The Influence of Surface Texture on Tribological Characteristics of Water-lubricated Rubber Bearing

Huanjie WANG1,a, Zhenglin LIU2,b

1College of Transportation Engineering, Wuhan Institute of Shipbuilding Technology, Wuhan Hubei, 430050, China;
2School of Energy and Power Engineering, Wuhan University of Technology, Wuhan Hubei, 430063, China
ae-mail: wanghaijinder331@163.com
be-mail: zliu812@163.com

Abstract: To study the effect of surface texture on the tribological characteristics of ship's water-lubricated rubber bearings, the surface texture modification technology is applied to the friction surface of the lining, and the tribological characteristics of the surface texture are studied. The tribological characteristics of the flow field, such as velocity change, water film pressure distribution, and the influence of water film thickness on the surface texture flow field were discussed by simulation analysis. The results show that the average velocity is decreased on the texture surface, and the water film pressure obtained by the inclined cylinder pitted surface texture is the least.

1. Introduction
At present, domestic and foreign underwater vehicles mostly use water lubricated rubber tail bearings with good Submergence of foreign bodies, vibration absorption and impact resistance. However, under special working conditions such as low speed and heavy load, the rubber bearings are easy to form boundary or mixed lubrication state, the tribological performance becomes poor, and it is easy to induce friction self-excited vibration, produce chattering and whistling, which has a great impact on the concealment of underwater vehicles. Therefore, it is of great theoretical and engineering practical significance to study various methods and measures to improve the tribological performance of the interface of bearing friction pair, to improve the bearing capacity, reliability and service life of water lubricated rubber stern bearing of underwater vehicle, to reduce friction and wear, and to suppress friction vibration.

In 1994, Suh [1] found through experimental research that the friction surface with grooves can collect and contain impurity particles, which can effectively reduce the particle wear between friction surfaces. Based on this, the wear reduction mechanism of surface texture was obtained. As a result, a large number of scholars began to study the related tribological properties of surface texture, and have proved that the preparation of suitable micro-pits texture on the friction surface can significantly improve the tribological properties between the friction surfaces and prolong the service life of the friction pairs, which has broad application prospects [2-18].

In the bearing field, Ma Chenbo et al. [19] studied the influence of the texture distribution position on the friction factor and bearing capacity of the bearing under different conditions. Costa, Zhu Hua et al. [20-21] studied the influence of texture density rate on the tribological properties of the bearing.
surface. Nacer Tala-Ighil et al. [22] for the two cases of whether the bearing surface has texture or not used the finite difference method to study the characteristics of the radial bearing model and the influence of heat on the bearing surface with or without texture. Qinbo [23] optimized water-lubricated stern bearing lining surface by using regular micro-convex textures, and focused on the local contact conditions of the bearing on various factors such as operating conditions, texture shape, size, and texture distribution. And the influence of tribological properties. But in general, the application of surface texture to improve the tribological performance of bearings and suppress the frictional vibration of water-lubricated rubber tail bearings is not in-depth. In order to improve the frictional vibration suppression effect of rubber bearings, the paper intends to apply the surface texture modification technology to the friction surface of the bearing lining, conduct research on the tribological characteristics of the surface texture, and reveal the influencing factors and tribological characteristics of the surface texture. The law of change provides relevant data for the study of frictional vibration suppression of surface texture.

2. Surface texture

2.1. geometry and characteristics

At present, the commonly used geometric shapes of surface texture mainly include cylindrical pit, cone pit, square pit, rectangular pit, etc. The hydrodynamic characteristics, tribological characteristics, and preparation technology of each shape texture are different. The pits are often used because of the convenience of processing. The main parameters of surface texture include texture geometry, diameter, depth, depth-to-diameter ratio and arrangement, etc. These parameters directly affect the tribological properties of surface texture.

The surface texture designed in the thesis mainly includes three types of cylindrical pits, oblique cylindrical pits, and spherical crown pits. The schematic diagrams of the structure are shown in Figures 1 to 3.

In the figure, \( r_d \) is the radius of the cylindrical pit; \( h_0 \) is the initial water film thickness; \( h_d \) is the depth of the cylindrical pit, Then the thickness of the water film near the cylindrical pit and the cylindrical pit that include the elastic deformation can be expressed as

\[
\tilde{h} = \begin{cases} 
    h_0 + \delta, & r > r_d \\
    h_0 + h_d + \delta, & r \leq r_d 
\end{cases}
\]

In the formula: \( \delta \) is the amount of elastic deformation.
The oblique cylindrical pit is formed by the inclined $\beta$ angle of the cylindrical pit, and its projection on the horizontal plane is an ellipse, and the longitudinal section is a triangle. It can be seen from Figure 2 that the water film thickness of the oblique cylindrical pit at any position on the longitudinal section, such as point B, is a variable, which can be expressed as:

$$h = \begin{cases} 
    h_0 + \delta, & \text{(pit-free area)} \\
    h_0 + 2r_\beta \sin \beta - x \tan \beta + \delta, & x > 0, \quad x < \frac{2r_\beta}{\cos \beta} \\
    h_0 + 2r_\beta \sin \beta - \frac{1}{\tan \beta} + \delta, & x < 0, \quad x < \frac{2r_\beta}{\cos \beta}
\end{cases}$$

(2)

Where: $r_\beta$ is the radius of the cylindrical section of the oblique cylinder.

The spherical crown pit is a symmetrical gyrator whose water film thickness $h$ is the same everywhere on the same circle $(2r)$, which can be expressed as:

$$h = \begin{cases} 
    h_0 + \delta, & r > r_\beta \\
    \left(\frac{r_\beta^2 + h_0^2}{2h_0}\right)^{1/2} - r^2 - \frac{r_\beta^2 + h_0^2}{2h_0} + h_0 + \delta, & r \leq r_\beta
\end{cases}$$

(3)

In the formula: $r$ is the radius of a certain circle section which is intersecting the spherical cap and parallel to the textured surface.

2.2. Layout

In the friction pair composed of the water-lubricated rubber bearing and the tail shaft copper sleeve, the former has a large deformation and the latter has a small deformation. Therefore, the surface texture of the pit should be built on the rubber material. The advantage is that the water stored in the pit is deformed and deformed. Under the action of sliding speed, it is easy to "pump out" the stored water to wet the periphery of the texture, reducing friction and wear. If the pit texture is constructed on the copper sleeve material, the rubber material may squeeze into the pit under a large load, and be sheared by the relative movement of the bearing (lower specimen) and the shaft (upper specimen). Then increase the wear; the sheared material is also easy to block the pits, so that the surface texture loses the original tribological characteristics.
3. Simulation analysis

3.1. Analysis model and boundary conditions
In order to simplify the complex calculation of the surface texture flow field, the upper and lower walls of the friction pair are regarded as rigid bodies, and the two-dimensional modeling method is used to establish two types of finite volume element models of rubber without texture and with texture respectively. Among them, the textured models include cylindrical pits, oblique cylindrical pits and spherical crown pits. Under the same conditions, the simulation calculation of flow field velocity and water film pressure distribution is carried out.

Assuming that the initial water film thickness is \( h_0 = 10 \mu m \), the moving speed of the upper wall of the model is 1 m/s. The main parameters of the four textured surfaces are the same: the nominal diameter of the pit is the same, \( D = 2r_d = 1mm \) (see Figure 1 to Figure 3), the depth \( h_d = 0.09 \) mm (the deepest \( h_{d_{max}} \) of the oblique cylindrical pit and the spherical crown pit = \( h_d \)), the inclination \( \beta \) of the oblique cylindrical pit is 10 °. Inclined cylindrical pits have two layouts, forward and reverse, and the distinction between forward and reverse is shown in Figure 2. If the surplus angle that flows through first is greater than the other surplus angle, the oblique cylindrical pits are considered to be arranged in a forward direction, and vice versa, which are referred to as forward and reverse respectively.

Using Fluent software, according to the mid-section (cross-section) structure size of the surface texture in Figures 1 to 3, the two-dimensional finite volume element models of the surface texture of the non-textured, cylindrical pit, oblique cylindrical pit and spherical cap pit with a water film thickness of 10 μm are established, as shown in Fig. 4.
boundary of the water film is a moving wall with a velocity of 1 m/s; the bottom boundary is a fixed wall.

3.2. Flow velocity changes in the flow field

The flow velocity changes of non-textured and textured surfaces (including cylindrical pits, oblique cylindrical pits (forward and reverse arrangement), spherical cap pits) are shown in Figure 5, respectively. There are partial enlarged diagrams in the figure to more clearly depict the changing situation of flow velocity of flowing field with different surface textures along the direction of fluid flow and film thickness direction, such as the vortex flow direction and vortex velocity.

![Image of flow velocity changes](image_url)

- **a)** Untextured surface
- **b)** Cylindrical pit surface
- **c)** Inclined cylindrical pit (positive direction)
It can be seen from Figure 5 that the top layer of the untextured surface has a high flow velocity, while the bottom layer has a small flow velocity, and the flow velocity along the flow direction remains constant. When the fluid enters the cylindrical pit, the oblique cylindrical pit (forward and reverse) and the spherical cap pit, the flow area increases instantly, the flow velocity decreases, and the top velocity is high and the bottom velocity is small. An annular return flow is formed at the bottom, and the return flow direction is clockwise (opposite to the flow direction); when the fluid flows out of the pit, the flow area becomes smaller and the flow velocity increases. The flow velocity and streamline distribution of the surface textures of different shapes are different. The maximum velocity is 1 m/s, which appears on the top layer, which is similar to the moving speed of the upper wall. Since there is no pressure difference between the inlet and outlet of each model, there is no pressure difference flow. However, due to the viscous effect of water, the movement of the upper wall of the model drags the fluid between the upper and lower walls to produce pure shear flow. The average flow velocity of the flow field on each texture surface is listed in Table 1.

| Texture shape                  | Untextured | Cylindrical pit | Inclined cylindrical pit (positive direction) | Inclined cylindrical pit (reverse) | Crown pit |
|-------------------------------|------------|-----------------|----------------------------------------------|-----------------------------------|-----------|
| Average velocity / (m/s)      | 0.50       | 0.23            | 0.17                                         | 0.20                              | 0.22      |

It can be seen from Table 1 that the average flow velocity of the untextured surface is \( v_p = 0.50 \) m/s, which is half the moving speed of the upper wall, \( v_p = v/2 \). The average velocity of the textured surface is the average velocity of the fluid after entering the pit. The average velocity of the three types of textures is different. The average velocity of the cylindrical pit is the largest, which is 9.5% ~ 35.3% higher than other pits; The oblique cylindrical pit (forward flow) is the smallest, 0.17 m/s. However, the average flow velocity of the textured surface is lower than that of the non-textured surface (0.50 m/s).
m/s). This is because the vortex backflow in the pit has an obstructive effect on the flow velocity and reduces the average velocity.

3.3. Water film pressure distribution

The water film pressure distribution of the surface texture affects the supporting force of the friction pair, the contact condition of the friction surface, and the lubrication state of the friction pair. The greater the water film pressure, the more conducive to reducing the contact area of the friction pair, increasing the fluid friction area, reducing the contact friction resistance, and helping to reduce the probability of inducing frictional self-excited vibration. The pressure distribution of the water film with different shapes and textures is shown in Figure 6.

![Water film pressure distribution](image)

**Figure 6** Cloud diagram of water film pressure distribution

In order to compare the influence of different surface textures on the water film pressure, the maximum water film pressure in the pit area was extracted along the fluid flow direction, and the non-textured surface was used as a reference object for comparison, as shown in Figure 7.

![Pressure distribution curves](image)

**Fig. 7** Curves of water film pressure along the flow direction with different surface textures
It can be seen from Figure 7 that the water film pressure on the untextured surface remains basically unchanged along the fluid flow direction, with only a slight increase at the outlet, the maximum change is only 30 Pa, and the fluctuation range is three ten thousandths, which can be ignored. It can be seen that when the surface deformation is not taken into account, the relative movement of the two parallel surfaces cannot produce the water film supporting force.

The water film pressure on the textured surface changes significantly along the fluid flow direction near the entrance and exit pits. When the fluid enters the pit, the circulation area increases sharply, and the local pressure decreases. When it flows out of the pit, the circulation area decreases sharply, and the pressure increases, that is, the upward trend of "sudden increase-gentle-sudden increase" is shown. The magnitude of the change is related to parameters such as the shape of the pit and the depth of the pit. The water film pressure change process in the model can be divided into an inlet interval, a gentle interval and an outlet interval. The inlet and outlet intervals have a shorter history, and the gradient of the water film pressure relative to the flow position is larger; the gentle interval has the longest history, and the pressure changes maximum. In the gentle interval, the water film pressure generated by the oblique cylindrical pit (reverse direction) is the largest, followed by the cylindrical pit and spherical cap pit, and the oblique cylindrical pit (forward direction) is the smallest. It can be seen that the shape of the surface texture and the orientation of the surface texture relative to the fluid flow direction have an important influence on the formation of water film pressure.

3.4. Analysis of the influence of water film thickness on surface texture flow field

While keeping the boundary conditions of the surface texture and flow field unchanged, the water film thickness is set to 1, 2, 4, 6, 8, and 10 μm, and Fluid hydrodynamic performance of different surface textures under different water film thicknesses are calculated respectively. Performance, discuss the influence of water film thickness on the average velocity of the flow field and the water film pressure.

3.4.1. Influence of water film thickness on average velocity of convection field

The variation of the average velocity of the flow field in the pits with different surface textures with the thickness of the water film is shown in Fig. 8.

It can be seen from Figure 8 that as the thickness of the water film increases, the average velocity of the pits with different surface textures decreases nonlinearly. In the case of the same water film thickness, the average flow velocity of the spherical crown pit and the cylindrical pit is larger, and the oblique cylindrical pit (forward) and the oblique cylindrical pit (reverse) are relatively small. The larger the average flow velocity, the better the formation of the water film and the improvement of the water film supporting force.

3.4.2. The Influence of Water Film Thickness on the Maximum Pressure of Water Film in Flow Field

Regardless of the area where the fluid flows out of the pit, only within the circumference of the pit, the water film pressure distribution in the flow field under different water film thicknesses is discussed, and the influence of the water film thickness on the water film pressure distribution in the pit is
discussed. The variation of the maximum pressure of the water film at the top layer of the pits with different surface textures with the thickness of the water film is shown in Figure 9.

Figure 9 Water film thickness-pit water film pressure
It can be seen from Figure 9 that when the water film thickness is 4-10 μm, the water film thickness has little effect on the pressure of the surface texture flow field. The relevant curves in the figure basically coincide, indicating that when the water film thickness is large to a certain extent, the hydrodynamic effect of the surface texture pits is not obvious, therefore, the water film pressure changes little. When the water film thickness is small to a certain extent (1~2 μm), the water film pressure of the surface texture flow field increases rapidly. The thinner the water film, the greater the water film pressure generated.

4. Conclusions
Through simulation analysis, the paper discusses the tribological characteristics of flow field velocity changes, water film pressure distribution, etc. on non-textured and textured surfaces, as well as the influence of water film thickness on the surface texture flow field. The results show:

1. The vortex backflow of the surface texture will hinder the flow velocity of the flow field between the contact surfaces, and the average velocity will decrease. Under the same water film thickness, the average velocity of the cylindrical pit will decrease the least.

2. The variable cross-section effect of the surface texture makes the water film pressure show a rising trend of "sudden increase-gentle-sudden increase". Among them, the water film pressure generated by the oblique cylindrical pit (reverse direction) is the largest.

3. After the water film thickness increases to a certain level, the water film pressure is not sensitive to the thickness; when the water film thickness decreases to a certain level (1~2 μm), the water film pressure increases sharply.

Acknowledgments:
The project of Science and Technology Department of Hubei Education Department "Application Research of water lubricated bearing for Inland River ships" (B2017512)

References:
[1] Suh N P, Mosleh M, Howard P S. Control of friction[J]. Wear, 1994, 175(1): 151-158.
[2] Lo S W, Horng T C. Lubricant permeation from micro oil pits under intimate contact condition[J]. Journal of Tribology-Transactions of the ASME, 1999, 121(4): 633-638.
[3] Wang X L, Kato K. Improving the anti-seizeability of SiC seal in water with RIE texturing[J]. Tribology Letters, 2003, 14(4): 275-280.
[4] Gualtieri E, Borghi A, Calabri L, et al. Increasing nano-hard-ness and reducing friction of nitride steel by laser surface texturing[J]. Tribology International, 2009, 42 (5): 699-705.
[5] Marchetto D, Rota A, Calabri L, et al. AFM investigation of tribological properties of nano-patterned silicon surface[J]. Wear, 2008, 265(5): 577-582.
[6] Etsion I. State of the art in laser surface texturing[J]. Journal of Tribology Transactions of the ASME, 2005, 127(1): 248-253.
[7] Tonder K. Hydrodynamic effects of tailored inlet roughnesses: Extended theory[J]. Tribology International, 2004, 37(2): 137-142.
[8] Fowell M, Olver A V, Gosman A D, et al. Entrainment and inlet suction: Two mechanisms of hydrodynamic lubrication in textured bearings[J]. Journal of Tribology, 2007, 129: 336-347.
[9] Schuh J K, Randy H. Ewoldt. Asymmetric surface textures decrease friction with Newtonian fluids in full film lubricated sliding contact[J]. Tribology International, 2016, 97: 490–498.
[10] Siripuram R B, Stephens L. Effect of deterministic asperity geometry on hydrodynamic lubrication[J]. Journal of Tribology, 2004, 126(6): 527-534.
[11] Shinkarenko A, Kligerman Y, Etsion I. The effect of surface texturing in soft elastohydrodynamic lubrication[J]. Tribology International, 2009, 42(2): 284-292.
[12] Xu S, An Soj, Atsushi D, et al. Development of low-cost deformation-based micro surface texturing system for friction reduction[J]. International Journal of Precision Engineering and Manufacturing, 2016, 17(8): 1059-1065.
[13] Hsu S M, Jing Y, Zhao F. Self-adaptive surface texture design for friction reduction across the lubrication regimes [J]. Surface Topography Metrology & Properties, 2016, 4(1): 014004.

[14] Etsion I, Halpering, Brizmer V, et al. Experimental investigation of laser surface textured parallel thrust bearings [J]. Tribology Letters, 2004, 17(2): 295-300.

[15] Zhou Yuankai, Zhu Hua, Tang Wei, et al. Research on antifriction performance of surface texture with circular pits under reciprocating motion [J]. Lubrication and Sealing, 2012(3): 45-48.

[16] Hao L C, Meng Y G, Chen C G. Experimental investigation on effects of surface texturing on lubrication of initial line contacts [J]. Lubrication Science, 2014, 26: 363-373.

[17] Sudeep U, Pandey R K, Tandon N. Effects of surface texturing on friction and vibration behaviors of sliding lubricated concentrated point contacts under linear reciprocating motion [J]. Tribology International, 2013, 62: 198-207.

[18] Wan Yi, Li Jianliang, Xiong Dangsheng. The influence of sliding speed on the lubrication state of textured surface [J]. Journal of Central South University (Natural Science Edition), 2015(12): 4442-4447.

[19] Ma Chenbo, Zhu Hua, Li Jianquan. Experimental study on the lubrication and anti-friction performance of different surface textures of friction pairs [J]. Journal of China University of Mining and Technology, 2010, 39(2):244-248.

[20] Costa H L, Hutchings I M. Effects of die surface patterning on lubrication in strip drawing [J]. Journal of Materials Processing Technology, 2009, 209(3): 1175-1180.

[21] Zhu Hua, Li Jianquan, Lu Binbin, et al. Variable density micro-circular pits indicate the antifriction effect of texture under reciprocating motion [J]. Journal of Southeast University, 2010, 40(4): 741-745.

[22] Nacer Tala-Ighil, Michel Fillon. A numerical investigation of both thermal and texturing surface effects on the journal bearings static characteristics [J]. Tribology International, 2015, 90: 228-239.

[23] Qin Bo. Research on fluid-solid coupling of water-lubricated stern bearing based on local contact [M]. Wuhan: Wuhan University of Technology, 2014.