Reliability Life Evaluation Model of Multifield Coupling Rotating Lip Seal based on Surface Simulation

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***Abstract*—Rotating lip seal as a common mechanical dynamic seal, mainly composed of a metal frame, a rubber sealing lip and a garter spring. Considering the complex microstructure of sealing lip and changing working conditions, this paper establishes a reliability life assessment model with multifield coupling based on the simulation of rough surface. In the surface simulation of sealing lip, compared with the traditional Gaussian filter random surface generation method, fractal theory is applied to fit the complex surface more objectively and accurately. Multi-field coupling is also considered comprehensively, including fluid mechanics, elastic deformation and thermal. Through the cycle iteration of model parameters, performance degradation parameters of the lip seal are obtained to evaluate the reliability life, including friction torque, pumping rate and contact temperature. Finally, the parameters are measured by reliability test of rotary lip seal to verify the accuracy of the model.**

Keywords: rotary lip seal, surface simulation, reliability assessment

I. INTRODUCTION

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Rotary lip seal is a common rubber seal. Figure 1 shows the main structure of a typical rotary lip seal. The position of seal ring is fixed by a metal skeleton and sealing lip is installed on rotating shaft by a fastening spring. Failure of rotary lip seal results in leakage of oil, which may cause contamination of the equipment and leave a hidden danger. So, it is necessary to conduct a reliability life evaluation model of rotary lip seal.

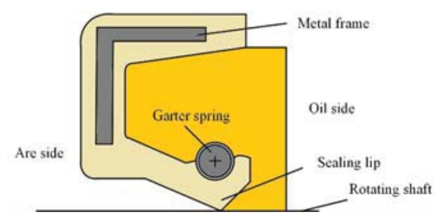

Figure 1. Schematic of a rotary lip seal

The sealing mechanism of rotary lip seal is the pump effect[1], which is currently recognized and tested. Under operating conditions, a layer of lubricant film exists between sealing lip and rotating shaft. The contact pressure of lubricant film is asymmetrically distributed under the asymmetric design of sealing lip on air and oil side. With the rotation of shaft, the rough peak of sealing lip, which is like a screw pump, sucks the oil from air side back to oil side to prevent oil leakage. So, the roughness peak distribution has a great influence on sealing performance. In the numerical simulation of rotary lip seal, it is necessary to simulate the surface accurately.

Some numerical methods have been proposed. Salant[2] simulated the rough peak distribution with a cosine function, which appears as a periodic regular structure. While the actual rough surface is randomly distributed. Thomas[3] used an exponential autocorrelation function model to simulate the random distribution of the rough surface, which can be better fitted under the certain circumstance. But using only one autocorrelation function to characterize all sealing lips is limited. Chen Hui[4] proposed a rough surface simulation method based on time series and stochastic process model. This

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method uses a digital filter to simulate its random rough surface by giving automorphic functions of different shapes, which is more comprehensive than the method of Thomas. But the accuracy of this method is limited by resolution of the instrument. Considering the special surface of sealing lip, it is difficult to characterize the complexity of the distribution of rough peaks.

Considering limitations of above methods, this paper adopts a method of fractal theory[5] to simulate the surface. According to fractal theory, parameters of the lip surface are independent of measurement resolution. In addition, the distribution of rough peaks can be characterized by fractal dimension. Based on the rough surface simulation, considering the effect of multifield coupling of the sealing zone, a reliable lip seal model can be built to assess its service life.

The main structure of this paper is as follows. In section 2, the establishment process of rotary lip seal reliability model is introduced. In section 3, the simulation results and experiments are compared and verified. Section 4 concludes the paper.

II. Reliability Model Establishment Process

Before the reliability model of rotary lip seal is established, the following assumptions are made:

1. The roughness of shaft is ignored.
2. The effect of temperature changes on aging of the material is ignored.
3. The effect of normal velocity of rotary lip seal is neglected.
4. Degradation of surface topography parameters of rotary lip seals is neglected.

A. *Rough surface modeling based on fractal theory*

Rough surfaces with fractal features can be simulated by W-M function[6]. The 2D mathematical expression is expressed as

$$Z(x) = G^{(D-1)} \sum_{n=n_l}^{n_{\max}} \gamma^{-(2-D)n} \cos(2\pi\gamma^n x) \tag{1}$$

where $Z(x)$ is 2D rough surface contour height, G is scale factor, D is fractal dimension, $1<D<2$, γ is a constant and the value is 1.5 when the surface is Gaussian, and n is spatial frequency ordinal, nmax is the highest frequency ordinal and the expression is $n_{\max} = \text{int}[\log(L / L_s) / \log\gamma]$,

where L is sampling length, and Ls is cutoff length, nl is the lowest frequency ordinal and the expression is $n_l = \text{int}[\log(1/L) / \log\gamma]$.

The contour shape is mainly determined by fractal dimension D and scale factor G. The effect of them on rough surface is shown in Figure 2.

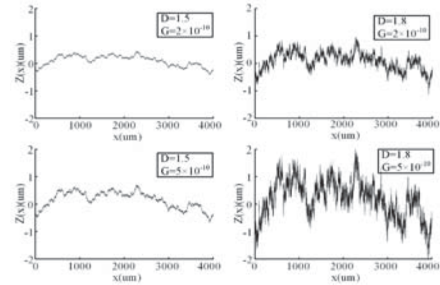

Figure 2. 2D rough surface simulation

As can be seen from Figure 2, only scale factor G is changed, the peak of rough surface changes. But when only changing fractal dimension, the surface changes and the distribution of rough peaks is more complicated. The two parameters are obtained as follows.

Fractal dimension D can be obtained by comparing the power spectrum of W-M function with the actual surface profile[6]. The power spectrum expression of W-M function is expressed as

$$S(\omega) = \frac{G^{2(D-1)}}{2\ln\gamma} \frac{1}{\omega^{(5-2D)}} \tag{2}$$

where $S(\omega)$ is power spectrum, and ω is spatial frequency, which is also expressed as γ_n .

Power spectrum of the measurement contour is expressed as[7]

$$S(\omega) \propto \omega^{-k} \tag{3}$$

where k is a parameter related to surface contours.

Comparing Eqs. (2) and (3), Fractal dimension D can be expressed as

$$D = (5\text{-}k)/2 \tag{4}$$

Scale factor G is obtained by height distribution variance of measurement. The height distribution variance of W-M function is expressed as [8]

$$m_0 = \int_{\omega_l}^{\omega_h} S(\omega)d\omega = \frac{G^{2(D-1)}}{2\ln\gamma} \frac{1}{(4-2D)} \left\{ \frac{1}{\omega_l^{(4-2D)}} - \frac{1}{\omega_h^{(4-2D)}} \right\} \tag{5}$$

where m_0 is height distribution variance, ω_l is surface contour minimum cutoff frequency, and ω_h is the upper limit of cutoff frequency, which is related to the resolution of measuring instrument.

Usually ω_h is much larger than ω_l [8]. So ω_h is ignored to get the following expression, as given by

$$G^{2(D-1)} = 2(4-2D) m_0 \omega_l^{(4-2D)} \ln\gamma \tag{6}$$

The 3D expression of W-M function is expressed as[9]

$$Z(x,y)=L(\frac{G}{L})^{(D'-2)}(\frac{\ln\gamma}{M})^{1/2}\sum_{m=1}^{M}\sum_{n=n_l}^{n_{\max}}\gamma^{(D'-3)n}$$
$$\times\left\{\cos\phi_{m,n}-\cos\left[\frac{2\pi\gamma^n(x^2+y^2)^{1/2}}{L}\times\cos(\arctan(\frac{y}{x})-\frac{\pi m}{M})+\phi_{m,n}\right]\right\} \tag{7}$$

where $Z(x,y)$ is 3D rough surface contour height, D' is 3D fractal dimension, which is expressed as $D'=D+1$, M is the number of overlaps of surface folds, $\varphi_{m,n}$ is a random phase and the range of value is [0, 2π], L, G, γ and n have the same meaning as Eq.(1).

B. Multifield Coupling Model Establishment Process

The multi-field coupling model of rotary lip seal includes fluid mechanics, elastic mechanics and thermodynamics.

According to the assumptions, Reynolds equation is expressed as[10]

$$\frac{\partial}{\partial x}(\frac{h^3}{\eta}\frac{\partial p}{\partial x})+\frac{\partial}{\partial y}(\frac{h^3}{\eta}\frac{\partial p}{\partial y})=6U\frac{\partial h}{\partial x} \tag{8}$$

where h is film thickness, p is film pressure, η is viscosity and U is shaft speed.

By giving an initial oil film thickness, the film pressure distribution in the contact area can be obtained. Under the action of film pressure, sealing lip is elastically deformed. By establishing the finite element model of rotary lip seal, the relationship between the deformation of sealing lip and the force under a certain interference can be obtained, as given by[11]

$$d(x_i,y_j)=\frac{2(1-\upsilon^2)}{\pi E}(I_\delta)_{ij}\iint\frac{p(x,y)}{\sqrt{(x-x_i)^2+(y-y_j)^2}}dxdy \tag{9}$$

where $d(x_i,y_j)$ is the elastic deformation, E is elastic modulus, υ is Poisson's ratio, and I_δ is radial deformation coefficient matrix.

The amount of elastic deformation obtained by Eq. (9) updates the film thickness, which is expressed as[12]

$$h(x,y)=h_0+Z(x,y)+d(x,y) \tag{10}$$

where h_0 is initial oil film thickness.

Considering the influence of temperature on oil viscosity, the global heat balance method is used to calculate temperature change, as given by[13]

$$\frac{2\pi^2 fURF}{60}=Qc(T-T_0)+\alpha 2\pi RL(T-T_0) \tag{11}$$

where Q is pumping rate, R is shaft radius, f is coefficient of friction, F is axial force, c is specific heat capacity, T is actual temperature, T_0 is initial temperature and α is heat exchange coefficient of oil.

The change in temperature affects the oil viscosity, as given by[13]

$$\eta=\eta_0 e^{-\alpha_T(T-T_0)} \tag{12}$$

where η_0 is viscosity at T_0, and α_T is viscosity temperature coefficient

The updated viscosity is brought to Eq. (8), and the iterative calculation of Eq. (8), (9), (10), (11), and (12) is performed until the film thickness converges. Finally, the balanced oil film pressure and thickness are obtained to solve characteristic parameters of rotary lip seal.

C. Characteristic Parameter of Rotary Lip Seal Solving

The characteristic parameters of rotary lip seal include lip temperature, friction torque, and pumping rate. The lip temperature can be obtained by Eq.(11), and the friction torque and pumping rate are expressed as[14]

$$T_f=2R\iint(\frac{h}{2}\frac{dp}{dx}+\eta\frac{U}{h})dxdy \tag{13}$$

$$Q=\int(-\frac{h^3}{12\eta}\frac{dp}{dx})dy \tag{14}$$

where T_f is friction torque, and Q is pumping rate.

Archard wear model[15] is used to solve the wear rate, and through the accumulation of simulation time, the wear depth can be obtained as given by

$$dh_w=\frac{K}{H}\times p\times U\times dt \tag{15}$$

where dh_w is wear depth, K is wear coefficient, and H is hardness of softer material in the sports pair.

The radial deformation coefficient matrix in Eq. (9) is changed with the wear value and a new round of iterative simulation is performed to obtain a reliable model of rotary lip seal with time.

D. Computational Procedure

The reliability life assessment model of rotary lip seal is implemented in Matlab, Figure 3 shows the solution flow chart.

1. Set initial value of simulation parameters.
2. 3D rough surface simulation of sealing lip is obtained by fractal theory.
3. Given an initial oil film thickness, combined with rough surface height obtained in step 2, Eq. (8) is solved to obtain oil film pressure distribution.
4. The oil film pressure distribution obtained in step 3 is brought into Eq. (9) to obtain the elastic deformation.
5. Calculate Eq. (10) to update oil film thickness, and bring the updated oil film thickness back to Eq. (8) for iterative calculation until the film thickness converges.

6. The viscosity is updated by Eq. (11) and (12). Bring it back to Eq. (8) for iterative calculation until the temperature converges.
7. Balanced oil film thickness and pressure distribution are obtained to solve characteristic parameters.
8. The radial deformation coefficient matrix in Eq. (9) is updated by wear depth. Reperform steps 3 to 7 until characteristic parameters can't meet the requirement.

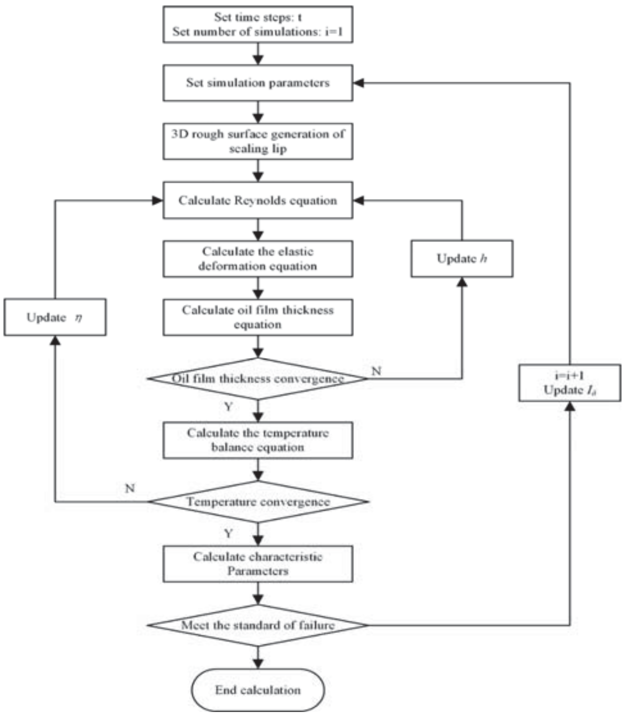

Figure 3. Numerical solution flow chart

III. Results and Discussion

The simulation parameters are shown in Table 1

Table 1. Simulation parameters

Parameter	Meaning	Value	Unit
M	Surface folds number	10	
L	Sampling length	0.4	mm
h_0	Initial oil film thickness	2.5	um
T_0	Initial temperature	30	℃
η_0	Initial viscosity	0.02	Pa.s
E	Elastic modulus	9.8	MPa
υ	Poisson's ratio	0.49	
U	Shaft speed	3000	rpm
P_0	Environment pressure	0.1	MPa
R	Shaft radius	8	mm

A. *Rough Surface Simulation of Sealing Lip*

A 2D surface contour is generated firstly. The characteristic parameters are obtained by using a roughness profiler to collect the surface contour curve of the sealing ring from horizontal direction, which is shown in Figure 4.

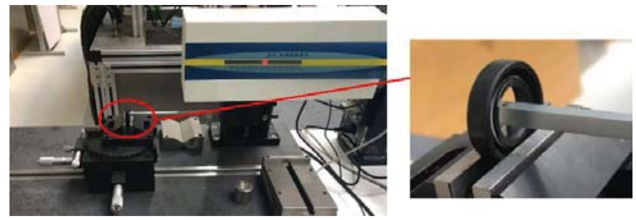

Figure 4. Roughness profiler

Figure 5 is a 2D contour curve of sealing lip measured by a roughness profiler. The power spectrum of the contour is obtained by Fast Fourier Transform (FFT)[16], as shown in Figure. 6.

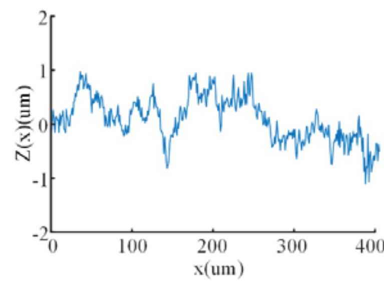

Figure 5. 2D contour curve of sealing lip

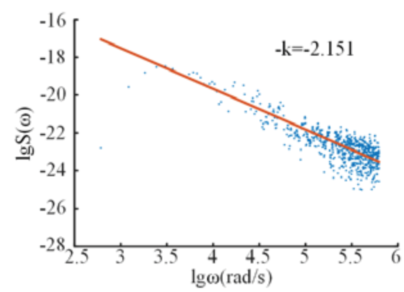

Figure 6. Power spectrum

The 2D fractal dimension D is calculated by Eq. (4), and the scale factor G is obtained by Eq. (6).

The 2D sealing lip rough surface simulation is shown in Figure 7, and then converted into a 3D rough surface by Eq. (7), as shown in Figure 8.

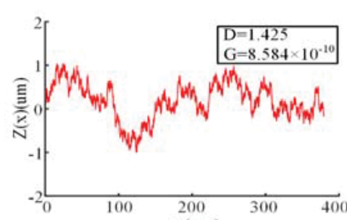

Figure 7. 2D surface simulation

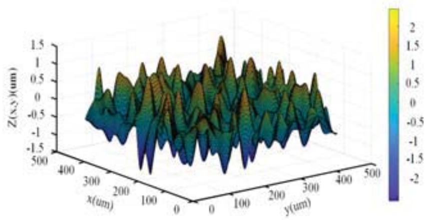

Figure 8. 3D surface simulation

The generated 3D rough surface is used in Eq. (9). Considering the influence of multifield coupling, the reliability life evaluation model is established to obtain performance parameters of rotary lip seal with time, which is verified by a test bench as shown in Figure 9.

Figure 9. Rotary lip seal performances test bench

B. *Degradation of Characteristic Parameters*

The most intuitive manifestation of degradation of rotary lip seal is the degradation of sealing lip. Using the wear formula, the amount of lip wear is calculated after each simulation to obtain the degradation curve of sealing lip wear depth, as shown in Figure 10. The wear rate of sealing lip gradually decreases with time. The actual wear depth is obtained by a roughness profiler measuring the contour of sealing lip over some time.

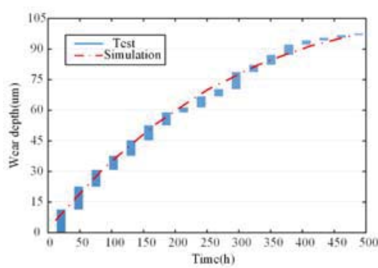

Figure 10. Lip tip wear degradation

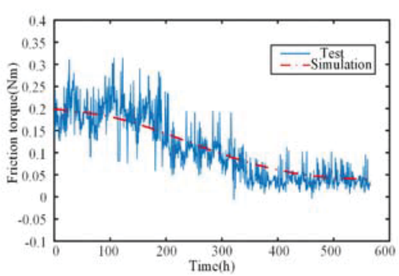

Figure 11. Friction torque degradation

The friction torque is a parameter that reflects the friction characteristic of rotary lip seal. Large friction torque indicates that the friction between sealing lip and rotating shaft is very intense, and the degradation is serious. Figure 11 shows that the friction torque value decreases gradually with time. The actual friction torque is measured in real time, which is small in magnitude and extremely susceptible to interference from the external environment.

The temperature of sealing lip also reflects the wear degree of sealing lip and rotating shaft. The degradation tendency is similar with friction torque degradation.

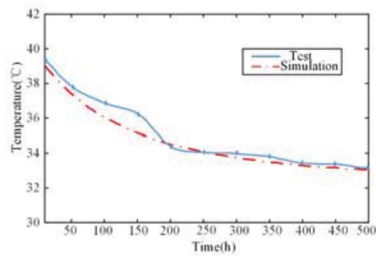

Figure 12.Lip temperature degradation

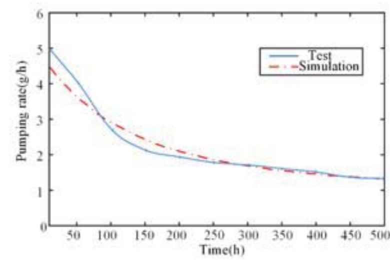

Figure 13.Pumping rate degradation

Pumping rate is an important parameter to characterize the sealing performance of lip seals. The sealing performance is better as the value is larger. As can be seen from Figure 13, pumping rate shows a significant degradation trend with time. The actual measurement of pumping rate is obtained by measuring the leakage of rotary lip seal by reverse mounting.

IV. CONCLUSION

The central contribution of this paper is to propose a modeling method of sealing lip surface based on fractal theory to establish the reliability model of rotary lip seal. Some conclusions are obtained as follows.

1. The reliability model can be relied upon to evaluate the service life of rotary lip seal by the initial lip seal parameters.
2. The fractal theory can be applied to the lip surface simulation. The simulation is not affected by the resolution of the instrument, which is more accurate and objective than the traditional method.
3. The degenerative process of the lip seal is nonlinear. It begins to degenerate dramatically and becomes slower over time.

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