*International Journal of Latest Research in Science and Technology* **ISSN (Online):2278-5299**
*Volume 9, Issue 2: Page No.6 -12, March-April,2020*
*https://www.mnkjournals.com/journal/ijlrst/index.php*

# Fault Diagnosis of Rolling Bearing Based on Correntropy Envelope Spectrum Analysis

Xuhan Liu
*Student*
*School of Mechanical Engineering & Tianjin University of Technology and Education*
*Email: 1436944367@qq.com*
*Tianjin, China*

Hui Li[*]
*Professor*
*School of Mechanical Engineering & Tianjin University of Technology and Education*
*Email: Huili68@163.com*
*Tianjin, China*

**Received** : 24 March 2020; **Accepted** :04 April 2020 ; **Published** :30 April 2020

*Abstract*— **The fault signal of rolling bearing is non-stationary and non-Gaussian. Many components mixed and the complex transmission path make the fault signal drowned in the noise, especially in the early stage of failure, the weak fault signal is extracted more difficult because of the interference of noise. To solve the problem of rolling element bearing fault signal denoising in the context of non-Gaussian noise, a new fault diagnosis technology based on correntropy envelope spectrum analysis is proposed. Firstly, the vibration signal of rolling bearing is denoised by correntropy, and then the denoised signal is processed using envelope analysis technique, so as to obtain the characteristic frequency of bearing fault. Finally, by comparing the correntropy envelope spectrum with the envelope spectrum of the traditional band-pass filter, it is verified that the fault diagnosis method of rolling bearing based on the correntropy envelope analysis has a better denoising effect in the non-Gaussian noise environment, and overcomes the problem of filter center frequency selection existing in the traditional band-pass filter noise reduction, and can accurately extract the fault characteristic frequency of rolling bearing.**

***Keywords***— **rolling bearings; correntropy; Gaussian kernel function; envelope spectrum; fault diagnosis; signal processing**

## I. INTRODUCTION

Rolling bearing is the most important part of mechanical equipment, the running condition of bearings may have a great impact on the whole unit. In the actual production, rolling bearing is also the most prone to failure parts, so it is significant to diagnosis the fault of rolling bearing. However, the fault signal of rolling bearing is mostly non-linear and non-stationary[1], and the working environment is mostly under non-Gaussian noise environment, which increases the difficulty of noise reduction and feature extraction of fault signal, especially in the early stage of rolling bearing fault[2], the fault signal is weak and the fault signal is very easy to be covered by noise, so it is difficult to obtain fault signal. Therefore, using effective noise reduction method to processing vibration signal is an important part of rolling bearing fault diagnosis. When the rolling bearing fault occurs, the fault signal is usually concentrated in the resonance frequency band of the system. It is a common method to extract he fault frequency by envelope demodulation. The selection of the center frequency of the envelope demodulation band-pass filter directly affects the amount of fault information contained in the signal. Therefore, the key of fault extraction technology based on envelope demodulation analysis is to select the parameters of band-pass filter reasonably. Many experts have made more researches on the construction and parameter selection of envelope demodulation band pass filter. T. F. Ming et al. proposed a Morlet wavelet combined band pass filter. Combined wavelet has better band-pass property[3], and correlation kurtosis has better sensitively to the pulse signal, the correlation kurtosis was taken as the evaluation standard of selecting the optimal filter, so as to effectively extract the bearing fault signal from the vibration signal. L. Zhang et al. proposed a method based on envelope spectrum band pass kurtosis[4], which performs better than fast spectrum kurtosis. Z. R. Yao et al. proposed a fault diagnosis method based on EMD and envelope spectrum analysis[5], which is superior to the traditional envelope analysis method. G. T. Wan put forward a denoising method based on LMD and band pass filtering technology[6]. Experiments show that this method can eliminate the modal aliasing and end-point effect of EMD for processing transient signals, and noise suppression effect is more obvious than EMD algorithm. In most practical cases, under the background of non-Gaussian noise, it is necessary to combine special methods to select the center frequency and bandwidth of the band-pass filter reasonably, which results in a large amount of calculation and complicates the process of noise reduction. All of the above methods have limitations. In order to overcome the problem of band-pass filter noise reduction, this paper proposed a method based on correntropy envelope analysis. The vibration signal is denoised by using correntropy method, and then the denoised signal is analyzed by envelope technique, so as to get the bearing fault characteristic frequency. This method is to reduce the noise of the whole vibration signal, which avoids the influence of the selection of resonance frequency band on the feature extraction of fault signal, and will not cause any loss of information components. The results show that the correntropy envelope analysis technology can effectively eliminate noise in the background of non-Gaussian noise and obtain the fault feature frequency of rolling bearing more accurately.

## II. FUNDAMENTALS OF CORRENTROPY BASED ENVELOPE SPECTRUM

### *A. Correntropy Function*

Correntropy is a kind of generalized correlation measure which maps nonlinear signal to feature space[7], its essence is to extend autocorrelation function to nonlinear space. For any variable sequence x and y, the number of samples is $n$, and correntropy function is defined as:

$$\mathrm{V}(x,y)=\mathrm{E}\{\mathrm{K}(x-y)\} \tag{1}$$

$E\{\cdot\}$ represents the mathematical expectation of random process, and $K(x-y)$ is a positive definite function satisfying Mercer condition. Because of the smoothness and strict positive solution of Gaussian kernel, it is usually chosen as Mercer kernel function[8]. The correntropy calculation formula of two variable sequences based on Gaussian kernel is as follows:

$$V(x,y)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{\|x-y\|_2^2}{2\sigma^2}\right) \tag{2}$$

σ is the kernel length, which is an important variable of the correntropy. The choice of kernel length has a great influence on the correntropy.

Assuming that the source signal is $S(t)$ , the source signal is time shifted and two time-shifted signals $s1=s(t+\frac{\tau}{2})$ and $s2=s(t-\frac{\tau}{2})$ are obtained. According to formula (2), the correntropy of two time-shift signals can be expressed as:

$$C(t)=V(t,\tau)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{\left\|s\left(t+\frac{\tau}{2}\right)-s\left(t-\frac{\tau}{2}\right)\right\|_2^2}{2\sigma^2}\right) \tag{3}$$

$C(t)$ is the denoised signal by using correntropy method. τ is the time-delay factor. $\left\|s(t+\frac{\tau}{2})-s(t-\frac{\tau}{2})\right\|_2$ behaves like an $L_2$ norm which is used to measure the similarity between two time- shifted signals. Gaussian distribution obtained by using formula (3) is shown in Fig. 1 and $L_2$ norm is in the area called the Euclidean zone. Outside of the Eucilidean zone $\left\|s(t+\frac{\tau}{2})-s(t-\frac{\tau}{2})\right\|$ behaves like an $L_1$ norm which is named the Transition zone. Eventually in the saturation zone as two points are further apart, the metric saturates and becomes insensitive to distance (approaching $L_0$ norm)[8]. Because the amplitude of noise is large and the distance between noise and mean value is far, the noise far away from mean value can be in the saturation zone by using correntropy denoising method, so as to minimize the interference of noise to important components of signal.

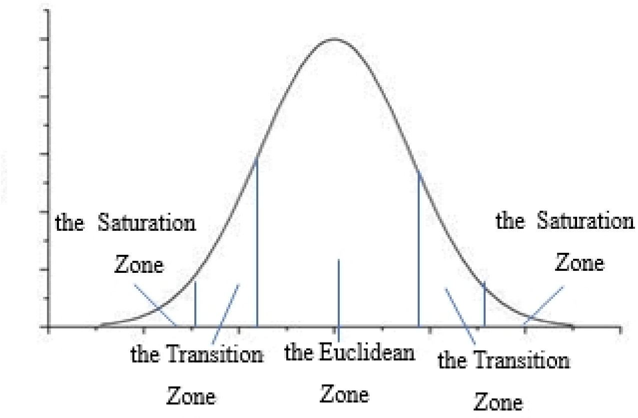

Fig. 1 Gaussian distribution

Because of these characteristics, the correntropy is widely used in machine learning and signal processing[9]. Many experts have carried out more research on the non-Gaussian noise suppression performance of the correntropy, and the Gaussian kernel function plays an important role in the non-Gaussian noise suppression[11]. The practical operation of correntropy is to transform the nonlinear signal from low dimension space to high dimension space, so that the indistinguishable features in low dimension space can be displayed in high dimension space and further distinguish various mixed components in the signal, which is conducive to the extraction of fault features. Gaussian kernel function is usually a better choice because its Hilbert space is infinite, including all hidden features. In addition, Gaussian kernel function is not a nonlinear mapping in space, but an inner product function, which solves the problem of high-dimensional calculation[12]. Therefore, introducing Gaussian kernel function can effectively map the low-dimensional nonlinear inseparable function to the high-dimensional space, so as to distinguish the mixed components in the signal. Band-pass filtering is used to denoise according to different frequencies. If the center frequency is close to the fault characteristic frequency, the effect of denoising will be affected seriously. The correntropy method is used to denoise according to the different amplitude of different components in the signal, so as to achieve the goal of no loss of any components in the fault signal and to denoise effectively when the signal-to-noise ratio is low in the non-Gaussian noise environment.

Let{$x_i$,i϶T}be a stochastic process with T being an index set and $x_i$϶Rd. The correntropy function $V(i_1, i_2)$ is defined as a function from $T * T$ into $R +$ given by Equation (4):

$$\mathrm{V}(i_1, i_2) = \mathrm{E}\{\mathrm{K}(x_{i_1} - x_{i_2})\} \qquad (4)$$

If the correntropy function is expanded by Taylor series formula (4) can be written as follows:

$$V(x_{i_1}, x_{i_2}) = \frac{1}{\sigma\sqrt{2\pi}}\sum_{n=0}^{\infty}\frac{(-1)^n}{\sigma^{2n}n!2^n}\mathrm{E}[\|x_{i_1} - x_{i_2}\|^{2n}] \qquad (5)$$

It contains all even moments of the random variable $\|x_{i1} - x_{i2}\|$. When n = 1, formula (3) can be expressed as:

$$E[\|x_{i_1}{}^2\|] + E[\|x_{i_2}{}^2\|] - 2E[< x_{i_1}, x_{i_2} >] = \sigma_x{}^2 + \sigma_y{}^2 - 2R_x(i_1, i_2) \qquad (6)$$

Where $R_x(i_{1_1}, i_2)$ is the covariance function of random process. Therefore, the information provided by the traditional correlation function is included in the new function. It can be seen that the correntropy is the second-order statistics of mapping feature space data. In addition, by adjusting the kernel size, the correntropy also can contain the higher-order moments of the random variable $\|x_{i_1} - x_{i_2}\|$. The second-order statistics are sensitive to non-Gaussian noise and higher-order statistics are more sensitive to Gaussian noise**Error! Reference source not found.**, so correntropy method is not only suitable for non-linear signal processing under non-Gaussian noise background, but suitable for Gaussian noise background.

### *B. Correntropy Based Envelope Spectrum*

Hilbert transform of the denoised signal is calculated as follows

$$\mathrm{H[C(t)]=C(t)}\frac{1}{\pi t} \qquad (7)$$

The analytical signal $Z(t)$ of signal $C(t)$ can be expressed as follows

$$\mathrm{Z(t)=C(t)+jH[C(t)]} \qquad (8)$$

The envelope signal is:

$$\left|Z(t) = \sqrt{[C(t)]^2 + H[C(t)]^2}\right| \qquad (9)$$

The modulation frequency and its harmonic components can be obtained by FFT transform of envelope signal.

## III. SIMULATION

In order to verify the effectiveness of the method proposed in this paper, the fault signal model of inner race of rolling bearing is constructed as the superposition of fault impact signal and α stable non-Gaussian noise, as follows:

$$A_i = \cos(2\pi f_r t + \varphi_A) + C_A + n(t) \qquad (10)$$

$$S(t) = e^{-Bt} sin 2\pi f_n t \qquad (11)$$

$$x(t) = \sum_i A_i S(t - iT - \tau_i) + n(t) \qquad (12)$$

Where $\tau_i$ is the small fluctuation of the i-th shock with respect to the average period T, $A_i$ is the amplitude of the i-th shock, $\varphi_A$ and $C_A$ are arbitrary constants, $f_r$ is the rotation frequency, n(t) is a non-Gaussian noise with alpha-stable distribution, dispersion coefficient of alpha-stable distribution was 0.5, and S(t) is an impact oscillation generated by pitting failure.

$x(t)$ is the bearing inner race fault signal. The sampling frequency is 12KHz and the number of data points is 16384. The resonance frequency of the system and the amplitude modulation frequency are respectively 7KHz and 75Hz. The fault characteristic frequency is 145Hz and the attenuation coefficient B is 1.

Set the kernel length σ = 0.6 of the correntropy, and the SNR of the simulation signal with the SNR=10dB, 5dB and 0dB respectively, and calculate the envelope spectrum of the denoised signal.

The time domain waveform (SNR = 10dB) of the simulation signal constructed according to Eq (12) is displayed in Fig. 2. The waveform of the denoised signal by correntropy is displayed in Fig. 3. Fig. 3 clearly displays the period of bearing inner race fault signal.

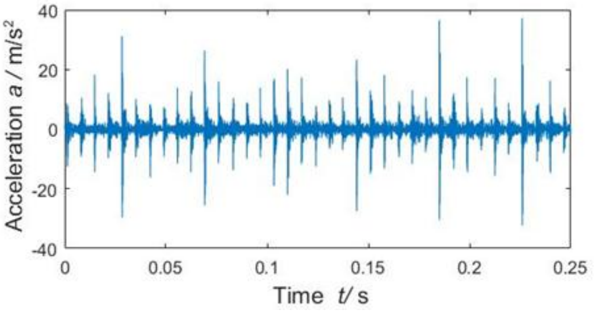

Fig. 2 Waveform of simulation signal (SNR = 10dB)

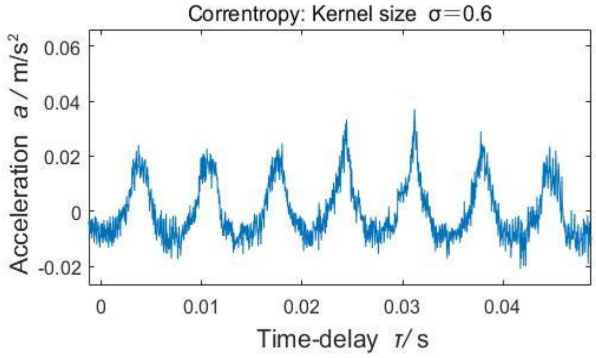

Fig. 3 The correntropy denoising waveform for the simulation signal

Fig. 4 shows the envelope spectrum. It can be seen from Fig. 4 that obvious wave peaks appear at $a1$, $a2$, $a3$, $a4$, $a5$, $a6$. The spectrum peaks $a1$ and $a2$ correspond to amplitude modulation frequency and its fault characteristic frequency, indicating that the bearing has inner race fault. Because the failure position of the inner race changes with the rotation of the shaft, the impact caused by pitting is obviously modulated by the journal. Some sidebands are formed around $a1$, $a2$, $a3$, $a4$, $a5$, $a6$. Corresponding to the carrier frequency $a2$ and its frequency doubling $a3$, $a4$, $a5$, and $a6$ are respectively 300Hz, 450Hz, 600Hz and 750Hz. Compared to the fault characteristic frequency at 150Hz and its harmonics, the impulsive noise is largely suppressed. Thus, the analysis results of the simulated signal under the non-Gaussian noise background demonstrate that the proposed method can detect the fault frequency effectively.

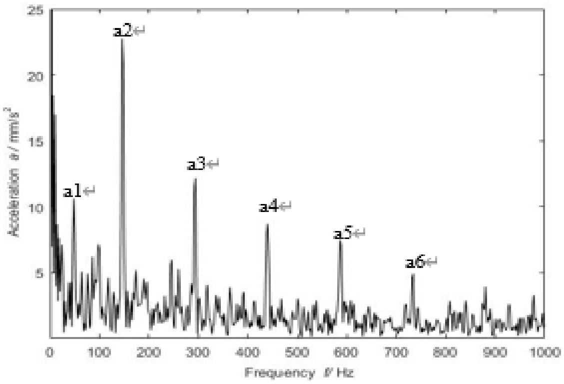

Fig. 4 Correntropy based envelope spectrum (SNR = 10dB)

Fig. 5 shows the envelope spectrum of the denoised signal obtained by band-pass filtering. When the SNR is 10dB, the band-pass filtering method can also get obvious spectral lines with good spectrum characteristics, but the spectrum lines obtained by using correntropy method are more significant.

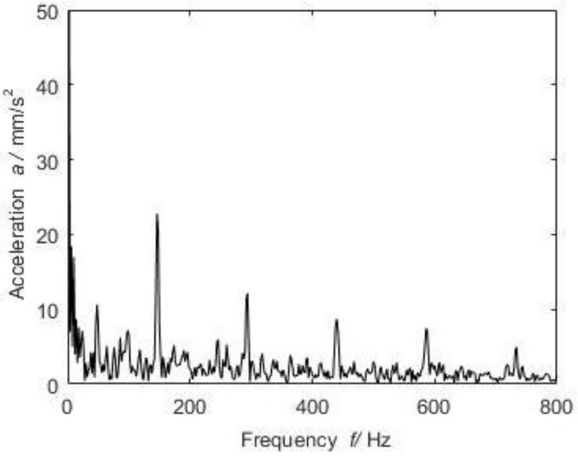

Fig. 5 Band-pass filtering based on envelope spectrum (SNR = 10dB)

Fig. 6 shows the waveform of simulation signal with SNR=5dB. The waveform of the denoised signal obtained by correntropy method is displayed in Fig. 7. In the case of SNR=5dB, the correntropy denoising method maintains good noise reduction performance, and the waveform still shows obvious periodicity.

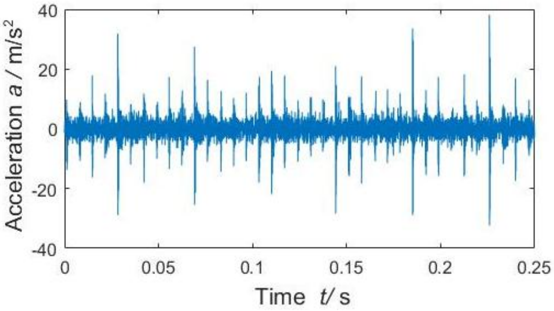

Fig. 6 Waveform of simulation signal (SNR = 5dB)

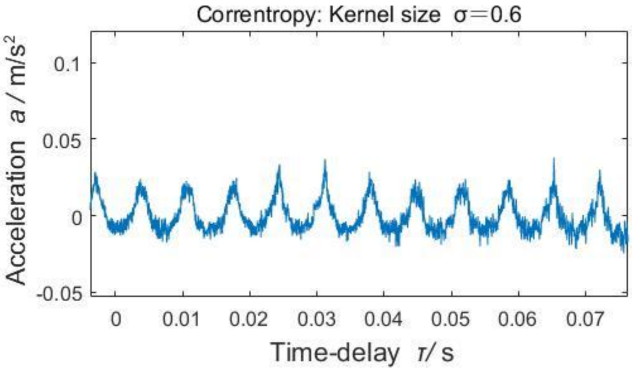

Fig. 7 The correntropy denoising waveform for the simulation signal

Fig. 8 shows the envelope spectrum obtained using the given method in this paper. From Fig. 8, we can still see the obvious wave peaks clearly, which is not significantly different from the envelope spectrum of simulation signal with SNR=10dB.

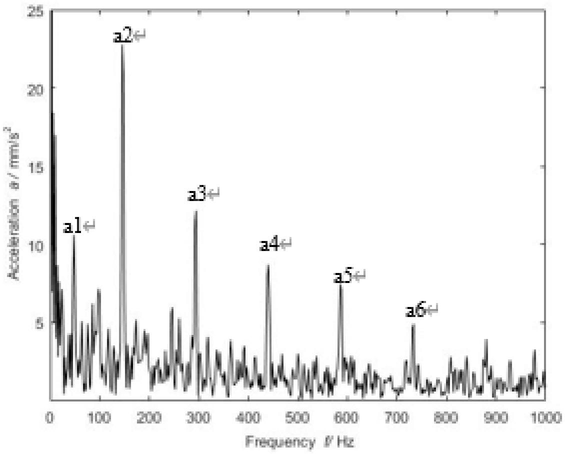

Fig. 8 Correntropy based on envelope spectrum (SNR = 5dB)

Fig. 9 shows the envelope spectrum after denoised using band-pass filtering. It can be seen from the figure that the spectral line is more obvious in the low-frequency segment and fuzzier in the high-frequency segment. When the SNR is 5dB, the spectral lines obtained by this method are more significant and the signal strength is higher.

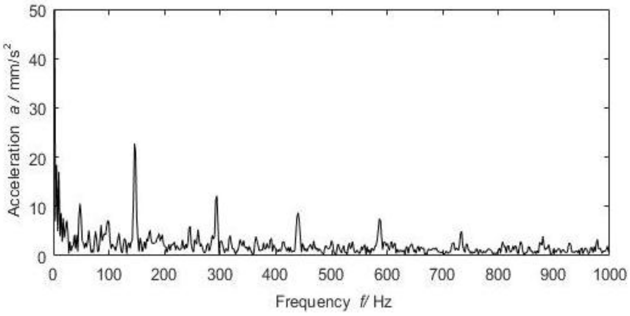

Fig. 9 Envelope spectrum of band-pass filtering method (SNR = 5dB)

Fig. 10 shows the waveform of simulation signal with SNR of 0dB. Fig. 11 is a waveform of the denoised signal obtained by correntropy. When the SNR is 0 dB, the performance of correntropy denoising method decreases, but the waveform still shows periodicity.

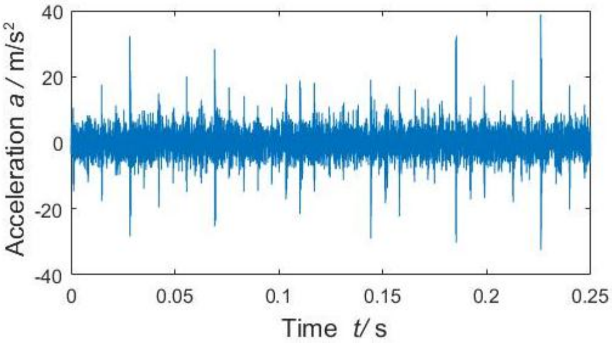

Fig. 10 Waveform of simulation signal (SNR = 0dB)

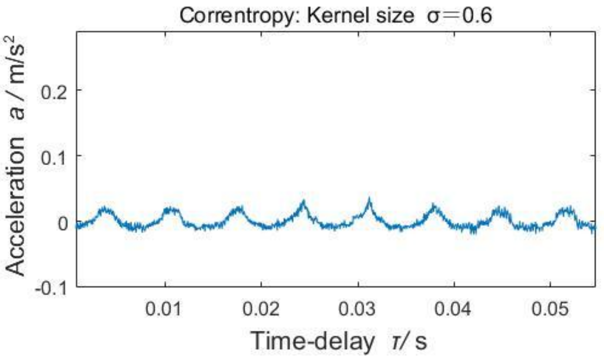

Fig. 11 The correntropy denoising waveform for the simulation signal

Fig. 12 shows the envelope spectrum obtained by the given method in this paper. Fig. 11 is displayed three spectral lines b1, a1 and a2, which can show modulation frequency, carrier frequency and twice carrier frequency, but the high frequency spectrum line is not significant. When the SNR is 0 dB, the noise reduction ability of the proposed method is weakened.

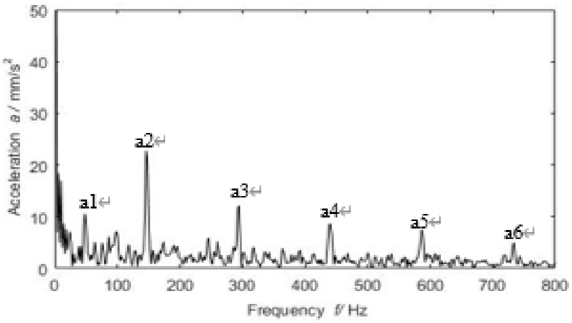

Fig.12 Correntropy based envelope spectrum (SNR = 0dB)

Fig.13 shows the envelope spectrum obtained by band-pass filtering method. When the SNR is 0 dB, the noise reduction ability of band-pass filter seriously declines, and the obvious spectral lines cannot be obtained, so the noise reduction fails.

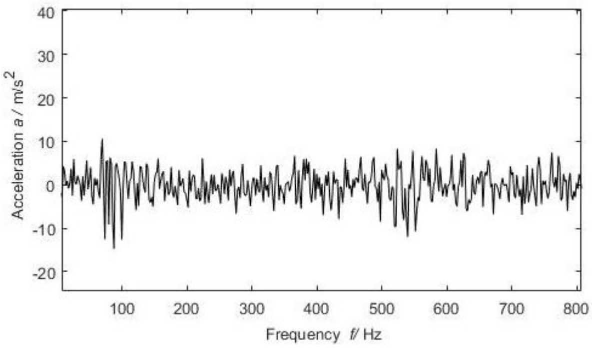

Fig.13 Envelope spectrum of band-pass filtering method

When the SNR is 0dB, the method of correntropy denoising method and band-pass filter denoising method both can get better spectrum characteristics, but the spectrum line obtained by using the correntropy denoising method is more obvious; when the SNR is 5dB, the performance of correntropy denoising method is still good, the performance of band-pass filter denoising method is slightly weakened, and no obvious spectrum line can be obtained in the high-frequency segment; when the SNR is 0dB, the performance of the correntropy denoising method is slightly weakened., but obvious spectral lines can still be distinguished in the low-frequency segment. The spectrum lines in the high-frequency segment are fuzzy, the noise reduction ability of band-pass filter is almost lost and the obvious spectral lines cannot be distinguished, so the noise reduction is invalid. The simulation results prove that the denoising method based on correntropy given in this paper can suppress the impulsive noise more effectively and obtain more significant spectrum characteristics under the background of non-Gaussian noise.

## IV. EXPERIMENTAL RESEARCH

In order to verify the effect of correntropy method in practical application, the experimental object is from the official bearing database of the Case Western Reserve University**Error! Reference source not found.**.The type of the bearing is 6205-2rs JEM SKF, the outer diameter of bearing is 52mm and the inner diameter of bearing is 25mm. The diameter of rolling element is d = 7.94mm, the number of rolling elements is Z = 7 and the contact angle is α = 0 °. Sampling length is 12000 and motor speed is 1772 r / min. Fr is rotation frequency, it is set to 29.5Hz. Sampling frequency $F_S$ is equal to 12000Hz. Fig. 14 is displayed the time domain waveform of the outer race fault signal.

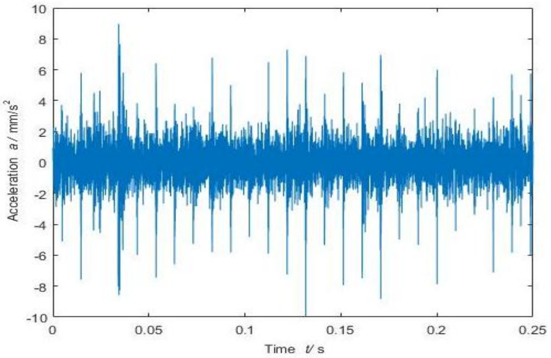

Fig. 14 Time domain waveform of outer race fault

Fig. 15 is the waveform of the denoised signal obtained by using correntropy method. The kernel length σ = 0.6 of the correntropy is taken, and the period of the fault signal is clearly visible in the Fig. 15.

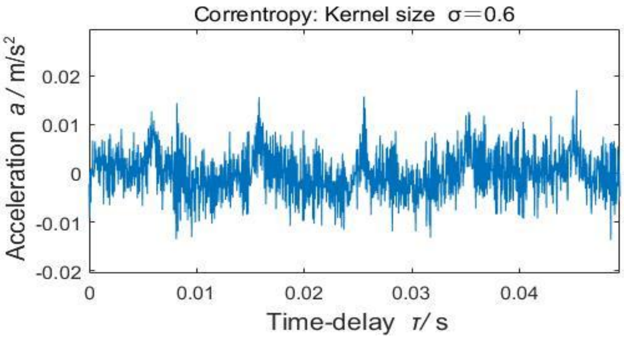

Fig.15 The correntropy denoising waveform for the outer race fault signal

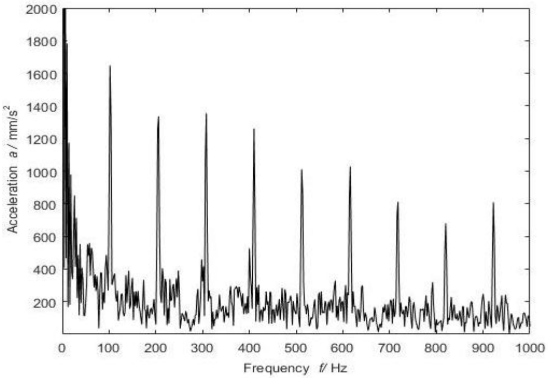

Fig. 16 Envelope spectrum of correntropy denoising

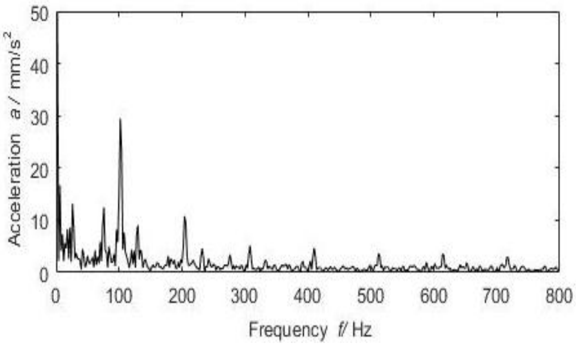

Fig. 17 Envelope spectrum of band-pass filtering method

It can be seen from Fig. 17 that the peaks of envelope spectrum obtained by using band-pass filtering method is not obvious. The selection of the parameters of the band-pass filter has a great influence on the noise reduction effect. The correntropy method has stable noise reduction performance and stronger noise reduction ability.

## V. CONCLUSIONS

In view of the problems existing in the envelope spectrum analysis of rolling bearing fault signal under the background of non-Gaussian noise, this paper proposed an envelope spectrum analysis method based on correntropy method. In this paper, the principle of noise reduction of correntropy function is discussed, and the correntropy method is used to reduce the noise of rolling bearing fault signal in non-Gaussian noise environments with different signal-to-noise ratio, and the envelope demodulation analysis of the signal after noise reduction is carried out. Simulation and experimental studies have indicated that under the condition of the same signal-to-noise ratio, the spectrum characteristics obtained by correntropy envelope analysis method are better than that obtained by band-pass filter, and have more advantages in noise reduction.

## ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (Grant: 51375319), Hebei Provincial Natural Science Foundation (Grant: E2013421005), Key project of scientific and technical research in Hebei Education Department (Grant ZD2018041). The authors are grateful for the financial support. The authors are also grateful to the editors and reviewers for their constructive comments.

## REFERENCES

[1] Gander W A, Introduction to random processes with applications to signals and systems, 1900, McGraw-Hill. NY.

[2] Roberts RS, Brown WA, Loomis HH, "*Computationally efficient algorithms for cyclic spectral analysis"*, Signal Processing, 1991(4), pp. 38-49.

[3] T. F. Ming, S. Zhang and Y. X. Zhang, "*Application of Molert Combined Wavelets Bandpass Filter to Fault Diagnosis of Rolling Bearing*", processing of the 12th National conference on vibration theory and Application, Nanjing, China, 2017, pp. 108-115.

[4] L. Zhang, Z. D. Mao, S. X. Yang and X. L. Li, "*An improved kurtogram based on band-pass envelope spectral kurtosis with its application in bearing fault diagnosis*", Journal of Vibration and Shock, vol. 37, 2013.

[5] Z. R. Yao, Y. Hu, "*Fault Diagnosis Research of Rolling Bearing Based on EMD and Hilbert Envelope Spectrum Analysis*", Equipment Machinery, 2019, pp. 58-61.

[6] G. T. Wan, "Fault Feature Extraction Method of Rolling Bearing under Variable Conditions Based on LMD and Bandpass Filter', Beijing Jiaotong University", Beijing, China, 2018.

[7] P. B, J. A, "*CS2 analysis in presence of non-Gaussian background noise—Effect on traditional estimators and resilience of log-envelope indicators"*, Mechanical System and Signal Processing, 2017(90), pp. 378-398.

[8] T. Liu, T. S. Qiu, "*Cyclic Correntropy: Foundations and Theories*", IEEE, 2018(6), pp. 34659-34669.

[9] W. F. Liu, Puskal P. Pokharel, J. C. Principe, "*Correntropy: Properties and Applications in Non-Gaussian Signal*", IEEE, 2007(11), pp. 5286-5298.

[10] Z. K. Zhu, Z. H. Feng, F. R. Kong, "*Cyclostationarity analysis for gearbox condition monitoring: approaches and effectiveness*", Mech. Syst. Signal Process, 2005(19), pp. 467-482.

[11] B. Scholkopf, A. J. Smola, K. R. Muller, "*Nonlinear component analysis as a kernel eigenvalue problem*", Neural Compute, 1998(10), pp. 1299-1319.

[12] A. G, Jose C. P, "*Correntropy as a novel measure for nonlinearity tests*", Signal Processing, 2009(89), pp. 14-23..

[13] P. Pennacchi, P. Borghesani, S. Chatterton, "*A cyclostationary multi-domain analysis of fluid instability in Kaplan turbines*", Mech. Syst. Signal Process, 2015(60-61), pp. 375-390.

[14] G. Yu, C. Li, J. Zhang, "*A new statistical modeling and detection method for rolling element bearing faults based on alpha-stable based on alpha-stable distribution*", Mech. Syst. Signal Process, 2013(41), pp. 155-175, 12//2013.

[15] P. Borghesani, M. R. Shahriar, "*Cyclostationary analysis with logarithmic variance stabilization*", Mech. Syst. Signal Process, 2016(70), pp. 51-72.

[16] I. Fontes, J. B. Rego, A. d. M. Martins, L. F. Silveira, J. C. Principe, "*Cyclostationary Correntropy-Definition and applications*", Except syst. Appl, 2017(69), pp. 110-117.

[17] J. W. Xu, A. R. Paiva, I. Park, J. C. Principe, "*A Reproducing Kernel Hilbert Space Framework for Information-Theoretic Learning*", IEEE Trans. Signal Process, 2008(56), pp. 5891-5902.

[18] D. Wang, K. L. Tsui, Q. Miao, "*Prognostics and health management: A review of vibration based bearing and gear health indicators*", IEEE Access, 2018, pp. 665-676.

[19] A. G, Jose C. P, "*Correntropy as a novel measure for nonlinearity tests*", Signal Processing. 2009(89), pp. 14-23.

[20] W. A. Smith, R. B. Randall, "*Rolling element bearing diagnostics using the Case Western Reserve University data: A benchmark study*", Mech. Syst. Signal Process, 2015(64), pp. 100-131