Wind turbine blade surface crack image enhancement based on curvelet transform

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Abstract

In order to improve the recognition and detection accuracy of wind turbine blade surface crack, a method based on curvelet transform is proposed. Firstly, the dodging algorithm is used to remove the influence of illumination unevenness, and then the image is processed by curvelet transform and get curvelet coefficients. Using the fractional differential and median filtering on the coarse scale image to enhance the crack and suppress the noise, and nonlinear enhancement and threshold denoising are performed on each detail scale coefficients separately, then according to each scale image to reconstruct the image. Finally, the enhanced crack image is obtained by contrast-limited adaptive histogram equalization. The experiment results show that the method can enhance the crack image of the wind turbine blade, and the enhanced image has better visual effect.

Keywords

Curvelet transform; fractional differential; dodging processing; blade crack; image enhancement.

1. Introduction

Wind turbine blade is the force source and main load bearing component for wind turbine ,and it is also the most vulnerable and expensive component. At present, the daily monitoring of wind turbine blades is mainly carried out through manual inspection by the staff, which is not only accurate and inefficient but also costly. With the development of digitization, digital image technology has been widely applied to processes such as medical treatment, traffic, monitoring, detection , and it is possible to monitor the state of wind turbine blade surface through image processing technology. However, due to the influence of environment and equipment conditions, the collected images will be degraded and distorted, which is not conducive to the reading and recognition of images. Therefore, the researchers research the image enhancement technology.

Literature [1] uses histogram equalization technology to achieve underwater image enhancement, literature [2,3] uses multi-scale Retinex for image enhancement, and literature [4] proposes dark channel prior method to achieve image dehazing, literature [5] Image enhancement using fractional differential, which can achieve image enhancement to a certain extent, but also has some limitations. In order to enhance the image of wind turbine blade surface crack and highlight the crack, this paper proposes a method to enhance the image of wind turbine blade surface crack based on the combination of multiple methods of curved wave transform [6-8].In this method, the original input image is first processed by dodging processing, and then the different scale coefficients are obtained by the curvelet transform. The Coarse-scale images and the fine-scale images are enhanced and denoised by different methods. Then the different scale images are fused by the inverse curvilinear transform, and finally the contrast is enhanced by histogram equalization.

2. Correlation theory

2.1 Curvelet transform

The curvelet transform [9] proposed by Candès et al. uses a local line of multiple scales to approximately show the curve, which can well approach the singular curve in the image and is very suitable for enhancing the image , such as the crack on the blade surface of a wind turbine.

The curvelet transform uses the inner product of the signal and the curvelet function to decompose the signal into different scales, angles, and positions. The continuous curvelet transform is defined as follows:

$$w_{j,l,k} = \langle f, \varphi_{j,l,k} \rangle = \int_{R^2} f(x) \overline{\varphi_{j,l,k}} dx \tag{1}$$

Where $\varphi_{j,l,k}$ is the basis function of the curved wave, f is the signal, j, l and k are respectively the scale, angle and position of the curved wave transform.

When the signal is a discrete signal $f(x,y)$, the formula of discrete curvelet transform which can be obtained from the definition of continuous curved wave transformation as follows :

$$w_{j,l,k} = \sum_{0 \le x,y < n} f(x,y) \overline{\varphi_{j,l,k}(x,y)} \tag{2}$$

Candès et al. proposed two fast discrete curvelet transform (FDCT) methods, USFFT and Wrapping, the two methods operation result is the same, but the Wrapping method is simple ,fast, and is a common method for fast discrete curvelet transform. In this paper, the Wrapping method is used to perform the curvelet transform. The enhanced image using the curvelet transform generally includes the curvelet decomposition of the image, the enhancement and denoising of the curvelet coefficient, the inverse transformation of the curvelet and the image fusion.

2.2 Fractional differential principle

Fractional order calculus is the generalization of integral order calculus. According to the application research of fractional order calculus in digital image, fractional order differential has the ability to detect fuzzy boundary and weak texture of image [10].

For any square integrable energy signal $f(t) \in L^2(R)$, the fractional derivative of order v is $D_t^v f(t)$, $v \in R^+$, and its Fourier transform is:

$$D_t^v f(t) \Leftrightarrow (\hat{D} f)^v(w) = (iw)^v \hat{f}(w) = \hat{d}^v(w) \cdot \hat{f}(w) \tag{3}$$

Where, $\hat{d}^v(w)$ is called the differential multiplier function of order v, and its exponential form is:

$$\begin{cases} \hat{d}^v(w) = (iw)^v = \hat{a}^v(w) e^{i\hat{\theta}^v(w)} \\ \hat{a}^v(w) = |w|^v, \hat{\theta}^v(w) = \dfrac{v\pi}{2} \operatorname{sgn}(w) \end{cases}, v \in Z^+ \tag{4}$$

Thus, the amplitude-frequency characteristic curve of fractional differential as shown in figure 1 can be obtained. Where, 0 < w < 1 represents the low frequency part, and w > 1 represents the high frequency part. The texture detail of the two-dimensional image does not change significantly in the low frequency region, while the gray level of the high frequency region changes drastically or is the edge portion of the image. When v > 0, the differential operation is realized, which is equivalent to a high-pass filter. At this time, the high frequency in the image is strengthened, and the low-frequency information is nonlinearly preserved to some extent, which is advantageous for highlighting the local details of the image, so the fractional differential can enhance the image edge and texture.

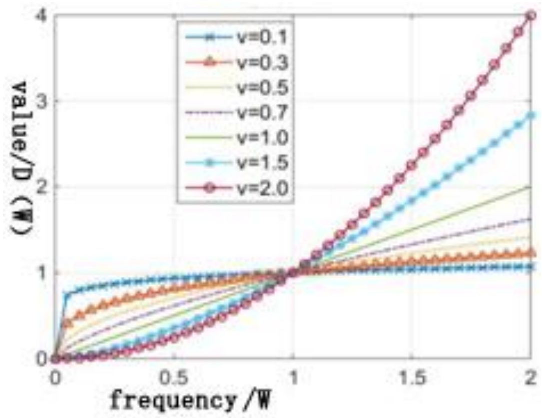


Fig. 1. Fractional differential amplitude-frequency characteristic curve

3. Methods

Figure 2 is a flow chart for enhancing the image of the surface crack of the wind turbine blade.

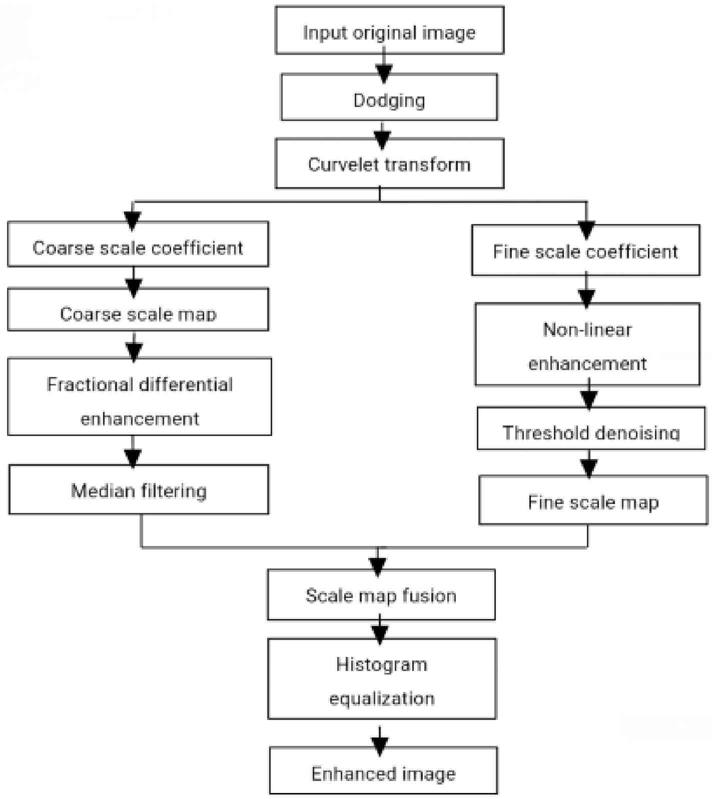


Fig.2. Wind turbine blade surface crack enhancement process

3.1 Dodging processing

Due to the influence of the angle and the direction during the shooting process, the image of the wind turbine blade may be unevenly illuminated. If not properly processed, the surface crack of the subsequent blade will be affected and detected.

Commonly used homogenization algorithms include Mask homogenizing algorithm, Retinex homogenizing algorithm, Wallis homogenizing algorithm, etc. In this paper, an adaptive correction algorithm for illumination non-uniform images based on two-dimensional gamma function is adopted [11]. Firstly, the image is transformed from RGB space to HSV space, then the multi-scale Gaussian function is used to estimate the illumination component of the V channel, and the two-dimensional gamma function is adjusted according to the distribution characteristics of illumination component, so as to realize the adaptive correction for the uneven illumination image. Finally, the image is converted to RGB space to achieve uniform light processing. Figure 3 is an image of surface crack 1 of a wind turbine blade processed with uniform light.

(a) original image (b) estimation of light component

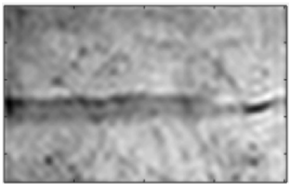
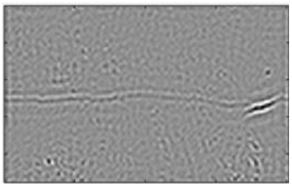
(C) after image dodging

Fig.3. Crack 1 image homogenization

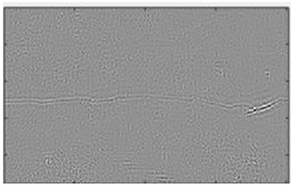
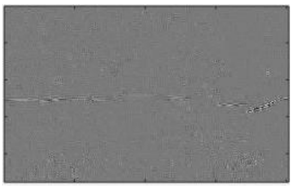
3.2 Curvelet transform

After homogenized-light processing the picture is converted into a wave transformation, as shown in Fig. 4. The scale of the curved wave transform n=floor(log2(min(M, n)-3)), and M and n are the size of the picture. In which Figure 4 (a) is a rough scale image, that rough scale reflect the edge and background texture profiles of the image, correspond to the low frequency information of the image. Figs. 4 (b) - (d) are each fine scale graphs, which reflect the edge and noise information of the image and correspond to the high-frequency information of the image.

To achieve enhancement of the wind turbine blade cracks image information while suppressing or eliminating background interference information, coarse scale and fine-scale (including a fine-scale) using different methods for each treatment.

(a) coarse scale (b) fine scale 1

(c) fine scale 2 (d) the fine-scale

Fig.4. Curvelet transform each dimension figure

3.2.1 Fractional differential enhancement of coarse scale graphs

The coarse-scale map mainly includes the main contour of the image background and the crack. The fractional differential can enhance the high-frequency information (crack) while greatly retaining the low-frequency smoothing information. The key to image enhancement by fractional order differential is the design of fractional order calculus mask. Usually, the size of fractional order differential mask is (2n+1) *(2n+1), and n is a positive integer. In this paper, the classical fractional order differential mask

Tiansi operator is adopted, the structure of which is shown in Figure 5. Where $a_0 = 1$, $a_1 = -v$, and $a_2 = \frac{(-v)(-v+1)}{2}$.

a_2	0	a_2	0	a_2
0	a_1	a_1	a_1	0
a_2	a_1	$8a_0$	a_1	a_2
0	a_1	a_1	a_1	0
a_2	0	a_2	0	a_2

Fig.5. 5 × 5 Tiansi Operator

After the coarse-scale graph of the crack is enhanced by the fractional differential, in order to reduce the influence of noise and the like on the image, median filtering is used to denoise. Median filter is a kind of nonlinear digital filter technology, which can reduce the noise and keep the edge without blurring.

3.2.2 Enhancement of fine-scale coefficients

(1) Nonlinear enhancement function enhancement

In literature [12], a nonlinear enhancement function is proposed to process the curve wave coefficients of images to achieve image enhancement. However, the nonlinear enhancement function needs to adjust more parameters, and it is more difficult to adjust to the appropriate parameter values. In this paper, when the fine-scale coefficients are enhanced, each scale is separately enhanced, and a nonlinear enhancement function is designed with less parameters and simpler.

$$c_k' = \begin{cases} c_k - (A-1)\sigma & c_k < -\sigma \\ Ac_k & |c_k| \le \sigma \\ c_k + (A-1)\sigma & c_k > \sigma \end{cases} \quad (5)$$

Where, c_k and c_k' are the curve wave coefficients before and after enhancement on scale k, threshold $\sigma = \max(|c_k|)\frac{e^{-k}}{1+e^{-k}}$, $A = \frac{\beta}{1+e^{-k}}$ and β are the adjustment coefficients. It can be seen that the nonlinear enhancement function has only one parameter β to be adjusted.

(2) Selection of denoising threshold T

Since the noise will be enhanced at the same time when the crack and other information are enhanced, in order to reduce noise in the image, it is necessary to denoise the fine-scale coefficients of the image. The threshold denoising method was used to remove the noise at each fine scale. The effect of threshold denoising depends on whether the threshold T is selected properly. If T is too small, the noise is not well removed; if T is too large, it will filter out a lot of details. The methods to select the threshold include GCV threshold, Donoho threshold, SURE threshold and Bayes threshold. According to the research, the direction coefficient of the image obeys the generalized gaussian distribution, which is consistent with the hypothesis condition of Bayes estimation method. Therefore, the Bayes estimation method is selected here to determine the threshold value.

$$T = r \times \frac{\sigma_n^2}{\sigma_s} \quad (6)$$

Where, r is $\sqrt{2}$, σ_n^2 and σ_s are the noise variance and standard deviation signals, which can be obtained from the following expression:

$$\hat{\sigma}_n = \frac{median(|c_k(i,j)|)}{0.6745} \quad (7)$$

$$\hat{\sigma}_s^2 = \max(\frac{1}{M \times N}\sum_{i=1}^{M}\sum_{j=1}^{N} c_k^2(i,j) - \hat{\sigma}_n^2, 0) \tag{8}$$

Where $c_k(i,j)$ is the curvelet coefficient of scale k and median() means the median value.

In the experiment, it was found that σ_s would appear to be 0, and the threshold T could not be obtained, leading to the failure of image enhancement. Here, σ_s can be obtained by using the following formula:

$$\hat{\sigma}_s^2 = abs(\frac{1}{M \times N}\sum_{i=1}^{M}\sum_{j=1}^{N} c_k^2(i,j) - \hat{\sigma}_n^2) \tag{9}$$

Where, abs() represents taking the absolute value.

(3) Denoising by soft and hard threshold method

Hard threshold denoising can better preserve local features such as the edge of the signal, but it will cause signal distortion to a certain extent; Soft threshold denoising results are relatively smooth, but it will cause edge blurring. This paper adopts soft and hard threshold compromised denoising method.

$$c_k'(i,j) = \begin{cases} sign(c_k(i,j))(|c_k(i,j)| - \alpha T), |c_k(i,j)| > T \\ 0, |c_k(i,j)| \le T \end{cases} \tag{10}$$

Where, sign() represents the symbol function, α is the denoising regulator, $\alpha \in [0,1]$, When it is 0, it is the hard threshold denoising; When it is 1, denoising is the soft threshold.

4. Experimental simulation and results analysis

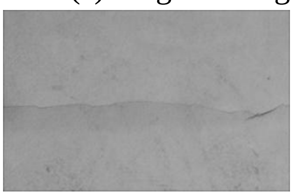
In order to effectiveness the validity of the method in this paper, with classic image enhancement method of histogram equalization HE, fractional order differential FD, single scale Retinex algorithm SSR, MSR multiscale Retinex algorithm and the algorithm for multiple wind turbine blade crack image enhancement.

Experimental environment: the operating system is Windows 7, the simulation software is MATLAB R2014b, the processor is Intel(R) Core(TM) i5-6500, and the memory is 4GB. In the experiment, the FD algorithm and the algorithm in this paper adopts Tiansi operator, the fractional order differential order of FD algorithm is 0.5. In this paper, the fractional differential order is 0.2, and the adjustment parameters α and β are 0.5 and 0.7 respectively.

The effect of image enhancement is evaluated from subjective and objective aspects. The subjective evaluation is based on the visual effect of the image, while there is no unified evaluation standard for the objective evaluation, which is mainly based on some information of the image itself. Fig.6 shows the enhancement effect of each enhancement algorithm on crack 1.

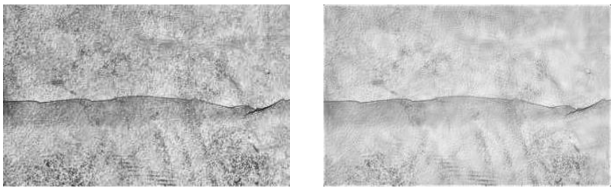
(a) Original image

(b) HE



(c) FD

(d) SSR



(e) MSR (f) ours

Fig.6. Crack 1 original drawing and enhancement effect of each algorithm

Subjective evaluation: as can be seen from figure 6, the image enhancement effect of FD algorithm is not obvious, while other algorithms can achieve the enhancement effect to varying degrees. Among them, the HE algorithm is obviously contrasted, but at the same time, the texture and background information on the wind turbine blade are greatly enhanced, resulting in severe interference of the texture and other information on the cracks. Both the SSR and MSR algorithms can enhance the crack information, but the texture and background information are also enhanced, although not as large as HE enhancement, but also seriously interfered with the fracture information. The algorithm in this paper not only enhances the crack, but also restrains the texture and background information to a certain extent, making the crack more prominent.

Objective evaluation: in order to objectively evaluate the effect of image enhancement, two indexes, Peak Signal to Noise Ratio (PSNR) and Structural Similarity (SSIM), are adopted in this paper to evaluate the effect of crack enhancement. The size of the image is assumed to be $M \times N$.

(1) PSNR is the logarithm value of the mean square error between the original image and the processed image relative to $(2^n-1)^2$, and the unit is dB, which is used to measure the quality of the processed image. The larger the value of PSNR, the less the distortion of the processed image.

$$PSNR = 10 \times \log_{10}\left(\frac{(2^n-1)^2}{MSE}\right) \tag{10}$$

MSE is the mean square error between the original image *f(I,j)* and the processed image *g(I,j)* :

$$MSE = \frac{1}{M \times N}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\left|f(i,g)-g(i,j)\right|^2 \tag{11}$$

(2) SSIM is used to measure the structural similarity of the original image and the processed image, especially the similarity of image contour and details, with the maximum value of 1.

$$SSIM(f,g) = \frac{(2\mu_f\mu_g + c_1)(2\sigma_{fg} + c_2)}{(\mu_f^2 + \mu_g^2 + c_1)(\sigma_f^2 + \sigma_g^2 + c_2)} \tag{12}$$

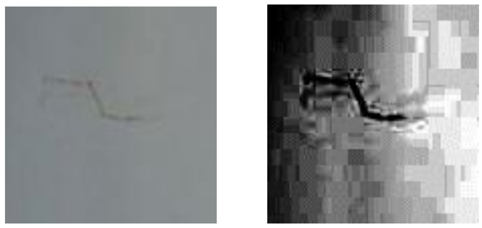
Where, μ_f represents the mean of image *f*, σ_f is the variance of image *f*, and σ_{fg} is the covariance of image *f* and *g*, $c_1 = (k_1L)^2$ and $c_2 = (k_2L)^2$ are constants that are used to maintain stability; *L* is the dynamic range of image pixel values, k_1 = 0.01, k_2 = 0.03.

Table 1 lists the PSNR and SSIM of each algorithm after crack 1 enhancement. As can be seen from Table 1, since the HE algorithm enhances the image by improving the contrast, the loss of detail information is large. Whether it is PSNR or SSIM, the value is the minimum and the enhancement effect is the worst. The SSIM value of FD algorithm is the largest. This is because fractional differentiation can preserve the texture balance region information in a large extent while enhancing the edge information. However, its PSNR value is small, resulting in poor image effect after enhancement. The SSR algorithm and the MSR algorithm have their PSNR and SSIM values centered, which can achieve image enhancement, but the effect is general. The PSNR value of the algorithm in this paper is the largest, and the SSIM value is second only to the FD algorithm, indicating that the wind turbine blade surface crack enhanced by the algorithm in this paper has the best effect.

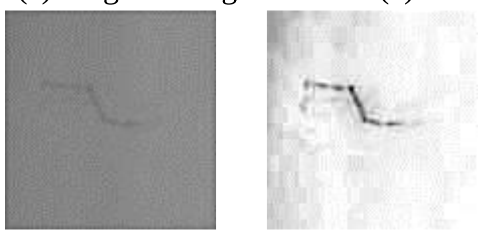
Table 1 Comparison of algorithm results of crack 1

	PSNR	SSIM
HE	26.4552	0.1781
FD	40.1048	0.9751
SSR	41.5699	0.5752
MSR	33.6045	0.3923
Ours	63.4889	0.7475

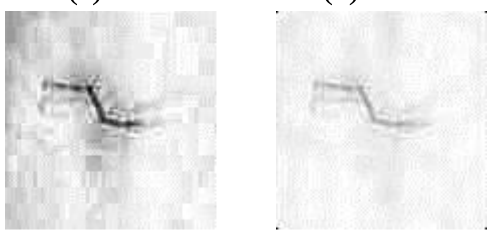
Figs.7 and 8 show the comparison of the enhancement effect of crack 2 and crack 3 on the blade surface of the wind turbine. Table 2 and table 3 respectively gives objective evaluation results.



(a) Original image (b) HE



(c) FD (d) SSR

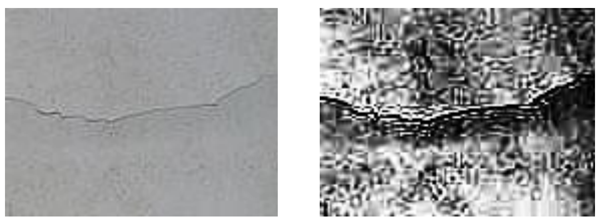


(e) MSR (f) ours

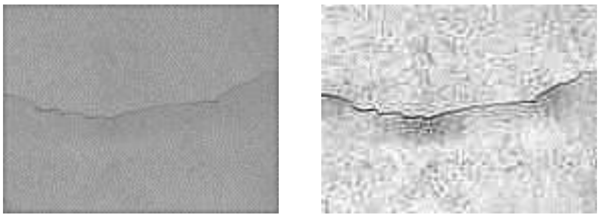
Fig.7 Crack 2 original drawing and enhancement effect of each algorithm

Table 2 Comparison of the results of each algorithm of crack 2

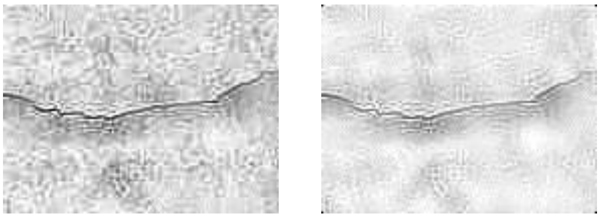
	PSNR	SSIM
HE	27.0009	0.3735
FD	36.9141	0.9968
SSR	48.9654	0.6844
MSR	43.3193	0.5623
Ours	58.6310	0.7514



(a) Original image (b) HE



(c) FD (d) SSR



(e) MSR (f) Algorithm

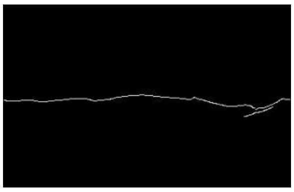
Fig.8. Crack 3 original drawing and enhancement effect of each algorithm

Table 3 Comparison of the results of each algorithm of crack 3

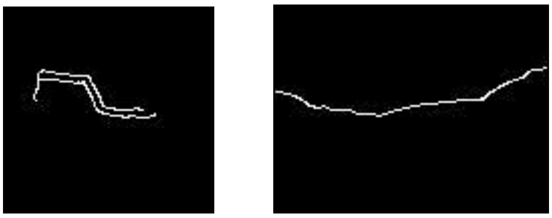
	PSNR	SSIM
HE	26.4866	0.1381
FD	36.2671	0.9661
SSR	42.8070	0.5357
MSR	40.6661	0.4602
Ours	49.8443	0.7068

From the results in figure 7 and figure 8 and table 2 and table 3, compared with other four algorithms, the algorithm proposed in this paper achieves better results when the surface crack information of wind turbine blade is enhanced.

In order to further verify the enhancement effect of the algorithm in this paper, Canny edge detection algorithm was used to detect the edge of the surface crack of the enhanced wind turbine blade, and the detection results are shown as fig.9. From the edge detection results, it can be seen that after the image enhanced by the algorithm in this paper, Canny operator can be used to correctly detect the crack information without or less interference by other texture information on the blade, indicating that the algorithm in this paper can indeed effectively enhance the surface crack information of the wind turbine blade.



(a) Crack 1



(b) Crack 2 (c) Crack 3

Fig.9 The results of the Canny operator test

5. Conclusion

To achieve the enhancement of the surface cracks in the wind turbine blades, This paper proposes an image enhancement method based on a combination of various methods of curvelet transform.. In this method, the original image was first processed with uniform light, and then the scale coefficients were obtained by using the curved wave transform, and then the scale images were enhanced and denoised respectively, and then the image after the inverse curved wave transform of each scale was fused together for contrast enhancement, so as to obtain the final enhanced image. It is shown by experiment that that algorithm can enhance crack information very well.

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References

[1] Yang Weizhong, Xu Yinli, Qiao Wei, et al. Image enhancement method of underwater sea cucumber based on contrast-limited histogram equalization[J]. Transactions of the Chinese Society of Agricultural Engineering, 2016, 32(6): 197-203.
[2] Yang Guopeng, Zhou Xin, Chen Dong, et al. Nonlinear enhancement of low illumination aerial image with multi-scale Retinex[J]. Sci-Tech Science, 2018(1): 15-19.
[3] ZHANG SH, WANG T, DONG J Y, et al. Underwater image enhancement via extended multi-scale Retinex[J]. Neurocomputing, 2017, 245: 1-9.
[4] He K M, Sun J, Tang X O. Single image haze removal using dark channel prior[J]. IEEE Transactions on Pattern Analysis and Machine Intelligence, 2011, 33(12): 2341-2353.
[5] Yang Zhuzhong, Zhou Jiliu, Pei Xiangyu, et al. Image Enhancement Based on Fractional Differential[J]. Journal of Computer-Aided Design & Computer Graphics, 2008, 20(3): 343-348.
[6] Zhang Shi, Yan Lihuang, Ge Xin. Enhancement Algorithm of Retinal Vessel Image Based on Curvelet Transform[J]. Journal of Northeastern University, 2016, 37(7): 922-926.
[7] Li Jicheng, Xie Kai, Yan Ningjun, et al. Medical image enhancement algorithm based on curvelet transform[J]. Computer Engineering and Design, 2017,38(1): 187-191.
[8] Guo Chunhua, Wang Tongqing. Image enhancement of track beam surface crack based on curvelet transform[J]. Journal of Scientific Instrument, 2012, 33(12): 2754-2760.
[9] CANDES E J, DEMANET L, DONOHO D L. Fast discrete curvelet transforms[R]. Applied and Computational Mathematics，California Institute of Technology，2005: 1-43.
[10] Yang Zhuzhong, Zhou Jiliu, Lang Fangnian. Noise Detection and Image Denoising Based on Fractional Calculus[J]. Journal of Image and Graphics, 2014, 19(10): 1418-1429.
[11] Liu Zhicheng, Wang Dianwei, Liu Ying, et al. Adaptive correction algorithm for illumination inhomogeneity based on two-dimensional gamma function[J]. Journal of Beijing Institute of Technology, 2016, 36(2): 191-196, 214.
[12] VESE L A, CHAN T F. A multiphase level set framework for image segmentation using the mumford and shah model[J]. International Journal of Computer Vision, 2002, 50(3): 271-293.