Simulation study and experimental verification of surface texture induced cavitation effect

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Abstract. Considering the cavitation effect, the numerical simulations were performed by using Ansys-Fluent17.0 software to study the lubrication processes of frictional pairs with surface micro-textures. And the simulation results were verified by designing and building a test bench to collect gas phase diagram of texture induced oil film cavitation. Studies have shown that in the entrance area of the texture, due to a sudden change in the section, a negative pressure is generated; when the speed reaches a certain level, the negative pressure value reaches the cavitation pressure value of the oil film, causing cavitation of the oil film; And the cavitation effect can improve the oil film bearing and the lubrication effect of friction pair. The greater the speed, the more intense the degree of cavitation, the more obvious the improvement effect.

1. Introduction

The traditional tribological theory holds that the smoother the surface, the better the frictional performance. However, with the deepening of the theory of tribology, the study found that the smoother the surface, not better the friction performance. On the contrary, the surface texture friction pair will exhibit superior tribological performance [1]. At present, surface texturing treatment has become one of the most effective means for reducing the frictional resistance between the friction pairs and improving the lubrication condition of the friction pair.

The effect of surface texturing on reducing friction has been partially confirmed by experimental and theoretical calculations. The influence of surface texture on tribological properties is derived from the theory of the use of surface micro-protrusions as a small hydrodynamic pressure lubrication bearing to generate additional hydrodynamic pressure lubrication effects proposed by Hamilton [2]. Later scholars continued to study in depth on this theory. Yu [3], Siripuram [4], and Peng Xudong [5] found that the concave micro-texture has a greater influence on the bearing capacity and friction coefficient by studying the friction properties of micro-textured friction pairs with convex/concave shapes. Andriy [6] measured by one-way sliding point contact experiments that the surface textured samples were less subject to friction under the same lubrication conditions than the smooth samples. C. Chouquet [7] performed partial texture processing on the board and performed pin-disk experiments. The results showed that the surface texture can significantly reduce the friction factor. Grabon W [8] has textured the surface of the cylinder liner. Under high speed and heavy load conditions, the surface texture reduces the friction and the effect of improving the lubrication effect is more obvious.
Since the existence of the texture forms a minute wedge-like effect, a negative pressure is generated at the diffused space formed by the texture, so that the gas contained in the lubricant is precipitated from the lubricant, thereby forming cavitation in the vicinity of the negative pressure region. Studies have shown that one of the mechanisms by which surface texture affects the bearing capacity is the cavitation effect in the flow field of the lubricating fluid due to the presence of texture [9,10]. Therefore, texture-induced cavitation effects should also be considered in the study of texture. Thus, under the condition of considering cavitation effect, the Ansys-Fluent software is used to numerically simulate the texture of the quadrilateral prism with surface morphology to study the phenomenon of surface texture induced cavitation effect and the preliminary experimental observation and research on texture induced cavitation were carried out by pin-disk experiment. In this way, it provides a theoretical basis for the rational design of surface micro-texture.

2. Texturing and simulation methods

2.1. Solving equation

Studies have shown that [11,12] in the case of micro-texture on the surface, the effect of inertial effects should not be ignored. However, the Reynolds equation ignores the inertial term and does not predict well the effect of micro-texture on the bearing. Therefore, based on the cavitation effect and the inertia term, the surface texture model is solved by the N-S equation. In order to simplify the numerical simulation calculation and ignoring some minor factors, the model has been simplified to some extent, and the following assumptions are made:

1) The lubricating medium is Newtonian fluid, incompressible, ignoring volumetric forces, and the viscosity is considered constant;
2) Fluid flow is a constant flow and the wall fluid flow rate is the same as the wall surface velocity;
3) The surface of the friction pair is not deformed and is a rigid body;
4) The remaining basic assumptions of the N-S equation.

Based on the above assumptions, the expansion of the N-S equation textured surface lubrication calculation model in the three-dimensional case in the fluid lubrication state is as follows in the x, y, and z directions:

\[
\rho \left( \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = - \frac{\partial p}{\partial x} + \eta \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \tag{1}
\]

\[
\rho \left( \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = - \frac{\partial p}{\partial y} + \eta \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \tag{2}
\]

\[
\rho \left( \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = - \frac{\partial p}{\partial z} + \eta \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \tag{3}
\]

the continuous equation is:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{4}
\]

In the equation, \( \rho \) is the density of lubricating oil; \( u, v, w \) are respectively the flow rates of x, y, and z; \( p \) is the oil film pressure; \( \eta \) is the viscosity of the lubricating oil.

2.2. Establishment of geometric models and boundary conditions

Figure 1 is a schematic diagram of the geometric model of the constructed texture. The parameters are expressed as: \( L \) is the length of the fluid domain along the x direction; \( W \) is the length of the fluid domain along the y direction; \( L_1 \) is the length of the texture; \( W_1 \) is the width of the texture; \( h \) is the oil
film thickness, and $h_1$ is depth of the texture; $v$ is the speed of movement of the upper wall relative to the lower wall.

![Figure 1. Schematic diagram of the geometric model of the constructed texture (the model takes $L/L_1=2.5$, $W/W_1=2.5$, $h/h_1=10$).](image)

Symmetrical boundary conditions are used at both left and right ends of the model. Inlet and outlet are periodic boundary conditions. The upper and lower walls are free of slip boundary conditions and the lower wall is a fixed wall surface. Since the single texture area is relatively small relative to the entire friction pair, it is possible to consider linear motion of the upper wall surface relative to the lower wall surface. The lubricating medium is a lubricating oil with a dynamic viscosity of 0.675 pascal seconds.

2.3. Solution results

Under the same conditions, the flow field pressure distribution diagram without considering and considering cavitation is shown in Figure 2. It can be seen from the Figure 2(a) that the flow field forms a gradually expanding space because of the presence of the texture on the surface. The cross-sectional area at the entrance to the texture increases and the cross-sectional area at the textured exit region decreases. In the gradually expanding area, the pressure is reduced, and conversely, in the gradually narrowing area, the pressure is raised. Since the lubrication medium is assumed to be an incompressible Newtonian fluid, the positive and negative pressure areas in the flow field are almost symmetrically distributed. However, under actual working conditions, the oil film has already cavitation when such a large negative pressure occurs. As shown in Figure 1.2(b), the pressure distribution diagram when considering the cavitation effect, it is still a high pressure area in the textured exit area, the pressure value is slightly higher than the pressure value when cavitation is not considered. However, at the entrance to the texture, the pressure is reduced to the cavitation pressure and remains unchanged, and the oil film begins to cavitation here.

![Figure 2. Pressure profile (Unit: Pascal)](image)
The cavitation gas phase diagram is shown in Figure 3. Cavitation begins to occur in the textured entrance area and the gas volume fraction decreases outwardly. There is also some gas that overflows in the textured exit area. When cavitation occurs, the pressure value in the textured inlet area is much higher than the pressure value when cavitation is not considered, so the bearing of the oil film is also higher than the bearing without considering cavitation. As speed increases and cavitation intensifies, the effect is better.

3. Experimental part

3.1. Experiment bench introduction

In order to verify the existence of surface texture induced cavitation and the effect of texture cavitation on the friction factor, setting up the test bench shown in Figure 4 collects the cavitation effect diagram and measure the friction factor. The slewing mechanism 7 drives the lower sample 6 fixed on it to perform a rotary motion. The loading mechanism 4 drives the upper sample 5 to move downward together to achieve contact between the upper and lower samples. The microscope 9 is mounted directly under the transparent sample, so that the movement state of the lubricant between the contact faces of the sample in the fixed area can be collected. At last, the picture is transmitted to the display 13 by the CCD unit 10 for display and storage. The friction coefficient measurement is achieved by the loading force sensor 1 and the friction sensor 2 mounted on the loading structure, and the change in film thickness was measured by the laser range finder 3 from time to time.
Because of the texture-induced cavitation effect research experiment, the upper or lower sample needs to be textured. In order to facilitate observation and acquisition of the cavitation effect diagram, the lower sample is made of quartz glass with a light transmittance of 90%, but its brittleness is high, and it is not suitable for texturing on its surface. And if the texture is textured in the lower sample, it will also affect the sharpness of the image. Therefore, only the upper sample can be selected for texturing.

The upper sample is selected from metal brass, and the surface is polished first, and then the laser is used to engrave the square texture. Since the influence of the single texture on the friction coefficient is limited, the texture of the 8*8 matrix arrangement is used for experimental research, as shown in Figure 5. Each texture has a size of 0.2*0.2 (mm) and a pitch of 0.3 mm.

![Figure 5. The Surface texture.](image)

3.2. Experimental result
In order to study the phenomenon of texture induced cavitation and the effect of velocity on the intensity of cavitation effect, it is first necessary to obtain cavitation effect diagrams under different speed conditions. The center of the upper sample is placed 40 mm from the center of the rotating table, and the texture area is located at the center of the upper sample. The model number of the lubricant is L-HM 100. Then, it changes the mutual movement speed between the upper and lower samples by changing the speed of the rotary table. The cavitation effect at different speeds is shown in Figure 6.

![Figure 6. Cavitation effect at different speeds.](image)
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Figure 6. Cavitation gas phase diagram at different speeds.

The above cavitation effect pictures were acquired when the microscope objective was 1X and the CCD was 0.5X. Under static conditions, when the upper and lower samples are in contact, the acquired pattern is shown in Figure 6 (a). Since the transmittance of the transparent glass is sufficiently large, the acquired image is sufficiently clear, and the brightness of the non-texture region on the surface of the upper sample can be observed to be high. However, the texture area is black because there is no light reflection. When the rotational speed of the rotary table was less than 6r/min (0.025m/s), no bubbles appeared near the textured area, and the oil film has not been cavitation. When the rotation speed was greater than 6 r/min, the texture of the uppermost row began to appear bubbles. This was because the line speed of the upper row texture was slightly larger than the texture of the lower row, so cavitation took precedence. As the speed increased, the entire texture area gradually became cavitation from the top to the bottom, and the formed bubbles were dragged backwards. The faster the speed, the more intense the cavitation and the longer the bubbles formed. When the rotational speed of the rotary table was less than 24r/min (0.10m/s), the bubbles formed by the cavitation of the oil film were relatively stable and always existed. When the speed was greater than 21r/min, the bubble formed by the cavitation of the oil film would be removed from the texture by the moving oil due to the relatively fast rotation speed. Then, the oil film was cavitation again at the texture, creating bubbles. A cycle of generating-taking-generating was formed like this. When the cavitation was more severe, the oil film thickness was obviously improved, which indicates that the cavitation effect played a positive role in the oil film bearing.

Figure 7. Comparison of friction coefficient between the smooth surface and the textured surface.
Figure 7 is a comparison of the friction coefficient between the textured sample and the smooth surface sample. As can be seen from the figure, for a smooth surface, the friction coefficient does not change much when the speed is small. As the speed increases, the friction coefficient will gradually increase. This is because as the speed increases, the surface of the upper sample wears up and the roughness increases, which leads to the increase in friction and friction coefficient. On the contrary, it can be clearly seen from the figure that the friction coefficient of the textured surface is significantly lower than it of the smooth surface. And as the speed increases, the degree of cavitation of the oil film increases and the friction coefficient continues to decrease. This shows that the surface texture can effectively improve the lubrication effect of the friction pair, and this effect is more obvious as the speed increases.

Compared with the simulation results, it can be seen that in the experimental and numerical simulations, the texture can induce the cavitation of the oil film and can effectively improve the lubrication effect of the friction pair. The reason for the difference between the experimental and simulated results is because the influence of the curvature and roughness of the upper wall surface (sliding wall surface) is neglected during the numerical simulation. It is also easier to mix air into the lubricating oil during the experiment, so that the gas content of the lubricating oil is higher than the value in the simulation. These make the oil film to cavitation at a lower rate during the experiment. Moreover, due to the cooperation of various mechanical components and the loss of energy transfer during the experiment, the friction coefficient obtained by the experiment is slightly larger than the simulated value.

4. Conclusions
The numerical simulation was used to study the texture induced oil film cavitation, and the rationality of theoretical modeling was verified by experiments. The following conclusions were obtained:

(1) Due to the existence of surface texture, a low pressure area is formed at the entrance to the texture. Oil film cavitation occurs at here and extends toward the exit of the texture direction.

(2) The existence of surface texture can effectively improve the lubrication state of the friction pair, and its induced cavitation effect of the oil film has a positive influence on the oil film bearing. The greater the speed, the better the improvement.

(3) The existence of cavitation is verified by experiments. When the oil film is thin and the lubricating oil contains a large amount of gas, cavitation easily occurs. And the greater the speed, the more severe the cavitation. Therefore, in the study of surface texture, the cavitation effect should not be ignored.

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