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Optimized design of spray parameters of oil jet lubricated spur gears

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ABSTRACT

The lubrication process in jet lubrication is significantly influenced by different spray parameters under different injection conditions. The computational fluid dynamics model of the jet lubrication process is established. The jet lubrication process is evaluated with different spray parameters, including the spray angle, position, and distance. The results indicate that for into mesh lubrication, a suitably small angle inclined to driving gear, deviation of injection position from into mesh side, and larger spray distance improve the lubrication effect. With out of mesh lubrication, a small angle inclined to driven gear, deviation of injection position from out of mesh side, and smaller spray distance provide the optimal lubrication effect. Finally, the analysis results are verified by experimental results.

1. Introduction

Jet lubrication is commonly used in the lubrication and cooling of high–speed gears. Jet lubrication mainly includes into mesh lubrication and out of mesh lubrication. In the meshing process, the meshing clearance between two teeth surfaces is very small. A gear with a high rotational speed shocks and agitates the lubricating oil jet and prevents it from entering the meshing zone, resulting in starved lubrication or a dry friction state of the high–speed gear [1–3]. This greatly reduces the reliability and lifetime of the transmission system. The orientation parameter of the nozzle has a direct effect on whether the oil jet can enter the meshing zone. In a traditional jet lubrication design, the injection orientation parameters are often based primarily on experience. However, this is still not considered adequate in studies on jet lubrication parameters and the lubrication mechanism, resulting in poor lubrication.

In the jet lubrication condition, the oil ejected from the nozzle is mixed with air in the environment to form a mixed jet of oil and air. Particularly when the gear speed is high, the impact of a rotating tooth surface with the jet increases the mixing degree of oil and air. Although the spray parameters determine whether the oil can be sprayed into the meshing zone, they have not been sufficiently investigated in the design of jet lubricated gears. Akin [4–6] studied the injection lubrication process under the out of mesh lubrication condition, and analyzed the relationship between the gear overlap and penetration capacity of the jet. Townsend [7,8] measured and analyzed the average and transient gear temperatures using a high-speed infrared tester, and studied the influence of the speed and load on the temperature increase of a jet lubricated gear. Zaretsky E V [9–11] investigated the influence of different distances and additives on the gear lubrication. Handschuh R F [12–14] measured the temperature of the tooth surfaces using an infrared temperature sensor and reported on the influence of different injection positions and oil pressures on the surface temperature of a gear. Evans H P, Snidle R W, and Sharif K J [15–17] studied the lubrication mechanism under mixed lubrication conditions when considering the roughness of the gear tooth surface. Höhn B R, Michaelis K, and Otto H P [18–20] studied the optimization of gears with minimum oil supply in an air/oil phase state. In addition, some scholars have done a lot work on the gear transmission loss. Concli et al. [21,22] developed a specific calculation-tool of the power loss in geared transmissions, and the model was validated with experimental tests. Hill et al. [23] studied the numerical and modeling approaches used for the analysis of gear windage losses and newly proposed tooth contour modifications. Talbot et al. [24] studied the prediction method of mechanical power loss of planet gear roller bearing deeply.

This study investigates the lubrication process of gears under different injection conditions (into mesh and out of mesh lubrication) and establishes an analysis model of the lubrication process of gears using the CFD method. Additionally, the influence of the spray parameters on the lubrication effect of different injection methods is studied. Finally, the paper presents a design method of the nozzle orientation parameters with different injection methods to provide guidance for a jet lubrication design and the methods are verified via experiments.

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2. Definition of spray parameters

According to the meshing principle, the entire meshing process of the gear proceeds through three stages, namely, double teeth, single teeth, and double teeth. The lubrication conditions are different at different stages under the jet lubrication condition. When the gears are in the first two stages under into mesh lubrication condition, the oil can flow into the meshing point through the clearance formed by the tooth surfaces of the two gears above the meshing point. When the gear is in the third stage, the oil is blocked by the next pair of teeth and cannot enter the meshing point directly.

For the first two stages, a suitable spray parameter must be selected so that as much oil as possible enters the meshing point. For the third stage, the meshing point is mainly lubricated by the oil absorbed on the tooth surface, and the oil mist within the environment. For the sake of convenience, different spray parameters, including the spray angle, position, and distance, are defined as shown in Fig. 1.

The spray angle is the intersection angle between the nozzle and the internal common tangent of the two pitch circles, as shown in Fig. 1a. The numbers 1, 2, 3, 4, and 5 in Fig. 1a denote five different spray angles. The spray position is the intersection of the straight line of the nozzle and the internal common tangent of the two pitch circles, as shown in Fig. 1b. The numbers 1, 2, 3, 4, and 5 in Fig. 1b represent five different spray positions. The spray distance is the distance between the nozzle export and the injection point, as shown in Fig. 1c.

3. Model and control equation

3.1. Model

The lubrication environment of the meshing point is extremely complicated because the oil jet lubricated gear is in a complex lubrication state of the two oil/air phases. The jet lubrication is a constantly changing transient process that is difficult to study experimentally. In this study, the computational fluid dynamics method and software are used to calculate the jet lubrication process at each meshing point, and to realize the theoretical study of the lubrication process.

A three-dimensional model of spur gear pairs is established using the three-dimensional CAD software Pro/Engineer (Pro/E). The parameters of the two gears are the same. In the analysis, the module is set at 4 mm, the pressure angle is 20°, the number of teeth is 25, and the gear width is 2 mm. The two gears are assembled in a standard form, as shown in Fig. 2a. To calculate the flow state of the lubricating oil between the teeth of the two meshing gears, it is necessary to establish the fluid computational domain according to the three-dimensional gear model. The fluid computational domain is established, as shown in Fig. 2b.

Based on the finite–volume method, the computational region model is discretized using a structural mesh to obtain a computational fluid dynamic analysis model. When mesh generation software (ANSYS ICEM) is employed to divide the finite–element model, the standard wall function is used. The numerical calculation requires high quality of computational mesh element. To satisfy the requirement of convergence calculation, it is necessary to modify the structure and quantity of the computational mesh element continuously. The mesh partition should not only ensure the mesh density of complex flow region, but also adapt to the mesh density of the boundary region. If the mesh density is exceedingly small, it will affect the accuracy of the calculation, resulting in significant errors; if the mesh is exceedingly dense, it will significantly increase the computational load and consume long time. To ensure high quality of the mesh element, it is necessary to verify the feasibility of the mesh element number. The nozzle is densified to 0.05 mm, and the number of the mesh element is changed from 100,000 to 4 million for numerical simulation. The influence of the mesh element number on the computational accuracy is shown in Fig. 2d. The results indicate that when the mesh element number is less than 1 million, the calculation error of mass flow is relatively large. When the mesh element number reaches 2 million, the calculation error of mass flow is controlled within 0.1% (Fig. 2d). The results indicate that when the mesh element number reaches 2 million, the calculation results are relatively stable, and the calculation accuracy basically satisfies the expected requirements. In this study, the mesh element number of the models is more than 2 million. The finite element model is shown in Fig. 2c.

3.2. Control equation

The injection process of oil jet lubricated spur gears is a two-phase flow problem. The Euler–Euler multiphase flow model is used to establish a mathematical model [21,25–28], and the heat transfer and chemical reactions are neglected. The governing equations are given as follows.

3.2.1. Volume conservation equation

$$r_\alpha + r_\beta = 1 \tag{1}$$

The lowercase letters a and β denote the fluid phase, and r_a represents the volume fraction of a phase. In this work, the fluid phases are oil and air.

3.2.2. Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho U) = 0 \tag{2}$$

where ρ denotes the density, which is calculated using the following formula:

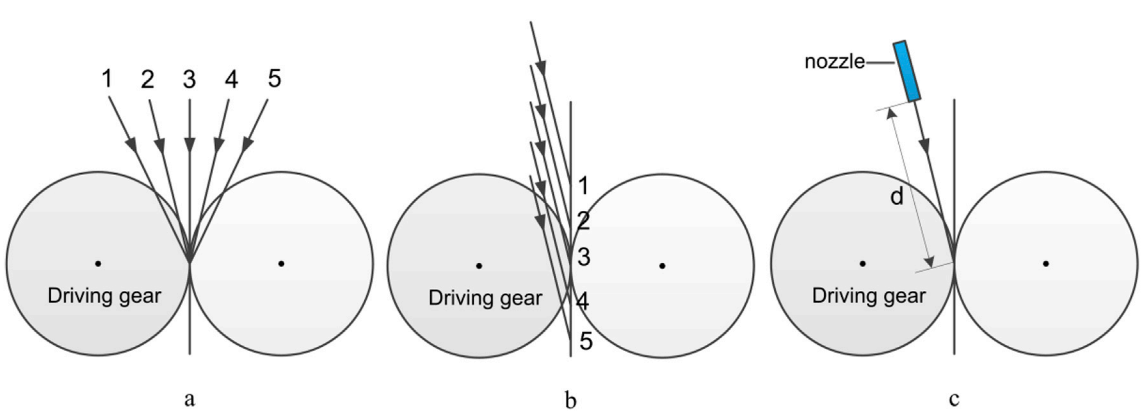

Fig. 1. Definition of different spray parameters.