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Simulation of nozzle position optimization based on single-phase flow

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Abstract: The numerical simulation on the lubrication of the complex gearbox was studied and an optimization for its injection lubrication system was carried out. Firstly, a pair of high speed gear test bench was built and related experiments were completed. The experimental results verified the correctness of the numerical simulation modeling method. Then the numerical model of the injection lubrication of the complex gear box was established, the simulation analysis was carried out. The results show that the overlong injection distance, the angle of the end face and the arrangement of the nozzle in the out of mesh side are not good for lubrication. And there is a trace in the center plane of the two meshing gear, along which the ejected oil will be under the least impact of the high speed airflow that driven by the rotating gears. When the nozzle axis is in the direction of the trace, the gear lubrication condition is the best.

1. Introduction

The gear transmission is gradually developing towards high speed, heavy load, compact and long-time operation. The harsh working environment of the gears causes a large amount of heat to be generated due to sliding friction between the tooth surfaces. If the heat cannot be dissipated in a time, the surface temperature of the gear teeth will rise sharply, the lubricant film will break, and the gear surface will be damaged by glueing, which will lead to transmission failure [1-4]. Therefore, a certain amount of lubricating oil supply is a prerequisite for high speed gear lubrication and timely heat dissipation.

High-speed gear transmission mostly adopts injection method to achieve tooth surface lubrication and cooling. On the one hand, the movement of the oil is greatly affected by the air flow driven by the rotating gear near the tooth surface [5]. Predecessors have conducted a lot of research on this phenomenon. Literature [6-7] studied the effect of a rotating single gear on the oil jet under different speeds and pressures through experimental methods. The results showed that the air flow field caused

by the high speed rotation of the gear could make the oil jet collapse. At the same time, the oil in the meshing area that actually participates in lubrication will decrease as the gear speed increases. Literature [8] studied the impact depth of oil jets with different transmission ratios through the combination of experiment and simulation, and reached the relevant conclusions. In literature [9], the VOF model was used to simulate the process of the oil jet impinging on the tooth surface to evaluate the resistance torque of the oil jet lubrication. On the other hand, the structure characteristics and the azimuth parameters of the nozzle will directly affect the movement of the oil jet, which will eventually affect the lubrication and cooling of the gear. The literature [10-15] shows that the internal geometry of the nozzle will affect the nozzle mass flow rate, particle size, spray macroscopic characteristics, and thus affect the cooling performance. The influence of injection distance and spray angle on the motion of lubricating oil is studied in literature [5,16], and valuable laws are obtained.

Taking the single stage gear as the research object, a pair of high speed spur gear transmission test rig using jet lubrication has been built. The related experiments were conducted. The experimental results provide a reference for the subsequent validation of the correctness of the numerical simulation of jet lubrication, and the validated numerical simulation modeling technique is applied to the jet lubrication simulation of the complex gear box. The lubrication condition under its working state is predicted, and a calculation method base on single-phase flow is proposed to find the optimal injection angle of the nozzle arrangement. After improving the lubrication effect of the meshing gear, the reliability and practicability of the single-phase flow calculation method are proved. Finally, this method is applied to the optimization of the entire complex gearbox to solve practical engineering problems.

2. Injection lubrication experiment

In order to verify the correctness of the numerical modelling of the injection lubrication, a high-speed gear transmission test bench using injection lubrication was built. As shown in Fig. 1. The test bench mainly includes four parts: driving and transmission system, nozzle position control system, oil supply system and experimental base. The left side of the picture is the assembly of the test bench, and the right side is the high-speed camera for data acquisition.
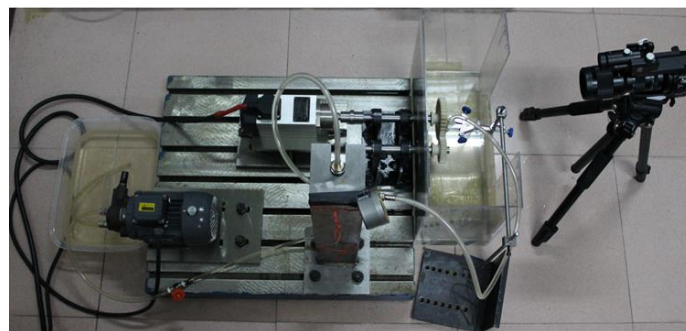

Fig.1 Experimental rig for spray lubrication

The exact position of the nozzle in space is determined by the three variables: jet distance, jet angle and end face angle. The three variables are defined as follows:

1) Injection distance: The injection is defined as the distance from the nozzle outlet to the intersection of the two gears' pitch circle, as L shown in Figure 2.

2) Injection angle: The injection angle is defined as the angle between the central axis of the nozzle and the common tangent of the two gears' pitch circle, as angle α shown in Figure 2.

3) End face angle: The end face angle is defined as the angle between the central axis of the nozzle and the gear face, as the angle β shown in Figure 2.
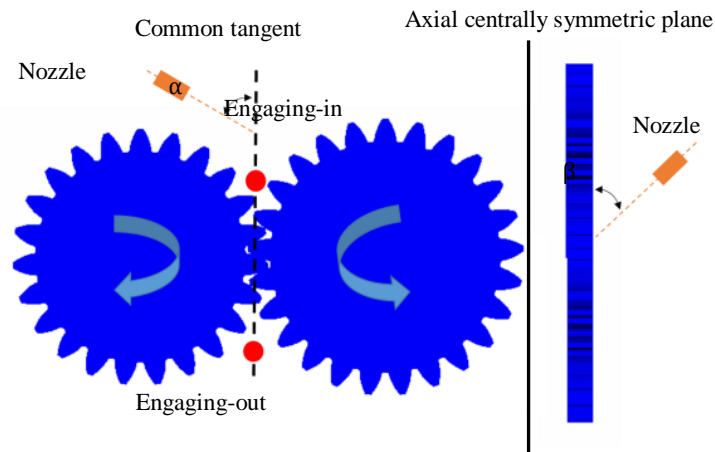

Fig.2 Parameters of nozzle's arrangement

Table 1 Experimental conditions of spray lubrication

Experimental condition	Flow rate (L•min⁻¹)	Injection method	Injection distance (mm)	Injection angle (°)	End face angle (°)	Rotational speed (r•min⁻¹)
①	0.3	Engaging-in	30	0	0	13371
②	0.3	Engaging-in	40	0	0	13371
③	0.3	Engaging-in	50	0	0	13371
④	0.3	Engaging-in	60	0	0	13371

The high speed cameras are mainly composed of 0~6 times lens, CCD, three tripod, main engine, optical fiber and other components. During the experiment, experimental data was collected with a shooting frequency of 250 frames per second. Since water and lubricating oils are very similar in many properties, the amount of oil needed in the experiment is very large. For environmental considerations and other factors, water is used instead of lubricating oil in experiments.

The high speed camera is used to collect and observe the jet flow's movement in the box as shown in Figure 3. As can be seen from the figure, due to the windage resistance effect caused by the rotation of the high speed gear, the liquid jet from the nozzle tends to deflect toward the bull gear side, which indicates that the pinion gear has a stronger windage resistance effect than the large gear. In addition, the deflection of the jet to the side of the large gear increases with the increase of the jet distance. The deflection of the oil trajectory is quite obvious when the injection distance is 60mm. It can be predicted that when the injection distance continues to increase to a certain value, the jet will deflect too far toward the bull gear to enter the meshing zone, and the amount of jet liquid in the meshing zone will be greatly reduced. Therefore, in the design process of the high-speed gear transmission injection lubrication system, the influence of the injection distance must be considered, and the injection distance should not be too large.
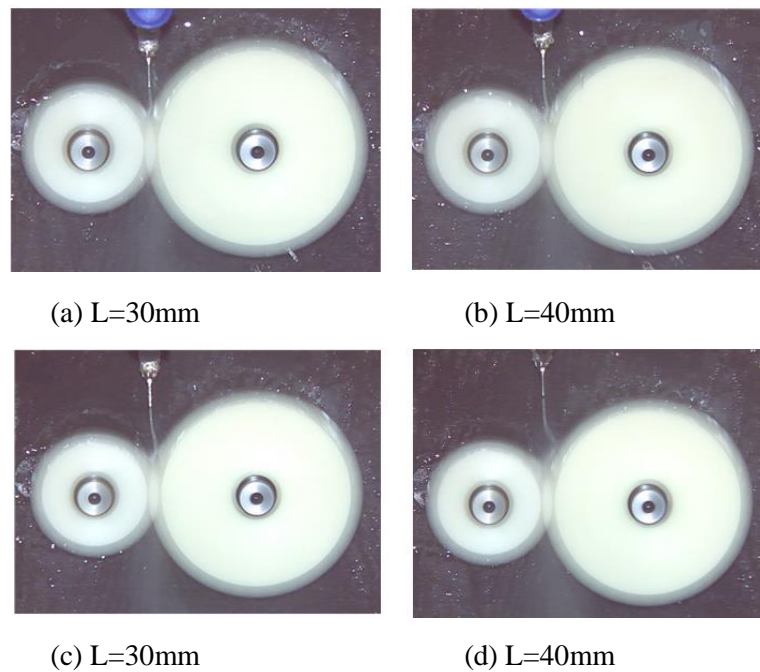
(a) L=30mm   (b) L=40mm

(c) L=30mm   (d) L=40mm

Fig.3 Jet flow at different spray distance

3. Injection lubrication simulation technology

In order to verify the correctness of the numerical modeling of the gear jet lubrication, a three-dimensional model of a pair of gear and box is built with the same size as the experimental size. The mesh model is shown in Figure 4.
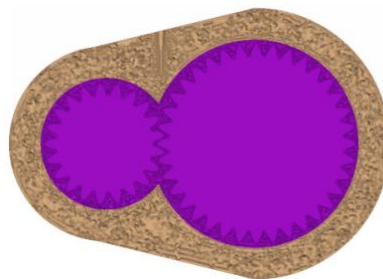

Fig.4 Three-dimensional numeric model

Because the nozzles are arranged on the engaging-in side, the movement of the jet on the this side is a focus of attention. In order to facilitate the observation and analysis, the motion trajectories of the fluid are locally enlarged and divided into three motion paths A, B, and C as shown in Fig. 5 . As we can see, the trajectory of the fluid in simulations and experiments agree well .
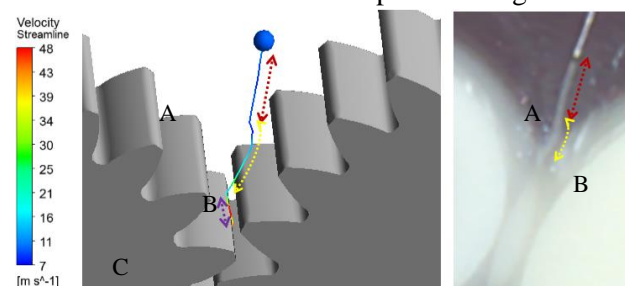

Fig.5 Comparison of the moving trail of jet flow between simulation and experiment

Path A: the liquid moves along a straight line. The path is relatively far from the gear, and the strength of the air is weak. The momentum of the liquid itself is big enough to overcome the influence of the airflow's effect.

Path B: The motion trajectory of the liquid appears to be deflected. The path now is much closer to the gear and in the region where the airflow driven by the bull gear and pinion gear intensely interact with each other. The limited momentum of the liquid is insufficient to overcome the resistant effect of the airflow. At the same time, the airflow driven by the pinion has greater strength than the one driven by the bull gear, which eventually causes the liquid to deflect toward the large gear side;

Path C: The liquid reaches the gear tooth surface for lubrication. The condition of the gear lubrication and the heat dissipation performance mainly depend on the amount of liquid that reaches this region.

4. Numerical simulation of jet lubrication for complex gear box

Taking a high-speed gear transmission system as the research object, a three-dimensional model was established. The model mainly includes the box and its five pairs of meshing gears on the 01 to 06 axis, and nozzles name A, B, D, E, and G. Five nozzles lubricate the 01-02, 02-03, 03-04, 04-05, and 01-06 gears in turn. The gear speed of the 05-axis gear is the highest, which is 27045r/min; the gear speed of the 03 and 06 gear is the lowest, which is 9280r/min. The rotation direction and nozzle distribution are shown in Fig. 6.
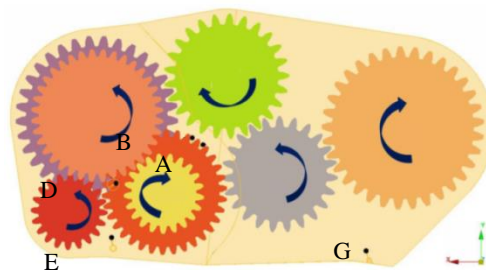

Fig.6 Rotational directions of the gears and distribution of the nozzles in a high-speed gear transmission system

The verified numerical simulation method mentioned has been applied to the simulation of the complex gear box model. The simulation calculation domain is a gas-liquid two-phase fluid domain in a complex gear box. The nozzle orientation information is as follow:

1) Injection distance: Nozzle G has the largest injection distance about 90mm, and the other nozzles have a injection distance of 31~53mm.

2) End face angle: Nozzle D has the largest end face angle about 50 degrees. Nozzle E has the end face angle about 48 degrees, and the end face angle of other nozzles are about 20 degrees.

3) Injection angle: The injection angle of nozzles are between 1 degrees ~9 degrees, nozzle D has the largest injection angle.

4) Nozzle arrangement: Nozzle A is arranged on the engaging-out side, other nozzles are arranged on the engaging-in side.

Three typical nozzles A, D and G are analyzed respectively (nozzle A is located on the engaging-out side, nozzle D has the largest end face angle and nozzle G has the largest injection distance). The oil flow velocity streamline of the three nozzles is shown in Figure 7, respectively. The red solid arrow is the axis of the nozzle, that is, the theoretical injection direction of the nozzles.
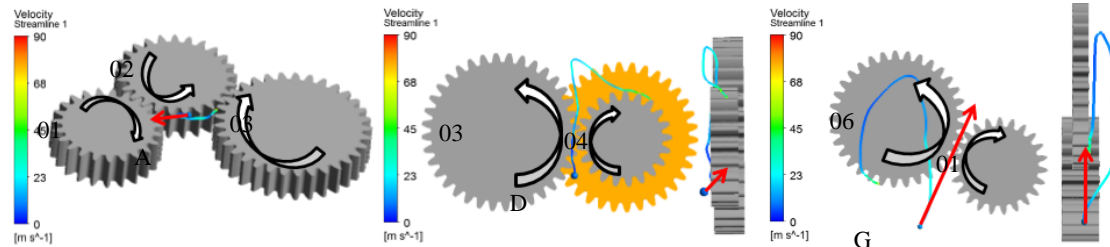

Fig.7 Velocity streamline of oil starting from nozzle A、D and G

As can be seen from the figure, none of the streamlines has entered the corresponding meshing zone along the theoretical injection direction. The theoretical injection direction of nozzle A is directing to the 01-02 gear meshing area, but its oil is brought into the 02-03 gear meshing area under the reversed action of the airflow driven by the gear0q and 02 gear. The oil velocity streamline ejected from nozzle D is initially biased toward the 03 gear, moving above the meshing area of the 03-04 gear, and finally moving with the direction of the 04 gear under the combined influence of the 04-shaft twin gear. The fluid velocity streamline ejected from the nozzle G is deflected directly towards the gear06.

Combining the information of each nozzle, the reasons are as follows:

1) Injection angle: Excessive injection distance will increase the difficulty of lubricating oil entering the meshing zone, especially for nozzle G. The actual design value should not be too large (this conclusion is consistent with the experimental conclusion)

2) End face angle: Nozzle A, B, D and E all have a certain end angle, D and E have end face angles much larger than the rest. The angle of end face will increase the difficulty of lubricating oil entering the meshing area.

3) The nozzle position relative to the gear rotational speed: The nozzle A is arranged on the engaging-in side and the lubricating oil flows backwards and cannot enter the meshing area directly.

5. Study on nozzle injection angle

According to previous studies, the injection angle has a great influence on the amount of the oil that can actually enter the gear meshing zone [16], which directly affects the lubrication condition of the gear. So what is the certain value of the injection angle to get the best fuel injection effect?

Taking the 03-04 gear as an example, in order to arrange the nozzle properly and make the gear lubrication best, we need to know the airflow distribution in the box first. At the same time, the presence of the end face angle of the nozzle will make the oil hard to get into the meshing zone, so the angle of the end face is set to 0 degrees. In addition, in order to explore the influence of the physical structure of the nozzle on the calculation results, three models were created. One has no nozzle body; one has a 0 injection angle, and the last one has a injection angle that is 10°. The model is shown in Figure 8.
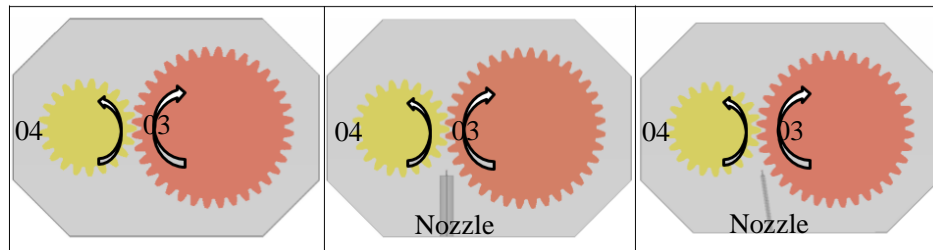
(a) No nozzle   (b) Injection angle = 0°   (c) Injection angle = 10°

Fig.8 Geometric model with no nozzle entity and different spray angles

The air velocity vector distribution diagram in the center plane is shown in Figure 9. It is found that there is a trace with the weakest air motion on the gear engaging-in side. Points A and B in the figure are located on the trace. Through data collection, it is found that the location of the trace in the three models basically coincides, which indicates that the solid structure of the nozzle does not affect the location of the AB trace. Based on this, it is inferred that if the oil is injected into the meshing area along the direction of the AB track, the impact of the airflow on the motion of the oil will be minimum, and the gear has the best lubrication condition

(a)
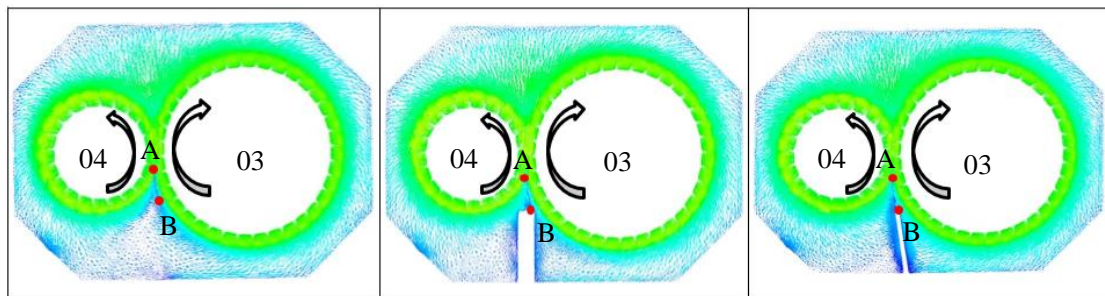
No nozzle   (b) Injection angle = 0°   (c) Injection angle = 10°

Fig.9 Velocity vector of airflow in the center plane of meshed gears under the circumstance of no

nozzle entity and different injection angles

In order to verify the above conjecture, the nozzles of three pairs of meshing gears are arranged as follows: (1) the nozzle axis is arranged along the direction of AB trace.(2) the nozzle injection angle is set to 0° .(3)the nozzle injection angle is set to 5° . The oil volume fraction distribution on the gear surface is shown in Fig10-11.

The oil volume fraction on the tooth surface is used to evaluate the lubrication of gears. The oil volume fraction is defined as the volume of the oil in unit grid space. So the oil volume fraction on the tooth surface can reflect the amount of oil in the gear meshing position, which also reflects the gears meshing area lubrication condition.

The left part of the Fig 10 shows the oil volume fraction distribution on the gear surface, the right part shows the velocity streamline of the ejected oil. Under this condition, the oil can be directly injected into the mesh area after leaving the nozzle. At the same time, comparing figure 10 and figure 11, it is found that when the nozzle axis is arranged along the trace, the distribution of oil volume fraction on the tooth surface in the meshing area is obviously superior to those of the other two, and the gear lubrication of it is the best, which proves the correctness of the above conjecture. This single phase flow method can be extended to obtain the optimal location of the nozzle for any spur gear pair.
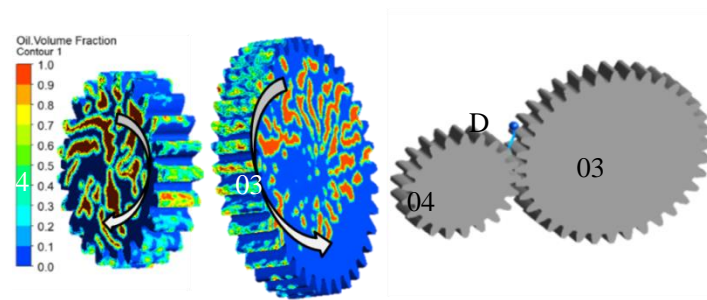
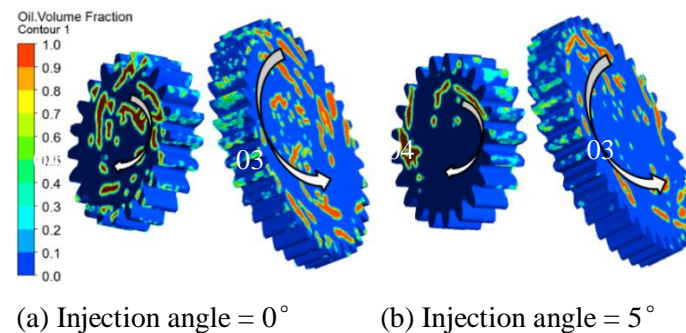Fig.10 Axis of the nozzle is in the direction where the motion of air is weakest

(a) Injection angle = 0˚   (b) Injection angle = 5˚

Fig.11 Axis of the nozzle is in the direction where the motion of air is not weakest

6. Conclusion

In this paper, the influence of nozzle injection distance on the motion of oil jet is obtained through high-speed gear jet lubrication experiment, and the experimental results verify the correctness of the numerical simulation model of high-speed gear under jet lubrication.

In a pair of meshing gears, the wind resistance effect caused by pinion gear is stronger than that caused by big gear, which results in that the oil trajectory tends to deflect to the side of big gear when the nozzle is arranged at the engaging-in side, the injection angle and the end angle are all 0 degrees, and the deflection degree increases with the increase of injection distance.

The excessive injection distance directly reduces the amount of oil in the meshing area, so the value should not be too large. The existence of the end angle will increase the difficulty of oil entering the meshing area, so it should be as small as possible or even 0 in design.

When the nozzle is located at the engaging-out side, most of the oil is affected by the cross wind resistance effect, and can not enter the meshing area because of the direct reverse flow. Therefore, in practical application, as far as possible, avoid the oil supply on the gear's engaging-out side.

In addition, this paper explores the optimum injection angle by solving single-phase flow, and obtains the optimum layout orientation of the nozzle in the central plane.

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