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Study on AE in Mechanical Seal Lift-off Recognition of Mechanical Main Shaft

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Abstract: For the problem of the determination of lift-off position and the measurement of end face thickness for mechanical seal more difficult, the method based on acoustic emission signal end face lift-off condition monitoring technology for mechanical seal was proposed. The electric eddy current sensor made direct measurement in the internal of mechanical seal device, and the acoustic emission sensor was fixed in the outside for indirect measurement. The acoustic emission signals were de-noised by wavelet threshold de-noising method. The representative energy features were selected by wavelet packet energy spectrum algorithm. It was established that the Radial Basis Function neural network model used for identification of the mechanical seal lift-off position, and the extracted wavelet energy features as its input. It was confirmed accurate and effective that the acoustic emission identification technology through comparing with the data detected by electric eddy current sensor. So using the acoustic emission technology realized the identification of the mechanical seal lift-off position of mechanical main shaft from inside to outside. It is convenient to be used and promotion in industrial field. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Mechanical main shaft, Mechanical seal, Acoustic emission, Wavelet packet, Neural network.

1. Introduction

Mechanical seal is widely used as one of dynamic seals for rotary shaft. Mechanical seals have a reliable performance, a long life and a lower consumption. The maintenance cost is not high, and it can work normally in different harsh conditions, such as high temperature, high pressure, high speed and strong corrosive medium.

Therefore, mechanical seals are commonly used in petroleum, chemical, metallurgy, aviation and other industries [1]. Mechanical seals play a very important role in the process of industrial safety production, especially in Petroleum chemical industry and nuclear power industry. That means the condition monitoring of mechanical seals, particularly the monitoring of end face is of much importance. Acoustic emission (AE) technique has been one of the important means of security monitoring of large bearing structures, cock valves and sealing devices. AE signals contain the characteristics of AE source, such as the type, size, location or change trend of the fault and friction condition among mechanical components, etc. The location and form of friction can be detected by AE. Base on those features, AE technique is very suitable for the condition identification and fault diagnosis of rotating ring and stationary ring scratches while mechanical seals running. AE technique provides a feasible way to recognize the condition of mechanical seals, especially the judgment of end face lift-off condition.

2. Acoustic Emission

2.1. Acoustic Emission Testing Technique

While the energy is released rapidly from a local area of the materials where the stress is concentrated, the transient elastic waves will be generated. This phenomenon is called AE or stress-wave emission. Modern AE technique started with the Kaiser's research in Germany in the early 1950s. In China, the research about AE started in the early 1970s. The Shenyang metal research institute of Chinese academy of sciences, 621 department of space, the Hefei general machinery research institute, Wuhan university and other Scientific research institutes have studied on the AE characteristics of metal and composite material. From the 1990s up to now, researches and applications on AE technology in our country have developed rapidly. However, the applications of AE technique on monitoring the condition of end face of mechanical seals are rare. Researchers lack of deep understanding of the mechanisms of AE source using AE testing technology. More time and effort is needed urgently to spend on studying on this for the researchers.

2.2. Installation of Acoustic Emission Sensor

AE signal is easily affected by environmental noise while transmitting. And when it transmits to soft cushion materials, AE signal will disappear. Hence that the sensor should be installed as near as the AE source, and in its transmission route, any gap and soft cushion material should be avoided. Fig. 1 shows the structure diagram of testing apparatus of mechanical main shaft hydrodynamic pressure seal and the AE sensor installation location.

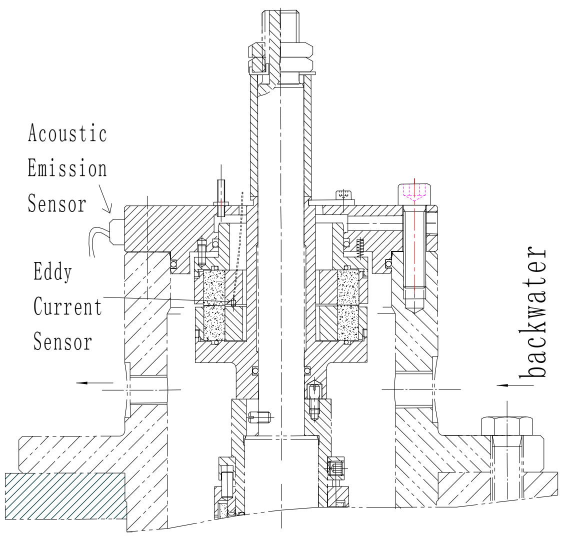


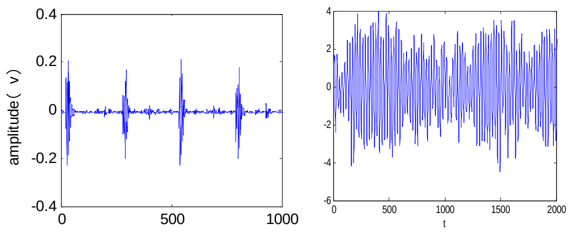
Fig. 1. Structure diagram of testing apparatus.

Stationary ring is thermal fixed in the middle of driving ring. Driving ring and base of stationary ring are installed by interference fit closely, which ensures that the AE signal can pass out through the base of stationary ring.

1.3. Parameters of the Acoustic Emission Signal of Mechanical Seals

There is two basic rules to consider when design the mechanical seals. The first and the most important thing is to make the seal leakage as small as possible. The second thing is to improve the contact situation of end face, i.e. reduce the friction of end face and extend the service life of seals. However, these are two rival rules. Considered about the basic principles of mechanical seals, the end face should contact closely to make the leakage as small as possible, in which condition the friction of end face will increase. While the mechanical seals starting or stopping, the condition of end face changes between contact and non-contact. The friction form between rotating ring and stationary ring changes while the rotating speed, pressure, temperature and other operating conditions changes. The friction form changes from contacting friction to fluid friction, and sometimes boundary friction occurs. While friction occurs, burst AE signal is the main form. When friction form changes, parameters of AE also changes and so does the friction mechanics characteristics.

AE signal have a large dynamic range. Its displacement amplitude ranges from 10-15 m to 10-9 m [2, 3]. The form of AE signal is varied. Usually, there are two forms, i.e. burst AE signal and continuous AE signal, as shown in Fig. 2.



(a) Burst (b) Continuous

Fig. 2. AE signal.

The burst AE signal is a time domain separable waveform, which consists of high amplitude, incoherent and duration for microseconds signals. Continuous AE signal is the signal, whose single pulse can not be resolved. Actually, burst AE signal always exist, but when the frequency of AE is so high that the signal is not separable in time domain, it becomes continuous AE signal. Plastic deformation of metal materials and leakage of fluid produce continuous AE signals while frictions produce burst AE signals. Typical AE signal waveform of the friction of end face mechanical seal is shown in Fig. 3. Such parameters of AE signal as amplitude, energy, rise-time, duration, and ringing count are shown in Fig. 3.

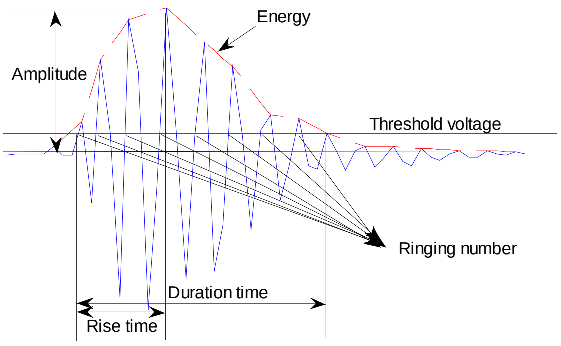


Fig. 3. Graph of AE signal.

AE signal contains a wealth of information of the friction and the change of wear of mechanical seal end face. Hence, AE detection method is different from other usual ones in the aspect of mechanical seal condition monitoring. Its advantages mainly include the following aspects [4-6].

1) AE is a dynamic test method, the energy detected by AE sensor comes from the tested object itself. Ideally, the friction between end face of mechanical seals is the only source of AE. 2) AE testing method is sensitive to linear wear and can detect the movements of the wear under structure stress. While the mechanical seals starting up, the stress of main shaft increases linearly basically. 3) The installation of AE sensor is very convenient. Once for the load test of detection of wear and tear is enough, which reduces the downtime of machinery. 4) AE signal can also provide such real time or continuous information as the variation of wear condition of end face with the change of load, time, temperature or other parameters. Hence, to prevent catastrophic failure caused by unknown defects is possible. AE technique is suitable for the condition monitoring online, real-time evaluation, and early damage prediction of industrial process.

AE technology has many advantages, but also has certain limitations in the application. It cannot provide the static stress information, and is susceptible to interference of environmental noise. In addition, the differences between the acquired signal and AE source signal affect the recognition of AE source.

In reference [7-10], the surface roughness, taper, waviness, steps, grooves and other factors, which affect the lift of the seal face and lift characteristics of corresponding seals is discussed. Also, several criterions for judgment of end face lift-off are presented. According to these criterions, a model is established for experimental verification, which indicates that the method is effective in judging whether the end face lifts off. However, in actual field, with the running of mechanical seals, the quantities concerned change constantly [11, 12]. The established model and the measured parameters can hardly meet the tracking measurement of the dynamic working condition accurately, i.e. the measurement or calculation of multiple parameters is a certain difficulty. Nevertheless, AE technique is not restricted by these factors. The measured AE signal can reflect the contact situation of end face of mechanical seal after effective analysis, and be able to monitor the friction condition effectively. Overall, as a dynamic testing technique, AE signal detection, which is highly sensitive to micro defects, friction and wear, can judge the severity of wear defects and even predict the residual life of the machinery.

Fig. 4 shows the power spectrums of AE signals acquired before and after the liquid-lubricated film forms. As the film forms, i.e. the end facelifts off, the contacting condition of end face changes. Before the end face lifts off, the direct contact friction between rotating ring and stationary ring enhances the power of stress wave signal. After the end face lifts off, liquid-lubricated film forms, which reduces the friction between the two rings and the power of stress wave signal.

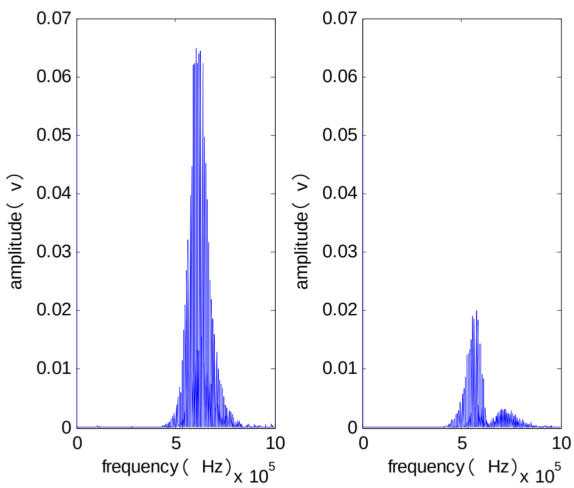


Fig. 4. The power spectrum of AE signals before and after end face lifts off.

In conclusion, the advantages of AE testing technology can meet the requirements of contacting detection of mechanical seal end face. When mechanical seals running, friction energy between end face transmit along the base of stationary ring in the form of stress wave. Based on the AE signal acquisition and analysis of end face contact, condition monitoring can be realized.

3. Wavelet Pack Transform

3.1. Wavelet Packet Decomposition

The frequency range of AE signals is large and the high frequency characteristics are complex and changeable. Therefore, wavelet pack transform continues to decompose the high frequency band based on wavelet decomposition, which makes low frequency band and high frequency band have the same time-frequency resolution.

The wavelet packet decomposition formulas are shown as followed.

$$d_k^{j+1,2n} = \sum_l h_{0(2l-k)} d_l^{j,n}, \tag{1}$$

$$d_k^{j+1,2n+1} = \sum_l h_{1(2l-k)} d_l^{j,n}, \tag{2}$$

The wavelet packet reconstruction formula is shown as followed.

$$d_l^{j\cdot n} = \left[h_{0(l-2k)} d_k^{j+1,2n} + h_{1(l-2k)} d_k^{j+1,2n+1} \right], \tag{3}$$

where $d_k^{j+1,2n}$, $d_k^{j+1,2n+1}$ are the kth sequences of the j-dimension decomposition of original signal, h0(n), h1(n), are the low-pass and high-pass filter coefficients of multi-resolution analysis.

Before or after the mechanical seal face lifts off during the operation, the time domain AE waveforms are quite different, which are respectively shown in Fig. 5 and Fig. 6. Before the end face lifts off, the amplitude of AE signal is larger and contacting friction exists as the main friction form. While the end face lifts off, a fluid lubricated film forms, which reduces the friction between end face and reduces the energy of stress waves generated by friction.

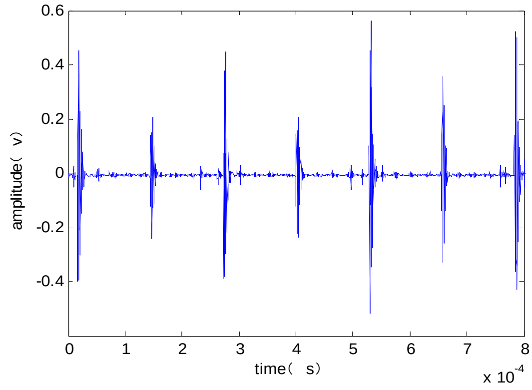


Fig. 5. Time domain AE waveform before face end lifts off.

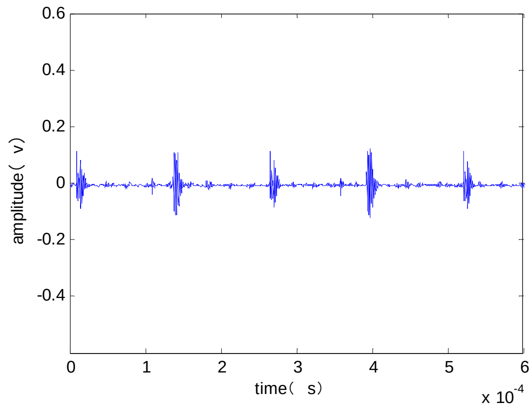


Fig. 6. Time domain AE waveform after face end lifts off.

Through the comparative analysis, db1 wavelet is adopted to decompose the AE signal in 3-dimension, for the characteristics of signal energy before or after end face lifts off are distinguished obviously. The wavelet pack decompositions of AE signals before and after the lubricated film forming are shown in Fig. 7.

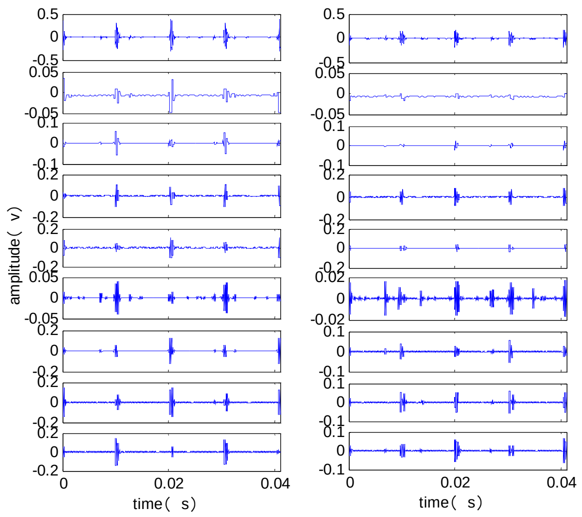


Fig. 7. The wavelet pack decompositions of AE signals before and after the lubricated film forming**.**

3.2. Feature Extraction

Calculate the energies of each sequence of reconstruction signal. In wavelet pack transform, the spectrum of signal in each subspace can choose as a symbol of energy. For each sequence of reconstruction signal, use the Fast Fourier transform; then calculate the mean square of the transformed amplitude to get the power spectrum.

The Fast Fourier transform is shown by the following formula.

$$F(X) = \sum_{n=0}^{N-1} x(n) W_N^{nk}, \tag{4}$$

where x is the original data, n is the sum of Fourier transform calculation points, X is the discrete Fourier transform.

Power spectrum calculation is shown by following formula.

$$P = |X(k)|^2 / N, \tag{5}$$

where P is the power spectrum estimation, X is the discrete Fourier transform of signal x(n), N is the length of signal.

As shown in Fig. 3, there is an obvious distinction between the power spectrums of AE signals of different conditions. Because of the existence of the interference factors in factory, the only one feature is not enough to judge the lift-off condition of end face. More features are needed. After wavelet pack transform, extract features from power spectrums of all decomposition sequences. The power spectrums of decomposed signals before end face lifts off are shown in Fig. 8.

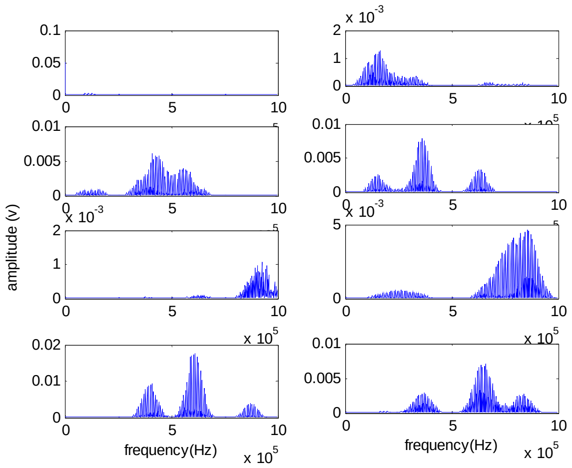


Fig. 8. The power spectrums of decomposed signals before end face lifts off.

The power spectrums of decomposed signals after end face lifts off are shown in Fig. 9.

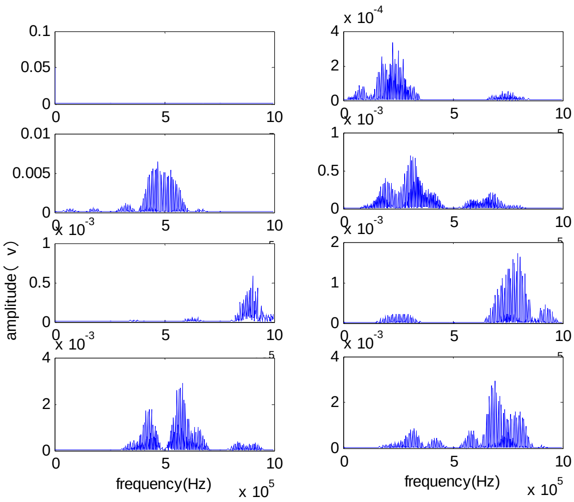


Fig. 9. The power spectrums of decomposed signals before end face lifts off.

Fig. 8 and Fig. 9 indicate the change of power spectrums of decomposed signals with end face lifting off. Before the end face lifts off, the energy of AE signal distribute in low frequency band and high frequency band. The energy of high frequency signals is greater than the energy of low frequency signals. This indicates that contacting friction exists between rotating ring and stationary ring. As shown in Fig. 9, after the end face lifts off, the energy of AE signal is less than before. The energy of high frequency signals reduces much more than the energy of low frequency signals. This is because the contacting friction is replaced by fluid friction. Under this condition, the energy of AE signal is mainly concentrated in the low frequency band.

Concerned about the correlation with eddy current signal, two characteristics are selected to represent the condition of end face. The two characteristics are valid value and standard deviation, whose calculation formulas are shown as followed.

Valid value:

$$Rms=\sqrt{\frac{1}{\mathrm{n}}\sum_{i=1}^{n}x_i^2}, \tag{6}$$

Standard deviation:

$$\mathrm{Std}=\sqrt{\frac{\sum_{i=1}^{n}(X_i-\overline{X})^2}{n}}, \tag{7}$$

The valid value of signal reflects the energy of signal, which indicates the friction form of end face. Standard deviation reflects the discrete degree of signal. In this paper, it means the change rule of the energy of the power spectrums of wavelet pack decomposed signal with the friction form of end face changing.

4. Condition Classification with Radial Basis Function Neural Network

4.1. Radial Basis Function Neural Network

Since Powell had proposed the radial basis function (RBF) to solve the problem of multi-dimensional space in 1985, Moody and Darken proposed a new neural network model, called radial basis function neural network (RBFNN). The main idea is that map the input vector from the lower dimension space to high dimension space by nonlinear transformation, and then calculate the weighted sum of the output of hidden unit to get the output of neural network [13, 14]. Due to its simple structure and excellent function approximation ability, the learning speed of RBFNN is hundreds times faster than back propagation neural network (BPNN). Therefore, RBFNN has attracted scientific research scholars and has been widely applied in pattern recognition and system identification.

The biggest difference between RBF neuron and BP neuron is that the input of RBF neuron equals to the ratio of the distance between the weight vector and the input vector and the threshold.

The response function of RBF neuron is shown by following formula.

$$y=\exp(-(\|X-W\|/b)^2), \tag{8}$$

where y is the output of RBF neuron, X is the input vector of RBF neuron, W is the connection weight vector between inputs and RBF neurons, b is the threshold of RBF neuron.

The output of RBF neuron y increases with the decreasing of the vector distance between X and W. If W is a cluster center, the transfer function of RBF neuron produces high output, only when the input vector is in a certain region near the cluster center of this neuron. In fact, the transfer function is a kind of model monitor. Threshold b is mainly used to adjust the range of the clustering center. The greater the threshold b is, the more smooth the output curve of RBF transfer function is, and the less sensitive to the changes of input [15].

Radial basis function neural network is usually a kind of three-layer feed forward network, whose topological structure is shown in Fig. 10.

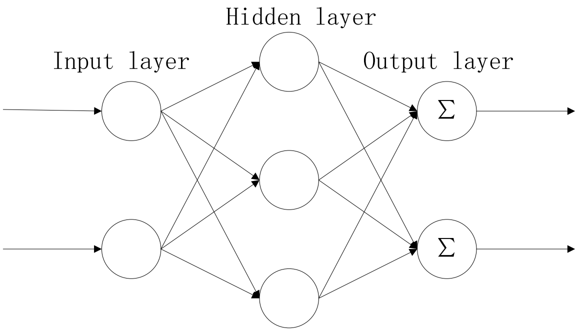


Fig. 10. The topological structure of RBFNN.

The input nodes input signals to the hidden layer. The base function of hidden layer is nonlinear. It produces a localized response to an input signal, which means each hidden node has a parameter vector called center. This center is used for comparing with the network input vector to produce a symmetric response. Only when the input falls in a small certain area, the hidden nodes response meaningfully. This response values are between 0 and 1. The closer the distance between input and center of base function is, the greater the hidden node response value is.

The output node is linear, which means that the output unit outputs the linear weighted sum of hidden nodes outputs. Thus, the entire network transforms from time domain R to time domain R1 nonlinearly by a linear combination of the nonlinear base function.

The output of the RBF neural network can be expressed as follow.

$$y_k = \sum_{j}^{h} w_k \phi_j(X) \qquad (k = 1, 2, ..., m), \tag{9}$$

As written in matrix form.

$$Y = W\Phi, \tag{10}$$

where $Y=(x_1, x_2,\ldots, x_m)T$ is the output vector, $W=(w_{k1}, w_{k2},\ldots, w_{km})$ is the connection weight vector, Φ =(1, 2,…, m)T is the output of hidden layer.

4.2. Experiment

Mechanical spindle fluid dynamic pressure testing apparatus provided by Sichuan Sunny Seal Co. Ltd is selected. The structure diagram of testing apparatus and the AE sensor installation location are shown in Fig. 1.

Parameters of this testing apparatus are shown as followed:

- Spindle speed: 0-1500 r/s;
- Material of rotating ring: silicon carbide;
- Material of stationary ring: cemented carbide;
- Test medium: Deionized water;
- Temperature: 20 ~ 80°C;
- Pressure: 0.2 ~ 10 MPa;
- AE sensor: KIStler8152B;
- Signal conditioning instrument: KIStler5125;
- Sampling frequency: 2 MHz

The experiment is repeated for 6 times, 3 groups of data for model training and other 3 groups for condition recognition. Each group contains 4 training samples; and each training sample contains 32 sets. Table 1 shows the values of two characteristics in different condition.

Table 1. The values of two characteristics in different condition.

Wavelet pack decomposition vector (mv)	Training group (2th)				Recognition group (5th)			
	Before lift-off		After lift-off		Before lift-off		After lift-off	
	Rms	Std	Rms	Std	Rms	Std	Rms	Std
D0	0.3716	0.0094	0.2546	0.0031	0.3492	0.0078	0.2343	0.0021
D1	0.2837	0.0089	0.1480	0.0040	0.2412	0.0079	0.1325	0.0043
D2	0.6157	0.0289	0.5123	0.0143	0.6021	0.0176	0.5146	0.0159
D3	0.6188	0.0214	0.2327	0.0081	0.6048	0.0178	0.2046	0.0064
D4	0.2312	0.0101	0.1394	0.0044	0.2376	0.0069	0.1254	0.0045
D5	0.5679	0.0164	0.2832	0.0085	0.5678	0.0175	0.2524	0.0078
D6	0.8777	0.0264	0.3947	0.0145	0.9085	0.0278	0.3725	0.0118
D7	0.6967	0.0228	0.3787	0.0129	0.6847	0.0209	0.3875	0.0118

The changing curve of Rms characteristics in training and recognition group is shown in Fig. 11.

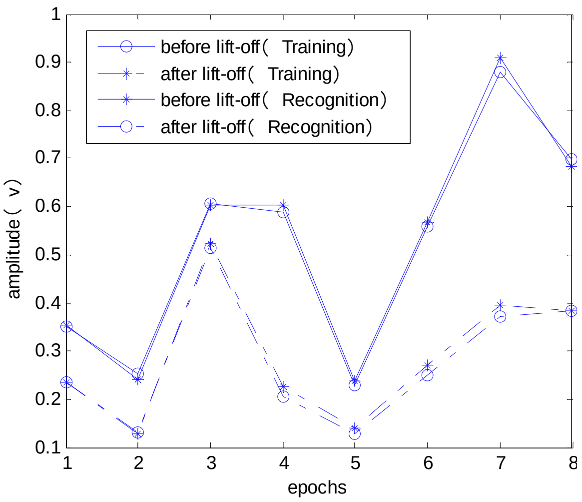


Fig. 11. The changing curve of Rms characteristics.

The changing curve of Std characteristics in training and recognition group is shown in Fig. 12.

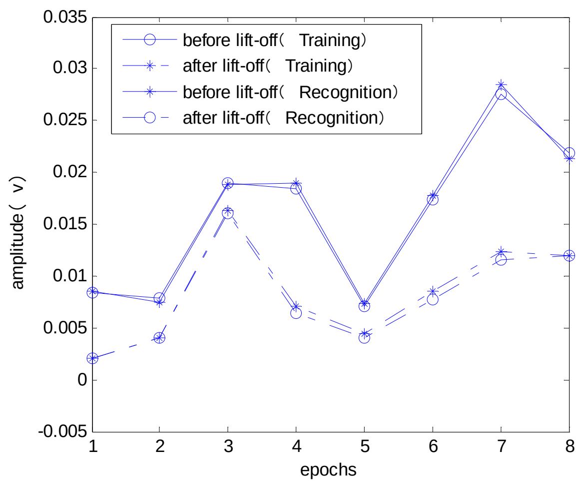


Fig. 12. The changing curve of Std characteristics.

Whether Rms or Std, it can be easy to distinguish between the characteristics before lift-off and the characteristics after lift-off. The amplitude is obvious different in the two conditions, especially in the point of "4" and "7". The former is the energy center of low frequency band and the latter is the energy center of high frequency band.

Decompose the 6 groups of AE signals acquired using wavelet pack and calculate the power spectrums, then extract the energy characteristics. Split these 6 groups of characteristics into 2 parts, 3 for training and 3 for recognition. Compare the recognition results and the results obtained by the eddy current sensor, which is shown in Table 2. With the characteristics extracted by wavelet pack decomposition, the trained RBFNN has recognized the proper condition of end face while mechanical seals running. Thus proves that the method based on AE technique is effective in monitoring the lift-off condition of end face while the mechanical seals run.

Table 2. The recognition results of RBFNN.

Training group		**Recognition group**	
Before lift-off	After lift-off	Result 1	Result 2
Condition 1	Condition 2	Touchdown (FIT)	Lift-off (FIT)

5. Conclusions

1) The accurate measurement of end face lift-off condition of mechanical seals is of much importance to know the performance of seals. Currently, the lift-off condition and the lubricated film thickness have been measured accurately using capacitance sensor and electric eddy current sensor, which is not suitable for industrial field measurement. However, AE sensor can be installed outside the seal devices, which will not influent the normal running of machinery.

2) The AE signal is mainly sensitive to the nonlinear changes in dynamic process. And the lift-off process of end face of mechanical seals belongs to this process. Thus, in the lift-off process, the information of friction between stationary ring and rotating ring can be collected by AE sensor. The signal collected by AE sensor belongs to the high frequency signal. Decompose the signal using wavelet pack and calculate the power spectrum, then extract the characteristics. Characteristics of the same state are of good reproducibility, while there is a clear distinction between the characteristics under different conditions.

3) The recognition model based on AE and neural network is of intellectual clarity. The requirement for data quantity of this model is not large, and its nonlinear recognition rate is high. Through the analysis of example validation shows that the method can accurately the mechanical seal liquid film open to identify. Through the experimental verification, the method presented in this paper is proved to be able to recognize the lift-off condition of mechanical seal end face accurately.

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