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Mechanical Seal Opening Condition Monitoring Based on Acoustic Emission Technology

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Abstract: Since the measurement of mechanical sealing film thickness and just-lift-off time is very difficult, the sealing film condition monitoring method based on acoustic emission signal is proposed. The mechanical seal acoustic emission signal present obvious characteristics of time-varying nonlinear and pulsating. In this paper, the acoustic emission signal is used to monitor the seal end faces just-lift-off time and friction condition. The acoustic emission signal is decomposed by empirical mode decomposition into a series of intrinsic mode function with independent characteristics of different time scales and different frequency band. The acoustic emission signal only generated by end faces friction is obtained by eliminating the false intrinsic mode function components. The correlation coefficient of acoustic emission signal and Multi-scale Laplace Wavelet is calculated. It is proved that the maximum frequency (8000 Hz) of the correlation coefficient is appeared at the spindle speed of 300 rpm. And at this time (300 rpm) the end faces have just lifted off. By a set of mechanical oil seal running test, it is demonstrated that this method could accurately identify mechanical seal end faces just-lift-off time and friction condition. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Mechanical seal, Acoustic emission, EMD, Multi-scale Laplace wavelet, Condition monitoring.

1. Introduction

Mechanical seal is an indispensable device of the rotating machinery. Because of it's reliable operation, low leakage and long service life and low power consumption, it is widely used on pumps, compressors, reactors, mixers, rotary towers, centrifuges and filter device. Mechanical seal directly affects the working status and security of the whole system. Statistics shows that about 95 % of the rotating equipment containing chemical process adopts mechanical seal for preventing medium leakage between power input shaft and shell [1].

Dynamic ring and stationary ring are two core components of mechanical seal. The gap of the two end faces should be appropriate. For keeping the equipment working normally, it must be sufficiently thin so that excessive leakage will not occur, but not too thin, or there will increase friction of the end faces and shorten the life of mechanical seal. In fact, the gap may get changed and the friction occurred because of transverse force, thermal deformation and other interference factors. So it is significant to monitor the end faces friction condition of mechanical seal.

Many researchers have spent a lot of time on study of mechanical sealing film measurement. In

1967, the fluid film had been measured by Astridge [2] and Cameron [3] *et al*. via the approach of capacitance and resistance. In 1984, Etsion [4] used the method of eddy current realized the mechanical seal film thickness measurement. In recent years, Anderson used ultrasonic sensor detected the seal face contact. Later, Reddyhoff [5] also estimated the film thickness based on ultrasonic. But all these approaches can't be used in industry, because some require modifying the device structure, others have very expensive cost.

The phenomenon of elastic deformation and stress wave emission occurred in material is named as acoustic emission (AE). The mechanical seal AE mainly generate between dynamic and stationary rings as friction occurred. AE signal contains abundant friction information. The amplitude of the acoustic emission signal is directly related to the energy released while friction occurred. Imbalance of the mechanical system or other condition information will not be reflected in the AE signal [6]. This characteristic is very suitable for the condition identification and fault diagnosis of mechanical seal. So AE technique has been proposed and it works as a feasible and effective approach for mechanical seal friction condition identification and fault diagnosis.

2. Mechanical Seal Friction Form

As mentioned before, AE is the elastic wave which is generated by sudden deformation or energy releasing in material [7]. Some researchers call it Stress Wave Emission. When the AE is directly caused by the deformation or fracture of materials, the wave source is defined as typical AE source. The other wave source about fluid leakage, friction, impact, combustion, which is not directly related to deformation or fracture, is defined as secondary AE source. The mechanical seal AE source is belongs to the latter. It is generated by friction or collision between dynamic and stationary rings.

According to viscous force hypothesis, mechanical seal end faces friction condition vary with the structure, characteristic of medium and working conditions (pressure, rotating speed, temperature, etc.). The friction condition between the dynamic and stationary rings can be classified as dry friction, fluid friction, boundary friction and mixed friction.

1) Dry friction.

Before the liquid film formed between the seal end faces, the dynamic ring and stationary ring closely contact together. When the equipment starts, the spindle speed and film pressure is very slow, so the seal end faces have not been separated. The direct contact friction (dry friction) occurs between the two rings, as Fig. 1 shows. In this case, there have serious friction, but have a small leakage. Certainly the acoustic emission signal's amplitude is strong and the frequency is high.

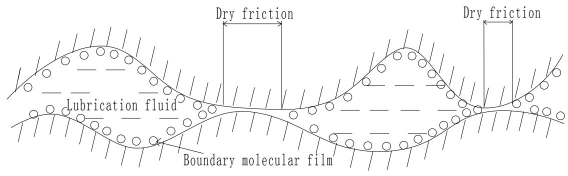

Fig. 1. Dry friction.

2) Fluid friction.

Between the mechanical seal friction pairs, there is likely to form and maintain a thin layer of lubricating oil film like as forming in the sliding bearing. This extremely thin lubricated film would separate the seal end faces completely. The friction is only generated by the viscous fluid shear friction in this case. The friction, wear and power consumption are all reduced, and the heating effect also is decreased. This kind of friction is called fluid friction which is shown in Fig. 2. The end faces wear is small. However, the leakage is big. The acoustic emission signals generated in this case is relatively weak.

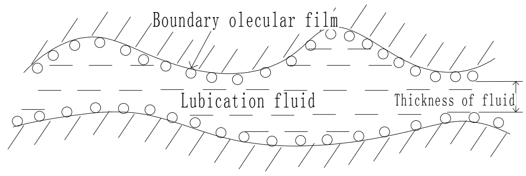

Fig. 2. Fluid friction.

3) Boundary friction.

Around the boundary of the mechanical seal end faces, there can generate a very thin liquid molecular membrane when the seal end faces contact tightly. The molecular membrane also can make the mechanical seal end faces separate. This friction status is called boundary friction which is shown in Fig. 3.

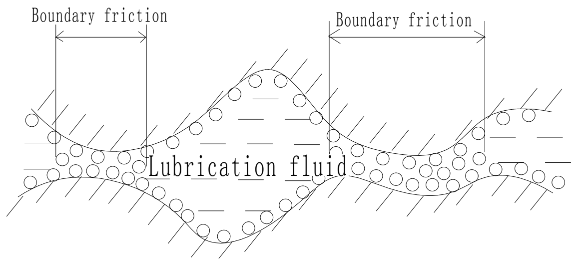

Fig. 3. Boundary friction.

Boundary film plays the main role of lubrication. Because the boundary lubrication film is very thin, it was hard to make a measurement of the liquid pressure [8]. For the boundary molecules membrane, generally speaking, there are just 3 or 4 molecular layers, and the thickness of them is about

20 nanometers [9]. Part of the end faces contact is discontinuous. The end faces pressure is almost borne by the surfaces of the peak. The viscosity of liquid film medium has little influence to friction properties. Friction performance mainly depends on the lubricity of the membrane and material of dynamic and stationary rings. The wear and tearis existence but very small, and the leakage is small too. This condition is a kind of relatively ideal mechanical seal friction condition. In this condition, the characteristics of AE signal are between dry friction and fluid friction.

4) Mixed friction

With the decreased of the end faces waviness degree, the friction pair gap decreased as well. The above mentioned three kinds of friction condition alternate between the mechanical seal end faces. This condition is called mixed friction. Normally the mechanical seal end faces working at the mixed friction status in addition to the condition of light load, high speed and high viscosity. In that condition the mechanical seal end faces mainly working at the membrane fluid friction [10]. In the mixed friction condition, the exterior load caused by spring pressure and sealing medium pressure is balanced by the film total friction force and micro convex body contact abrasion. It is obvious that the total friction force includes two parts, the viscous shear friction caused by liquid membrane in the lubrication region and the friction caused by the micro convex body deformation in the micro convex body contact region.

During the mechanical seal whole operation process from starting to stopping, the condition of the friction between dynamic and stationary rings is changed with the spindle speed. The degree of friction is also change with the variation of end faces contact condition. In the complete process, the AE signal's amplitude is also entirely different. When the spindle speed first rising from 0 rpm to 1500 rpm, then declining to 0 rpm, the complete AE signal waveform appears as dumbbell shape, which is shown in Fig. 4.

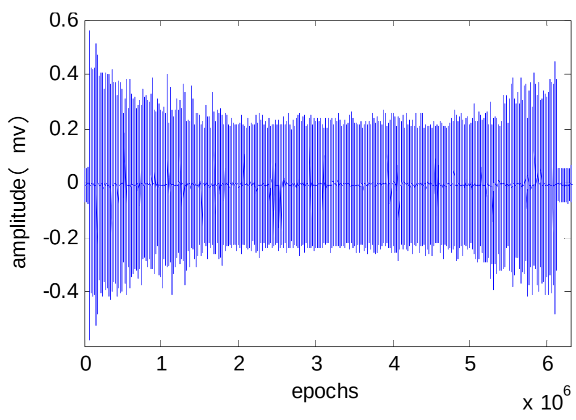

Fig. 4. Mechanical fluid seal end faces AE signal time domain waveform.

Even many scholars have devoted to the study of mechanical seal AE technique. In condition of end faces grooving, light load, high speed or high viscosity condition, the mechanical seal end faces is in full membrane fluid friction condition. Boundary friction condition is likely to appear in heavy-load low-speed contact-type liquid mechanical seal [10]. The majority of ordinary mechanical seal is working under the condition of mixed friction. Comparing with the dry friction and fluid friction, the study of boundary friction and mixed friction is not mature enough at present. Especially there have a big gap in experiment research.

3. Mechanical Seal AE Signal Characteristics

The end faces friction condition is changed with the spindle speed. Under different end faces friction condition, AE signal has completely different characteristics. So it is very useful to identify the friction condition in varied speed by the characteristic of AE signal. It has a large dynamics range. It's displacement amplitude can be from 10^{-15} m to 10^{-9} m, with the range of 10^6 magnitude [11]. The waveform of acoustic emission signal is varied. Generally the acoustic emission signal is artificially classified into pulse type and continuous type, as shown in the Fig. 5.

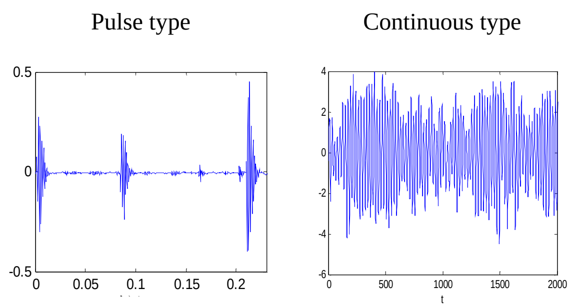

Fig. 5. Acoustic emission signal.

The pulse type AE signal waveform is separable and discrete in time domain. This type signal has characteristics of high amplitude, discontinuous, duration of microsecond. If the AE signal single pulse is not distinguished in time domain, these signals is called continuous AE signal. In fact all of the acoustic emission is intermittent process. However, when the impact frequency of AE signal is very high or exceed the extremity degree which could be separated in time domain, it's waveform display continuously. In the process of plastic deformation of metal materials and leakage of gas or liquid and so on, all of them produce continuous type acoustic emission signal. On the contrary, in the process of collision and friction the acoustic emission signal is presented in the form of pulse type waveform.

The frequency range of AE signal is very wide, from infrasonic to ultrasonic (from Hz to MHz). It's amplitude range is also have a large span, from micro fracture dislocation to macro large-scale displacement change. Even the weak acoustic emission can be detected by high sensitive sensor.

The ultimate goal of application AE technology is to set up the relationship between the measured signals and the AE source. This relationship is usually used for mechanical structure health condition detection and rotating machinery fault diagnosis.

In the end of last century, America, Japan and some other countries applied AE sensor technology in the nuclear reactor cooling pump and aerospace fields liquid oxygen pump, developed mechanical seal monitoring system [12]. China university of petroleum successfully applied the mechanical seal phase monitoring system developed by themselves in industry. The AE technology also has been used in the manifold plug valve seal testing and achieved very perfect results in Karamay oil company. Customers are very satisfied with it. It is also confirmed that the AE technology is one of the most important and effective detection means for the mechanical seal [13]. Since the high sensitivity and reliability of the testing of AE technology, it has been recognized by clients. At present, the use of AE technology for detecting mechanical seal performance has become an important technique for the company in Sinkiang autonomous region. Most of the customer request the seal testing must be using AE technology every time [13].

4. AE Signal EMD Decomposition

4.1. EMD

Traditional signal time-frequency analysis method is almost based on Fourier transform, which have many limitations of itself. In 1998, National Aeronautics and Space Administration (NASA) Chinese American scientists Norden E. Huang proposed Empirical Mode Decomposition (EMD) method. This signal processing method is considered to be a major breakthrough relative to Fourier transform in recent years [14]. This kind of method has its advantages for nonlinear nonstationary signal processing. The most important thing is that EMD decomposition results have clear physical meaning.

The EMD is a kind of analysis method based on the data and has good adaptability. Especially for nonlinear and non-stationary data the effect is particularly obvious. The decomposed results Intrinsic Mode Function (IMF) have actual physical significance. In a word the EMD has obvious advantages in processing of the nonlinear signal for machinery like as mechanical seal products [15].

4.2. Intrinsic Mode Function

The EMD's role is to convert the original signal into IMF. The IMF need to satisfy two conditions:

1) The number of extreme value point and the zero number should be equal or only differ by one.

$$(N_z - 1) \le N_e \le (N_z + 1) \quad (1)$$

2) Local mean value of the up envelope defined by the maximum and the down envelope defined by the minimum should be equal to zero.

$$[f_{max}(t) + f_{min}(t)]/2 = 0 \quad (2)$$

4.3. Empirical Mode Decomposition Process

EMD method dissociates IMF from the complex original signal, so EMD method also known as the sifting Process. The EMD decomposition process based on the following assumptions:

1) Signal at least has a maximum and a minimum;

2) Signal characteristics are determined by the distance between the extreme points;

3) If lack of extreme point, however signal data sequence contains turning points. The extreme point can obtain through making derivative of the signal for one or many times. The decomposition result can be obtained by integrating the extreme points.

Based on the above assumptions, the specific shifting process is as follows:

1) For a signal *x(t)*, first of all count all the extreme value point of it. Using the third-order spline interpolation obtain the original signal's up envelope and down envelope. Working out the average of the up envelope and down envelope, the result recorded as *m(t)*:

$$m(t) = \left[x_{max}(t) - x_{min}(t)\right]/2 \quad (3)$$

2) *x(N)* subtract $m_1(N)$, the results recorded as $h_1(N)$.

$$x(N) - m_1(N) = h_1(N) \quad (4)$$

3) If the spline curve of $h_1(N)$ meet the *IMF* two conditions, then

$$imf_1(N) = h_1(N) \quad (5)$$

If the spline curve of $h_1(N)$ not satisfy the *IMF* two conditions, then repeat the step (1) and step (2) until the spline curve of $h_1(N)$ meet the *IMF* two conditions, and the abstracted result recorded as:

$$imf_1(N) = h_{1k}(N) \quad (6)$$

4) $imf_1(N)$ is separated from the sequence *x(N)*. The residual data $r_1(N)$ is recorded as:

$$r_1(N) = x(N) - imf_1(N) \tag{7}$$

5) If the average of the up and down envelope is a monotonic function or the average amplitude is less than the threshold set, the process of decomposition should be end; If not, $r_1(N)$ should be defined as original signal to repeat the above steps. The residual signal of the each stages are written as

$$\begin{aligned} r_2(N) &= r_2(N) - imf_2(N) \\ &\vdots \\ r_2(N) &= r_2(N) - imf_2(N) \end{aligned} \tag{8}$$

Once $r_n(N)$ was a monotonic function or it's amplitude is less than the threshold, the loop should terminate. $x(N)$ is given by the expression:

$$x(N) = \sum_{i-1}^{n} imf_i(N) + res(N) \quad , \tag{9}$$

where $res(N)$ is the residual function. It represents the signal average trend. The essence of the EMD method is that the decomposition processing is a shifting process. First separated the smaller time scales partial component from the original signal, then separated the bigger time scales partial component. So the EMD is considered a set of high-pass filter.

5. Laplace Wavelet

Laplace wavelet is a kind of unilateral attenuation negative exponential wavelet, and its expression is given as follow:

$$\psi(\omega\ \xi,\ \tau,\ t) = \psi_v(t) = \begin{cases} Ae^{-\frac{\xi}{\sqrt{1-\xi^2}}\omega(t-\tau)} e^{-j\omega(t-\tau)}; & (t \in [\tau, \tau+W_s]) \\ 0; & (else) \end{cases} \tag{10}$$

where $\omega(\omega \in R^+)$ is the frequency, $\xi \in [0,1] \in R^+$ is the Viscous damping ratio, $\tau \in R$ is the time parameter.

When $\omega = 10$, $\xi = 0.05$, $\tau = 0$, the Laplace waveform is shown in follow Fig. 6.

Laplace wavelet has the character of unilateral oscillation damping, like as AE signal waveform. The signal's pulsating can be extracted by Laplace wavelet correlation filtering method. The correlation coefficient is got through calculating the inner product of AE signal and Laplace wavelet. Using Laplace wavelet correlation filtering method can effectively extract the dynamic and stationary rings friction characteristic. This method anti-interference ability is stronger than the commonly used wavelet method. It can accurately captured shock response signal in the strong noise or interference. This method has been successfully used for rolling bearing fault diagnosis. It also can be sued in mechanical seal friction condition diagnosis.

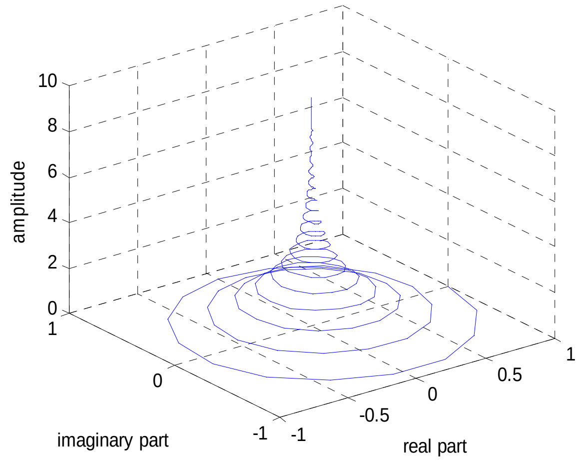

Fig. 6. Laplace wavelet.

6. The Engineering Application

Mechanical spindle hydrodynamic pressure seal experimental device structure and the acoustic emission sensor installation position are shown in Fig. 7. This test bench was provided by Sichuan sunny seal co., LTD.

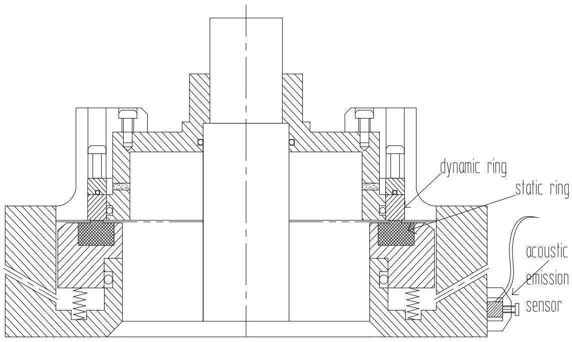

Fig. 7. Mechanical fluid seal structure.

Experimental conditions:

Acoustic emission sensor: KIStler8152B;

Signal conditioning instrument: KIStler5125;

Spindle speed: 0-1500 rpm (frequency conversion control);

Dynamic ring material: sic;

Stationary ring material: carbide;

The test medium: 32 # turbine oil;

The temperature: 20-80 ^{o}C;

Pressure: 0.2-5 MPa.

When mechanical sealing spindle just start rotating, the dynamic and stationary rings end faces is still contact together. The mechanical seal end faces is in the condition of dry friction. The AE signal amplitude is very high. The AE signal time domain waveform shown in the Fig. 8.

The AE signal is decomposed by EMD method into IMF component, each of IMF is shown in the Fig. 9.

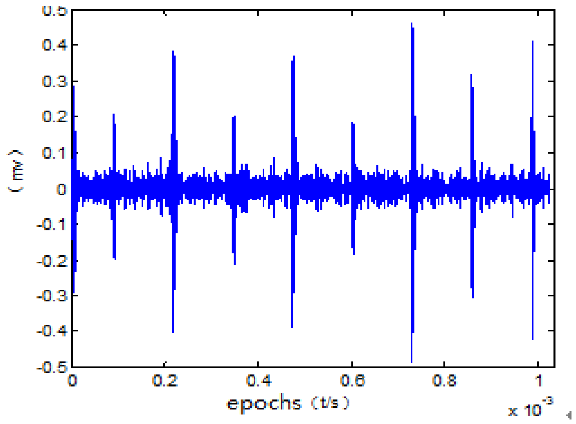

Fig. 8. AE signal time domain waveform of the seal device has just started.

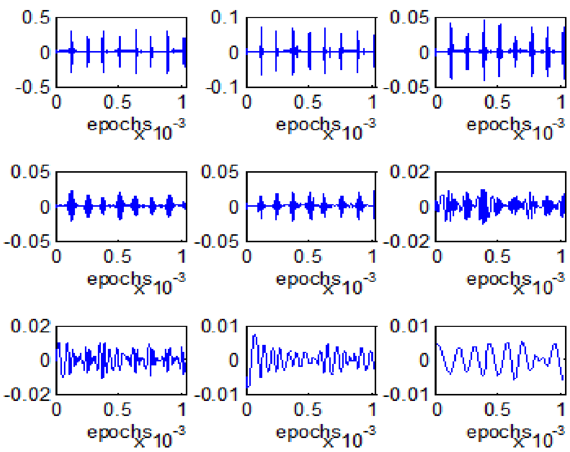

Fig. 9. The IMF component waveform.

The following Fig. 10 is show for each IMF component spectrum. According to power spectral distribution characteristics of each component, the false components are eliminated by correlation coefficient filtering of empirical mode decomposition.

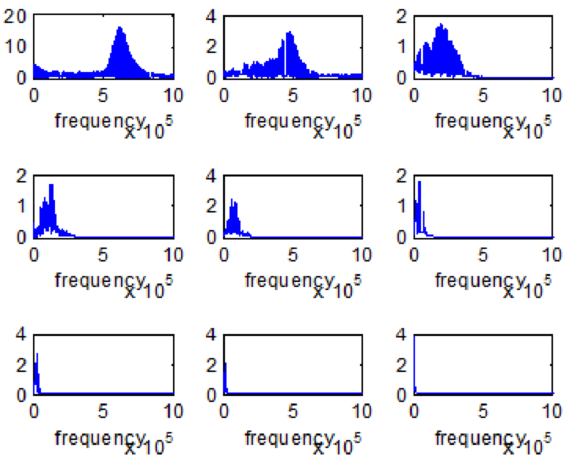

Fig. 10. Each IMF component spectrum.

From the above figure we can see that the power of AE signal is mainly concentrated in the top five components. The subsequent components are basically clutter interference. The first two components have the same frequency, which are generated by end faces friction. The following three components have the same frequency, which are mainly generated by friction or collision of other parts. Refactoring the top five components (the following three component's amplitude is adjusted) to get the end faces AE signal. The refactoring AE signal is shown in the Fig. 11, which have obvious pulses. It has the same basic characteristics of the Laplace wavelet: pulsating and unilateral attenuation.

Laplace wavelet correlation coefficient filtering method can effectively extract the signals impulse response. Because its anti-jamming capability is stronger than wavelet decomposition, the method of Laplace wavelet filtering is very useful to extract the frequency features of end faces AE signal's pulse response.

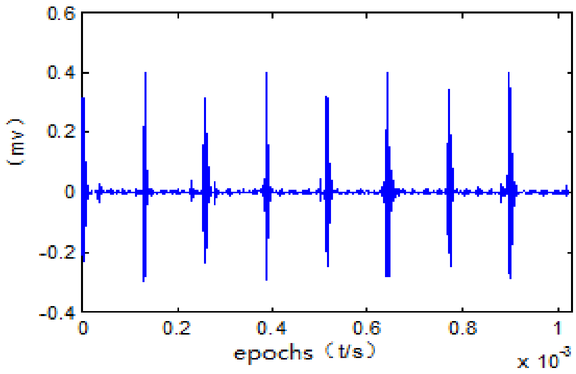

Fig. 11. AE signal time domain waveform after filtering.

The inner product of the Laplace wavelet basis functions and the AE signals is figured out. The correlation degree of AE signal and Laplace wavelet basis functions can be reflected by their inner product. The frequency feature of inner product could be used to determine the mechanical seal friction condition and degree of wear. And this is the essence of the Laplace wavelet filtering that using of correlation coefficient to determine where and when the friction happened in the mechanical seal operation process.

Working out the correlation coefficient of the AE signal and the Laplace wavelet basis functions by correlation filtering, the filtering result was shown in Fig. 12. It can be see from Fig. 12 that those Laplace filtering coefficients have strong pulse and simple frequency structure.

The frequency of filtering coefficients was calculated, and the spectrum of Laplace wavelet filtering coefficients was shown in Fig. 13. It was obvious that the Laplace wavelet filtering coefficients frequency is 7956 Hz observing from the

Fig. 13. That is to say when the mechanical seal device was just starting, the mechanical seal end faces contact friction AE signal's frequency is 7956 Hz.

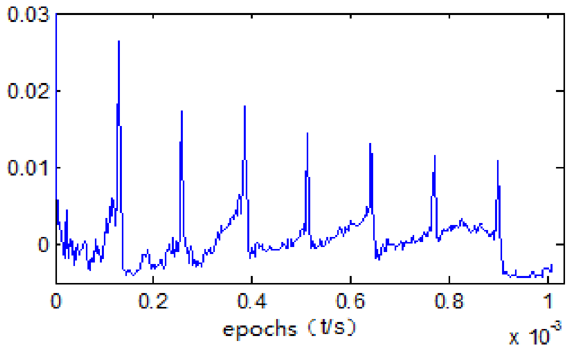

Fig. 12. Laplace wavelet filtering correlation coefficients.

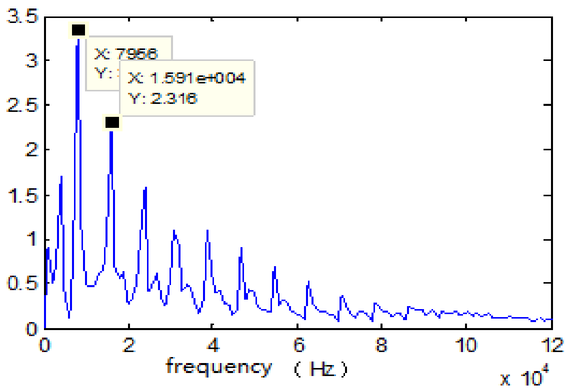

Fig. 13. Laplace wavelet correlation coefficient frequency spectrum (speed at 10 rpm).

As the spindle speed reaches 300 rpm, the dominant frequency of Laplace filtering coefficients of the mechanical oil seal rise to 8000 Hz, the most high frequency of the mechanical seal in the working process (Fig. 14).

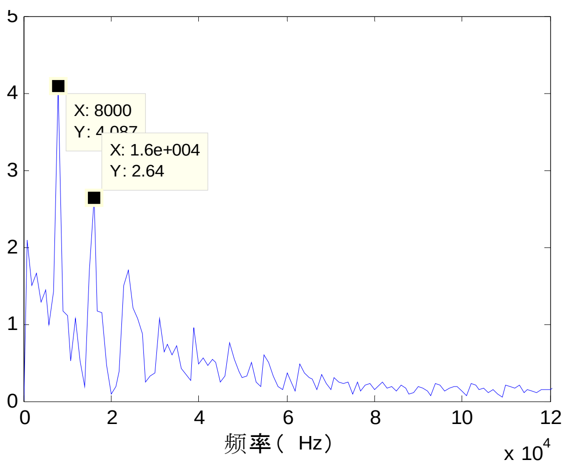

Fig. 14. Laplace wavelet correlation coefficient frequency spectrum (speed at 300 rpm).

A test with spindle speed of 1500 rpm has been done for confirming whether the frequency of 8000 Hz is the max and whether the pair of faces have been separated as the spindle speed increases. When the speed reaches 1500 rpm, the dominant frequency of Laplace wavelet filtering coefficients is only 3955 Hz and much lower than 8000 Hz. It is proved that the friction type has changed from contact friction to fluid friction or mixed friction (Fig. 15).

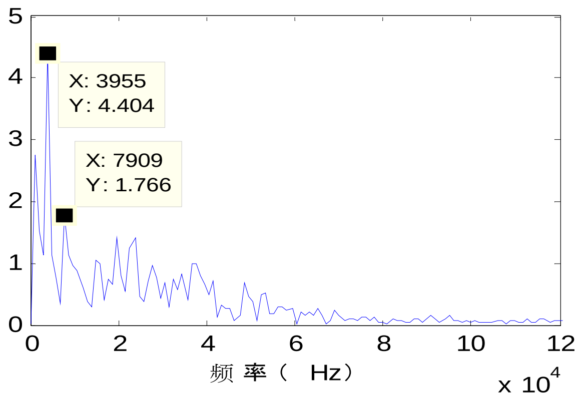

Fig. 15. Laplace wavelet correlation coefficient frequency (speed at 1500 rpm).

It can be known from the experimental data that during the operation process from starting to stopping, the Laplace wavelet filtering coefficients dominant frequency first increase, then decrease as the film has been formed. It reaches the lowest when the spindle speed gets max. When the mechanical seal device running under different pressure (0.5 MPa, 2 MPa, 5 MPa) and at varied speed respectively, the Laplace wavelet correlation coefficient frequency are shown in the Table 1.

Table 1. Correlation coefficient frequency.

Pressure (MPa)	Spindle speed (rpm)					
	10	**300**	**600**	**900**	**1200**	**1500**
0.5	7956	8000	7343	5680	4663	3955
2	7547	7890	7132	5368	4423	3890
5	7321	7812	6950	5218	4235	3697

It is very easily to get the obvious conclusion that the Laplace wavelet correlation coefficient first increase then decrease with the spindle speed from 0 rpm up to 1500 rpm, which is show in Fig. 16.

In actual industrial, according to this feature we can use to not only identity the just-lift-off time of end faces, but also accurately judge the end faces under which specific friction conditions. It also can be provide real and reliable data analysis for the whole plant prognostic and health management (PHM) and fault diagnosis.

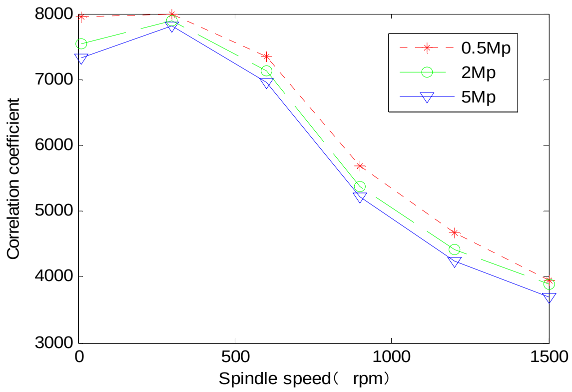

Fig. 16. The curve of Laplace wavelet correlation coefficient.

7. Conclusions

1) The AE signal generated from the mechanical seal contains rich information. Condition monitoring method based on AE signals can effectively detect the just-lift-off time, and identify the friction condition of the end faces.

2) EMD can be used as an adaptive filter. The AE signal is decomposed into independent IMF of different frequency bands. EMD can inhibit the interference of the noise and highlight the mechanical seal friction condition information.

3) The frequency of the correlation coefficient could be calculated by MLM method. The spindle speed and film thickness could be identified through the AE signals frequency characteristics.

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