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ANALYSIS OF FRICTION AND WEAR PROCESSES IN GEAR TRANSMISSIONS BASED ON LUBRICATION THEORY

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Abstract

This paper investigates the mechanisms responsible for the formation of micro-pitting and scuffing in gear transmissions, as well as their influence on lubrication processes. Friction and temperature rise generated during gear operation lead to a reduction in lubricant film thickness, resulting in localized damage on contacting surfaces. In this study, gear tooth surfaces affected by micro-pitting are treated as topographic surfaces, and the motion of a thin lubricant film over these surfaces is mathematically modeled. The modeling approach is based on the lubrication approximation of the Navier–Stokes equations for an incompressible Newtonian fluid. In addition, the hydrodynamic behavior of a thin liquid film flowing over topographic irregularities on an inclined surface is analyzed. The obtained results provide a scientific basis for improving lubrication performance, reducing friction and wear, and enhancing the reliability and service life of gear transmissions used in electric vehicles, wind turbines, and other mechanical systems.

Annotatsiya.

Mazkur maqolada tishli uzatmalarda yuzaga keladigan mikro o'yiqlar va tirnalib yeyilish hodisalarining paydo bo'lish mexanizmlari hamda ularning moylash jarayonlariga ta'siri o'rganilgan. Tishli g'ildiraklarning ish jarayonida hosil bo'ladigan ishqalanish va haroratning ortishi moy plyonkasi qalinligining kamayishiga olib keladi, natijada kontakt yuzalarida lokal shikastlanishlar yuzaga keladi. Tadqiqotda mikro-o'yiqlarni tish yuzalari topografik sirt sifatida qaralib, ular ustidagi yupqa moy plyonkasining harakati matematik modellashtirilgan. Modellashtirish jarayonida siqilmaydigan Nyuton suyuqligi uchun Navye–Stoks tenglamalarining moylash nazariyasiga asoslangan yaqinlashuvi qo'llanilgan. Shuningdek, qiya tekislikdagi topografik notekisliklar ustidan oqayotgan yupqa suyuqlik qatlamining gidrodinamik xususiyatlari tahlil qilingan. Olingan natijalar tishli uzatmalarda moylash samaradorligini oshirish, ishqalanish va yeyilishni kamaytirish hamda elektromobillar, shamol turbinalari va boshqa mexanik tizimlarda qo'llaniladigan tishli uzatmalarning ishonchliligi va xizmat muddatini oshirish uchun ilmiy asos yaratadi.

Keywords: gear transmission, micro-pitting, scuffing, tribology, lubrication theory, thin lubricant film, Navier–Stokes equations, friction, wear, topographic surface.

Kalit so'zlar: tishli uzatma, mikro-o'yiq , tirnalib yeyilish, tribologiya, moylash nazariyasi, yupqa moy plyonkasi, Navye–Stoks tenglamalari, ishqalanish, yeyilish, topografik sirt.

INTRODUCTION

Gears are among the most important mechanical components used to transmit rotational motion from one shaft to another parallel shaft. The optimal configuration and efficiency of a gear transmission significantly influence the overall performance and reliability of a mechanical system. Depending on the application requirements, gears are specifically selected according to operating speed, load-carrying capacity, strength, durability, and other design criteria. Consequently, various gear types have been developed to satisfy different engineering requirements.

Spur gears are among the most widely used types of gear transmissions and are characterized by a cylindrical pitch surface. They offer high manufacturing accuracy and relatively simple production processes. However, when operating at high rotational speeds, spur gears tend to generate significant noise and vibration, which may limit their application in high-speed mechanical systems.

Gear transmissions play a crucial role in power transfer and motion control in modern engineering systems. Their operational performance is strongly affected by friction, wear, and lubrication conditions. Insufficient lubrication can lead to severe surface damage, reduced efficiency, increased maintenance costs, and premature failure of transmission components. Therefore, understanding the tribological behavior of gear tooth contacts is essential for improving system reliability and durability.

Micro-pitting is one of the most significant failure mechanisms occurring in gear tooth contacts. It is characterized by the formation of microscopic pits on the tooth surface due to repeated contact stresses and inadequate lubrication conditions. Over time, micro-pitting develops progressively and may result in substantial surface degradation, increased noise levels, reduced transmission efficiency, and eventual mechanical failure. Consequently, the investigation of micro-pitting and related tribological phenomena has become an important research area in gear engineering and lubrication science.

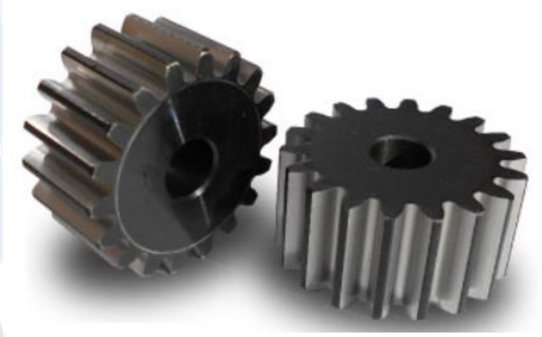

Figure 1. Spur gears

Spur gears are among the most widely used types of gear transmissions and are characterized by a cylindrical pitch surface. These gears provide high manufacturing accuracy while maintaining a relatively simple production process. However, when operating at high rotational speeds, spur gears tend to generate higher noise levels, which limits their application in high-speed mechanical systems [1].

Spur gears are generally classified into two categories: external gears and internal gears. External gears rotate in opposite directions when meshing with each other, whereas internal gears rotate in the same direction during operation**.**

Figure 2. Helical gears

Helical gears offer several advantages over spur gears, including improved tooth engagement and lower noise generation at high operating speeds. In helical gear systems, multiple teeth are engaged simultaneously, which reduces the load acting on individual teeth and enables a smoother transfer of forces from one tooth to another.

As a result, vibration levels, impact loads, and wear rates are significantly reduced. However, because helical gears are designed to withstand substantial axial forces, their manufacturing process is more complex and their production cost is generally higher than that of spur gears.

Lubricants can generally be classified into two main categories: liquid lubricants and gaseous lubricants. These substances are used in mechanical systems to reduce friction and wear, thereby improving system efficiency and extending service life. More than 10,000 different types of lubricants are available worldwide, among which liquid lubricants are the most widely used and extensively studied. Liquid lubricants include both synthetic oils and petroleum-based oils.

Different mechanical systems require different lubricant materials depending on their operating conditions and performance requirements. Selecting an appropriate lubricant requires a thorough understanding of tribology and lubrication theory. Although friction and wear cannot be completely eliminated in mechanical systems, they can be significantly reduced through the proper selection and application of lubricants.

Gears are among the most critical components of mechanical systems, playing a fundamental role in power transmission and rotational speed control. Micro-pitting is one of the primary causes of failure in geared systems and is recognized as a significant form of surface fatigue wear occurring on gear tooth surfaces. Micro-pitting develops gradually through the formation of microscopic pits on the tooth surface and may eventually lead to mechanical failure. Consequently, it can result in increased maintenance costs, reduced transmission efficiency, and elevated noise levels during operation.

Figure 3. Damage on gear teeth caused by insufficient lubrication

Gear system failures are influenced by several factors, including configuration, friction, temperature, insufficient lubrication, improper lubrication practices, and other operating conditions. Most failures are associated with inadequate lubrication, as lubrication plays a crucial role in temperature control, friction reduction, protection against surface wear, and corrosion prevention.

Scuffing occurs when the lubricant film thickness becomes significantly smaller than the surface roughness of the contacting gear teeth. Under such conditions, direct metal-to-metal contact takes place at or near the pitch point, which may eventually lead to severe surface damage and system failure. Furthermore, scuffing contributes to increased noise generation and accelerated wear.

Gear tooth damage may also result from the ingress of foreign particles into the transmission system or from improper gear configuration. This type of damage is commonly observed in the addendum region of the tooth and can be minimized by operating the transmission within a properly sealed environment [2].

Gear wear is defined as the gradual removal of metallic material from the tooth surface during operation. It is primarily caused by friction and leads to changes in tooth thickness and geometry. The severity of this problem can be significantly reduced through appropriate lubrication practices.

Friction generated during gear meshing leads to an increase in operating temperature. As the temperature rises, the viscosity of the gear lubricant decreases, resulting in a reduction in lubricant film thickness and a deterioration of lubrication performance.

The starting point for modeling thin-film flow is the Navier–Stokes equations. In the present study, the lubrication approximation of the Navier–Stokes equations, also referred to as the reduced Reynolds number approximation, is employed to analyze the behavior of the lubricant film and its influence on gear tribological performance.

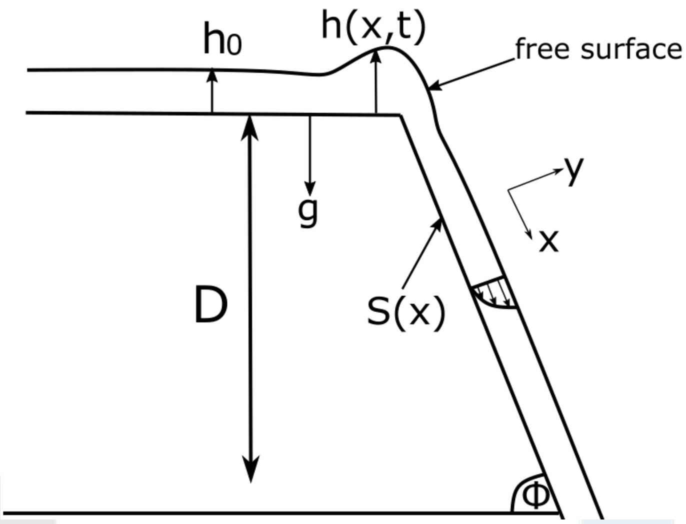

Figure 4. Schematic representation of fluid flow along a gear tooth surface modeled as a topographic step-down on an inclined plane at an angle φ.

The fluid flows from left to right with a characteristic velocity ***U*** and an initial film thickness h_0 in regions far from the topographic irregularity. The surface feature is represented by a topographic step-down profile on the inclined plane, which is described by the following function:

$$S(x) = D\left[\frac{1}{2} - \frac{1}{\pi}\arctan\left(\frac{x}{\delta}\right)\right]$$

where D is the depth of the irregularity and δ is the wall steepness. The origin of the orthogonal xy coordinate system is located at the step-down point [3].

If we derive the lubrication-film approximation for the problem illustrated in Figure 2, the thin film is assumed to be an incompressible Newtonian fluid with density p, dynamic viscosity μ, and kinematic viscosity $v= \mu/p$ [4].

The velocity vector is given by: $U(x,y,t)=(u,v)$

the pressure is: $P(x,y,t)$, the constant surface tension is: σ and the thin-film surface is expressed as: $y=h(x,t)$ in the Cartesian coordinate system.

The gravitational vector is: $g=(pg \sin \phi; pg \cos \phi)$

In general, when surface tension is incorporated into lubrication theory, the resulting equation becomes a fourth-order nonlinear parabolic equation, which takes the following form:

$$\frac{\partial h}{\partial x} + \frac{\partial}{\partial x}\left(C\frac{h^3}{3}\frac{\partial^3 h}{\partial x^3} + f(h, h_x, h_{xx})\right) \quad (2)$$

Non-dimensionalization of the Navier–Stokes Equations

The continuity equation and the Navier–Stokes equations are non-dimensionalized using the method presented above. The inclusion of surface tension requires the consideration of van der Waals forces, which are expressed as follows:

$$\vartheta = \vartheta_0 + \frac{\eta}{H^3}$$

where η is the Hamaker constant, which is given by:

$$\eta = \frac{\eta_0}{6\pi\varepsilon L^2\mu U}$$

As a result, the following leading-order terms of the Navier–Stokes equations are obtained:

$$\begin{cases} (p+\vartheta)_x = u_{yy} + B_0 \sin\phi, \\ (p+\vartheta)_y = -\epsilon B_0 \cos\phi. \end{cases} \tag{3}$$

For different parameter values, the fluid height near the topographic step-down increases with increasing step-down depth, while the wall steepness remains constant.

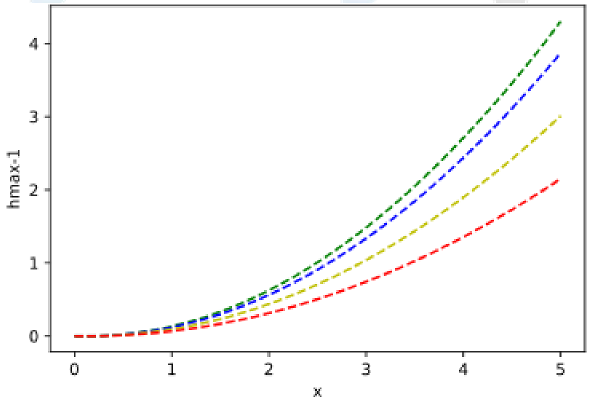

Figure 4. Variations in fluid height in the vicinity of the surface topography.

The numerical simulation of the steady-state solution shows that the fluid height changes significantly due to the influence of the surface near the topographic step-down, where

$$S(x) = D\left[\frac{1}{2} - \frac{1}{\pi}\arctan\left(\frac{x}{\delta}\right)\right]$$

Taking the external shear stress τ into account, the model can be generalized, and the velocity profile is given by:

$$U = \frac{\tau h}{2\mu}$$

The fluid height near the topographic step-down is expressed as follows,
and is determined by the depth D, the wall steepness δ and the non-dimensionalization constant $\epsilon = \frac{h_0}{L}$.
[5]

Conclusion

In this paper, we considered the problem of fluid flow over a topographic surface and applied it to gear tribology. The lubrication approximation, or Reynolds equation, was derived and a finite-difference scheme was employed.

It should be noted that the mathematical models consist of nonlinear differential equations, which are solved using the finite-difference method. This creates significant challenges in the implementation of numerical methods because of the highly complex nature of the governing equations.

The importance of thin-film equations can hardly be overstated, as they play a vital role in manufacturing, physics, and chemistry. In tribology, numerical computations have led to significant advances in solving governing equations, thereby contributing to the development of new and improved products.

It is hoped that this work will make a useful contribution to the field of gear tribology and related areas, including coatings, electronics, and optics.

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