Reliability Analysis and Design of Internal Clearance of Rolling Bearings

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1. Introduction

Aero-engine main shaft bearings usually use rolling bearings, which are key components of aero-engines. They always operate at high speed, high temperatures, and complex loading conditions, which have a direct impact on their quality, performance, life, and reliability. With the continuous increasing in the value of DN of the aero-engine main shaft bearings, the frictional heat generation of the bearing is aggravated, and the fatigue life is reduced. Internal clearance is an important parameter of the aero-engine main shaft bearing, which will affect its load distribution, vibration, noise, friction torque and life [1-3].

In this study, the main factors affecting the working clearance of the bearing are analyzed, and the calculation method of the bearing working clearance is established. Finally, based on the reliability design method, the solution of the clearance design is proposed.

2. Working clearance calculation of rolling bearings

The bearing is installed in the shaft and the housing. The interference fit between the shaft and the bearing inner ring causes the inner ring raceway to expand. The interference fit between the housing and the outer ring of the bearing causes the outer ring raceway to contract, and the bearing clearance called assembly clearance (installation clearance) at this time. Generally the inner ring temperature is higher than the outer ring temperature during the operation of the bearing, and the expansion of the inner ring will reduce the clearance. When the inner ring speed is particularly high, the expansion of the inner ring due to centrifugal force will also reduce the clearance. The clearance is called working clearance after proceeding considerations.

The interference fit between the bearing and the shaft will cause the expansion of the inner ring raceway [4]. According to the thick ring theory, the increase in the clearance of the inner ring due to press-fitting as in Eq. (1).

$$\Delta G_i = \frac{2I_{\text{iw}}\left(\dfrac{D_{i1}}{D_i}\right)}{\left[\left(\dfrac{D_{i1}}{D_i}\right)^2-1\right]\left\{\left[\dfrac{\left(\dfrac{D_{i1}}{D_i}\right)^2+1}{\left(\dfrac{D_{i1}}{D_i}\right)^2-1}+\nu_1\right]+\dfrac{E_1}{E_s}\left[\dfrac{\left(\dfrac{D_i}{D_\text{s}}\right)^2+1}{\left(\dfrac{D_i}{D_\text{s}}\right)^2-1}-\nu_s\right]\right\}} \tag{1}$$

where ν_1 is the inner ring Poisson's ratio and ν_s is the shaft Poisson's ratio. D_i is the shaft outer diameter or bearing inner diameter and D_s is the hollow shaft inner diameter. E_1 is the inner ring elastic modulus and E_s is the shaft elastic modulus. D_{i1} is the inner ring groove diameter. I_{iw} is the effective interference between the inner ring and the shaft.

The variation of clearance caused by temperature differential expansion as in Eq. (2) [5].

$$\Delta G_T = \Delta G_{To} - \Delta G_{Ti} - 2G\Delta_{TB} \tag{2}$$

where ΔG_{To} is the expansion of the inner diameter of the bearing outer ring. ΔG_{Ti} is the expansion of the outer diameter of the bearing inner ring. ΔG_{TB} is the expansion of the rolling elements.

The variation of clearance caused by high-speed rotation as in Eq. (3) [6].

$$\begin{aligned}\Delta G_{ci} =& \mathrm{D}_i(1+\nu_1)\frac{(3-2\nu_1)}{8E_1(1-\nu_1)}\rho_1\omega^2 {D_{i1}}^2 \\ &\times[(1-2\nu_1)(\frac{{D_{i1}}^2}{{D_i}^2}+1)+1-\frac{(1-2\nu_1)}{3-2\nu_1}\frac{{D_i}^2}{{D_{i1}}^2}]\end{aligned} \tag{3}$$

where ρ_1 is the inner circle density. ω is the inner ring angular velocity.

By analyzing the influence of fit interference, rotation speed and working temperature, the radial working clearance of the bearing can be calculated as in Eq. (4).

$$G_w = G_0 - \left(\Delta G_{ci} + \Delta G_i \pm \Delta G_T\right) \tag{4}$$

3. Reliability design of rolling bearing clearance

In this study, considering the working clearance as a factor that causes failure, and the optimal working clearance is a factor that prevents failure. Since the initial clearance, the environment and working conditions affecting the clearance are random variables, the working clearance must also be a random variable and have a certain distribution (generally should be normally distributed) [7].

If the probability density distribution of the working clearance obtained by the probability and statistical analysis method is $x \sim N(\mu, \sigma^2)$, the optimal working clearance interval is $[\lambda_1, \lambda_2]$ by researching the bearing failure mode. According to the generalized stress-strength interference model, the reliability as in Eq. (5).

$$R = \Phi(\frac{\lambda_2 - \mu}{\sigma}) - \Phi(\frac{\lambda_1 - \mu}{\sigma}) \quad (5)$$

where Φ is the PDF of the standard normal distribution, then Eq. (5) can be rewritten as in Eq. (6).

$$\int_{-\infty}^{\frac{\lambda_2-\mu}{\sigma}} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx - \int_{-\infty}^{\frac{\lambda_1-\mu}{\sigma}} \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx - R = 0 \quad (6)$$

The rolling bearing clearance reliability design process as in Fig. 1.

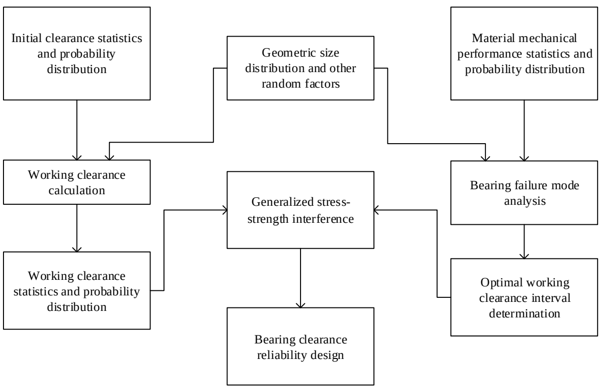

Fig. 1. Bearing clearance reliability design process diagram

4. Case of study

Taking deep groove ball bearing as an example. The dimensional parameters of the bearing as in Table 1, the material parameters as in Table 2.

Table 1 Dimensional parameters of the bearing

Number of balls	Ball diameter (mm)	Inner diameter (mm)	Outer diameter (mm)	Pitch diameter (mm)
12	28	75	160	117.5

Table 2 Physical properties of GCr15A

Density	Elastic modulus	Poisson's ratio	Thermal conductivity
7.81	2.19e+06	0.3	44

Under the conditions of radial load of 4000N and rotation speed of 14000r/min. Considering the randomness of various parameters, the probability distribution of the working clearance under this condition is obtained. The probability distribution of the working clearance is $Gw \sim N(-1.6, 0.22643)$ μm. Assuming that the optimal working clearance interval is $[-2,-1]$ μm, the reliability of the bearing can be calculated by the generalized stress-strength interference model and the reliability value is 0.9573.

5. Conclusion

The working temperature, interference fit and the rotation speed will change the radial clearance of the bearings. In particular, the effect of temperature is most obvious.

Reliability can be calculated under specific conditions by the clearance reliability model. If the design reliability, related dimensions, and material properties are known, the model can be used to select the optimal initial clearance.

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