Influence of injection angle on oil splash of herringbone gear

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Abstract. Oil injection lubrication is a common lubrication method for aviation gear transmission. Due to the high-speed rotation of the gear, a part of the lubricating oil splashes off the gear surface after colliding with the gear surface. The amount of oil splashing under the oil injection condition affects the cooling effect of gear lubrication. In this paper, according to the characteristics of aviation herringbone gear injection lubrication, an oil splash calculation model of aviation herringbone gear injection lubrication is established by using advanced computational fluid dynamics theory and method, and the influence of different injection angles on oil splash is analyzed, which can provide theoretical guidance for the design of injection lubrication parameters.

1. Introduction
Oil injection lubrication is a common lubrication method for high-speed transmission parts, such as aviation gear lubrication [1-3]. In the work of aviation gear, the lubricating oil is injectioned to the tooth surface in the form of liquid column. Due to the high-speed rotation of the gear, the tooth surface collides with the oil jet, part of the lubricating oil is dispersed into a large number of oil droplets by the rotating gear, and the oil mist is formed in the surrounding environment. In the meshing position where the oil supply of the gear is insufficient and the jet cannot flow, the lubrication mainly depends on the oil mist generated in the environment [4-6]. A part of the lubricating oil splashes off the tooth surface after colliding with the tooth surface, forming a splash jet to lubricate and cool other rotating parts of the system [7]; other lubricating oil is adsorbed on the tooth surface to lubricate and cool the gear. It can be concluded that the adhesion amount and splash amount of lubricating oil affect the cooling effect of gear lubrication. However, in the design and analysis of the traditional lubrication system, little attention is paid to the splash and adhesion of the oil injection parameters. The design of the oil injection lubrication parameters is mainly based on experience, and the effect of the oil injection lubrication is not good. Therefore, it is urgent to study the influence of jet lubrication parameters on adhesion and splash to meet the design requirements of aviation gear high efficiency lubrication system.

In this paper, according to the lubrication characteristics of aviation herringbone gear, the calculation model of oil splash is established using the CFD method [8]. On this basis, the influence of different injection angles on oil splash is analyzed, which can provide theoretical guidance for the design of injection lubrication parameters, and provides a basis for the design and manufacture of injection lubrication system of modern high-performance aircraft and engine gear transmission system.
2. Mathematical model

2.1. CFD model

According to the geometric structure of herringbone gear and box, the fluid calculation domain model is established using Pro/E, as shown in Figure 1. Because the fluid domain of herringbone gear is symmetrical about the central plane, the fluid domain is symmetrically simplified. Then, the simplified computational domain model is imported into CFX and meshed by ICEM platform, as shown in Figure 2. The unstructured tetrahedral mesh is used for the mesh, and the total number of meshes after division reaches 5 million.

![Figure 1. Fluid calculation domain](image1)

![Figure 2. Grid discrete model](image2)

2.2. Governing equation

After the lubricating oil from the nozzle enters the air, it interacts with the air flow field produced by the rotation of the gear to form the two-phase flow of lubricating oil and air. Here, the VOF model of Euler multiphase flow is used to model the two-phase flow [9-12]. In order to ignore the unnecessary influence and simplify the model, it is assumed that there is no heat transfer behaviour and chemical reaction during the injection process. The governing equations of the model are as follows:

1. Volume conservation equation

\[ \sum_{\alpha=1}^{N} r_{\alpha} = 1 \]  

Where, \( \alpha \) is the fluid phase (lubricating oil in liquid phase and air in gas phase), \( r_{\alpha} \) is the volume fraction of \( \alpha \) phase, \( N \) is the number of phases [13], which is 2 in this paper.

2. Mass conservation equation

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \]  

Where, the density \( \rho \) is calculated by the following formula:

\[ \rho = \sum_{\alpha=1}^{N} r_{\alpha} \rho_{\alpha} \]  

Where, \( \rho_{\alpha} \) is the density of \( \alpha \) phase and \( U \) is the flow velocity.

3. Momentum conservation equation

\[ \frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U U) = -\nabla P + \nabla \cdot \tau + S_{M} \]  

Where, \( S_{M} \) is the external volume force, \( P \) is the fluid pressure, and \( \tau \) is the stress tensor.

\[ \tau = \mu \left( \nabla U + (\nabla U)^{T} - \frac{2}{3} \nabla \cdot U \right) \]

Where, \( \mu \) is the fluid viscosity.
2.3. Boundary condition

The fluid properties and boundary conditions are set in the pre-processing module CFX pre: the computational domain is two-phase fluid computational domain, in which the liquid phase is lubricating oil, the fluid properties of the lubricating oil are shown as Table 1, and the gas phase is air; The flow rate of No.1~4 nozzle is 0.5795 L/min, and the flow rate of No.5~8 nozzle is 5.2295 L/min; the tooth surface is set as the rotating wall, with the rotational speed of the driving gear tooth surface is \( n_1 = 7236 \, \text{r/min} \), and the rotational speed of the driven gear tooth surface is \( n_2 = 7765 \, \text{r/min} \); the surrounding and top surface of the box are set as the wall boundary, and the bottom surface of the box is set as the outlet boundary.

| Brand       | Mobile Jet Oil II |
|-------------|-------------------|
| Density (kg/m³) | 956              |
| Dynamic viscosity (mPa·s) | 10.06         |
| Specific heat capacity (J/kg/℃) | 2066            |
| Thermal conductivity (W/m/K) | 0.152           |

In the CFX software platform, the momentum equation is discretized by the high-order difference scheme, and the turbulence equation is discretized by the first-order difference scheme. Then the PISO (pressure implicit split operator) algorithm is used to solve the discrete algebraic equation. In order to ensure the calculation accuracy, the root mean square residual (RMS) is set as the convergence criterion, which is set as \( 1 \times 10^{-5} \). The step time is set as \( 1 \times 10^{-5} \, \text{s} \), and the maximum iteration step is set as 1000.

3. Parameter definition and model calculation

3.1. Definition of injection angle

Under the condition of herringbone gear injection lubrication, the injection angle is divided into axial injection angle \( \alpha \) and end injection angle \( \beta \), as shown in Figure 3. Subscript 1 indicates the “into mesh” side, subscript 2 indicates the “out of mesh” side, and the angles in the figure below are all positive.

3.2. Calculation of the model

The calculation model with the initial oil injection angle parameters \( (\alpha_1 = 0^\circ, \alpha_2 = 0^\circ, \beta_1 = 0^\circ, \beta_2 = 0^\circ) \) is established. Run the CFX solver to calculate until the calculation converges and completes, then use the post-processing software CFX post to obtain the calculation results (Figure 4). In order to measure the degree of oil splash in the process of injection lubrication, two reference planes are made in the calculation domain, as shown in Figure 5. The oil quantity in the reference plane is used as the
characterization parameter of the degree of jet splash. In the next section, the oil splash at different
injection angles will be discussed in detail.

Figure 4. Schematic diagram of lubricating oil splash at initial injection angle

Figure 5. Schematic of the reference plane

4. Results and discussion

4.1. Effect of injection angle $\alpha$ on oil splash
In order to study the influence of injection angle $\alpha_1$ on oil splash, the calculation models with injection
angle $\alpha_1$ of -10°, 0°, 5° and 10° were established respectively. In the case of keeping other parameters
and boundary conditions unchanged, a series of calculations are carried out on the injection lubrication
model, and the influence law of the injection angle $\alpha_1$ on the meshing process can be obtained. After
the model is solved, the oil flow through reference plane 1 is obtained, and the influence of different $\alpha_1$
on the oil splash degree is quantitatively compared. The variation law is shown as Figure 6. It can be
seen from the figure that the axial angle $\alpha_1$ deviates to the driven wheel, which makes the splash
intensity of the oil weaken. The deflection of the axial angle $\alpha_1$ to the driving wheel is unfavorable to
reduce the splash intensity of the oil. Similarly, the oil flow through reference plane 2 is obtained,
and the influence of different $\alpha_2$ on the oil splash degree is quantitatively compared, as shown in
Figure 7. It can be seen from the figure that when the reverse nozzle does not deviate, the splash
intensity of oil is the weakest, and the deviation of the nozzle to any side will increase the splash
intensity of the oil. In contrast, when the nozzle deviates to the driving wheel, the splash intensity of
the oil is more obvious.

Figure 6. Oil splash under different $\alpha_1$

Figure 7. Oil splash under different $\alpha_2$
4.2. Effect of injection angle $\beta$ on oil splash
In order to study the influence of injection angle $\beta_1$ on oil splash, the calculation models with injection angle $\beta_1$ of -10°, 0° and 10° were established respectively. In the case of keeping other parameters and boundary conditions unchanged, a series of calculations are carried out on the injection lubrication model, and the influence law of the injection angle $\beta_1$ on the meshing process can be obtained. After the model is solved, the oil flow through reference plane 1 is obtained, and the influence of different $\beta_1$ on the oil splash degree is quantitatively compared. The variation law is shown as Figure 8. It can be seen from the figure that the outward deflection of the end angle $\beta_1$ makes the oil splash weaken. The reason for this trend is that when the nozzle deflects to the outside, the injection direction of the lubricating oil is consistent with the spiral angle of the gear teeth, the relative velocity between the oil and the tooth surface is relatively small, which weakens the impact strength of the oil and the tooth surface. Similarly, the oil flow through reference plane 2 is obtained, and the influence of different $\beta_2$ on the oil splash degree is quantitatively compared. The variation law is shown as Figure 9. It can be seen from the figure that the reverse end angle $\beta_2$ has little effect on the oil splash. This is because the change of $\beta_2$ has little effect on changing the relative velocity between the oil and the tooth surface.

5. Conclusion
In this paper, the oil splash calculation model of oil injection lubrication for high-speed herringbone gear is established. The process of oil splash is deeply analyzed, and the relationship between oil splash and injection angle is established, which provides a theoretical basis for the optimization design of injection lubrication parameters. Through the research of this paper, the following useful conclusions are obtained.

1. When the axial injection angle $\alpha_1$ is deflected to the driven gear, the oil splash can be reduced.
2. When the axial injection angle $\alpha_2$ is the initial value ($\alpha_2=0$), the degree of oil splash is the least.
3. Outward deflection of the injection angle $\beta_1$ makes the oil splash weaken.
4. Injection angle $\beta_2$ has little effect on the oil splash.

Acknowledgment
This research was supported by a National Natural Science Foundation of China (Grant number: U1937603) and a National Key Research and Development Program of China (No. 2019YFB2004400).

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