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Computer Vision-Based Research on the Mechanism of Stick–Slip Vibration Suppression and Wear Reduction in Water-Lubricated Rubber Bearing by Surface Texture

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Abstract: Water-lubricated rubber bearings are a critical component of the propulsion systems in underwater vehicles. Particularly under conditions of low speed and high load, friction-induced vibration and wear often occur. Surface texturing technology has been proven to improve lubrication performance and reduce friction and wear; however, research on how different texture parameters affect friction-induced vibration and wear mechanisms remains insufficient. In this study, various texture patterns with different area ratios and aspect ratios were designed on the surface of water-lubricated rubber bearings. By combining these designs with an in situ observation system based on computer vision technology, the effects of texture parameters on bearing friction, vibration, and wear were thoroughly investigated. The experimental results show that surface textures play a critical role in improving hydrodynamic effects and stabilizing the lubrication film at the friction interface. Specifically, textures with a high area ratio (15%) and aspect ratio (3:1) exhibited the best vibration suppression effect, primarily due to the reduction in actual contact area. However, excessively high area ratios may lead to increased surface wear. This study concludes that a reasonable selection of texture area and aspect ratios can significantly reduce frictional force fluctuations and vibration amplitude, minimize surface wear, and extend bearing life.

Keywords: water-lubricated rubber bearings; surface texture; texture parameters; friction-induced vibration; wear

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1. Introduction

Water-lubricated rubber bearings play a critical role in the propulsion systems of underwater vehicles [1]. Especially under specific conditions such as low speed and high load [2], their performance directly impacts the overall operation and stability of the vehicle [3]. These bearings are typically made from non-metallic materials like rubber and Thordon [4–6] and are widely used due to their excellent vibration resistance and impact endurance [7]. However, in practical applications, the bearings are subjected to special working conditions in complex underwater environments, such as high pressure, low speed, and overload, which often lead to boundary or mixed lubrication states. These lubrication changes can cause friction-induced vibrations, such as chatter and squeal, significantly increasing noise radiation, which in turn affects the stealth, reliability, and comfort of the vehicle [8,9].

Friction-induced vibration in water-lubricated rubber bearings is one of the key issues in the field of marine engineering [10]. Traditional research has mainly focused on wear mechanisms and the measurement of friction coefficients, with less attention given to vibration control and noise suppression [4]. In recent years, researchers have begun to explore how improvements in bearing materials and structural designs can reduce friction-induced vibrations [11]. For example, optimizing rubber formulations and enhancing surface treatment techniques aim to reduce instability at the friction interface, thereby minimizing vibrations and noise caused by friction fluctuations [12]. Recent advances also include the application of surface engineering technologies, such as laser texturing and micro–nano machining, to create specific surface geometries. These textures help form more stable lubrication films and reduce direct surface contact [13]. These surface characteristics not only improve lubrication performance but also significantly reduce friction and wear and lower vibration and noise, thereby enhancing overall operational efficiency [14].

Significant progress has been made in fluid dynamic lubrication and friction control for water-lubricated rubber bearings, particularly through the use of surface texturing to enhance the hydrodynamic effects and lubrication performance at the friction interface [15,16]. Studies have shown that surface textures can reduce friction and wear to some extent by altering hydrodynamic lubrication effects. Simulation research has also played a critical role in optimizing surface texture design, especially under water-lubricated conditions [17–19]. Some studies have developed various texture distribution models to investigate the impact of texture spacing and arrangement density on lubrication performance, finding that appropriate texture spacing and aspect ratio can effectively improve the load-carrying capacity and pressure stability of the oil film [20]. However, although these simulation studies reveal the role of surface textures in stabilizing lubrication films under complex working conditions and provide a scientific basis for optimization, there is still a lack of systematic research on how specific texture parameters influence friction-induced vibration and wear mechanisms in rubber bearings [21]. Additionally, most current studies remain focused on traditional wear and friction tests, which are limited in comprehensively analyzing the dynamic behavior during the friction process [22,23].

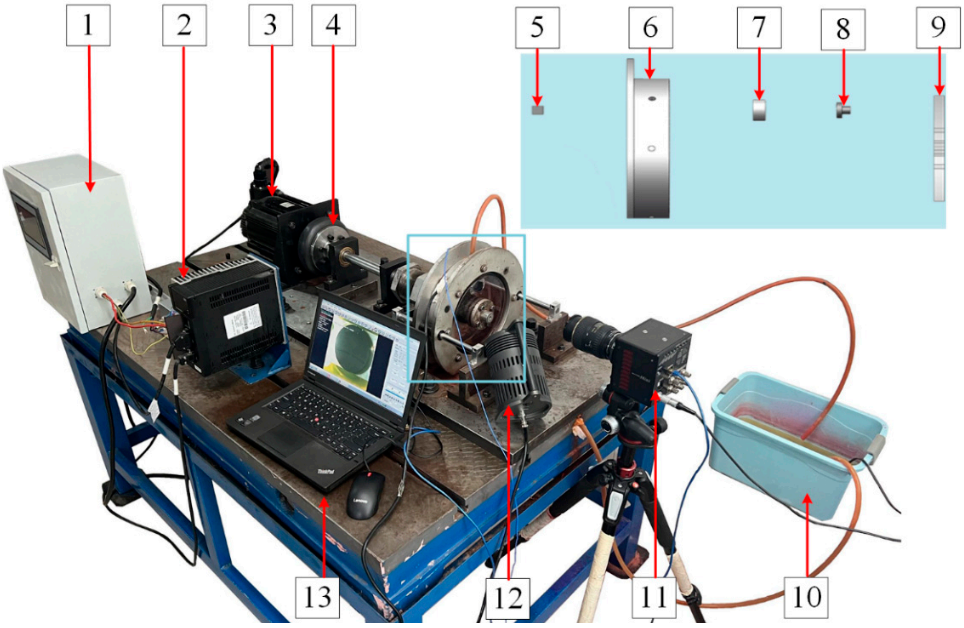
To address these issues, this study developed an in situ visualization system based on computer vision technology, combined with high-precision friction force measurement and vibration monitoring devices, to systematically explore the effects of different surface texture parameters (area ratio and aspect ratio) on the frictional vibration and wear behavior of water-lubricated rubber bearings [24]. By continuously monitoring the dynamic changes at the friction interface, particularly the role of textured surfaces in the formation and maintenance of water films, this study seeks to uncover the potential mechanisms by which different texture designs improve bearing performance [25]. Ultimately, this research aims to provide a more scientific theoretical basis and optimization strategies for the design of bearings in underwater vehicles [26,27].

Additionally, this study innovates experimental design by utilizing a visual friction pair system coupled with high-speed cameras and fluorescent imaging techniques [20,28]. This approach offers a more intuitive and detailed display of the friction behavior of different textured surfaces under actual working conditions. Not only does this method capture the dynamic changes in water film formation during friction, but it also deeply analyzes the effects of different textures on friction force and vibration response, providing practical design guidance for further optimization of bearings [29,30].

2. Materials and Methods

2.1. Experimental Apparatus

To investigate the mechanisms by which surface texturing reduces vibration and wear in water-lubricated rubber bearings under various operating conditions, this study used a specialized KMZ-2 test rig (Anhui Agricultural University, Hefei, China), as shown in Figure 1. The rig integrates a visual friction pair system and a high-speed vibration measurement system based on computer vision. By analyzing friction, vibration, displacement, and water intake, the system effectively examines how different surface texture parameters influence wear reduction and vibration suppression.



1—Distribution cabinet; 2—Controller; 3—Servo motor; 4—Coupling; 5—Vibration sensor; 6—Lubricating water chamber; 7—Force sensor; 8—Test block; 9—Glass disc; 10—water tank; 11—High-speed camera; 12—Light; and 13—Computer control and data acquisition system.

Figure 1. Water-lubricated bearing friction interface visualization test rig (KMZ-2).

The experimental disc was made of borosilicate glass, with specific dimensions shown in Figure 2. The disc had an outer diameter of 200 mm and a thickness of 10 mm. To more accurately simulate the wear conditions of water-lubricated rubber bearings under actual working conditions, a metal disc made of 1Cr18Ni9Ti stainless steel was used as a replacement in the wear tests. The rubber test blocks in this experiment were made of nitrile butadiene rubber (NBR) with a small end diameter of 26 mm and a thickness of 22 mm. The test blocks were divided into two categories: textured and non-textured, with a Shore hardness A (HSA) rating of 70. A UV laser engraving machine was used to texture the surface of the test blocks. The basic operating principle is as follows: an appropriate laser wavelength is selected based on the material properties of the sample, and the laser is directed onto the surface of the area to be processed, gradually melting the material. Laser engraving is not completed in a single pass; instead, the laser beam is repeatedly directed onto the same area, progressively melting the material until the desired shape and dimensions are achieved. The precise shape and depth of the surface textures are controlled by a computer system, which adjusts parameters such as the laser's scanning path, scanning frequency, scanning speed, and the number of passes. The structure and dimensions of the samples are shown in Figure 2.

To simulate real operating conditions and ensure consistent linear velocity for a single texture, elliptical surface textures were designed along the tangential direction of the friction pair, allowing water to flow into the texture along the tangential path during relative motion, as shown in Figure 3a (using a 10% area ratio and 2:1 aspect ratio as an example). Figure 3b provides a schematic of the single texture unit, where L represents the side length of the square texture unit, a is the minor axis of the elliptical texture, and b is the major axis. The aspect ratio is defined as the ratio of the major axis to the minor axis—b/a. The formula for the area ratio is given by $Sp = \pi ab/4L^2$.

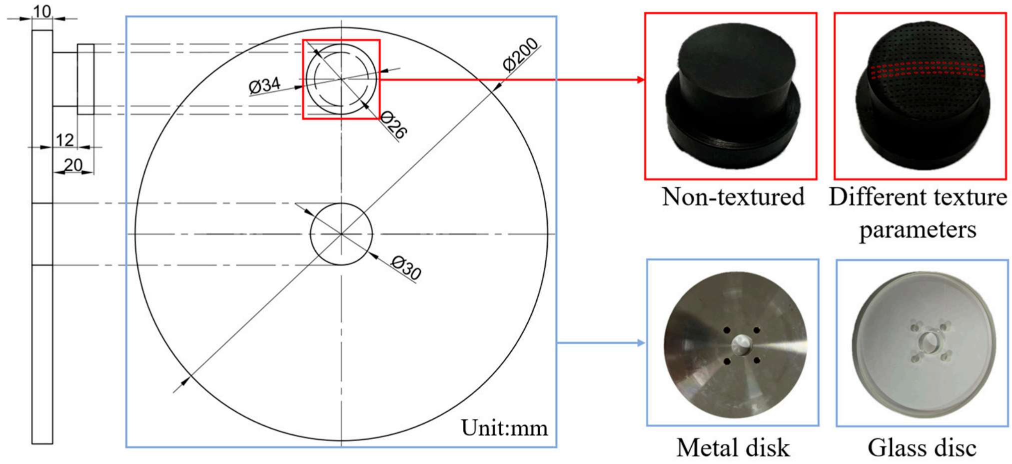


Figure 2. Schematic diagram of the dimensions of the experimental disc and rubber test block.

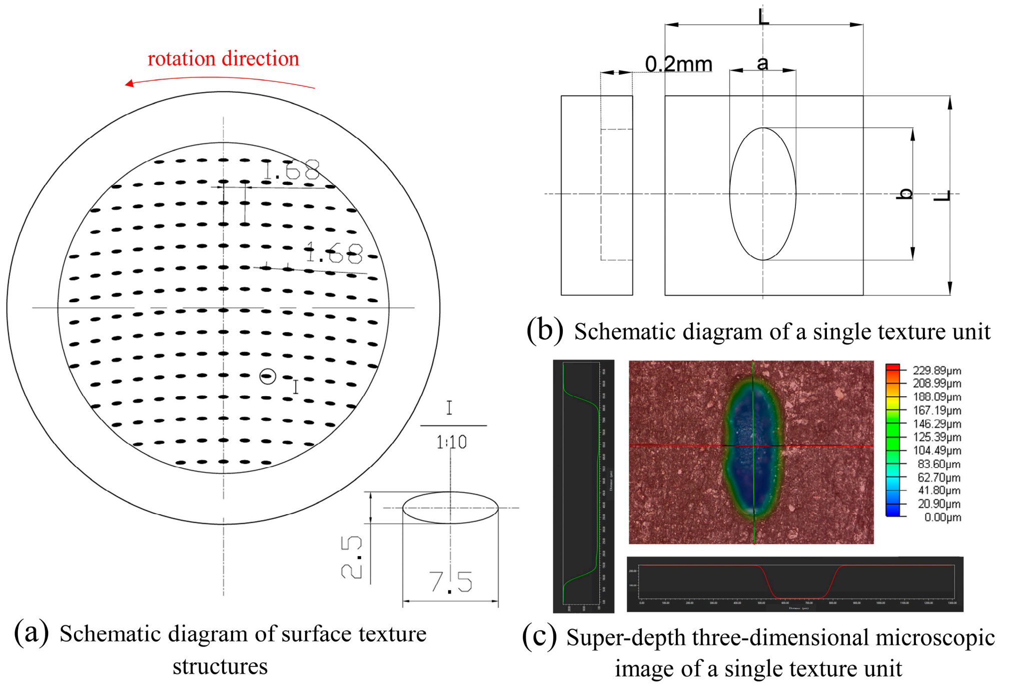


Figure 3. Schematic diagram of surface texture structures and single texture unit, along with a super-depth three-dimensional microscopic image.

Figure 3c displays a super-depth 3D microscopic image of the single texture unit, clearly showing the detailed 3D morphology of the texture, including precise dimensions and depth information. This allows for a direct evaluation and verification of the machining accuracy of the surface texture to ensure it meets the precise requirements of the experiment. The actual dimensions of the surface textures were referenced from the relevant literature [18–20].

To systematically analyze the effect of geometric parameters of surface textures on the vibration suppression performance of water-lubricated rubber bearings, nine different texture configurations were designed in this study. These textures vary in terms of area ratio and aspect ratio (Sample 10 serves as the untextured control group). The specific design parameters are shown in Table 1.

Table 1. Textured sample parameters.

Number	Area Ratio	Aspect Ratio
1	5%	1:1
2	5%	2:1
3	5%	3:1
4	10%	1:1
5	10%	2:1
6	10%	3:1
7	15%	1:1
8	15%	2:1
9	15%	3:1
10	-	-

This design aims to evaluate the specific impact of the area ratio and aspect ratio of textures on the friction and wear behavior of the bearings, providing a scientific basis for optimizing the surface textures of the bearings. The goal is to determine which geometric parameter combinations can most effectively reduce friction and suppress vibration, thus extending the lifespan of the bearings.

2.2. Testing

Due to the susceptibility of water-lubricated rubber bearings to vibration under harsh conditions, such as low speeds and high loads, this experiment was conducted with a load of 300 N and rotational speeds of 10, 30, and 50 rpm. The corresponding sliding speeds, calculated based on the outer diameter of the disc, were 0.0785, 0.2356, and 0.3927 m/s, respectively. Throughout the tests, the laboratory temperature was maintained at approximately 20 °C to ensure stable environmental conditions.

(1) Run-in test: Prior to the main experiments, a run-in procedure was performed in clean water using a metal disc and various test blocks. The conditions were as follows:

Load: 200 N
Rotational speed: 50 rpm
Duration: 10 min
The goal of this stage was to ensure smoother contact surfaces between the test blocks and the disc by reducing initial roughness.

(2) Friction test: After the run-in phase, the metal disc was replaced with a transparent glass disc. The testing conditions were set as follows:

Load: 300 N
Rotational speeds: 10, 30, and 50 rpm
Duration: 5 min
Once the system stabilized, the friction measurement system, vibration measurement system, and high-speed camera were activated simultaneously to record detailed data. After data collection, the rubber test blocks with different surface texture parameters were replaced to conduct a series of experiments, aiming to explore the friction behavior under various conditions.

(3) Lubrication Test: Before starting the lubrication tests, the clean water in the system was replaced with a Rhodamine 6G solution to better simulate real-world conditions. The initial testing conditions were:

Load: 100 N
Rotational speed: 50 rpm
Duration: 5 min
This ensured that the solution fully filled the surface textures. The load was then increased to 300 N, and once the system reached stability, a xenon lamp and high-speed camera were used to thoroughly record the water ingress into the surface

textures. After data collection, rubber blocks with different texture parameters were used to continue the experiments, examining the effect of various surface textures on water ingress.

(4) Wear test: For the wear test, the glass disc was replaced with a metal disc. The conditions were:

Load: 300 N
Rotational speed: 10 rpm
Duration: 1 h
After completing the test under low-speed conditions, test blocks with different parameters were swapped in, and further experiments were conducted.

These experiments aim to systematically evaluate the friction, vibration suppression, and wear performance of rubber bearings with different surface textures under water-lubricated conditions, with the goal of optimizing texture design to enhance bearing longevity and performance.

2.3. Data Acquisition and Data Processing

As shown in Figure 4, the experimental setup simultaneously collected data on applied load, friction force, vibration, and high-speed imaging signals during testing. To capture more high-frequency image signals, the experiment selected the smallest possible capture area to improve image resolution and accurately record the surface of the test blocks and their changes.

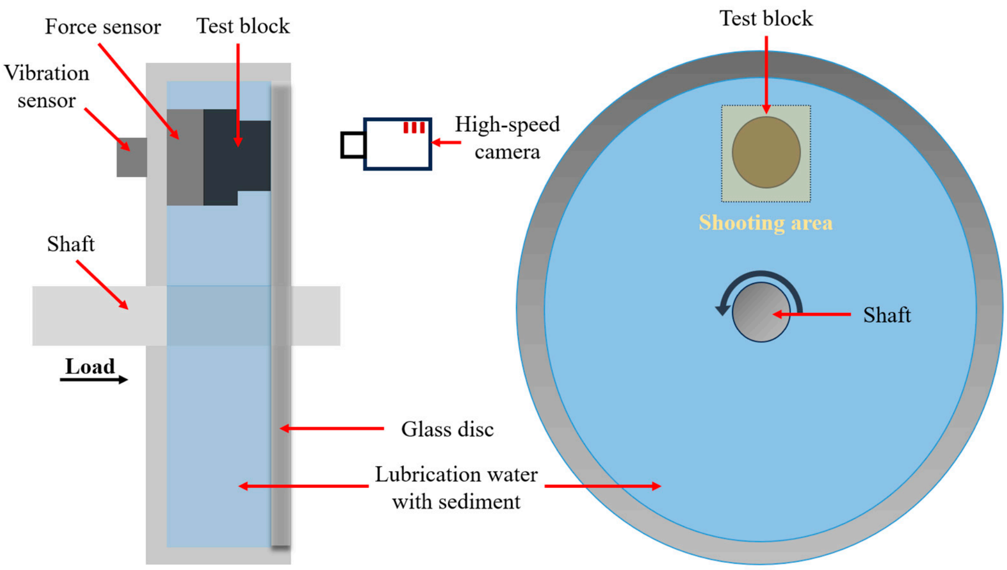


Figure 4. The acquisition diagram of force, vibration, and high-speed image signals.

Table 2 provides the model and manufacturer information for the testing equipment used in this study. The sampling frequency for force, vibration, and image data was uniformly set at 4000 Hz. The measurement and calculation of friction force and vibration followed standard methods. The following sections will focus on the acquisition and processing of image data.

The high-speed camera used in this study supports a maximum resolution of 1280 × 1024 pixels and a maximum shutter speed of 216,000 frames per second. To balance the duration of recording with precision, the resolution was set to 640 × 640 pixels, and the frame rate was configured at 4000 frames per second. This setup ensured a high measurement accuracy of 0.01 pixels, optimizing the camera's performance to meet the experimental requirements.

Table 2. Test equipment information.

Test Item	Sensor	Manufacturer
Friction force	Three-dimensional force sensor (LZ-SW40/18)	Hefei Lizhi Sensor Co., Ltd., Hefei, China
Vibration	Vibration sensor (IA313E)	Donghua Testing Technology Co., Ltd., Wuxi, China
Image	High-speed camera (AX200)	Photron, Tokyo, Japan
Light source	Xenon lamp (CEL-S500L)	Zhongjiao Jinyuan Technology Co., Ltd., Beijing, China

By replacing the water in the tank with a Rhodamine 6G fluorescent aqueous solution (100 mg/L) and leveraging the light absorption and emission properties of Rhodamine 6G, combined with a xenon lamp and optical filters for excitation, images were captured using a high-speed camera (as shown in Figure 5). This method effectively captures the distribution of the water film on textured surfaces with different parameters. Additionally, it helps study the uniformity and coverage of the water film, providing a more direct experimental basis for analyzing lubrication performance under water-lubricated conditions [31].

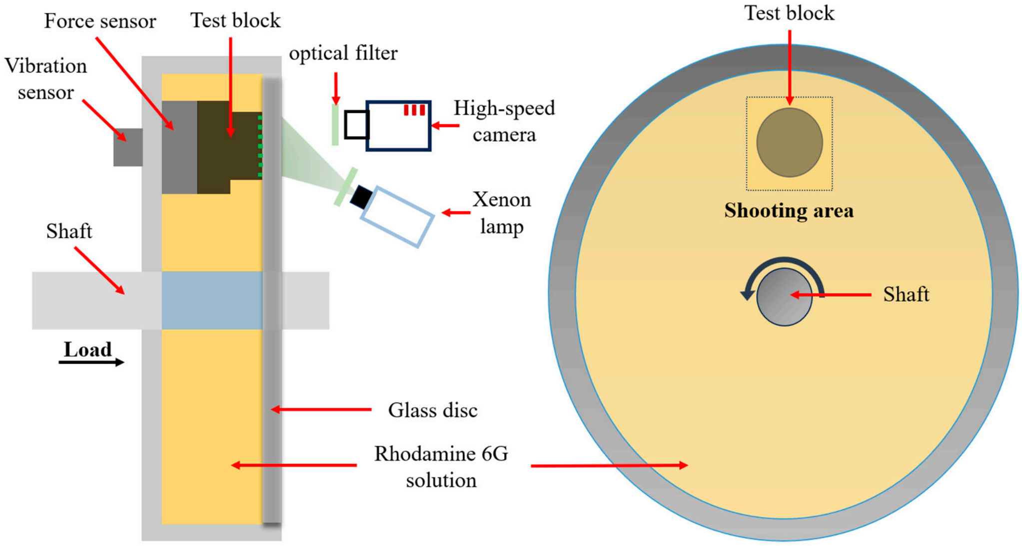


Figure 5. Schematic diagram of the water film distribution observation system.

3. Results

To further explore the role of surface textures in vibration suppression and wear reduction, this study systematically conducted friction and wear experiments on test blocks with varying texture parameters under heavy load conditions. Figure 6 presents the time-domain vibration signals, time-domain friction force signals, and displacement measurements for the non-textured test block at rotational speeds of 10 rpm, 30 rpm, and 50 rpm. The following analysis will use the experimental results of the non-textured block as a baseline, focusing on comparing the data of test blocks with different texture parameters. In conjunction with the average roughness (Sa value) of the worn surfaces, this study will evaluate the optimization effect of surface textures in reducing vibration, friction, and wear. Through comparative analysis, this study aims to reveal the specific performance improvements and advantages of different texture designs in enhancing these aspects.

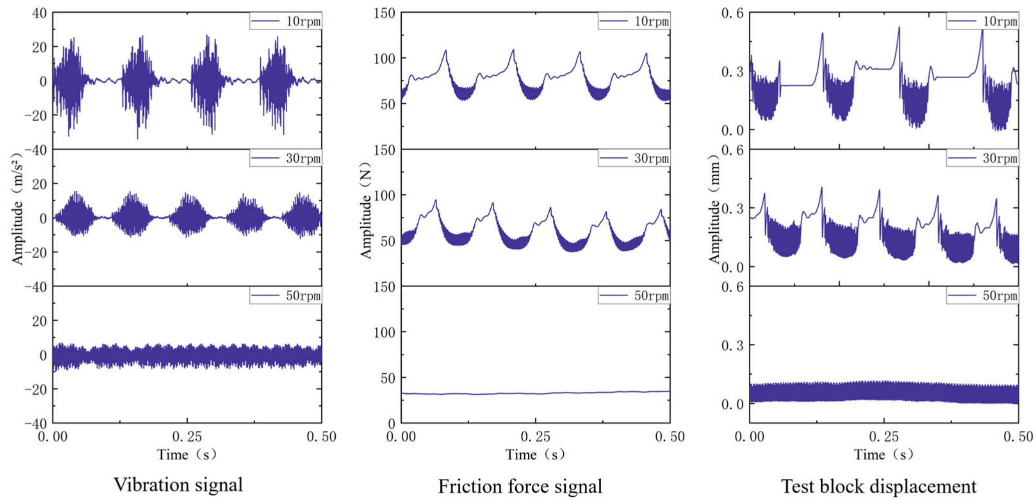


Figure 6. Vibration, friction force, and displacement signals of the non-textured test block at different rotational speeds.

3.1. The Influence of Texture Parameters on Friction Vibration in Water-Lubricated Rubber Bearings at Different Rotational Speeds

Figure 7 illustrates the vibration response of textured test blocks with varying area ratios and aspect ratios at rotational speeds of 10 rpm, 30 rpm, and 50 rpm. Each column represents a specific aspect ratio (1:1, 2:1, and 3:1), while each row corresponds to a different area ratio (5%, 10%, and 15%). It is evident from the figure that the texture parameters have a significant impact on vibration amplitude. The changes in stick–slip vibration responses can be categorized into three primary forms:

- **Chatter:** This phenomenon is primarily observed under low-speed and high-load conditions, particularly at 10 rpm. Chatter is typically associated with stick–slip behavior at low speeds.
- **Squeal:** As the rotational speed increases to 30 rpm, the chatter gradually diminishes, giving way to more continuous vibration signals, commonly referred to as "squeal."
- **Smooth vibration:** When the speed is further increased to 50 rpm or under lighter load conditions, the vibration signals become smooth, indicating that the system has reached a relatively stable operating state.

Figure 7 shows that most textured test blocks follow this pattern. Compared to the non-textured test block, those with textured surfaces exhibit significantly reduced vibration amplitudes. As the area ratio increases, the vibration amplitude tends to decrease for the same aspect ratio. Although the impact of aspect ratio on vibration amplitude is less pronounced than that of area ratio, an increase in aspect ratio still leads to a certain degree of vibration reduction. The subsequent discussion will focus on classifying and analyzing these three types of vibration behaviors to further explore the optimization effects of different texture parameters on vibration response.

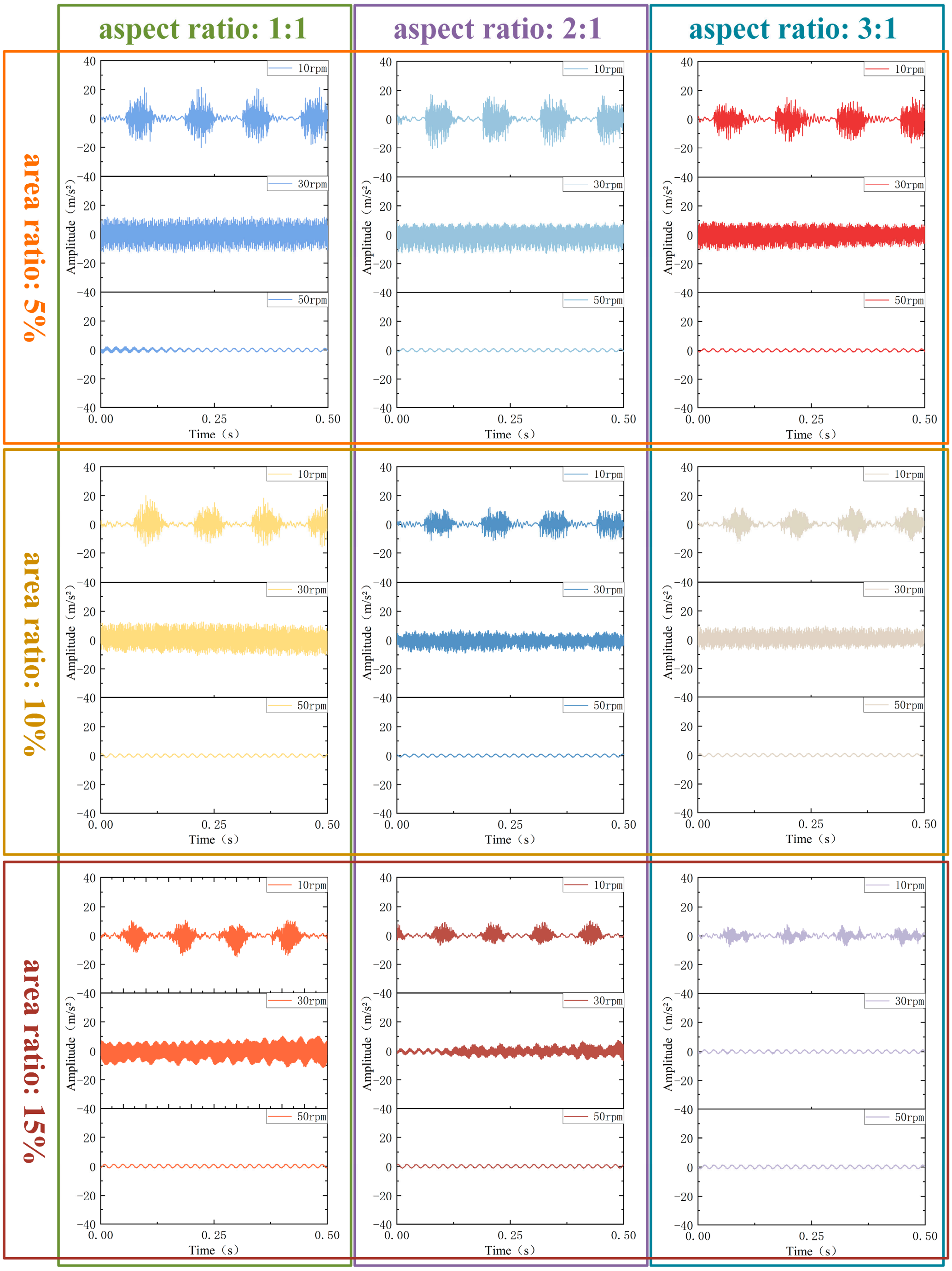


Figure 7. The Effect of texture parameters and rotational speed on vibration response.

3.2. The Impact of Texture Parameters on Friction Force Fluctuations at Different Rotational Speeds

As shown in Figure 8, while the time-domain friction force signals for the textured test blocks with different aspect ratios and area ratios exhibit some differences, the overall trends are similar. At the low speed of 10 rpm, the friction force signals display significant fluctuations, which are typically associated with stick–slip phenomena at low speeds. However, as the area ratio and aspect ratio increase, the amplitude of the friction force fluctuations decreases, indicating that the texture design effectively suppresses abrupt changes in friction force under low-speed conditions. In contrast, the non-textured test block shows much stronger fluctuations under the same conditions, highlighting the significant improvement that textured surfaces have in reducing the stick–slip effect.

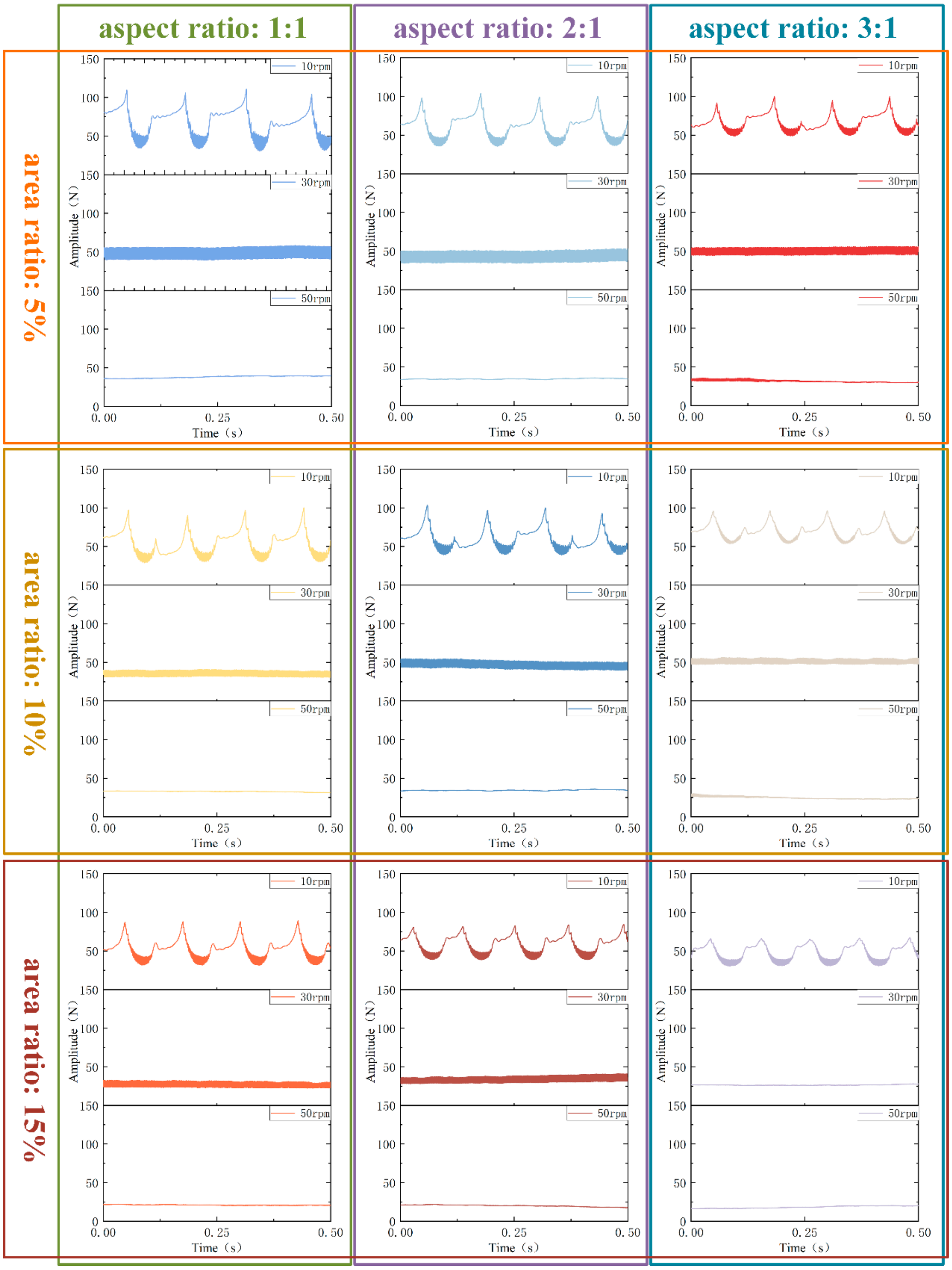


Figure 8. The effect of rotational speed and texture parameters on friction force.

When the rotational speed increases to 30 rpm, the friction system enters a "squeal" state, and the friction force signals become more stable. The textured test blocks, regardless of parameter variations, show similar characteristics in terms of friction force fluctuations but with differences in frequency and amplitude. In particular, test blocks with a high area ratio (15%) and high aspect ratio (3:1) exhibit smoother friction force fluctuations, suggesting that these texture parameters effectively reduce the range of friction force variations. Meanwhile, the non-textured block still shows noticeable fluctuations at this speed, with a larger range of variation, indicating its poorer frictional stability under medium-speed conditions.

At 50 rpm, the friction force signals become generally continuous and smooth across all textured test blocks, indicating good frictional performance with minimal fluctuations. This suggests that textured surfaces can maintain stable friction force signals at higher speeds. In comparison, while the non-textured block also shows a smoother signal at this higher speed, its fluctuation range remains larger than that of the textured blocks, demonstrating that surface texture design continues to play a significant role in reducing vibration and stabilizing friction at high rotational speeds.

Overall, the area ratio and aspect ratio of surface textures have a significant impact on the stability of the friction force signal, particularly under low- and medium-speed conditions. Textures with larger area ratios and aspect ratios are more effective in suppressing friction fluctuations, thereby enhancing the friction stability of the system.

3.3. The Effect of Texture Parameters on the Displacement of the Test Block at Different Rotational Speeds

By importing the images captured by the high-speed camera into TAMA software 2017 (TEMA Motion, Photron Ltd., Tokyo, Japan) for analysis and utilizing its tracking and micro-deformation capturing capabilities, the displacement variations in the test block under different rotational speeds and texture parameters were accurately measured. Through high-precision image processing algorithms, TAMA software can identify and track feature points in the images, capturing minute displacements and deformations to comprehensively analyze displacement amplitude under various vibration states [32]. As shown in Figure 9, the results indicate that texture parameters significantly affect displacement amplitude across different vibration states. Particularly, at lower rotational speeds and high-load conditions, optimized texture parameters significantly suppress displacement fluctuations of the test block.

At the low speed of 10 rpm, when the system is in a “chatter” state, the test block displacement exhibits clear periodic fluctuations. These fluctuations correspond to changes in both vibration and friction signals, suggesting that variations in surface friction directly cause periodic displacement changes. Compared to the non-textured blocks, the textured blocks show significantly reduced displacement amplitudes under the same conditions. This reduction is especially pronounced in the blocks with a 15% area ratio and a 3:1 aspect ratio, where the displacement fluctuations are notably suppressed.

As the rotational speed increases to 30 rpm, the system enters a “squeal” state, and the displacement fluctuations decrease. The textured blocks with different area and aspect ratios show relatively minor displacement fluctuations in this state, with high area ratios and high aspect ratios (such as 15% and 3:1) producing near-stable displacement. Compared to the non-textured blocks, the textured blocks exhibit smaller and more stable displacement amplitudes in the “squeal” state, demonstrating that the introduction of texture effectively mitigates friction-induced vibration.

When the speed further increases to 50 rpm, the system reaches a stable state, and the displacement amplitudes become smooth or near zero. This suggests that the stability of the friction system improves significantly at higher rotational speeds. While the displacement of the non-textured blocks also stabilizes at this speed, their stability remains inferior to that of the textured blocks. In particular, test blocks with high area ratios show almost complete suppression of displacement.

In summary, surface texture has a significant impact on the displacement of test blocks under various operating conditions, especially during “chatter” and “squeal” states. Texture designs with higher area ratios and aspect ratios effectively reduce displacement amplitudes and provide superior vibration suppression compared to non-textured surfaces. This further confirms the role of surface texture in mitigating friction-induced vibration.

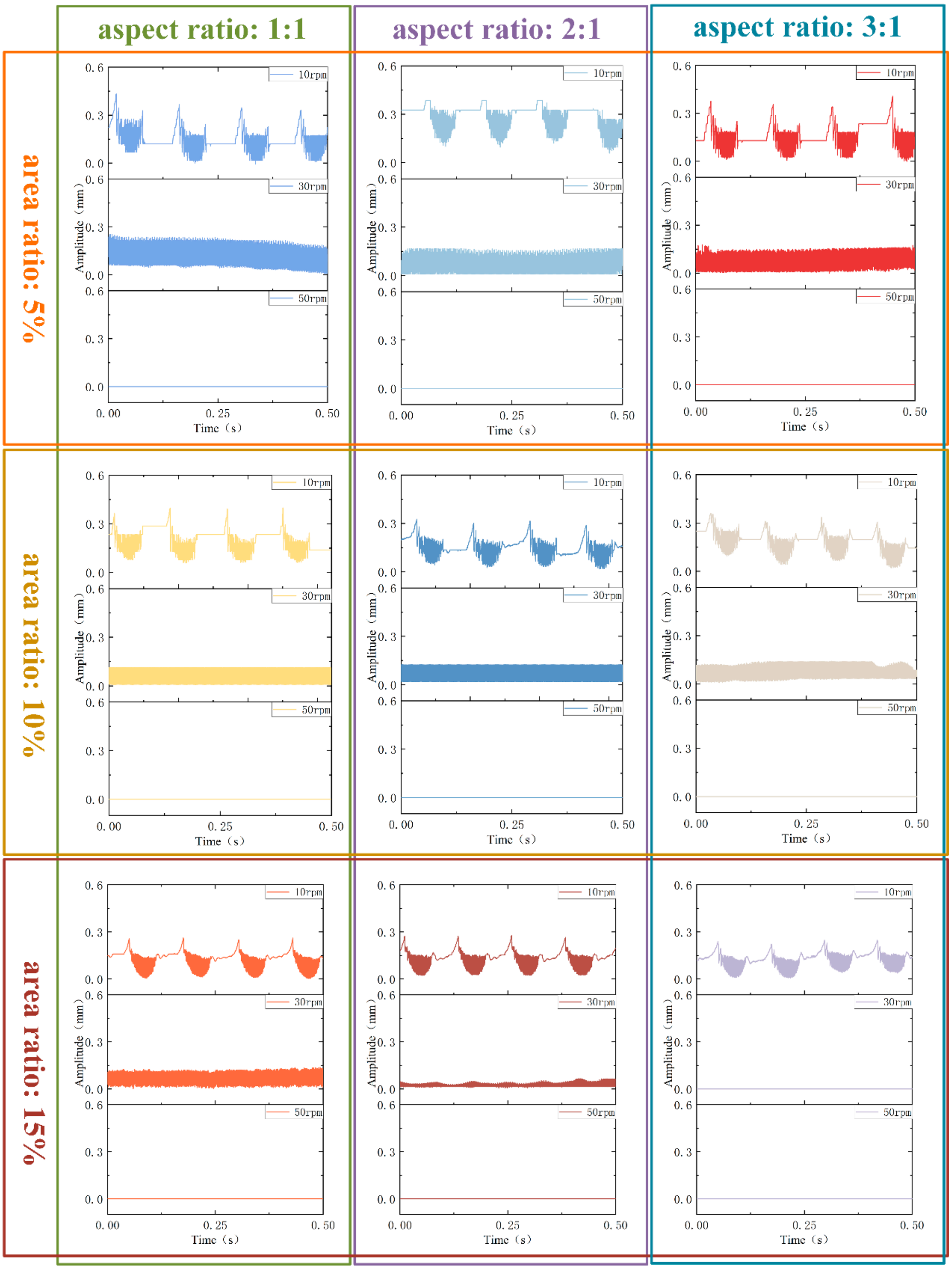


Figure 9. The effect of rotational speed and texture parameters on test block displacement.

3.4. The Effect of Different Texture Parameters on the Worn Surface of the Test Block

As illustrated in Figure 10, the surface roughness (Sa value) of textured test blocks with varying area ratios and aspect ratios was compared against that of the non-textured test block following the wear test. The non-textured block (Sample 10) exhibited a significantly higher surface roughness, with a greater standard deviation compared to the textured blocks.

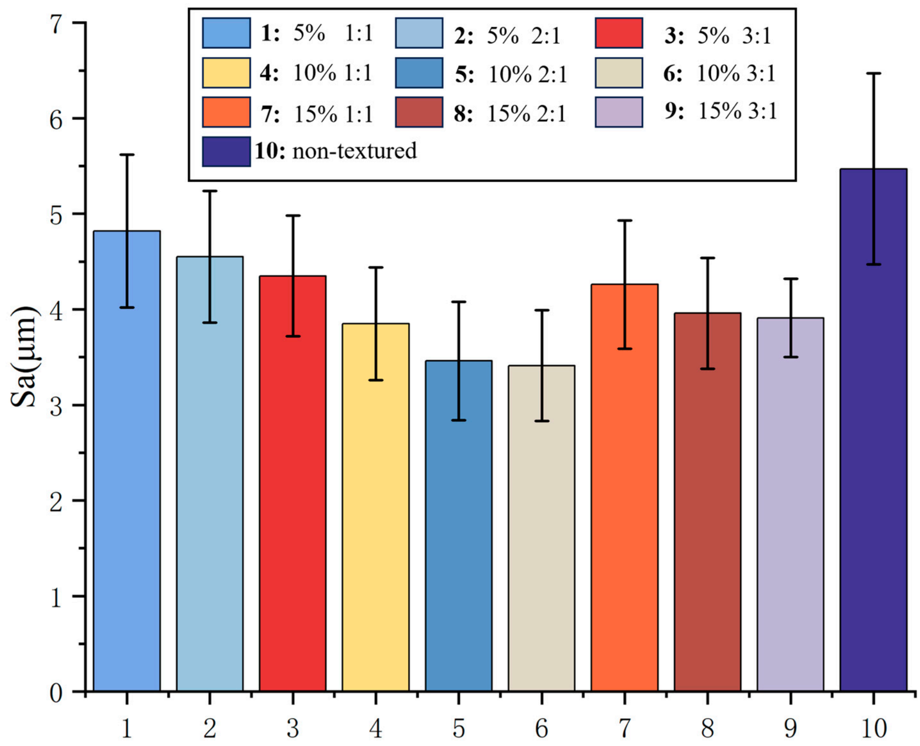


Figure 10. The effect of load and texture parameters on the worn surface of the test block.

In terms of area ratio, surface roughness generally decreased as the area ratio increased from 5% to 10%. However, when the area ratio increased from 10% to 15%, a slight rise in surface roughness was observed, though it remained considerably lower than that of the 5% area ratio samples.

Regarding the aspect ratio, its influence on Sa values was also pronounced. Test blocks with an aspect ratio of 1:1 (Samples 1, 4, and 7) displayed relatively higher surface roughness. As the aspect ratio increased to 3:1 (Samples 3, 6, and 9), surface roughness values showed a declining trend. Particularly, Sample 6 (with a 10% area ratio and a 3:1 aspect ratio) demonstrated the lowest Sa value, indicating that a larger aspect ratio is more effective in mitigating surface wear.

In conclusion, selecting appropriate combinations of texture area ratios and aspect ratios can significantly reduce the surface roughness of the test blocks. These results suggest that such texture designs are beneficial for minimizing wear and enhancing lubrication performance.

4. Discussion

The results above indicate that under extreme conditions, water-lubricated rubber bearings experience friction-induced vibrations in the form of flutter and squeal due to stick–slip phenomena at the friction interface. Surface texturing can mitigate these vibrations. However, the following questions arise: (1) Why can surface texturing alleviate the friction-induced vibrations in water-lubricated rubber bearings? (2) What effect do different texture parameters have on the vibration of the test blocks? (3) How does surface texturing influence the wear characteristics of water-lubricated rubber bearings?

4.1. Why Do Surface Textures Mitigate Friction Vibration in Water-Lubricated Rubber Bearings?

Surface textures can effectively mitigate friction-induced vibrations in water-lubricated rubber bearings. The primary mechanism behind this is their ability to store and redistribute lubricating water, which generates a hydrodynamic pressure effect. Experimental results indicate that different surface texture parameters significantly influence lubrication performance and vibration characteristics at the friction interface. As shown in Figure 11, the non-textured test block (Sample 10) displayed weaker fluorescence signals, indicating a larger contact area at the friction interface, which resulted in increased friction force and intensified vibration. In contrast, the textured test blocks exhibited uniformly distributed fluorescence signals, showing that the micro-textures facilitated the storage and redistribution of lubricating water. These micro-reservoirs help optimize lubrication conditions, thereby reducing the friction coefficient at the interface. By creating a hydrodynamic effect, multiple small lubrication "support points" are formed, reducing the actual contact area and effectively alleviating friction-induced vibrations.

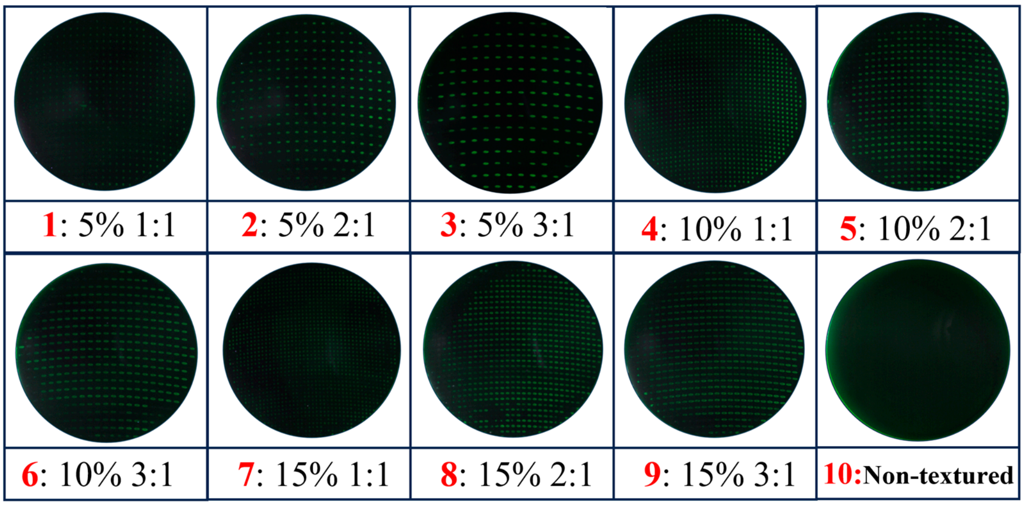


Figure 11. Schematic diagram of lubricating water distribution for test blocks with different texture parameters.

Based on hydrodynamic theory, surface textures create multiple small depressions or grooves between the rubber and metal through their micro-geometrical structures. As shown in Figure 12, these structures not only facilitate the storage and redistribution of lubricating water at the friction interface but also enhance the hydrodynamic effect of the liquid [33]. When the bearing operates in water, the frictional movement causes water to circulate within the textured grooves. This circulation leads to a more even pressure distribution across the water film, helping to form a continuous lubrication layer. This layer reduces direct contact between the rubber and metal surfaces [34]. Additionally, the micro-structures of the textured surface guide the lubricating liquid into the contact area and help create a stable hydrodynamic region. This hydrodynamic region can support part of the load on the bearing, reducing the actual contact area between surfaces and thereby minimizing friction and wear.

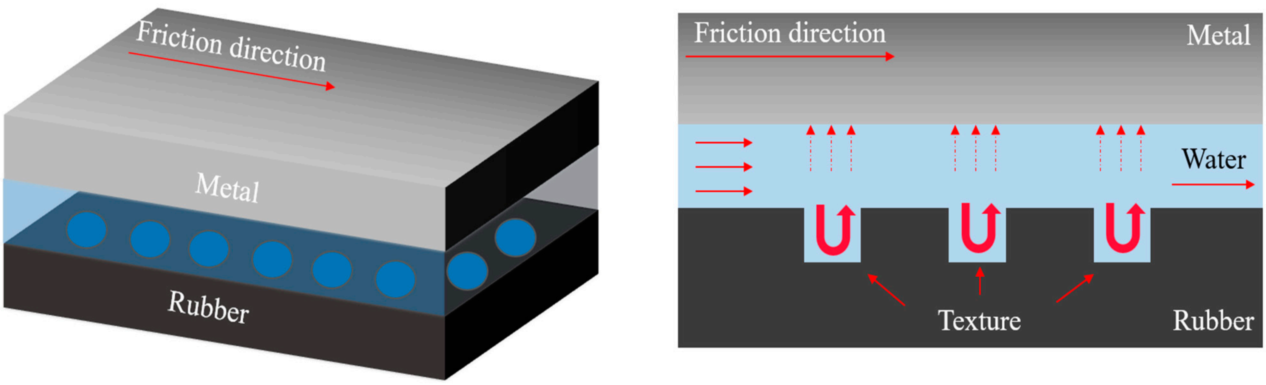


Figure 12. Schematic diagram of the effect of surface texture on lubricating film formation and hydrodynamic pressure effects.

Thus, by optimizing the distribution of the lubricant and enhancing the hydrodynamic effect, surface textures effectively reduce vibration and wear in water-lubricated rubber bearings.

4.2. What Is the Effect of Different Texture Parameters on Test Block Vibration?

As shown in Figure 13, different texture parameters have a significant impact on the vibration and displacement of the test blocks. As the rotational speed increases, both vibration amplitude and displacement amplitude show a decreasing trend overall. Notably, the vibration and displacement amplitudes of the non-textured test block are consistently higher than those of the textured blocks at all speeds, indicating that the introduction of surface textures greatly enhances vibration reduction and mitigates friction-induced vibrations.

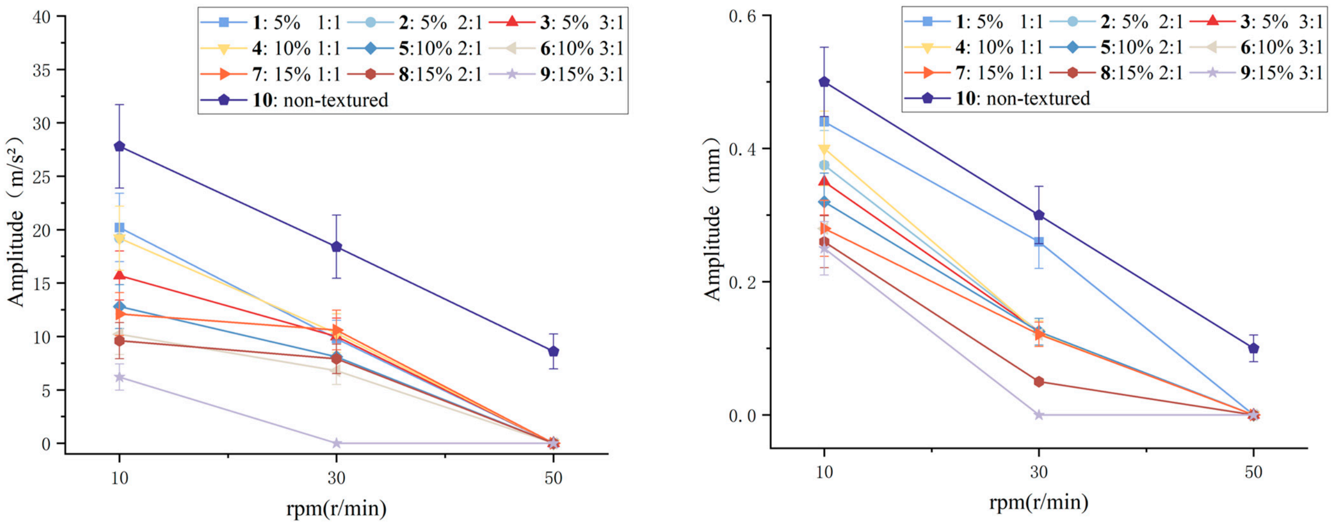


Figure 13. Variation in vibration and displacement amplitude of test blocks with different texture parameters at different rotational speeds.

From the perspective of area ratio, as the area ratio increases from 5% to 15%, the vibration and displacement amplitudes of the test blocks show a clear decline. This suggests that larger area ratios contribute to reducing vibration and displacement.

In terms of aspect ratio, the impact on vibration and displacement is also significant when the area ratio is held constant. Test blocks with a 3:1 aspect ratio exhibited lower vibration and displacement amplitudes than those with aspect ratios of 2:1 and 1:1, demonstrating superior vibration reduction performance. This indicates that the larger the aspect ratio, the better the lubrication effect and vibration reduction capacity of the texture at the friction interface.

In summary, both the area ratio and aspect ratio of the surface textures are key factors influencing the vibration reduction performance of the test blocks. Larger area ratios and aspect ratios help optimize vibration reduction effects.

4.2.1. Effect of Area Ratio of Texture

In analyzing the effect of different area ratios of surface textures on the vibration of water-lubricated rubber bearing test blocks, as shown in Figure 14, it was found that the texture with a 15% area ratio exhibited the best vibration reduction. The reason for this is that as the area ratio increases, the actual contact area per unit decreases, resulting in a greater number of texture "support points" within each unit area. These support points, formed by the grooves in the texture, provide additional micro-hydrodynamic pressure zones. The increased number of support points allows the lubricant to distribute more evenly across the friction interface, forming a more continuous and robust lubrication film, which reduces direct contact between the rubber and metal surfaces.

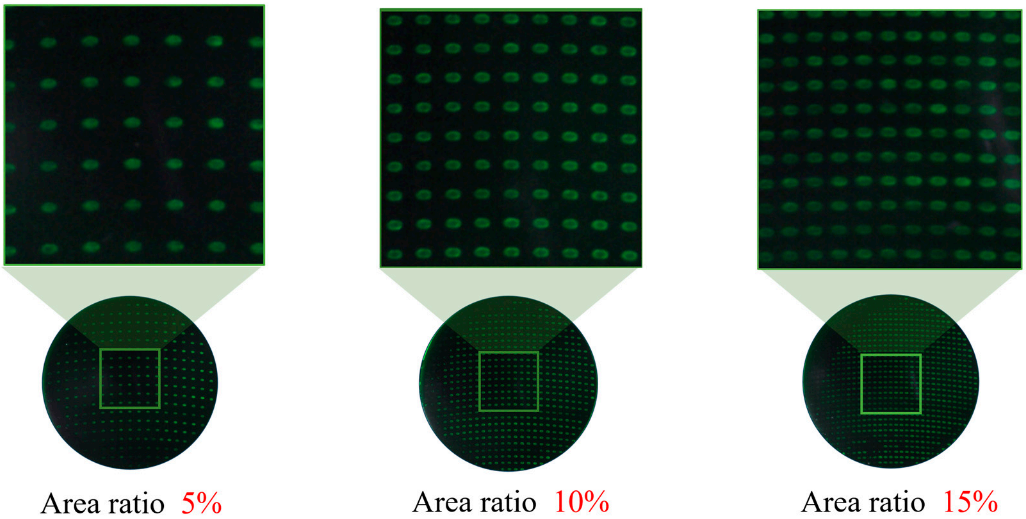


Figure 14. Fluorescence images of test blocks with different area ratios of texture.

Additionally, the higher number of support points helps distribute the load pressure more effectively, reducing localized contact pressure and further decreasing friction-induced vibrations. Therefore, the texture with a 15% area ratio not only improves lubrication by increasing the number of support points but also enhances vibration reduction, making it the best-performing configuration in the experiment.

4.2.2. Effect of Aspect Ratio of Texture

In analyzing the effect of different aspect ratios of surface textures on the vibration of water-lubricated rubber bearing test blocks, as shown in Figure 15, it was found that textures with a 3:1 aspect ratio performed significantly better in vibration reduction than those with aspect ratios of 2:1 and 1:1. This phenomenon can be explained by the impact of texture shape and distribution on the formation of the lubrication film. The elongated texture with a 3:1 aspect ratio is more effective in supporting and distributing the load, thereby reducing direct contact between the test block and the metal surface, which in turn decreases friction-induced vibrations.

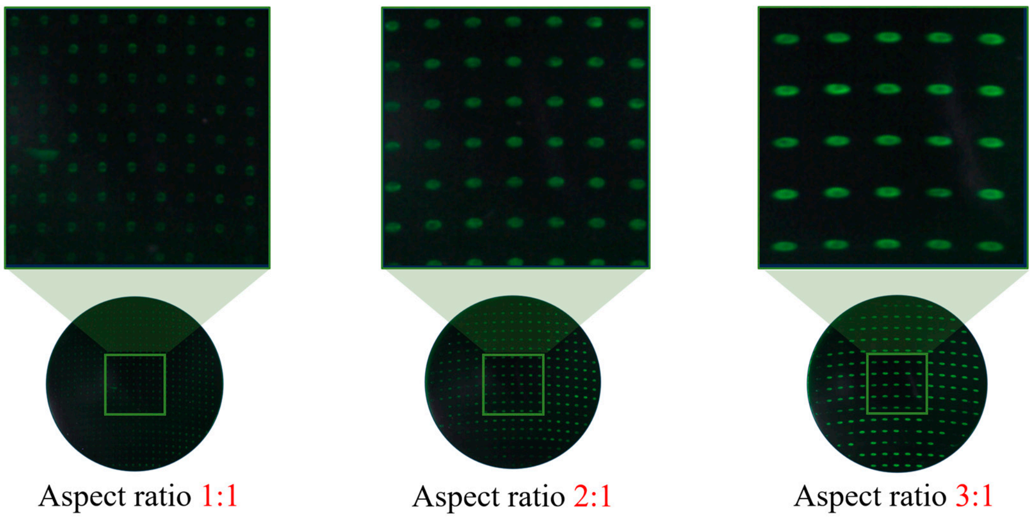
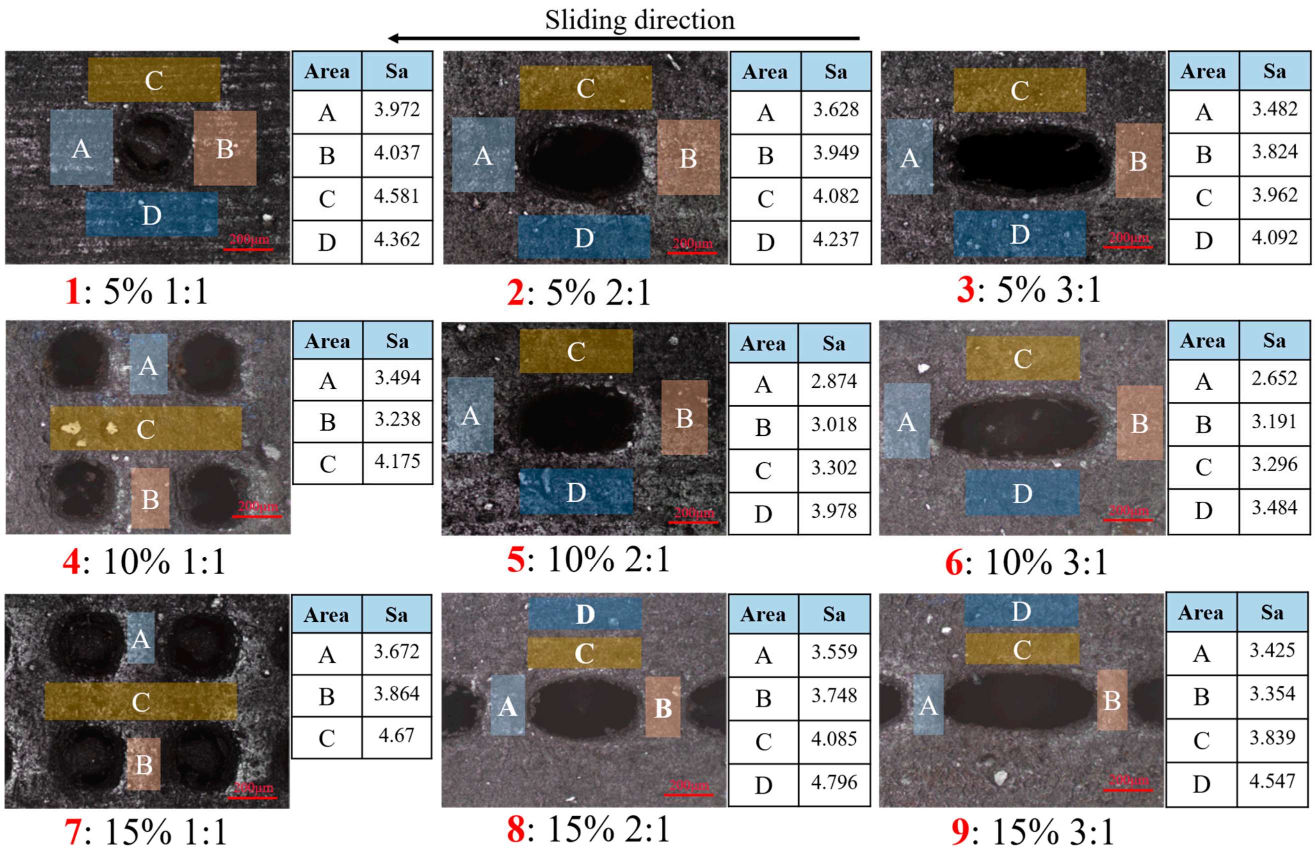


Figure 15. Fluorescence images of test blocks with different aspect ratios of texture.

This observation is further supported by fluorescence imaging. Test blocks with a 3:1 aspect ratio exhibited the highest fluorescence intensity, indicating a more continuous and uniform lubrication film in this design. The more stable lubrication film not only improves lubrication efficiency but also significantly enhances vibration reduction. Therefore, the texture design with a 3:1 aspect ratio shows clear advantages in optimizing water-lubricated conditions and reducing vibration.

4.3. How Do Textures Affect the Wear Characteristics of Water-Lubricated Rubber Bearings?

As shown in Figure 16, the surface roughness distribution and contact area analysis of test blocks with different texture parameters were conducted. Precise measurements of surface roughness in different areas of the test blocks were obtained using a laser confocal microscope. The comparative analysis of roughness at various positions on the textured surfaces revealed the following patterns: the roughness in the outlet region was significantly lower than that in the inlet region. This indicates that during the friction process, the actual contact area in the outlet region was smaller, leading to better formation of the lubrication film and reduced wear caused by direct contact. The roughness on the sides of the texture was generally higher than that at the inlet and outlet, likely due to greater shear forces on the sides, resulting in increased localized contact areas. The roughness in non-textured areas was noticeably higher than that around the textured regions, clearly showing that the larger contact area in the non-textured regions led to more severe surface wear due to friction.



1: 5% 1:1

Area	Sa
A	3.972
B	4.037
C	4.581
D	4.362

2: 5% 2:1

Area	Sa
A	3.628
B	3.949
C	4.082
D	4.237

3: 5% 3:1

Area	Sa
A	3.482
B	3.824
C	3.962
D	4.092

4: 10% 1:1

Area	Sa
A	3.494
B	3.238
C	4.175

5: 10% 2:1

Area	Sa
A	2.874
B	3.018
C	3.302
D	3.978

6: 10% 3:1

Area	Sa
A	2.652
B	3.191
C	3.296
D	3.484

7: 15% 1:1

Area	Sa
A	3.672
B	3.864
C	4.67

8: 15% 2:1

Area	Sa
A	3.559
B	3.748
C	4.085
D	4.796

9: 15% 3:1

Area	Sa
A	3.425
B	3.354
C	3.839
D	4.547

Figure 16. Surface roughness distribution and contact area analysis of test blocks with different texture parameters.

Furthermore, the surface roughness of test blocks with different area ratios varied significantly. The surface roughness of the test block with a 15% area ratio was noticeably higher than that of the 10% area ratio block. This could be because increasing the area ratio reduces the actual contact area. Under heavy load conditions, smaller contact areas may lead to higher localized contact pressure, thereby intensifying surface wear. However, while the roughness of the 15% area ratio block increased, it remained lower than that of the

5% area ratio block. This suggests that a moderate increase in area ratio helps to distribute stress more effectively under high-load conditions, reducing overall wear.

In summary, the analysis of surface roughness across test blocks with different texture parameters demonstrates that surface texture design plays a significant role in regulating the frictional contact area, optimizing lubrication performance, and reducing wear. While a larger area ratio (such as 15%) may increase localized contact pressure under heavy load conditions and intensify wear, its overall performance still surpasses that of blocks with smaller area ratios (such as 5%). This indicates that a moderate increase in area ratio can effectively distribute load and reduce localized wear. Additionally, the lower roughness in the outlet region further confirms the effectiveness of lubrication film formation and maintenance on textured surfaces. Overall, these findings suggest that optimizing surface texture design requires balancing area ratio, load conditions, and lubrication to achieve optimal wear reduction and extended service life.

In the mixed lubrication state of the friction interface, the lubrication film cannot fully separate the contact surfaces, causing some rough peaks to still make direct contact. This results in more severe vibration and wear. The design of surface textures plays a crucial role in mitigating this phenomenon, but it is essential to balance friction reduction and wear rate.

Small Area Ratio (5%): When the surface texture area ratio is 5%, the texture can effectively improve local lubrication conditions. Compared to non-textured surfaces, vibration and wear are significantly reduced. However, due to the small textured area, poor lubrication may still exist in the non-textured regions.

Moderate Area Ratio (10%): As the surface texture area ratio increases to 10%, the lubrication effect improves significantly. The occurrence of direct contact between rough peaks is reduced, resulting in a substantial decrease in vibration and wear. Textures with this area ratio effectively enhance the performance of the friction interface.

Large Area Ratio (15%): When the area ratio is further increased to 15%, the texture reduces the direct contact points between rough peaks, lowering friction and vibration. However, the reduced contact area increases the pressure per unit area, leading to faster wear and greater surface damage.

Thus, surface texture design must balance friction reduction and wear rate. Insufficient texture may fail to adequately improve lubrication, while excessive texture may reduce friction but accelerate wear. Therefore, an optimal area ratio is key to improving the performance of the friction interface.

5. Conclusions

(1) Effect of Surface Texture on Friction and Vibration: Experimental validation demonstrated that surface texture design can significantly improve the friction behavior and vibration characteristics of water-lubricated rubber bearings under low-speed and high-load conditions. In particular, test blocks with higher area ratios and larger aspect ratios exhibited superior vibration reduction performance. The experimental results showed that surface textures contribute to the formation of a more stable lubrication film at the friction interface, which effectively reduces friction-induced vibration, minimizes fluctuations in friction force, and thereby enhances the overall performance of the bearing.

(2) Selection of Surface Texture Parameters: This study found that textures with a 3:1 aspect ratio performed exceptionally well in reducing vibration. This design effectively distributes the load and reduces the contact area. Additionally, an increase in area ratio within a certain range enhances vibration reduction. However, when the area ratio increased from 10% to 15%, surface roughness also increased, suggesting that an excessively large area ratio may lead to intensified localized wear. Therefore, a balanced selection of area ratio and aspect ratio is critical to optimizing the performance of water-lubricated rubber bearings.

This study developed a visualization system based on computer vision technology to analyze the vibration suppression and wear reduction mechanisms of the friction interface in water-lubricated rubber bearing–rotor systems. Results indicate that surface textures significantly reduce friction-induced vibrations and wear. However, the practical application of these findings in bearing design requires consideration of complex working conditions, long-term wear effects, texture parameter optimization, and industrial production feasibility. Therefore, further experimental validation and process adjustments are necessary to ensure stability and adaptability under various conditions, ultimately facilitating the application of these findings in real-world bearings.

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