Acoustic Emission Signal Feature Extraction of Inter-shaft Bearing Based on Quantum Entropy

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***Abstract*—For In order to solve the problems of weak signal characteristics and extraction difficulty during early fault stage of inter-shaft bearing, this paper introduces quantum theory into the calculation of information entropy, and proposes a new fault feature extraction method of inter-shaft bearings, quantum entropy. Firstly, based on the basic principle of quantum theory, the multi-qubit system of acoustic emission signal is established, and the calculation method of quantum entropy is constructed. Then, the four different working conditions of acoustic emission signal, i.e. outer ring fault, rolling element fault, inner ring fault and trouble-free, are simulated by the fault simulation test bench of inter-shaft bearing, and the acoustic emission signal is collected. After discussing the influence of different key parameters on quantum entropy, the quantum entropy of acoustic emission signals of inter-shaft bearings in four states is calculated, and the calculation results are analyzed. The experimental data analysis shows that the quantum entropy proposed in this paper can effectively extract the running state characteristics of the inter-shaft bearing and determine the fault types.**

Keywords- Inter-shaft bearing; Acoustic emission; Quantum entropy; Feature extraction

I. INTRODUCTION

In modern mechanical equipment, the energy of bearing vibration acceleration signal extracted by sensors to reflect state information is very weak, and it has non-stationary characteristics, which brings difficulties to fault diagnosis[1]. The key of bearing fault diagnosis is how to extract fault feature information from non-linear and non-stationary vibration signals. Most fault diagnosis methods are based on time domain and frequency domain analysis of fault vibration signals to identify and monitor the working status of bearings. However, due to load, speed and other non-linear factors, it is difficult to accurately diagnose the working state of bearings only in time domain and frequency domain[2].

Fault diagnosis process of inter-shaft bearing is complex, especially the early fault signal of inter-shaft bearing is very weak, which is easily submerged in the noise signal of other parts and components and cannot be detected[3]. Acoustic emission signals have high frequency characteristics and high sensitivity, and can effectively extract the early fault signal characteristics of inter-shaft bearings [4].

In recent years, the theory of entropy has been widely used in bearing fault diagnosis technology. Common entropy values include information entropy, sample entropy, permutation entropy, fuzzy entropy, frequency band entropy and energy entropy. Song Xiaoxia et al. [5] proposed an improved spatial correlation denoising algorithm based on sample entropy. The results show that this method can restore the characteristic frequencies of signals better and achieve better denoising effect than other traditional algorithms. Chen Xianglong, et al. [6] proposed a fault feature extraction method for rolling bearings based on improved permutation entropy. The results of simulation and test data analysis show that the method can effectively identify the resonance frequency band of rolling bearings and accurately extract the fault characteristics of rolling bearings. Zheng Jinde, et al.[7] proposed a rolling bearing fault diagnosis method based on improved multi-scale fuzzy entropy and support vector machine. Finally, the proposed fault diagnosis method is applied to the analysis of rolling bearing test data, and the results verify the effectiveness and superiority of the proposed method. Wang Xiaoling, et al. [8] proposed a fault diagnosis method for rolling bearings based on band entropy. Through the analysis of simulation signals and test data of different signal-to-noise ratios, it was proved that this method can effectively determine the frequency and bandwidth of the filtering center, thereby improving the signal-to-noise ratio of the signal and realizing the fault diagnosis of bearing. Xu Le, et al. [9] proposed a fault feature extraction method for rolling bearings based on LMD energy entropy. The experimental results show that LMD energy entropy has strong signal characterization ability and can effectively extract fault features of rolling bearings.

II. QUANTUM ENTROPY

A. Quantum Theory

Quantum bit is the basic unit describing quantum world in quantum theory system. The state it expresses is a superposition state. Its mathematical expression is:

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$$\left|\phi\right\rangle = \mathrm{a}\left|0\right\rangle + \mathrm{b}\left|1\right\rangle \ . \tag{1}$$

Where, $\left|0\right\rangle$ and $\left|1\right\rangle$ are quantum ground states of quantum bits, coefficients a and b are probability amplitudes of quantum states, real or complex, and the modular squares of probability amplitudes are quantum probabilities, $\left|\mathrm{a}\right|^2$, $\left|\mathrm{b}\right|^2$ denote the probability of the occurrence of two ground states of quantum bits $\left|0\right\rangle$ and $\left|1\right\rangle$ respectively. The quantum probability amplitude satisfies the normalization condition.

$$|\mathrm{a}|^2 + |\mathrm{b}|^2 = 1 \, . \tag{2}$$

Equations (1) and (2) show that quantum bits can describe various states composed of two ground states with different probabilities.

B. Information Entropy Theory

Information Entropy is a description of the degree of uncertainty of the system, so it can be used to measure the change of bearing operation state. System information entropy is defined as:

$$H(A) = -\sum_{i=1}^{n} u(A_i) log_2 u(A_i) \, . \tag{3}$$

Where $u(A_i)$ is the measure of set A_i , $\mathrm{i} = 1,2,\cdots,\mathrm{n}$.

C. Basic Principles of Quantum Entropy

Information Entropy is very similar to the way in which quantum ground or vector states and their probabilities are used to express information states in quantum theory. Therefore, the combination of quantum theory and information entropy can be used to describe and describe the operation state of bearings. Its basic principles are as follows:

1) Signal normalization:Let AE signal time series $X=\{x(i), i=1,2,\cdots,N\}$ .According to the (4), the time series of AE signals are normalized, and the normalized time series are $Y=\{y(i), i=1,2,\cdots,N\}$.

$$y(i) = abs\left(\frac{x(i)}{max(abs(x))}\right) . \tag{4}$$

*2) Phase space reconstruction:*The normalized time series is reconstructed in phase space and the matrix Y_0 is obtained.

$$\mathrm{Y}_0 = \begin{bmatrix} \mathrm{Y}_0(1) \\ \mathrm{Y}_0(2) \\ \cdots\cdots \\ \mathrm{Y}_0(\mathrm{j}) \\ \cdots\cdots \\ \mathrm{Y}_0(\mathrm{K}) \end{bmatrix} = \begin{bmatrix} y(1) & y(1+\lambda) & \cdots & y(1+(m-1)\lambda) \\ y(2) & y(2+\lambda) & \cdots & y(2+(m-1)\lambda) \\ \cdots\cdots & \cdots\cdots\cdots & \cdots & \cdots\cdots\cdots\cdots\cdots \\ y(j) & y(j+\lambda) & \cdots & y(j+(m-1)\lambda) \\ \cdots\cdots & \cdots\cdots\cdots & \cdots & \cdots\cdots\cdots\cdots\cdots \\ y(K) & y(K+\lambda) & \cdots & y(K+(m-1)\lambda) \end{bmatrix} \tag{5}$$

Where, $j = 1,2,\cdots,K$, m is the embedding dimension, λ is the delay time, $K=N-(m-1)\lambda$, where $Y_0(j)$ is called the reconstructed component.

3) Quantization of reconstructed components:

$$\begin{aligned} \left|Y_0(j)\right\rangle &= \omega_{j,1}\left|00\cdots0\right\rangle + \omega_{j,2}\left|00\cdots1\right\rangle + \cdots + \omega_{j,n}\left|11\cdots1\right\rangle \\ &= \sum_{K=1}^{n} \omega_{j,K}\left|i_b\right\rangle \end{aligned} \, . \tag{6}$$

Where $\left|i_b\right\rangle$ is the i state vector of the reconstructed component $Y_0(j)$ quantum system. $\omega_{j,K}$ is the state vector $\left|i_b\right\rangle$ probability amplitude, $\left|\omega_{j,K}\right|^2$ state vector $\left|i_b\right\rangle$ probability, which satisfies the normalization condition.

4) Calculating the probability of each state vector:

$$P_K = \sum_{j=1}^{K} \left|\omega_{j,K}\right|^2 \, . \tag{7}$$

Where, $K = 1,2,\cdots,n$.

*5) Computing quantum entropy:*The probability of occurrence of state vectors is regarded as the probability of occurrence of events, and the information entropy is calculated.

$$H_q^*(x) = -\sum_{i=1}^{K} p_K log_2 p_K \, . \tag{8}$$

*6) Quantum Entropy Normalization:*When $\mathrm{p_K} = 1/\mathrm{n} = 1/2^{\mathrm{m}}$, the quantum information entropy $H_q^*(x)$ reaches the maximum value m .In order to facilitate comparison, the maximum $H_q^*(x)$ is usually used for normalization.

$$H_q(X) = \frac{H_{\mathrm{q}}^*(X)}{m} \, . \tag{9}$$

After standardization, $0 \le H_{\mathrm{q}}(X) \le 1$ is satisfied.

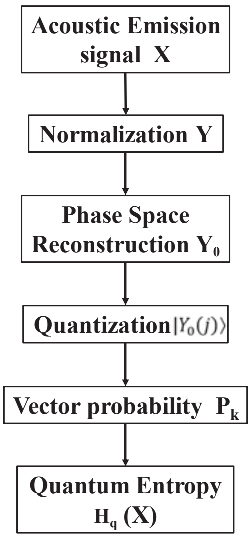


Figure 1. Inter-shaft Bearing Fault Simulation Test Bench

III. DIAGNOSTIC EXAMPLE

A. *Fault Simulation Test of Inter-shaft Bearing*

The test bench is composed of two motors, a rotating shaft, three bearing supports, two acoustic emission sensors and a preamplifier. The overall structure of the test bed is shown in Fig. 2. The NU202 cylindrical roller inter-shaft bearing used in this test is shown in Fig. 3. The geometric parameters of the bearing are shown in Table 1. Express-8 acoustic emission system is used to collect and analyze the acoustic emission signals. Acoustic emission sensors are arranged in the radial direction of the bearing seat. The rotation direction of inner and outer rings of bearings is reversed. The rotational speed range of each fault is limited to 0-1000r/min. A total of 80 samples are collected, and each sample is collected for 10 seconds.

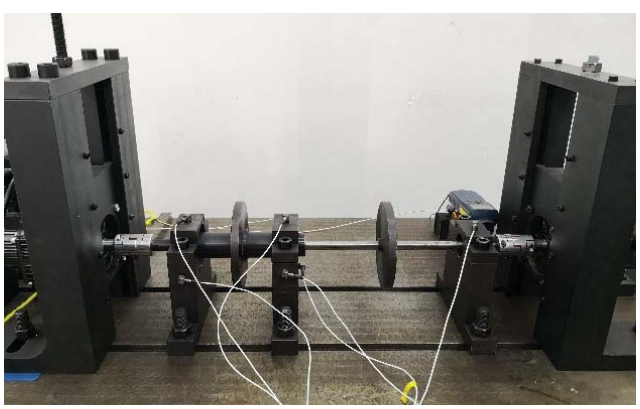
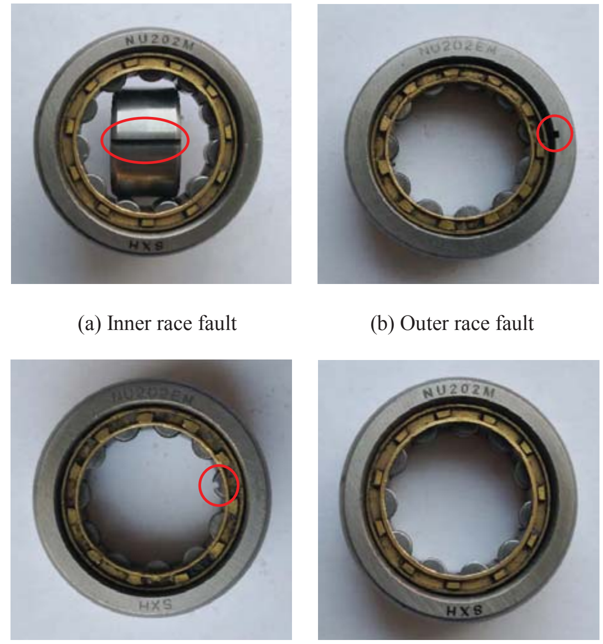


Figure 2. Inter-shaft Bearing Fault Simulation Test Bench



(a) Inner race fault (b) Outer race fault

(c) Rolling elements fault (d) trouble-free

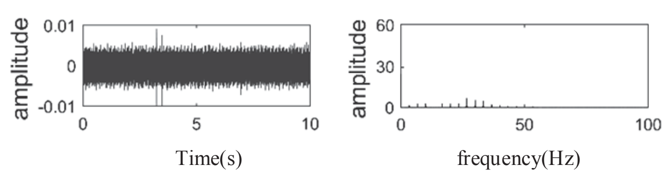
Figure 3. Inter-shaft Bearing with Local Failure

TABLE I. NU202 BEARING PARAMETERS

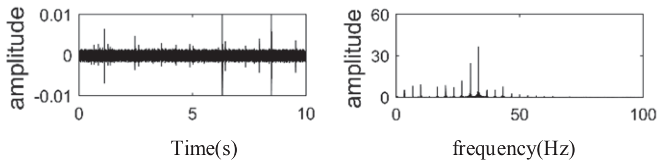
Parameter name	numerical value
Inner ring diameter (mm)	15
Outer ring diameter (mm)	35
Pitch diameter (mm)	25
Roller diameter (mm)	5
Bearing thickness (mm)	11
Roller number (mm)	11
Contact angle (°)	0

B. *Analysis of experimental data*

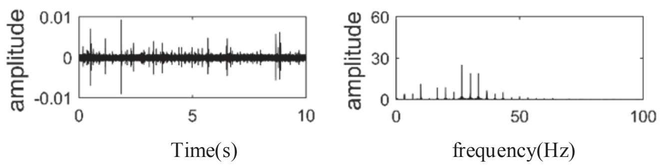
When the inner ring speed is 400 r/min and the outer ring speed is 600 r/min, the time-frequency diagrams of AE signals collected from the four states are shown in Fig. 4. From the waveforms in time domain and frequency domain of the four states, it can be seen that the frequency components in each state are very complex, and the difference is very small, and the fault information is submerged. It is difficult to judge the operation status of the inter-shaft bearing only according to the frequency domain analysis at this time.



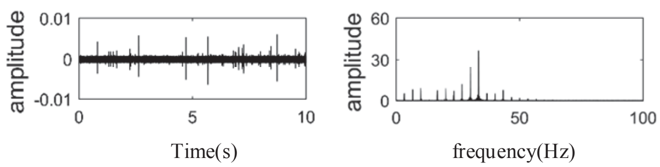
(a) Normal



(b) Inner



(c) Ball



(d) Outer

Figure. 4 Time-domain and Frequency-domain Waveforms of Inter-shaft Bearings under Four Conditions

The quantum entropy proposed in this paper is used to extract acoustic emission signals of four kinds of inter-shaft bearings. Because of the definition of quantum entropy, the calculation of quantum entropy is related to embedding dimension m, time delay λ and data length N. In order to study the influence of data length N on quantum entropy, the quantum entropy values of AE signals with length of 50 000, 100 000, 15 000 and 200 000 were calculated under different embedding dimensions. The calculation results are shown in Fig. 5.

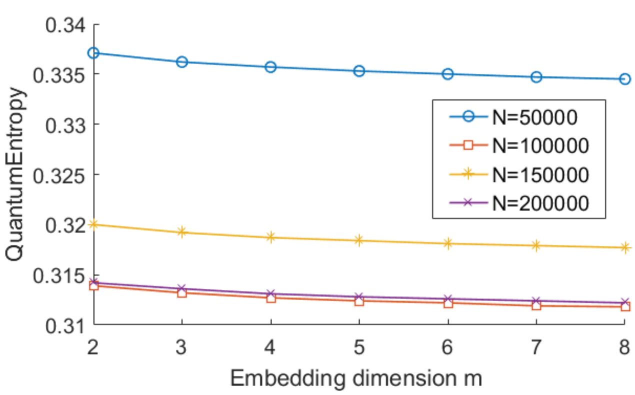


Figure. 5 Quantum Entropy Value of Acoustic Emission Signal of Inter-shaft Bearing under Different Data Length

Time delay has little influence on time series calculation. Taking AE signal with length of 20000 as an example, the relationship between quantum entropy and embedding dimension under different time delay is shown in Fig. 6. It can be seen from the graph that time delay has little influence on quantum entropy.

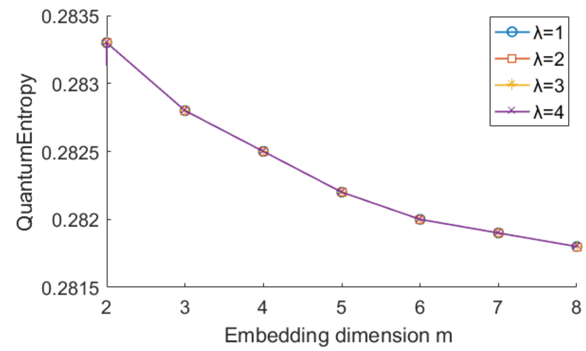


Figure. 6 Quantum Entropy Value of Acoustic Emission Signal of Inter-shaft Bearing under Different Time Delays

In summary, the quantum entropy values of 20 groups of test samples in four states are calculated by embedding dimension m=4, time delay lambda=1 and data length N=200000. The results are shown in Fig. 7.

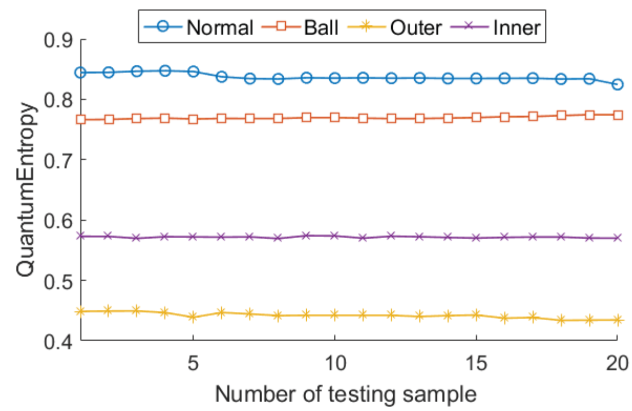


Figure. 7 Quantum Entropy Value of Acoustic Emission Signal of Inter-shaft Bearing under Four Conditions

C. Result Analysis

From Fig. 7, we can see that quantum entropy can clearly distinguish the signals of four states, and the entropy values of each state remain stable. Different faults have different effects on the distribution of state vectors, so they have different entropy values. The relationship between the acoustic emission signal entropy values of the four states is QE (Normal) > QE (Ball) > QE (Inner) > QE (Outer). When the inter-shaft bearing fails, the impact and frequency change caused by the fault have a greater impact on the signal, resulting in the weakening of the uniformity of the state vector distribution, resulting in the reduction of quantum entropy. Because the outer ring speed is higher than the inner ring speed, theoretically, the frequency change and impact of the inter-shaft bearing with outer ring fault are higher than that of the inter-shaft bearing with inner ring fault, and the entropy value of the acoustic emission signal is smaller than that of the inter-shaft bearing with inner ring fault. When the rolling element fails, the rolling element not only rotate on its own axis, but also rotate along with the inter-shaft bearing. The AE signal of the rolling element is more complex than that of the inner and outer rings. Therefore, the entropy of AE signal of inter-shaft bearing with rolling element fault is larger than that of inner ring and outer ring fault.

D. *Comparing with the results of PE and FE*

To further illustrate the advantages of quantum entropy in feature extraction of inter-shaft bearings, permutation entropy and fuzzy entropy are used to extract acoustic emission characteristics of inter-shaft bearings in four states. The calculation results are shown in Fig. 8 and Fig. 9. From the graph, it can be seen that the features extracted by PE and FE for the four states of the inter-shaft bearing fluctuate greatly, and the stability is poor, and the characteristic curve is not separated, so it can not be used as an effective feature to accurately judge the operation state of the inter-shaft bearing. Compared with PE and FE, the quantum entropy proposed in this paper has more advantages in the feature extraction of acoustic emission signals from inter-shaft bearings.

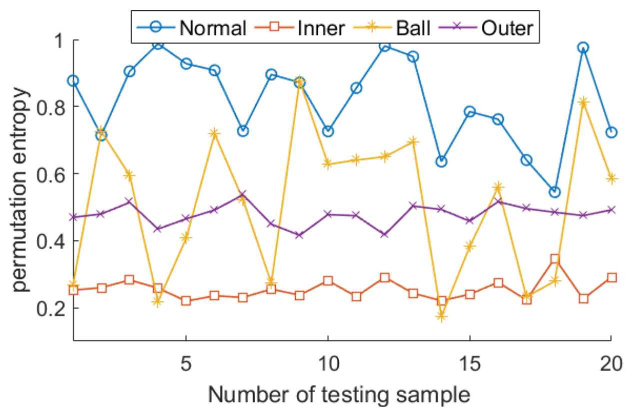


Figure. 8 Permutation Entropy Value of Acoustic Emission Signal of Inter-shaft Bearing under Four Conditions

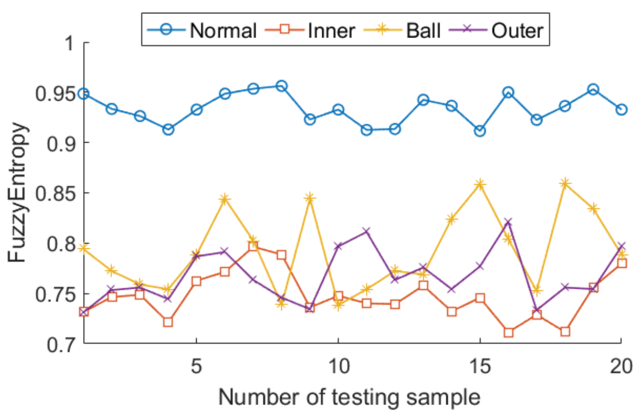


Figure. 9 Fuzzy Entropy Value of Acoustic Emission Signal of Inter-shaft Bearing under Four Conditions

IV. CONCLUSION

In this paper, a new feature calculation method, quantum entropy, is used to extract the features of inter-shaft bearings and in order to judge its operation status. The main conclusions are as follows:

- The experimental data analysis shows that the quantum entropy proposed in this paper can effectively extract the running state characteristics of the inter-shaft bearings and determine the fault types. Compared with PE and FE, quantum entropy is more effective and more stable for feature extraction of acoustic emission signals from inter-shaft bearings.
- The magnitude of quantum entropy is related to the distribution of state vectors corresponding to acoustic emission signals. Without any faults, the entropy of AE signal is the largest, and the corresponding state vectors are more uniform. On the contrary, the probability of some state vectors increases or decreases due to the frequency changes caused by faults, meanwhile, the uniformity of the distribution of state vectors weakens, which leads to the decrease of quantum entropy.

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