyadic wavelet transform $s=2^j$, Lipschitz exponent α and the wavelet transform modulus maxima of the signal f(t) come into:

$$\log_2 \left|W_f(s,t)\right| \le \log_2 A + j\alpha \tag{6}$$

Lipschitz exponent α can be estimated according to this formula,

$$\alpha = \log_2 M_{i+1} - \log_2 M_i \tag{7}$$

Wherein $M_i=|W2^j f(x_k)|$, In (6), jα connects wavelet transform scale with Lipschitz exponent α, usually Lipschitz exponent α of the steel core defect signal based on the metal magnetic memory technology is α>0, Modulus maxima diminishes with scale increases or remains the same; but the Lipschitz exponent α of the noise signal is α<0, the corresponding the wavelet transform modulus maxima of noise decreases with scale. From here you can see that the Lipschitz exponent of the steel cord defect signal is different from noise signal. Therefore, the wavelet transform can locate the singular points of the useful signal with low signal to noise ratio [21-22].

4. Gradient Maxima Value and Singularity of The Magnetic Memory Signal

Twitching and fracture usually take place at the stress concentration zone of steel cord conveyor belt joints, the magnetic field will have mutations, and mutations of the signal contain the information needed. In this paper, through using metal magnetic memory to detect the stress concentrated zone of steel cord conveyor belt joint, and then locate the mutation points of the magnetic memory signals by using wavelet transform modulus maxima along the scale trends, through contrasting with the actual measurement failure location can be found in the conveyor belt. Implementation steps are as follows:

(1) Firstly, analyze the affection of background magnetic field to the acquisition of magnetic memory signal.

(2) Secondly, the magnetic memory signals through wavelet multi-scale decomposition to extract the approximate coefficients and detail coefficients of signal wavelet that can identify the singular points through the detail coefficients accurately. In the signal singularity detection, usually the wavelet function selected with a certain vanishing moments. Steel core magnetic memory signals with weak magnetic non-smooth features, many experiments found that the db4 wavelet function of decomposition scale at 7 is more appropriate, so that wavelet has the local characteristics of time-frequency two domain of signal, so that is conducive to detection of singular points of the magnetic memory signals.

(3) Finally, positioning the singular points generally take the dyadic wavelet transform algorithm from coarse to fine, and find the wavelet transform modulus of the various scales maxima in respectively, starting with the coarsest scale and then a one refinement until search for the smallest scale. The modulus maxima of high-frequency details will appear small offset due to the different scales, using the mean method, take the average of the modulus maxima. Modulus maxima in the average processing not only retained the peak positions but also good to remove the pseudo-extreme points. Wavelet transform modulus maxima curve along the direction of scale reducing within a cone to find the location of the signal singular points.

5. The Simulation

Using EMS-2003 Intelligent Magnetic Memory/ Eddy Current Detector to detect the steel cord belt, under laboratory conditions of the steel cord conveyor belt failure detection system, using steel cord conveyor belt has been scrapped. The model of the steel cord conveyor belt is the ST2500, total length of 6m, width 800mm, 50 steel core inner with spacing of 1.5mm, the diameter is 7.2mm, with three joints curing process. We had used eight-channel sensor comes with a small round to walk on the steel cord conveyor belt, collected eight groups signals, then selected a group of typical fault signal and determined the sampling points used in the simulation. The detector is based on the geomagnetic field as the background magnetic field.

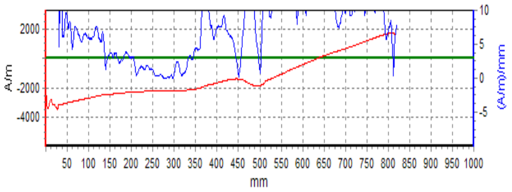

Figure 3-1. The Strength and Gradient Value of Background Magnetic Field

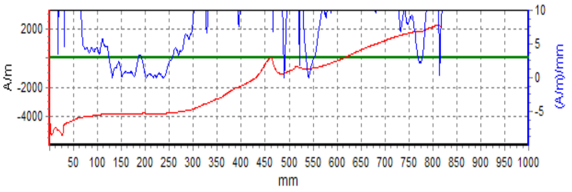

Figure 3-2. Magnetic Memory Signal of Steel Cord Conveyor Belt with the Geomagnetic Field

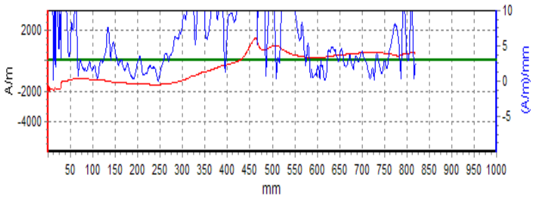

Figure 3-3. Magnetic Memory Signal of Steel Cord Belt without the Geomagnetic Field

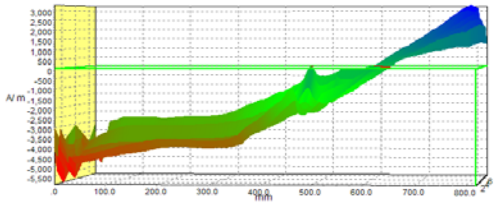

Figure 3-4. 3D View of Magnetic Memory Signal with the Geomagnetic Field

Figure 3 is a collection to the background magnetic field, in which the red line indicates the intensity of the geomagnetic field; the blue line represents the gradient values of the geomagnetic field intensity changes. It can be seen from Figure 3-1 that the amplitude of the geomagnetic field changes, so that will affect the actual measured magnetic field, gradient value has changed much. Figure 3-2 shows the detected magnetic memory signals of the steel cord conveyor belt with the geomagnetic field, we can see from Figure 3-2 (except for the interval at both ends by the sensor lift-off effect of) there are singular points in the signal, this indicates the location of the signal mutation may be the stress concentration zone. The blue line represents the gradient line, as can be seen the gradient changes very dramatic and could not tell the position of the stress concentration zone. In order to find the stress concentration zone we use wavelet singularity judgment. Figure 3-3 is the magnetic memory signals of steel cord conveyor belt without background geomagnetic field; the signal has a certain shift through the zero point, amplitude changes, and the gradient line change much. Contrast to Figure 3-2 and Figure 3-3, we can see that the geomagnetic field have a certain impact on the amplitude of magnetic memory signals collected, but does not affect the judgment of the stress concentration zone. Figure 3-4 shows 3D view of magnetic memory signal with background magnetic field, and it is more obvious to see the mutation of signal. It can be seen from Figure 3-2, Figure 3-3 signal has mutation point, the next step is to determine the specific location of the signal mutation, we will use the wavelet toolbox in MATLAB software to process the magnetic memory signal collected of the steel cord conveyor belt.

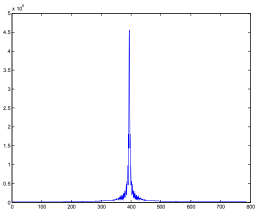

Figure 4. The Signal Frequency Spectrum of Magnetic Memory

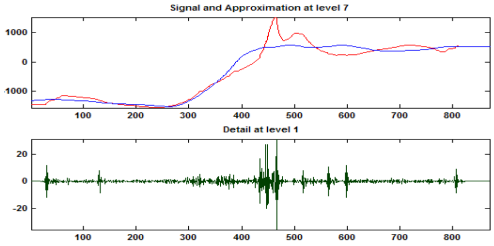

Figure 5. The Approximate Coefficients and Detail Coefficients of Magnetic Memory Signals Extracted by the Wavelet Decomposition

Figure 4 shows the frequency spectrum of magnetic memory signal after Fast Fourier Transform, the Fourier transform assumed that the signal is stable throughout the timeline, which means it is a view to see the whole composition of the signal frequency. Magnetic memory signals are non-stationary signals, the Fourier transform do not reflect the frequency characteristics of magnetic memory signals in the local time domain.

The approximate coefficients and detail coefficients of magnetic memory signal decomposed in seven layers by adopting db4 wavelet is shown in Figure 5, the red line stands for the original magnetic memory signal, the blue line represents the extracted approximate coefficient after wavelet decomposed in the seven layers. The green line shows the extracted detail coefficients after wavelet decomposed in second layers. It can be seen from Figure 5, the approximate coefficients of magnetic memory signal after wavelet decomposed in seven layers is becoming smooth, and from the detail coefficients at second layer we can see that the location of mutation signal is in the vicinity of 466mm.

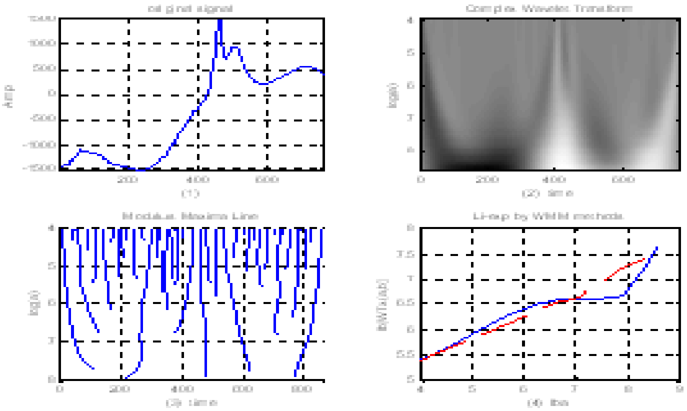

Figure 6. Time-frequency Domain Waveforms, the Wavelet Transform Modulus Maxima Line and its Slope of Magnetic Memory Signals

The time-domain waveform of collected original magnetic memory signal is shown in Figure 6(1), the wavelet transform of the magnetic memory signals is shown Figure 6(2), the corresponding modulus maxima line is shown in Figure 6(3), the slope of modulus maximum line is shown in Figure 6(4). In Figure 6(4), the blue line shows the negative maximum, red line indicates the positive maximum. We can see from Figure 6(2), Figure 6(3), remove the maximum value of signal edge, the wavelet transform modulus maxima curves of intermediate mutant signal within a cone-shaped area converge to the location of signal singular points along the direction of reduced scale, which is the point of failure. It can be seen, the singular point of the magnetic memory signals can be detected by the modulus maxima lines. The Lipschitz exponent obtained by the positive modulus maxima lines of magnetic memory signals is 0.475. Obviously the rules of the magnetic memory signals less than 1, so it is singular. Thus we can determine the location 466mm near is the stress concentration zone, through contrast with the actual failure of the steel cord belt, 466mm near is the failure point of twitch joints.

6. Conclusion

The metal magnetic memory technology is an effective method of steel cord conveyor belt fault detection and determine the stress concentration zone, this paper made use of the singularity detection method based on wavelet transform modulus maxima, which is applied to the judgment of stress concentration zone on steel cord conveyor belt, and can identify the singular point of signal. Consequently, the method can correctly judge the twitching and fracture location of the steel cord conveyor belt joints, and verified by experiments that this method is effective.

This experiment is done in the laboratory platform, and thus there is no noise impacting, when we will acquire data in field and analyze signal, we must first de-noising and then select the sampling points. Thus this experiment will be more universal and accurate to accurately and simply judge the failure location of steel cord belt joint which is widely used in coal mines, docks, power and other sectors.

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