Crack Detection under Coating of Flow Passage Parts based on Adaptive Second Generation Wavelet

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Abstract. Cracks under coating of flow passage parts of hydropower station is a very serious fault, which can directly lead to fatigue fracture. This will directly affect the safety of the entire hydropower unit. The array eddy current testing method has been studied, and crack signals are found with a lot of noise. In order to improve the signal quality, adaptive second generation wavelet transform is applied to the array eddy current signal analysis to reduce the signal noise. A test block with some cracks under the coating was tested, and the tiny crack defect with size of 0.13mm × 0.5mm × 5mm was identified. The experimental results show that the array eddy current detection method based on adaptive second generation wavelet transform can effectively identify the cracks under the coating of flow passage components of hydropower station, with high detection accuracy and strong adaptability, and has good engineering application value.

Keywords: Over-Current Components, Under-Coating Cracks, Array Eddy Current Testing, Adaptive, Second Generation Wavelet Transform

1. Introduction
In hydropower, the cracks and wear of flow passage components have always been one of the important factors threatening the operation safety of hydropower equipment. Under the combined action of cavitation and sediment abrasion, the cracks and wear of flow passage parts will damage the flow around the flow passage parts and affect the output efficiency of the motor. Even to the extent that, it will lead to the failure of the flow passage components and threaten the safety of the whole unit. Therefore, high velocity flame spraying (HVOF) process was often used to spray tungsten carbide coating on the surface of flow passage parts to improve their wear resistance and corrosion resistance [1].

The tungsten Carbide Coating can protect the flow passage parts from erosion to a certain extent, but it will cause great interference to the crack detection under the coating of flow passage parts. The stress concentration exists in the manufacturing process because of the complex structure of flow passage parts. However, shot peening is needed in the process of tungsten Carbide Coating spraying, which further aggravates the stress concentration. The stress concentration evolves and causes cracks under the coating. According to the investigation, in recent years, nearly 10 hydropower stations.
Therefore, it is necessary to study a crack detection method under the coating of flow passage parts suitable for hydropower station.

Eddy current testing is a non-destructive testing method based on the principle of electromagnetic induction [2]. However, conventional eddy current testing has skin effect, which can not effectively suppress the interference of lift off and jitter signals, and affected by the crack direction, the field implementation effect is not good. Therefore, array eddy current testing (AECT) is proposed. In the method, several small eddy current coils are formed into array coils according to certain rules by special design, which are densely distributed on the open or closed interface to form a special array sensor, so as to overcome the defects in conventional eddy current testing and realize the efficient defect identification of the detected objects. Many scholars at home and abroad have carried out research on eddy current array testing technology, with lots of remarkable achievements. Li Yuntao et al. Used eddy current array to detect uniform surface defects of austenitic stainless steel, and found that the detection effect was better than the traditional solvent removal type dye penetration testing technology [3]. Guo Yongliang et al. Established the relationship between crack length and waveform width and carried out error analysis [4].

However, there were still some signal interferences in the eddy current array signal. So the adaptive second generation wavelet transform was proposed to denoise the signal. The traditional signal denoising methods were inefficient and easy to damage the effective components in the signal. Therefore, combined with lifting operator, an adaptive second generation wavelet transform construction method was developed, which can adaptively match signal features, extract useful information and reduce noise interference [5]. Zhang Zhibin et al. Applied adaptive second generation wavelet transform to noise reduction of vibration signal, and verified the advantages of adaptive second generation wavelet through experiments [9]. He Wei et al. applied adaptive second generation wavelet transform to noise reduction of mine hoist vibration signal, and obtained higher signal-to-noise ratio [10]. Therefore, adaptive second generation wavelet transform will be used to improve the signal quality of eddy current array and improve the detection effect of cracks under coating.

2. Eddy Current Array Testing Technology

Eddy current array testing is an important branch of eddy current testing. According to the structure of the tested object, the coil is arranged, and the array eddy current probe is constructed. Then, it is excited according to certain rules and cooperates with each other to complete the efficient and flexible detection of complex detection objects. When a single eddy current probe is used for testing, it is often affected by the shape of the object and the direction of the defect. The array eddy current testing can avoid these interferences. It can carry out array combination according to the shape of the detected object, and detect small defects of the complex surface and the near surface. Moreover, the flexible combination mode can just eliminate the interference between coils, minimize the influence of interference signal, and effectively suppress skin effect.

Although eddy current array testing can well suppress the lift off effect and is not affected by the defect direction, there is still some noise in the eddy current signal. Therefore, a certain signal extraction method is needed to improve the signal quality and improve the detection effect [5].

3. Adaptive Second Generation Wavelet Transform

The second generation wavelet transform was proposed by Dr. Sweldens W. of Bell laboratory in 1995, and constructed by lifting method in time-frequency domain [6, 7]. The biggest difference between it and the first generation wavelet is that it does not rely on Fourier transform to construct wavelet basis function, but uses lifting operator to change the characteristics of original wavelet filter to obtain biorthogonal wavelet with different properties, which has strong flexibility. However, the construction of its wavelet function is not related to the signal and can not adaptively match the local characteristics of the signal. Therefore, Gouze et al. proposed an optimization method to design adaptive second generation wavelet transform [8].
3.1. Construction of Adaptive Second Generation Wavelet Transform

The construction method of adaptive second generation wavelet transform is as follows: Firstly, the kurtosis index which is very sensitive to the early fault of equipment is set as the evaluation standard, and the predictor with the best matching signal features is designed by using the genetic algorithm with strong robustness. Then the update device is designed with the minimum reconstruction error as the objective function, and the second generation wavelet with adaptive signal characteristics is constructed.

3.1.1. Design of Adaptive Predictor. The objective function of the predictor, \( K_p \), is defined as:

\[
K_p = \frac{E((d-d)^4)}{\sigma^4}
\]  

(1)

Where, \( \bar{d} \) and \( \sigma \) denote the mean and standard deviation of detail signal \( d \), respectively, and \( E\{\cdot\} \) represent the mathematical expectation. The second generation wavelet problem of constructing matched signal features is transformed into the optimization problem of maximizing the objective function \( K_p \) under the constraints of the following formula.

\[
p_r = p_{r+1} \sum_{r=1}^{N/2} p_r = \frac{1}{2}, r = 1, 2, \ldots, N/2
\]  

(2)

However, there is no direct relationship between the objective function and the predictor coefficients with the complex indirect relationship. Genetic algorithm has strong robustness, global and parallel search characteristics. So the genetic algorithm is used to construct the predictor of the adaptive matching signal characteristics with the objective function, \( K_p \), as the fitness function. With the initial population of 50 and the evolution algebra of 100, the predictor coefficients of adaptive matching signal characteristics \( P_{opt} = [p_{-N/2+1}, \ldots, p_1, \ldots, p_{N/2}] \) can be calculated by the genetic algorithm.

3.1.2. Design of Adaptive Updater. The reconstruction error, \( J_U \), is expressed as

\[
J_U = E\{(\hat{s}^{(0)} - s^{(0)})^2\} + E\{(\hat{d}^{(0)} - d^{(0)})^2\}
\]  

(3)

Among them, \( \hat{s}^{(0)} \) and \( \hat{d}^{(0)} \) are even sequence samples and odd sequence samples of reconstructed signals \( \hat{x} \), when detail signals \( d = 0 \) are used. The design of adaptive updater can be transformed into the problem of minimizing the reconstruction error under the following constraints.

\[
u_l = u_{-l+1} = u_{-l+1} \sum_{l=1}^{\tilde{N}/2} u_l = \frac{1}{4} l = 1, 2, \ldots, \tilde{N}/2
\]  

(4)

When the detail signal \( d = 0 \), the process of the second generation wavelet inverse transform is shown in Fig. 3. \( \hat{s}^{(0)} \) and \( \hat{d}^{(0)} \) can be expressed as follows

\[
\hat{s}^{(0)} = s
\]  

(5)

\[
\hat{d}^{(0)} = P \ast s
\]  

(6)

In formula (6), "\( \ast \)" represents convolution operation. \( \lambda \) isthe Lagrange operator. From the constraint condition (4), the objective function \( J_U \) can be transformed into \( J_U(u, \lambda) \):

\[
J_U(u, \lambda) = E\{(\hat{s}^{(0)} - s^{(0)})^2\} + E\{(\hat{d}^{(0)} - d^{(0)})^2\} + \lambda(\frac{1}{4} - \sum_{l=1}^{\tilde{N}/2} u_l)
\]  

(7)
The coefficients \( [u_1, u_2, \ldots, u_{n/2}] \) can be obtained by solving the above equations. According to the symmetry of the update coefficients, we obtained the update operator \( U_{\text{opt}} = [u_{-n/2+1}, \ldots, u_n, u_{n/2}] \) of adaptive signal features.

### 3.2. Decomposition and Reconstruction of Adaptive Second Generation Wavelet

The decomposition process of adaptive second generation wavelet is divided into three steps, for example, prediction process, update process and standardization process. The original signal sequence is \( x \), \( c_k \) is the \( k \) layer approximation signal, and \( c_{k+1} \) is the \( k+1 \) layer approximation signal. So \( r_{k+1} \) is the \( k+1 \) layer detail signal. Where, \( P_{\text{opt}}, U_{\text{opt}} \) are predictor, updater. \( s_{k+1}, d_{k+1} \) are update sequence. And \( a_{k+1}, b_{k+1} \) are standardization coefficients. The reconstruction process of adaptive second generation wavelet is also composed of three steps, such as, normalized inverse process, recovery update process and recovery prediction process, as shown in Figure 1.

![Figure 1. Reconstruction of adaptive second-generation wavelets](image)

### 3.3. Denoising Principle of Adaptive Second Generation Wavelet

The principle of adaptive second generation wavelet de-noising is to eliminate the noise by thresholding the decomposed wavelet coefficients. There are usually two kinds of hard threshold method and soft threshold method. The hard threshold method is direct, setting a fixed threshold, when less than the threshold, the parameter returns to 0. The soft threshold method obtains information from the signal, sets the threshold, eliminates the noise, but also maintains the signal stability. The research selects the soft threshold filtering method.

### 4. Experimental Study

In order to test the effectiveness of eddy current array testing, a special specimen is made for crack detection. Firstly, the signal is obtained by eddy current array probe, and then the signal is extracted by adaptive second generation wavelet, and compared with the original signal.

#### 4.1. Eddy Current Array Testing Experiment

4.1.1. Testing Object. 0Cr13Ni4Mo is used to make standard specimen, and width 0.13mm × depth 0.3mm × length 5mm, width 0.15mm × depth 0.5mm × length 5mm, width 0.17mm × depth 1mm × length 5mm are machined on the specimen, and the WC coating of 0.7mm is sprayed on the specimen, which can cover all cracks well. See Figure 2 for comparison specimen.
4.1.2. **Testing Equipment.** The eddy current array testing site is shown in Figure 3. The testing equipment is smart-208 multi frequency eddy current detector. Its main parameters include 8 physical channels, 2 testing frequencies, 2 impedance planes, frequency detection range 64Hz ~ 5MHz, gain 0 ~ 90dB, high pass filter 0 ~ 500Hz, low pass filter 10Hz ~ 10kHz. The main parameters of eddy current probe are: response frequency 100Hz ~ 100kHz, which is mainly used for crack detection of ferromagnetic materials.

![Array eddy current testing equipment](image)

**Figure 3.** Array eddy current testing equipment

4.1.3. **Detection Steps.** The eddy current probe was placed in the middle of the test block and slid from left to right to detect three kinds of crack defects with different specifications.

4.2. **Data Analysis**

The results of the three tests are very consistent. The cracks of 0.15 mm × 1 mm × 5 mm and 0.17 mm × 2 mm × 5 mm can be clearly identified, but the signal of 0.13 mm × 0.5 mm × 5 mm is difficult to identify with lots of noise, which is related to the surface roughness. Then adaptive second generation wavelet transform is used to improve the signal quality.

Figure 4 shows the original signal detected by 0.13mm × 0.5mm × 5mm eddy current array. It is not difficult to see that in the original signal of eddy current testing, whether the real part of impedance or the imaginary part of impedance, there are huge interference signals, resulting in the complexity of the impedance diagram and it is difficult to identify the existence of crack defects.
The adaptive second generation wavelet transform is used to filter the signal, and the predictor and updater are designed to match the characteristics of eddy current testing signal. After the test, it is found that the optimal number of predictor coefficients is 8, and the optimal number of updater coefficients is 4. The predictor coefficients calculated are [0.13, -0.094, -0.016, 0.48, 0.48, -0.016, -0.094, 0.13], and the update coefficients are [0.14, 0.12, 0.12, 0.14]. The eddy current signal is decomposed into approximate signal and detail signal by using the predictor and update device of adaptive matching signal features. Then the noise threshold of the signal is set as 6% of the peak value of the signal, and the corresponding value in the signal is 5. When the wavelet coefficient is less than 5, it is forced to set to 0. Then the adaptive second generation wavelet signal reconstruction is carried out to obtain the denoised signal, as shown in Figure 5-6. Figure 5 shows that the real part signal and imaginary part signal of impedance are greatly improved, and the corresponding noise is eliminated. The filtered impedance diagram shown in Figure 6 can clearly identify 0.13mm × 0.5mm × 5mm crack defects.
5. Conclusion
Based on the adaptive second generation wavelet transform, a crack detection method under the coating of flow passage components is proposed. The adaptive second generation wavelet transform is applied to the array eddy current detection, and obtained the good results. The conclusions are as follows:

1) The array eddy current can suppress the lift off effect and is not affected by the direction of defects. It has good universality to detect cracks under the coating of flow passage components in hydropower station.

2) The adaptive second generation wavelet can effectively match the signal features, eliminate the influence of noise and improve the signal quality.

3) The eddy current signal array based on adaptive second generation wavelet transform greatly improves the diagnosis effect, and can identify 0.13 mm × 0.5 mm × 5 mm crack defects, with high detection accuracy and strong adaptability, which has good engineering application value.

In the future, the adaptive second generation wavelet algorithm will be developed and integrated into the eddy current array detection software to detect the cracks under the coating of the flow passage parts of the water turbine.

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