Power Engineering and Engineering Thermophysics
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Effects of Fit Clearance and Viscosity of Lubricating Oil on Shaft Center Orbit of Camshaft

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Received: 01-01-2023 **Revised:** 02-10-2023 **Accepted:** 03-06-2023

Citation: Z. S. Zhang and Y. Wang, “Effects of fit clearance and viscosity of lubricating oil on shaft center orbit of camshaft,” *Power Eng. Eng. Thermophys.*, vol. 2, no. 1, pp. 42-48, 2023. https://doi.org/10.56578/peet020104.

Abstract: In an oil-film lubricating system, fit clearance and the different types of lubricating oil can result in changes in the orbit of shaft center, thereby affecting the stability of the system. Subject of this paper is the camshaft lubricating system of airspace engine, to figure out the effects of fit clearance and the type of lubricating oil on the shaft center orbit of camshaft, in this study, a 3D model of the camshaft lubricating system was built for simulation purpose based on Reynolds equation, and the calculation results suggest that, as the fit clearance grows larger, the convergence position of shaft center gradually moves away from the starting position, and the stability of shaft center declines; in terms of the type of lubricating oil, the higher the viscosity of the lubricating oil, the closer of the position of shaft center to the starting point, and the higher the stability. Our research method can be applied to common oil-film lubricating systems and we hope it could provide a theoretical evidence for the selection of fit clearance and type of lubricating oil for such systems.

Keywords: Oil-film lubricating system; Shaft center orbit; Fit clearance; Airspace engine; Camshaft

1. Introduction

Camshaft is a core component for airspace engines, it can lead to serious accidents once a camshaft looses or breaks [1]. Bearings and rotors are inextricable parts in airspace engine, they jointly determine the stability and reliability of the rotating parts, which are usually regarded as a system during fault detection. By monitoring the shaft center orbit and judging its instantaneous motion states, we can perform fault detection on the system [2, 3].

Many reports on fault monitoring of rotating systems such as engines are about the relation between shaft center orbit and the fault [4, 5], however, researchers usually lay their eyes on aspects such as variable-load conditions [6], extraction of shaft center orbit under multi-conditions [7], identification of shaft center orbit based on neural network and affine transformation [8], or calculation of shaft center orbit based on dynamic mesh method and Fluent [9], and few of them have concerned about the effects of fit clearance of shaft and the different types of lubricating oil on shaft center orbit. Calculation of shaft center orbit under the condition of oil-film lubrication is a difficult problem, since the strong coupling between fluid and rotating machinery is involved, it’s very hard to solve the non-linear kinetic equations. Wu et al. [10] simplified the structure of connecting-rod piston, built differential equations of motion, and figured out the law of the motion of shaft center under the action of lubricating oil film. Kai et al. [11] used a matching pursuit algorithm to extract the characteristic frequency of rotating shaft and synthesized its orbit. Li et al. [12] adopted BP neural network and error calibration fitting to predict the shaft center orbit of machine tool spindle. Li et al. [13] built a transient state model for the sliding bearing of fuel-fired gear pump with the cavitation effect of oil film and nonlinear dynamic load taken into consideration, and successfully attained the shaft center orbit under the coupling action of transient flow field and dynamic load. Zhu et al. [14] drew on the idea of deep learning and proposed a method for signal noise reduction and frequency multiplier extraction based on 2D shape invariant moment and support vector machine, and got clear images of shaft center orbit.

As deep learning has been greatly promoted these days, researchers generally prefer to use neural networks to predict and extract shaft center orbit [15-17], but few of their works have mentioned the effects of fit clearance and the type of lubricating oil on shaft center orbit, so this paper took the camshaft lubricating system of airspace engine as subject and modeled it under 3D conditions with the cavitation of lubricating oil films taken into account, and the calculation results provide a useful reference for researchers to select proper value of fit clearance and the suitable type of lubricating oil.

2. Numerical Model

2.1 Finite Element Model

Figure 1 shows the model of an airspace engine camshaft. When calculating the shaft center orbit, in order to reduce the nonlinearity of the computational model, the camshaft was simplified: the flywheel at the end of the camshaft was removed, and a local load was applied at different positions of the rotating shaft to approximately replace the uneven mass distribution caused by the camshaft and the flywheel, then simulation was performed in ANSYS, and the finite element model is shown in Figure 2.

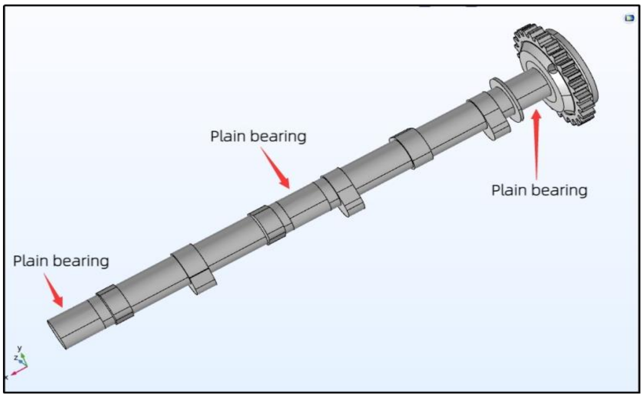

Figure 1. Model of an airspace engine camshaft

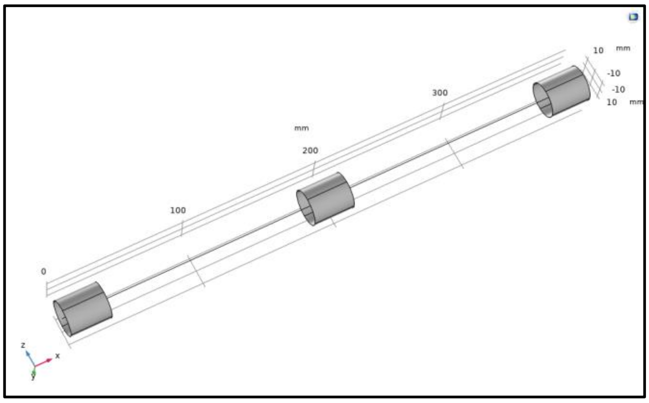

Figure 2. Finite element model of shaft center orbit

Rotating speed of the camshaft was set to 1200 rpm, material of the rotating shaft was set as high-strength alloy steel, oil films were draw at three supporting positions, and the initial parameters of oil film were set. Table 1 lists the calculation parameters.

Table 1. Calculation parameters of shaft center orbit

Variable name	Parameter value	
C_eval	2*pi*RPM	Maximum angular speed of shaft
RPM	1200[1/min]	Maximum rotating speed of shaft
D2	26.18[mm]	(Outer circle) Radius of supported hole of journal
D1	26.33[mm]	(Inner circle) Radius of shaft
mu1	0.019[Pa*s]	Dynamic viscosity of mineral oil “Exxon Mobil-20W-50”
rho1	860[kg/m^3]	Density of mineral oil “Exxon Mobil-20W-50”
Miu	0.3	Poisson’s ratio
E	206[Gpa]	Young’s modulus of shaft

2.2 Control Equation

Since the fit clearance between the bearing and the journal is in micron size, changes in the pressure gradient along the direction of fit clearance can be ignored, by applying the Reynolds equation [18] in the broad sense, there is:

$$\frac{\partial}{\partial \theta}\left(o\bar{\beta}H^3\bar{A}_2\frac{\partial \Phi}{\partial \theta}\right)+\frac{\partial}{\partial Z}\left(o\bar{\beta}H^3\bar{A}_2\frac{\partial \Phi}{\partial Z}\right)=\frac{\partial}{\partial \theta}\left[\left(1-\frac{\bar{A}_1}{\bar{A}_0}\right)H\Phi\right]+\frac{\partial \Phi H}{\partial t} \tag{1}$$

where, θ and Z are dimensionless coordinates; Φ is density ratio; β is dimensionless elastic modulus; H is dimensionless thickness; $\bar{A}_0$, $\bar{A}_1$, and $\bar{A}_2$ are viscosity factors, and their calculation methods are:

$$\begin{aligned}\bar{A}_0&=\int_0^h \frac{\mathrm{d}y}{\mu(y)}, \bar{A}_1=\int_0^h \frac{y\mathrm{d}y}{\mu(y)}\\ \bar{A}_2&=\int_0^h \frac{1}{\mu(y)}\left(y^2-y\frac{A_1}{A_0}\right)\mathrm{d}y\end{aligned} \tag{2}$$

In the oil film region, due to the existence of pressure difference, the oil film will be cavitated, and the position of oil film cavitation could be controlled by the switch function g derived by Elrod and Adams; then the speed term in the Reynolds equation was corrected:

$$\mathbf{v}_{av}=\mathbf{v}_{av,c}-g v_{av,p}\nabla_t p_f \tag{3}$$

$$g=\begin{cases}0, & \text{Cavitation region}\\ 1, & \text{Oil film region}\end{cases} \tag{4}$$

The first and second terms on the right side of the equation respectively correspond to the average Couette speed and the average Poiseuille speed, the switch function set the average Poiseuille speed of the cavitation region as zero.

3. Result Analysis

Two groups of calculations were set with the effect of fit clearance and the effect of viscosity of lubricating oil respectively taken into consideration, calculation time was 1s, and the calculation contents of two examples are:

(1) Under actual conditions, generally, the range of fit clearance is between 0.05 mm and 0.15 mm, so in our calculations, the value of fit clearance took 0.05 mm, 0.1 mm, 0.12 mm and 0.15 mm respectively, the viscosity of lubricating oil was 0.019 Pa·s, the calculation results are as follows are shown in Figure 3.

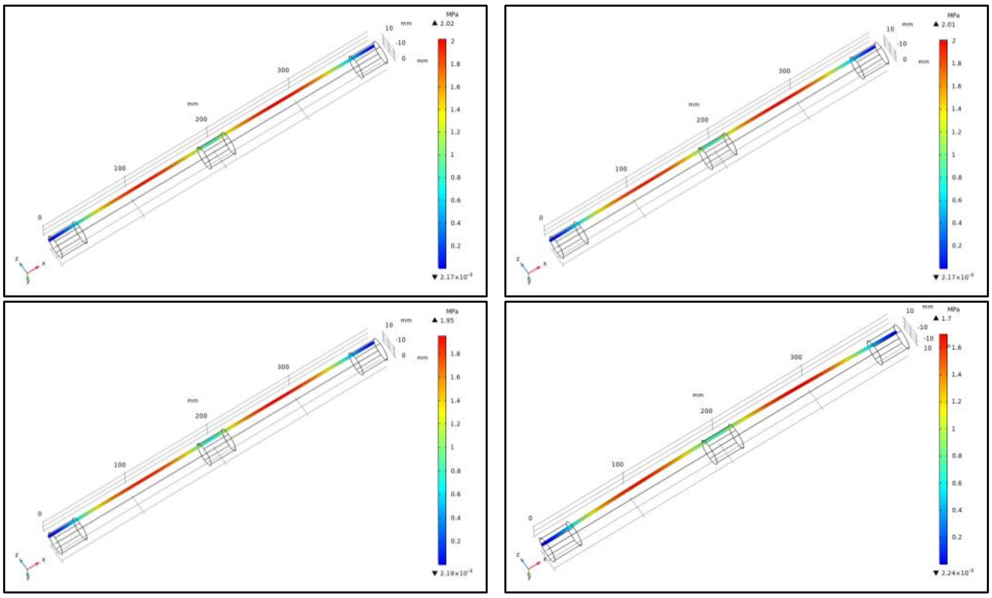

Figure 3. Distribution of surface stress of shaft under four values of fit clearance

According to the stress distribution of the rotating shaft, stress distributed unevenly on the shaft, positions with large deformation were between two supporting shaft diameters, and the closer the position to the center, the greater the stress, and the larger the deformation; with the increase of fit clearance, the surface stress of the rotating shaft decreases gradually.

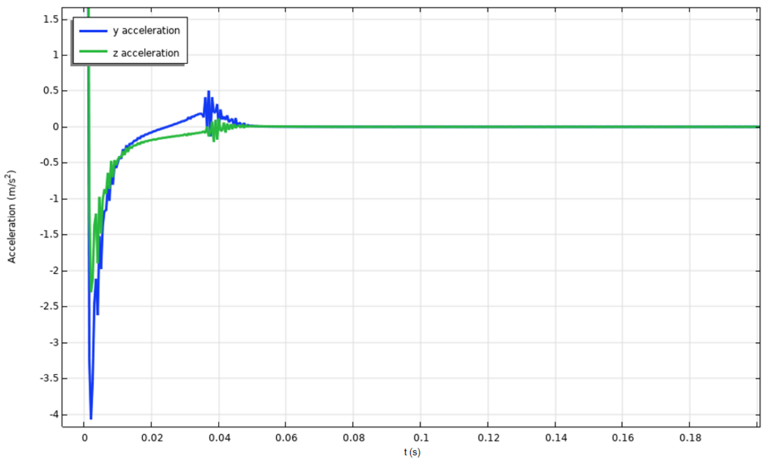

Figure 4. Vortex acceleration of shaft within 0.2s in case of a 0.05 mm fit clearance

As shown in Figure 4, in the start-up stage, the radial acceleration of the rotating shaft in x and y directions was large and continued with the rotation, at about 0.04 s, the vortex acceleration of the shaft fluctuated greatly, tended to be stable in the radial direction with small fluctuations.

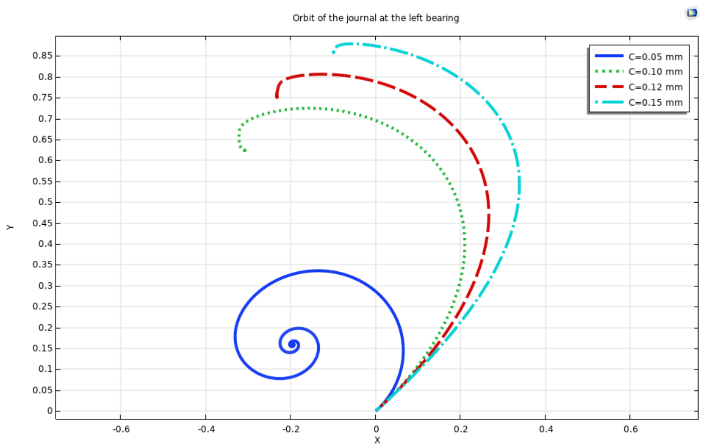

Figure 5. Orbit of shaft center in case of four values of fit clearance

Calculation results indicate that, the shaft started moving from point (0,0), the oil film pressure at the journal changed with the rotation of the shaft, under the joint action of gravity and oil film pressure, the shaft center rotated around its own balance position, and the balance position of shaft center converged to a point. Within the 2s rotation time, under the conditions of four values of fit clearance, the convergence positions of shaft center were different, the smaller the fit clearance, the closer the convergence position to the initial position, the faster the convergence speed of the shaft, and the better the convergence effect, as shown in Figure 5.

According to stress distribution of the shaft, the stress distribution on the rotating shaft was uneven, positions with large deformation were between two supporting shaft diameters, and the closer the position to the center, the greater the stress, and the larger the deformation; with the increase of the viscosity of lubricating oil, the stress on shaft surface gradually decreases.

(2) The viscosity of five types of lubricating oil SEA 5W-20, SEA 5W-30, SEA 10W-30, SEA 10W-40 and SEA 20W-50 increases in sequence, in case of a fit clearance of 0.05 mm, the calculation results are shown in Figure 6.

In the start-up stage, the radial acceleration of the rotating shaft in x and y directions was large, the shaft fluctuated greatly and the fluctuation continued with the rotation, acceleration in the radial direction tended to be stable and the fluctuation tended to be stable as well, as shown in Figure 7.

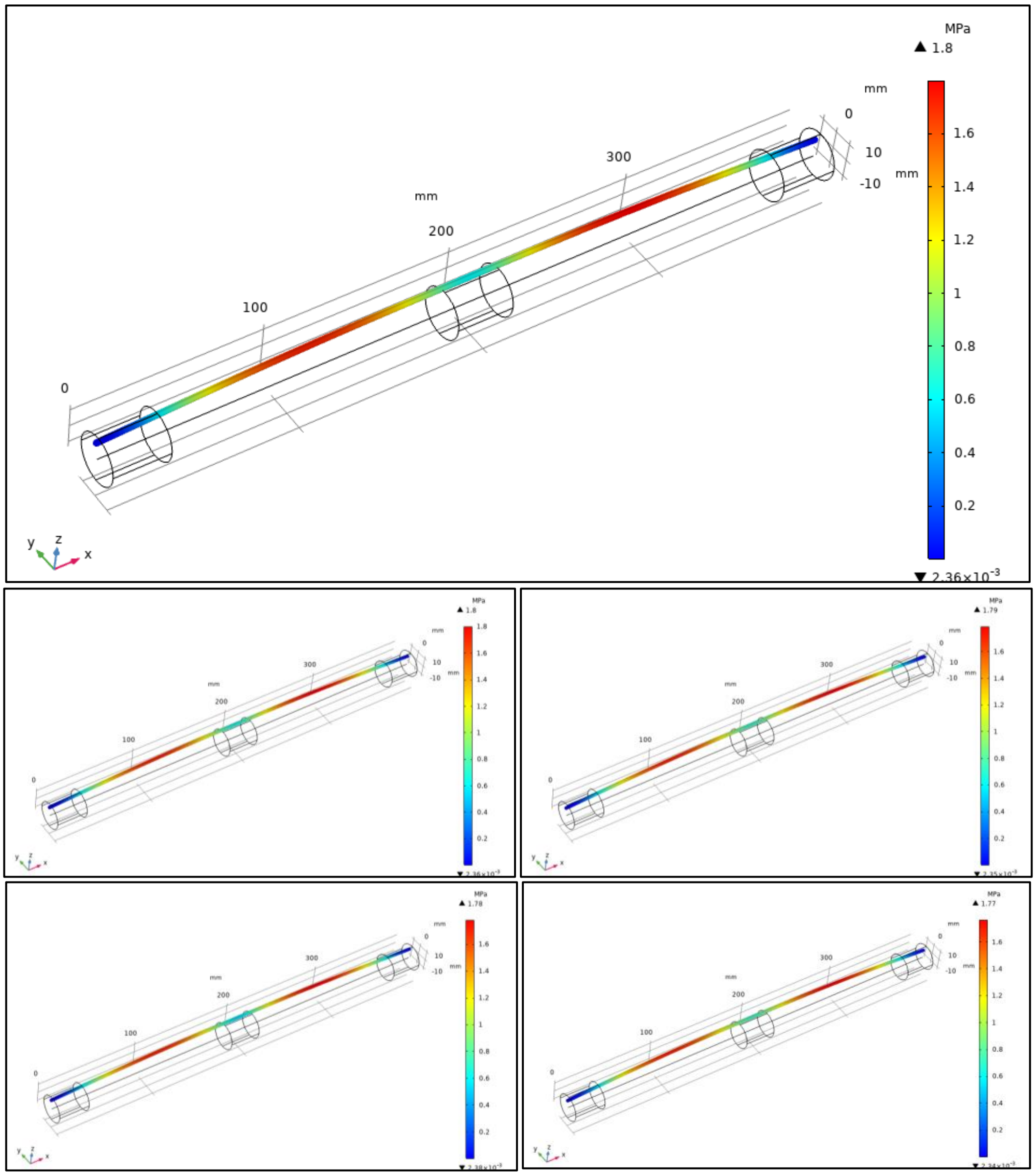

Figure 6. Distribution of shaft surface stress in case of five types of lubricating oil

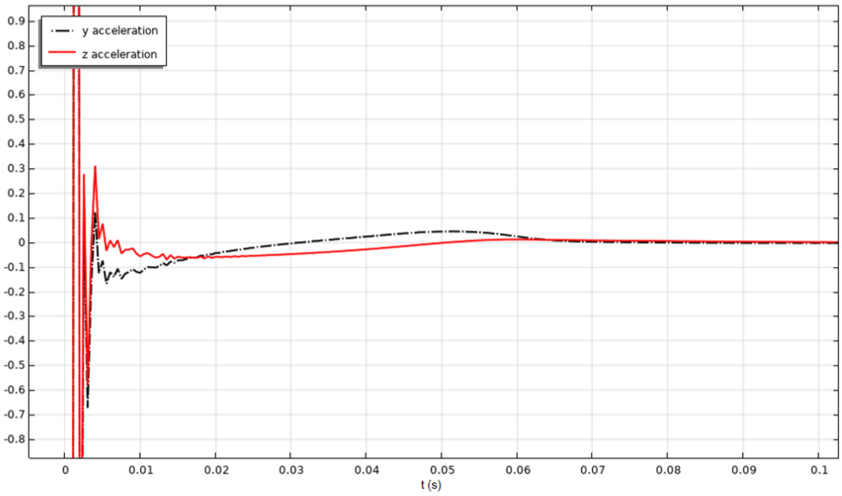

Figure 7. Vortex acceleration of shaft within 0.1s in case that the lubricating oil is SAE 5W-20

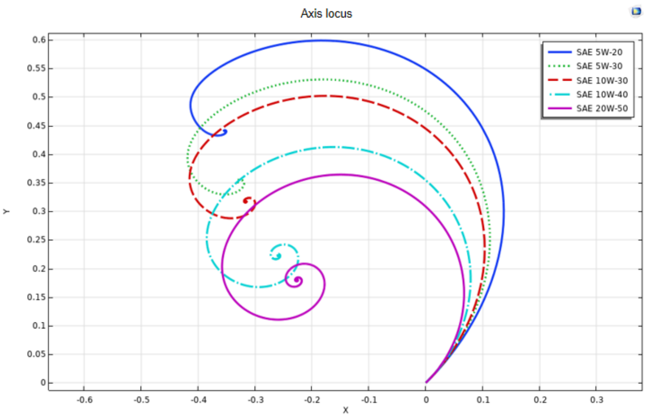

Figure 8. Orbit of shaft center in case of five types of lubricating oil

Calculation results reveal that with the increase of the viscosity of lubricating oil, the radial acceleration of shaft in radial direction fluctuated gently in the start-up stage and the convergence effect of the shaft was better, as shown in Figure 8. Comparison of the shaft center orbits of five types of lubricating oil suggests that, with the increase of viscosity, both the convergence position and convergence speed of the shaft had been improved, indicating that viscosity can affect the convergence position and convergence speed of the shaft, and the convergence effect gets better as viscosity grows.

4. Conclusions

This paper studied the orbit of camshaft center in oil film lubricating system, and discussed the changes of the orbit under the conditions of different values of fit clearance and different types of lubricating oil, the attained conclusions are:

(1) The larger the fit clearance, the longer it takes for the shaft center to reach the position of stable convergence point; as the fit clearance increases, it takes longer for the shaft to reach stable rotation. According to the results of several selected values of fit clearance, within the limited range, a fit clearance of 0.15 mm is the best.

(2) With the increase of the viscosity of lubricating oil, the convergence speed and convergence position of the shaft center could be improved, the viscosity of lubricating oil has a great effect on the movement of shaft center.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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