The research of oil film thickness on the gear tooth surface: A review

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ABSTRACT

Increasingly demanding performance standards and operating requirements are driving the growing interest on the influence of gear oil film on reliability under the conditions of high speed and heavy load. The fatigue life of gears can be increased by optimizing the oil film thickness on the gear tooth surface. The oil film thickness can reflect the ability of the gear to resist pitting and gluing failure. Many theories and experiments are devoted to the study of the oil film thickness. The improvement of gear manufacturing accuracy also makes the influence of tooth surface roughness on oil film thickness not negligible. In order to compile and categorize key investigations in an expansive field with substantial recent research, this work reviews oil film thickness with focus on numerical calculation methods, influence of gear surface roughness on oil film thickness and fatigue life analysis based on oil film thickness.

1. INTRODUCTION

Gear transmission can be used to transmit motion between any two axes in space. It is widely used in industrial production because of the advantages such as precise transmission ratio, smooth transmission and long service life. With the development of modern machinery, the efficiency and reliability of gear transmission are more and more demanding. Gear lubrication can effectively improve the efficiency and reliability, so it has received great attention from engineers and technicians. In the gear transmission process, power loss mainly comes from gear meshing friction power loss, lubricating oil splash loss and wind resistance loss. The oil film thickness on the gear tooth surface reflects the distribution and size of the power lost by the lubricant splash. Therefore, studying the simulation of the oil film thickness is beneficial to improve the gear transmission efficiency [1, 2]. Fatigue analysis becomes the focus of gear research as the environment of gear transmission becomes harsh. Most of the gear failures are surface failures, such as pitting and gluing, as shown in Figure 1 [3, 4]. Related theories and experiments show that the gear is prone to pitting and gluing failure when the lubricating film is too thin. The value of oil film thickness on the gear tooth surface reflects the ability of gear to resist pitting and gluing failure [5]. It can be seen that the study of oil film thickness on the gear tooth surface has great theoretical research and engineering application value [6, 7].

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Figure 1: Gear pitting and gluing damages [3, 4]

There are many research achievements in the method and application of the oil film thickness on the gear tooth surface. The present work reviews relevant studies and experimental investigations, on the numerical calculation methods of oil film thickness on the gear tooth surface, influence of gear surface roughness on oil film thickness, fatigue failure analysis of gear based on oil film thickness, especially under high speed and heavy load conditions, aiming to provide more inclusive references for gear research.

2. NUMERICAL CALCULATION METHODS OF OIL FILM THICKNESS ON GEAR TOOTH SURFACE
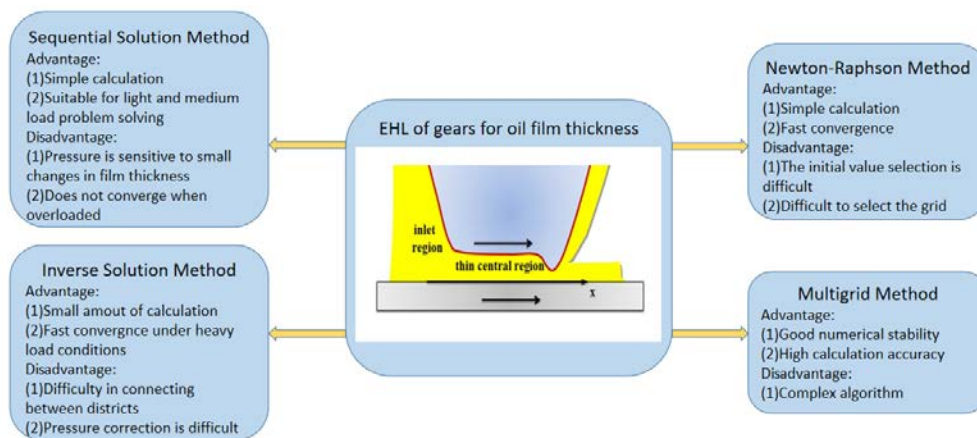

Figure 2: Comparison of four solutions for EHL

The gear lubrication theory developed from the early hydrodynamic lubrication to the present elastohydrodynamic lubrication (EHL). The numerical simulation of oil film thickness is based on the theory of gear EHL. EHL theory includes Hertz elastic contact theory and Reynolds fluid lubrication theory. Deeply considering the influence of time-varying effect, thermal effect, surface topography effect and lubricant rheological properties on the shape and thickness of oil film, new branches are formed—unsteady EHL, thermal EHL, micro EHL and non-Newton EHL [8].

Numerical solution methods for EHL of gears mainly include sequential solution method, inverse solution method, Newton-Raphson method and multigrid method. The comparison of four solutions for EHL is shown in Figure 2.

The sequential solution method is as follows: use the Reynolds equation to iteratively solve for the oil film thickness until it converges under the requirement of accuracy. Stephenson [9] solved the EHL problem numerically based on the sequential solution method and the low relaxation algorithm and improved the convergence speed of the algorithm. Kim [10] considered the influence of thermal effect on gear lubrication performance and numerically solved the gear thermal EHL. The research results show that under high speed conditions, the heat of engagement friction has a great influence on the change of lubricating oil parameters, and the thermal effect will reduce the lubricating oil film thickness by more than 10%.

The inverse solution method is as follows: the oil film thickness is corrected by comparing the numerical difference obtained by the elastic equation and the Reynolds equation, and repeated iterations meet the accuracy requirements. Based on the inverse solution method, Dowson and Higginson [11] solved the EHL equation of gear line contact, analyzed the influence of material parameters, velocity and load on oil film thickness, and gave the D-H minimum film thickness formula. However, the influence of variable load, extrusion and sliding on oil film thickness is not considered in the meshing process, and the inverse solution method is not suitable for solving under light load conditions.

The Newton-Raphson method is as follows: The Reynolds equation is discretized by difference method or finite element method, and then the oil film thickness is solved iteratively. Based on the Newton-Raphson method, Rohde [12] used a third-order spline basis function to numerically solve the gear contact EHL under different load conditions. The results show that this method is not suitable for solving heavy load conditions. Hughes [13] used the fully coupled finite element method to calculate the EHL film thickness. The convergence and calculation accuracy of the algorithm were improved.

The multigrid method is as follows: iterate the discretized equations in dense grids and sparse grids, so that the high-frequency and low-frequency deviation components can be quickly eliminated, thereby reducing the calculation work on a large scale under the condition of ensuring accuracy. Figure 3 shows the principle of multigrid method. Larsson [14] numerically solved the transient EHL of gears under Newtonian and non-Newtonian fluids based on the multigrid method. Ouyang [15] adopted an iterative algorithm that integrated Runge-Kutta and multigrid methods to solve the axial velocity finite line contact EHL model to study the effect of axial velocity on lubrication performance. Barbieri [16] studied the influence of the dynamic load on the oil film thickness and oil film pressure during gear meshing based on the multigrid method. The research results show that the dynamics of the gear greatly changes the pressure and film thickness. The maximum and minimum oil film thickness in the gear meshing area are respectively related to the maximum and minimum values of the dynamic contact force.
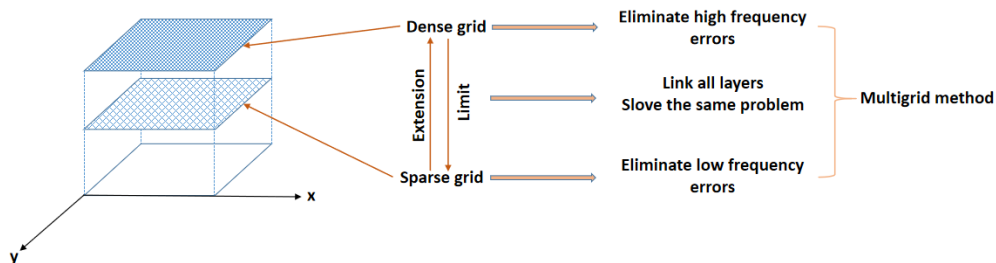
Figure 3: Principle of multigrid method

Among the above four oil film thickness solving methods, the sequential solution method, the inverse solution method and the Newton-Raphson method have greater limitations in the solution of the working conditions and the convergence speed. The multigrid method becomes the mainstream algorithm for solving the oil film thickness on the gear tooth surface due to its good numerical stability, fast convergence speed, high calculation accuracy, and comprehensive application conditions.

3. INFLUENCE OF GEAR SURFACE ROUGHNESS ON OIL FILM THICKNESS

When EHL of gears is used to solve the oil film thickness, the tooth surface is often set to a smooth surface, ignoring the roughness of the tooth surface. However, with the improvement of gear manufacturing accuracy, gear roughness and oil film thickness are in the same order of magnitude. Considering the effect of roughness on gear lubrication performance, more accurate oil film thickness distribution can be obtained, which can be used to guide precise modeling design and dynamic performance analysis of gear.

Akbarzadeh and Khonsari [17] established a thermal EHL model of spur gear with surface roughness considered based on the theory of load sharing. The study shows that the gear is easy to wear at the meshing area where the oil film is thinner. Han [18] considered the EHL problem of helical gear surface morphology and solved the change of oil film thickness and friction coefficient by using Moes formula and Johnson roughness sharing theory. Ren [19] launched research on line contact EHL. The results show that the thickness of the transverse sinusoidal rough surface is larger than that of the longitudinal sinusoidal rough surface. And with the increase of roughness, the directional effect is more and more significant. Considering the surface morphology and fluid compressibility, Bobach [20] established a transient thermal EHL model of spur gear, and obtained the minimum oil film thickness and friction coefficient of tooth surface. Figure 4 considers the surface morphology of the gear tooth and compares the minimum oil film thickness of smooth and rough tooth surface. The results show that smooth tooth surface can significantly reduce the oil film thickness on the gear tooth surface. Snidle and Evans [21] studied the multi-scale texture effect of gear surface by establishing a pressure deformation coupled lubrication model. The research shows that gear modification can improve oil film forming ability effectively. Choo, Olver and Spikes [22] studied the influence of gear tooth surface morphology on oil film thickness based on 3D Slim film thickness measurement technology.
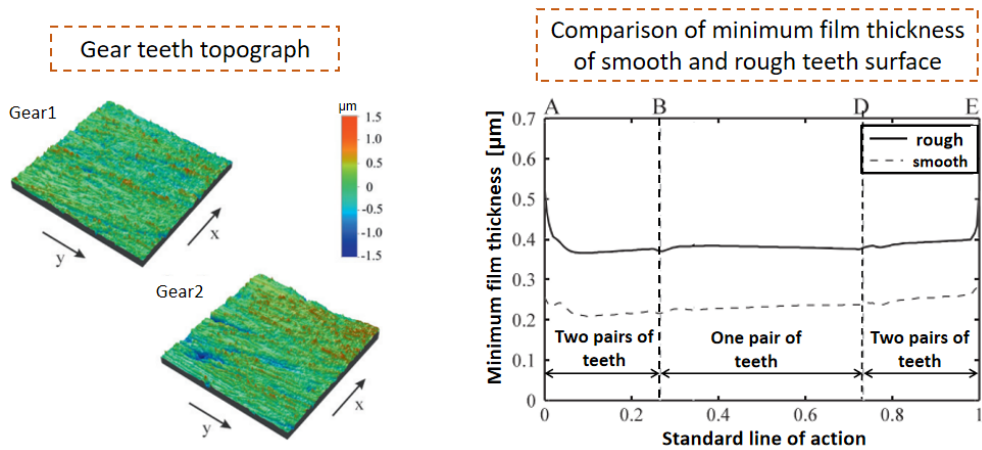
Figure 4: Surface morphology of gear tooth and comparison of minimum film thickness of smooth and rough tooth surface [20]

4. FATIGUE FAILURE ANALYSIS OF GEAR BASED ON OIL FILM THICKNESS

Pitting and gluing are the main failure forms of gear transmission system under the conditions of high speed and heavy load. The related research shows that the fatigue life of gear can be effectively increased by improving gear lubrication performance. The thickness of oil film reflects the pitting and gluing damages of tooth surface to a certain extent. Figure 5 shows the calculation process of gear contact fatigue life based on oil film thickness.

The pitting of the tooth surface is represented by small pits formed by fatigue peeling of the surface material of the tooth surface under load. Epstein [23] solved the contact fatigue model of circular loading under mixed EHL according to the subsurface stress. The results show that the roughness of gear surface has an important effect on pitting damage. Onions and Archard [24] concluded that the ratio of tooth surface roughness to oil film thickness had a key impact on the fatigue life of gears according to the results of fatigue pitting experiment. The gear disc experiment would make the fatigue life higher due to the failure to consider the dynamic effects of gear meshing. Webster and Norbart [25] found through the disk experiment that heavy load, reduced oil film thickness and increased slip ratio would increase the probability of gear pitting damage, and pointed out that the reduction of the slip ratio to a certain extent would eliminate pitting failure. Cardoso and Martins [26] studied the effect of lubricant type on fatigue pitting life through FZG testing machine. The results show that the pitting corrosion resistance of ester lubricants is stronger than that of mineral oils. Ester lubricants can effectively reduce pitting corrosion growth and crack formation, as well as crack depth. Fajdiga [27] considered the residual stress generated by internal lubrication and heat treatment of the gear crack and simulated the fatigue crack propagation based on the virtual crack extension method.

The gluing of the tooth surface is represented by the shear failure of the metal of the tooth surface. The gluing is divided into hot gluing and cold gluing. Hot gluing is often seen in gears under high speed and heavy load. Cold gluing is often seen in gears under low speed and heavy load. Thakre [28] studied the anti-gluing properties of non-extreme pressure lubricants with different viscosities through disc experiments, and found that high viscosity lubricants can significantly increase the critical load of gear gluing. Imrek [29] studied the influence of gear geometry and lubricating oil parameters on the gluing load capacity of the gear transmission system under low speed and light load conditions. The results show that the reasonable selection of lubricating oil can prevent the failure and improve the fatigue life of gear. Li and Kahraman [30] proposed the solution of contact fatigue of gear under point-contact hybrid EHL and verified it with the experimental results.
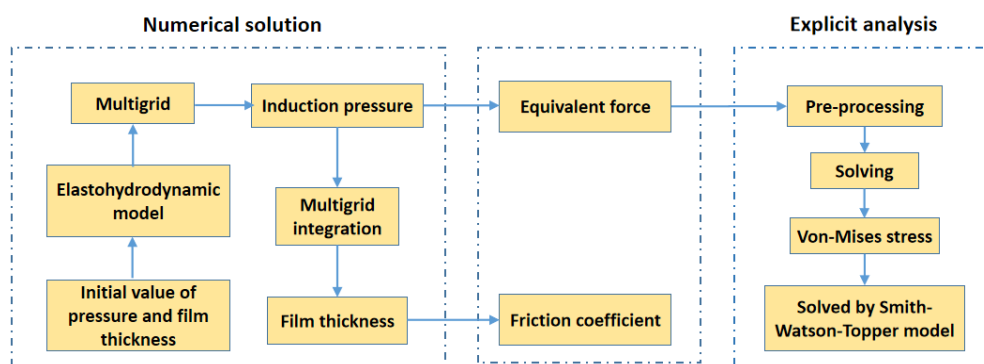

Figure 5: Calculation process of gear contact fatigue life

5. CONCLUSIONS

In this work, theoretical and experimental conclusions are made from three aspects: the numerical calculation methods of the oil film thickness on the gear tooth surface, the influence of the tooth surface roughness on the oil film thickness, and the analysis of gear fatigue failure based on the oil film thickness. The main conclusions can be summarized as follows:

(1) Among the four methods for solving oil film thickness, the multigrid method has become the main numerical algorithm for EHL due to its advantages such as good numerical stability, fast convergence speed, high calculation accuracy and comprehensive adaptability to working conditions.

(2) Smooth tooth surface can significantly reduce the oil film thickness on gear tooth surface. Gear modification can improve oil film forming ability. The oil film thickness of transverse sinusoidal rough surface of gear is larger than that of longitudinal sinusoidal rough surface. In addition, as the roughness increases, the directional effect increases.

(3) The thickness of oil film on the gear tooth surface reflects the resistance to pitting corrosion and gluing failure of gear to a certain extent. The reduction of oil film thickness will increase the failure probability of gear. Lubricant parameters can affect the oil film thickness of gear. Reasonable choice of lubricant can improve the fatigue life of gear.

According to the above research, studying the lubricating performance of gears can help improve the reliability of the gear system. As the gear transmission system is more widely used under bad working conditions such as high speed and heavy load, the solution of the oil film thickness on the gear tooth surface becomes very complicated because the chemical composition of lubricants may change at high temperatures caused by the gear meshing. In future research, the thickness of the oil film on the gear tooth surface is a numerical calculation problem under the multi-factor and multi-disciplinary coupling mechanism.

ACKNOWLEDGEMENTS

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