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Review

Implication of Surface Texture and Slip on Hydrodynamic Fluid Film Bearings: A Comprehensive Survey

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Abstract

Numerous published studies on the non-wettable surfaces with surface texture and slip conditions have been reviewed comprehensively to evaluate the performance of hydrodynamic bearings from last two decades. The recent numerical and experimental studies have been explored to observe the individual and combined influence of surface texture and slip. A variety of texture shapes and optimized slip zone profiles have also been discussed in this article. It has been observed from the literature that a suitable combination of modified slip and the conventional no-slip zone is effective in improving dynamic and static performance of hydrodynamic bearings. Many experimental studies also revealed that micro-scale textures are significantly capable of improving the tribological performance. Moreover, slip boundary condition is more beneficial at low and medium eccentricity ratios.

Keywords

hydrodynamic thrust bearings, hydrodynamic journal bearings, super hydrophobic surfaces, slip/no-slip boundary condition, navier slip boundary condition

1 Introduction

Supporting components play a very important role in the healthy and efficient working of any machinery. Hydrodynamic bearings are known as important supporting components for any rotating machinery. These are used to support radial and axial load for medium to high speed rotating shafts. Sufficient viscosity of the lubricant, relative motion, and wedge shape gap between contacting surfaces is necessary to avoid surface to surface contact in hydrodynamic bearings [1]. High level of friction and wear during the starting/stopping period, dynamic instability at high speed, and temperature rise with continuous working are the factors which limit the widespread development and application of hydrodynamic bearings [2, 3]. Microscale hydrodynamic bearings require high external force for its smooth operation because for small scale bearings inertia forces are more reduced as compared to the forces of adhesion [4, 5]. High force of adhesion causes an increase in temperature at the interface. Bearing operation ceases due to continuous running at high temperatures [6]. One way to increase the tribological performance of micro and macro scale hydrodynamic bearings is to replace the conventional no-slip boundary condition with slip boundary condition. Bearing performance significantly depends on boundary conditions. Bearing issues like rising in temperature, dynamic instability, rising in friction, and others can be controlled by updating the boundary condition. Navier [7] was the first person who proposed the concept of a boundary slip condition as shown in Fig. 1. In this condition, the slip velocity magnitude ‘u0’ is proportional to the magnitude of the gradient of velocity at the fluid-solid interface.

$$u_0 = b \left| \frac{\partial u}{\partial y} \right| \tag{1}$$

Where $\partial u/\partial y$ is the gradient of velocity and b is the slip length. Surfaces with finite slip velocity are called non-wettable surfaces [8-10]. Many experimental studies observed that slip effect for

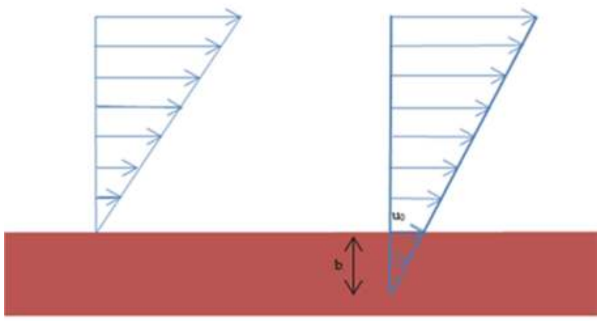

Fig. 1 Schematic of fluid at fluid-solid interface

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fluids on wettable surfaces is in very small length scales about in nanometers. Due to this reason effect of slip-on wettable surfaces is neglected [11, 12]. The parameter like surface energy of both solid and liquid, static contact angle at the solid-liquid interface, and contact area of liquid on solid play very important role in deciding whether a surface is wettable to liquid or not. Table 1 shows the classification of surfaces for water and other liquid-based on static contact angle. In this review study, we are restricting our discussion on those surfaces which are interacting with water only. The wettable surface produces low slip length because the contact area at the liquid-solid interface is large. For non-wettable surfaces contact area at the liquid-solid interface is reduced. It was observed from experimental studies that slip length for non-wettable surfaces is in the range of few nanometers to serval micrometers [13, 14]. Mostly available surfaces for commercial applications are hydrophobic or hydrophilic in nature. Furthermore, Surface treatment is necessary to convert the hydrophobic and hydrophilic surface into super-hydrophobic surfaces. It has already been observed from recent studies that hydrophobic surfaces with micro scales regular or irregular roughness give highly non-wettable nature [15-18]. Microscale random & regular roughness pattern on any hydrophobic surface creates an air gap at interface between liquid and solid as shown in Fig. 2. The contact area at the interface between solid and liquid is reduced due to the fraction of the air gap between the interfaces [18].

The slip length is also increased by creating a micro-nano (micro/nano) level roughness pattern on any normal non-wettable surface [19-22]. Figure 3 shows a comparison of slip length for smooth non-wettable surface and surface with micro-scale random and regular textures. The maximum value of slip length is achieved when a complete air gap is maintained between liquid and solid interface as shown in Fig. 3b. The complete air gap is not stable for a long time. So surface with a complete air gap is an ideal situation of non-wettable nature [23].

Jung and Bhushan [24] replicate micro-nano scale lotus plant and sharkskin structure on smooth non-wettable silicon samples. They observed an increase in slip length for silicon surface with micro-nano scale hierarchical textures. Lee and Kim [25] observed the effect of random roughness on the wettability behavior of the smooth non-wettable surface. They show that wettability is reduced with random roughness pattern on any smooth surface.

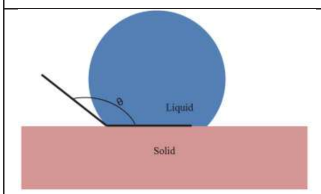
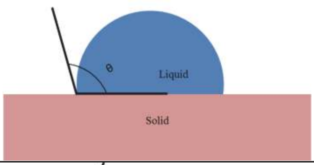
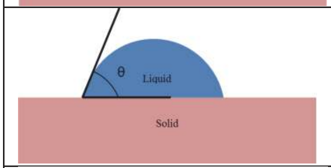
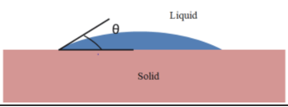
A number of techniques to fabricate surface textures have been developed over the decades as the interest of researchers in wettability effects of surface texturing grows. At an early age creating regular surface texture on any surface is really very difficult. Random surface texturing with chemical etching was commonly used in the 20th century. But nowadays with development in technology, the number of new techniques has been invented like laser surface texturing, micro-electric discharge machining, CNC ultrasonic machining, chemical machining, focused ion beam machining, abrasive jet machining, vibro-mechanical texturing, micro-grinding and micro-casting [26, 27]. Among these new techniques, laser surface texturing gives high accuracy and precise control over the shape and size of surface textures [28].

Young [29] derived a force balanced mathematical Eq. (2) to predict surface energy at the interface of liquid, air, and smooth solid surface. This mathematical equation describes the relationship between interfacial energy of all three phases and static contact angle as shown in Fig. 4.

$$cos\theta = \frac{(\sigma_{sa} - \sigma_{sl})}{\sigma_{la}} \qquad (2)$$

σ_{sa}, σ_{sl}, σ_{la} represent surface energy of solid-air, solid-liquid, and liquid-air interface. According to Eq. (2) static contact angles (θ) is greater than 90°, when the surface energy of the solid-air interface is greater than the liquid-air interface [30]. Cassie & Baxter [31] proposed a mathematical model to predict the contact angle on texture/rough hydrophobic surfaces. According to the proposed mathematical model as shown in Eq.

Table 1 Classification of surfaces based on static contact angle for water and other liquids

Interface Profile	Static Contact Angle (θ)	For Water Only	For Water & Other Liquids
	$\theta > 150^{\circ}$	Superhydrophobic	Superamphiphobic
	$90^{\circ} \leq \theta \leq 150^{\circ}$	Hydrophobic	Amphiphobic
	$10^{\circ} \leq \theta \leq 90^{\circ}$	Hydrophilic	Amphiphilic
	$0^{\circ} \leq \theta \leq 10^{\circ}$	Superhydrophilic	Superamphiphilic

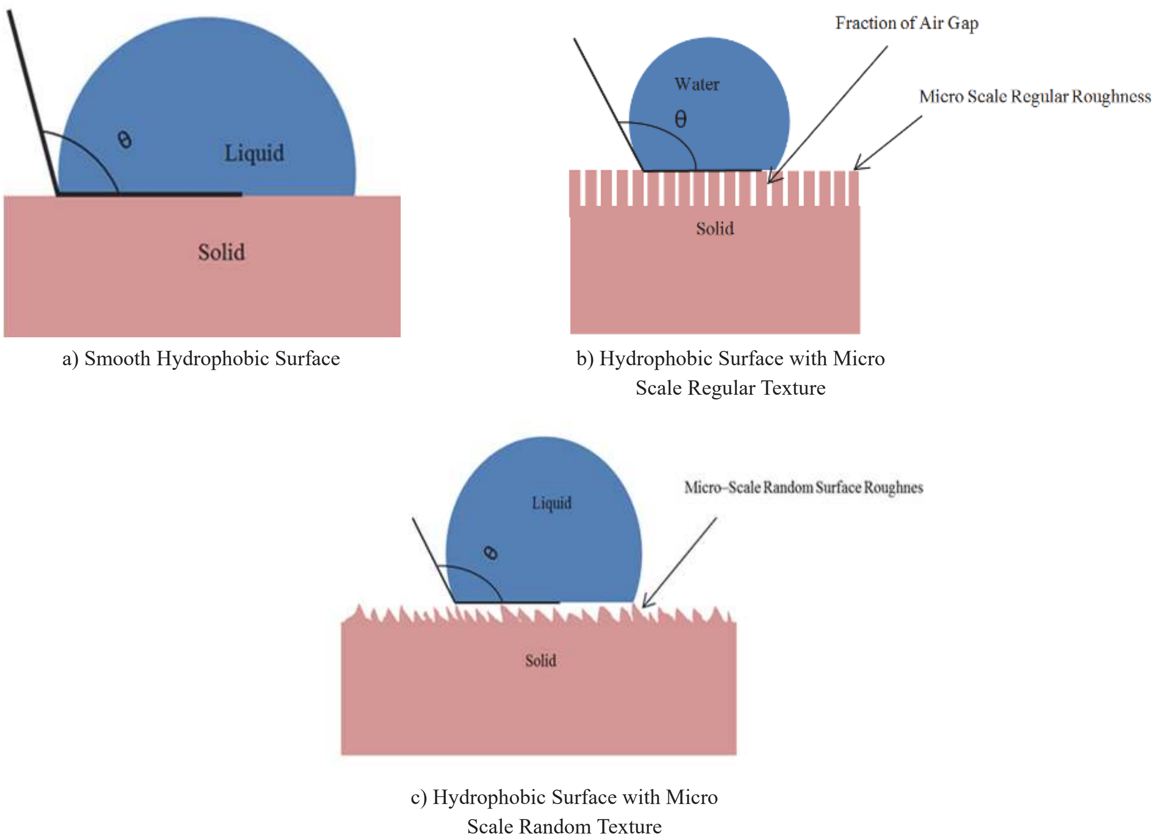


Fig. 2 Effect of micro scale random and regular roughness pattern on hydrophobic surface

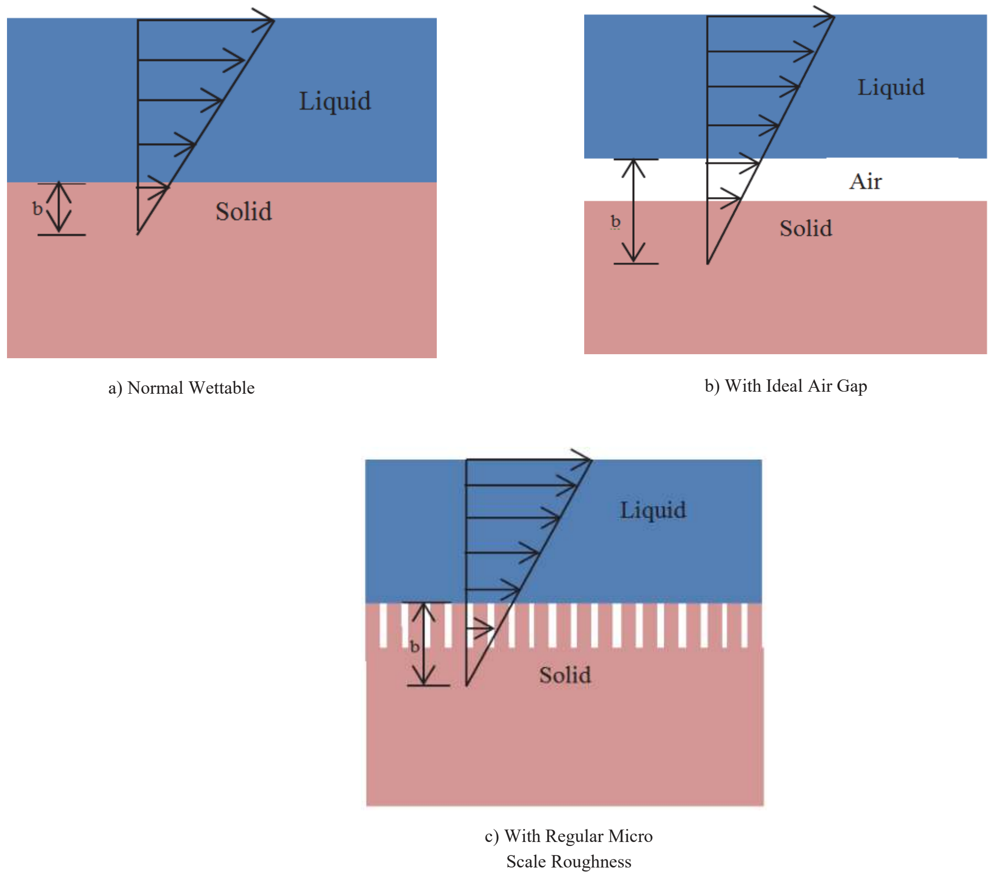


Fig. 3 Effect of Micro-Nano level roughness and ideal air gap on slip length

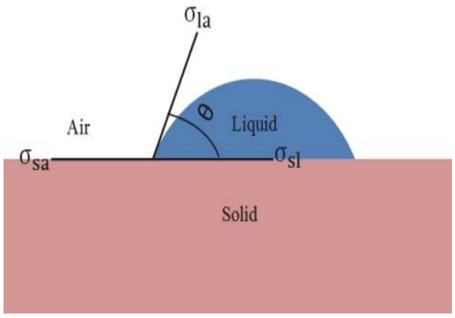


Fig. 4 Interaction of surface energy for liquid on smooth surface

(3) contact angle on texture/rough surface (θ_r) is proportional to the fraction of liquid area in contact with solid (f_{sl}) and contact angle of the liquid on a smooth solid surface (θ).

$$\cos\theta_r = f_{sl}\,(\cos\theta + 1) - 1 \tag{3}$$

2 Hydrodynamic bearings with slip & texture

From the last two decades, many researchers are showing curiosity in using slip effect to improving the performance of fluid film bearings [32]. Conventional hydrodynamic bearings are most commonly made up of metal and metals alloys [33]. The metal surfaces are mostly wettable in nature and strictly follow no-slip boundary condition. The metal surface showed strong wettability nature because atoms of the outermost surface layer on the metal surface are strongly bonded with high surface energy covalent bonding. The surface energy values of common engineering materials are shown in Table 2. Plastics are non-wettable in nature, because plastic has very low surface energy value than metals as shown in Table 2.

Surface texturing alone has the potential for improving performance in terms of reducing wear, friction, and lubrication consumption [35]. In general, a surface texture may protrude out of the surface like square and cylindrical pillars, or within the surfaces, such as spherical or cylindrical dimple. It can also be made up of channels, continuous radial, or circumferential grooves. It can be discrete shapes, such as circular, square, triangular, or hexagonal, those are distributed evenly or randomly. In the present review paper literature survey on hydrodynamic bearings with surface texturing and slip boundary conditions is presented. The classification scheme adopted to explain the literature survey is as shown in Fig. 5.

2.1 Numerical study

Combined mass conservation and momentum equations into a single equation are used to simulate numerically the performance of hydrodynamic bearings. The general equation used to evaluate static and dynamic characteristics is called Reynolds equation [36]. Reynolds equation is a second-order non-linear partial differential equation. Certain assumptions are made while deriving this equation like fluid is incompressible and Newtonian, inertia forces are neglected, no-slip boundary condition on both surface, surfaces are in relative motion and flow is laminar. According to conventional Reynolds equation pressure generated in bearing depend on the viscosity of lubricant, shape, and size of the gap between surfaces and velocity of surfaces in relative motion. To consider the effect of slip and surface texturing on hydrodynamic bearing Reynolds equation need to be modified with updated boundary conditions. The detailed literature related to the individual and combined effect of slip and surface texturing on Slider/Thrust and Journal bearing is discussed below.

2.1.1 Slider bearing with slip

The classical Reynolds equation with conventional no-slip boundary condition is an important mathematical model in bearing design and analysis. Therefore, to effectively consider the effect of modified slip boundary condition researchers modified the Reynolds equation. A solution for the modified Reynolds equation with an updated slip boundary condition considering Newtonian and incompressible lubricants was given by Spikes [37, 38]. Many experimental observations Pit et al [39], Craig et al [40], Zhu & Granick [41-43] show that Eq. (1) could not effectively define the slip velocity at the fluid-solid interface. The experimental observations on slip velocity at non-wettable surfaces show the presence of critical shear stress (τ_c). When, the surface shear stress (τ_s) < τ_c, then no slip occurs. However, slip occurs, when $\tau_s > \tau_c$. Therefore, it is more practical to adopt the τ_c criterion in the numerical modeling of the lubrication problem with boundary slip. Spikes [37] modified the slip boundary condition to consider the effect of critical shear stress in bearings. He observed that the slip effect is beneficial on the

Table 2 Surface Energy of Common Engineering Materials; reproduced with permission from [34] Copyright (2005) Taylor & Francis Group LLC - Books

Common Engineering Materials		Plastics			
Materials	Surface Energy (mJ/m^2)	Material	Surface Energy (mJ/m^2)	Materials	Surface Energy (mJ/m^2)
Copper	1100	Kapton	50	PVC	38
Stainless Steel	900	Phenolic	47	Polystyrene	36
Aluminium	840	Nylon	46	Acetal	36
Zinc	750	Polyester	43	Polyethylene	31
Tin	525	Polyurethane	43	Polypropylene	29
Lead	460	ABS	42	PTFE	18
Glass (Porcelin)	375	Polycarbonate	42	Polystyrene	36

stationary surface. Li et al [44] derived generalized modified Reynolds equation with slip boundary condition on both moving and stationary surface of hydrodynamic bearings. They assumed a slip boundary condition with zero critical shear stress. Salant & Fortier [45] optimized slip zone profile as shown in Fig. 6 a & b for parallel and convergent slider bearings.

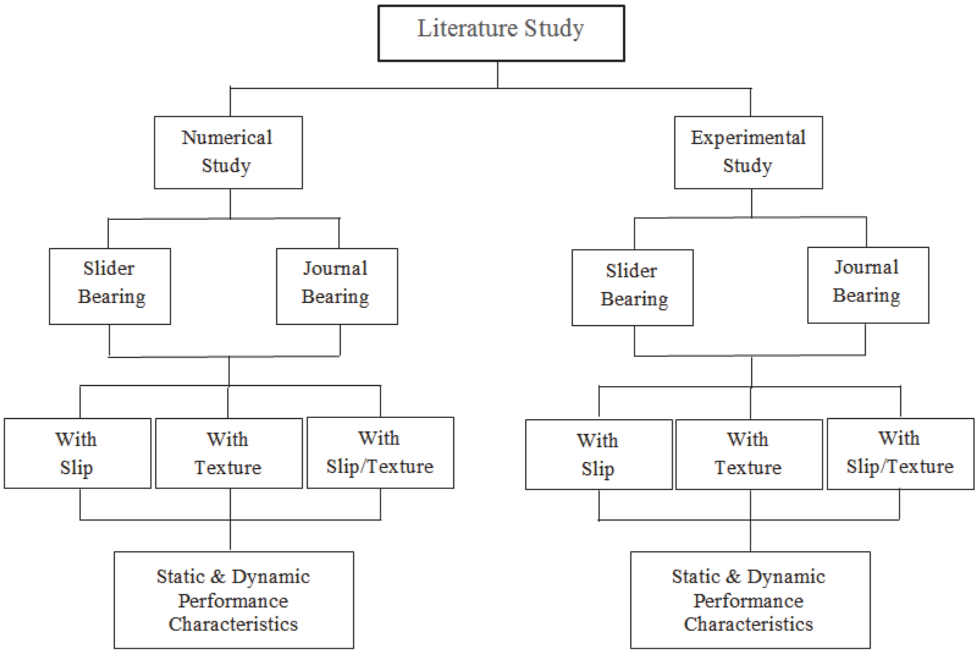
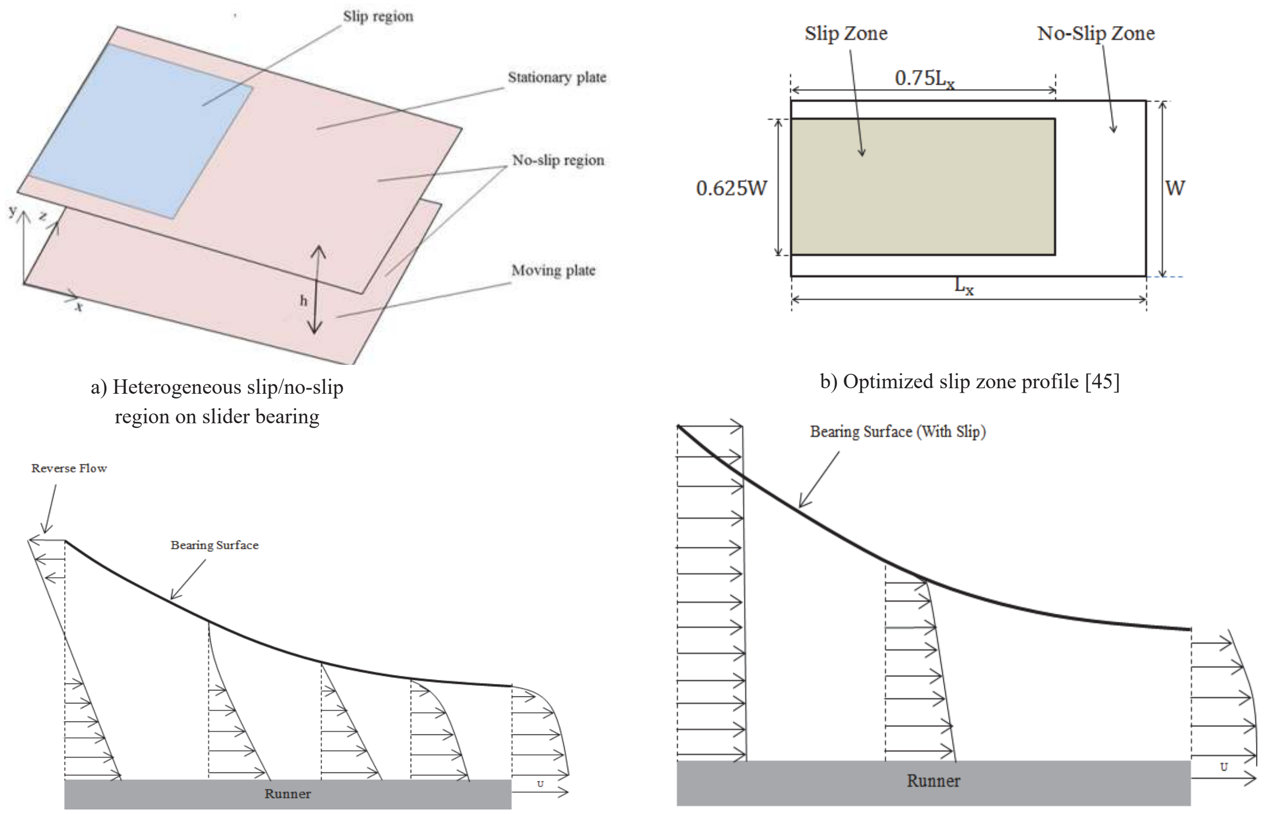


Fig. 5 Classification scheme adopted to explain the literature survey



a) Heterogeneous slip/no-slip region on slider bearing

b) Optimized slip zone profile [45]

c) Velocity profile with conventional No-slip boundary condition [47]

d) Velocity profile with slip boundary condition [47]

Fig. 6 Heterogeneous slip/no-slip boundary condition for slider bearings; (c, d) reproduced with permission from [47] Copyright (2011) American Society of Mechanical Engineers ASME

They observed that slider bearing carrying incompressible and Newtonian fluid with heterogeneous slip/no-slip boundary condition on the stationary surface give an improvement in bearing performance. Wu et al [46] compared hydrodynamic pressure and friction drag for different converging, diverging and parallel configuration with bearing surface carrying slip/no-slip boundary condition. When both moving and stationary surfaces of the bearing are in the conventional no-slip boundary condition then the flow of lubricant occurs in the reverse direction at the inlet of the bearing. The introduction of slip boundary condition on the stationary surface of the bearing reduced the reverse flow of the lubricant. In other words, the introduction of slip boundary condition is increasing the intake rate of the lubricant as shown in Fig. 6 c & d [47]. Zhang [48], Song et al [49], and Zhu et al [50] compared static performance characteristics for thrust bearing carrying slip/no-slip boundary with conventional no-slip boundary condition. Similarly, Park et al [51] and Bailey et al [52, 53] compared dynamic performance characteristics for thrust bearing carrying slip/no-slip boundary with conventional no-slip boundary condition. The results for performance characteristics with slip boundary conditions & assumptions used for the study are listed in Table 3. The following points highlight important observations regarding the effect of slip boundary condition on performance parameters of thrust bearings:

- The slip boundary condition on the moving surface has not beneficial in improving bearing performance. While stationary surface with slip boundary has reduced the load-carrying capacity and friction force [37, 38].
- Load carrying capacity and friction force improved with an increase in slip length for partial slip/no-slip stationary surface [45].
- Bearing stationary surface with heterogeneous slip/no-slip surface give a maximum tribological performance for concentric configuration [46].
- When 80% of stationary surface area covered with slip boundary condition then bearing give the lowest coefficient of friction [48].
- Slip effect gives a reduction in power loss and minimum film thickness [50].

2.1.2 Slider bearing with surface texturing

A great deal of research works mainly involve studies of textured lubricated contacts. Texture shape and size play a very important role in improving the bearing performance [55]. Many texture shapes like square [56-58, 73], circular [59-61], elliptical [54, 62, 63], circumferential grooved [64, 134], radial grooved [64-66] as shown in Fig. 7 are used to improve thrust bearing performance. Brizmer et al [59] & Rahmani et al [56] observed that texturing on partial surface of thrust bearing is effective in improving the bearing performance. Cupillard et al [67] explained the pressure build-up mechanism for rectangular textured parallel thrust bearings. They observed that surface texturing reduces recirculation flow at the inlet, due to reduction in recirculation flow positive pressure is built at the inlet. Textured bearing performance significantly varies with

Table 3 Hydrodynamic slider/thrust bearing with slip

Author	Assumptions	Results
Frontier &Salant (2004)	• Flow is steady. • Fluid is Newtonian. • Flow is laminar. • Flow is incompressible. • Inertial forces are neglected. • Heterogeneous slip/no-slip boundary condition on stationary surface. • No-slip boundary condition on moving surface. • Temperature condition is isothermal.	• At zero critical shear stress with optimized slip/no-slip zone significant improvement in load-carrying capacity and friction force is observed. • For non-zero critical shear stress up to certain value, bearing behave like conventional ones and after crossing that limit bearing behave like bearing with slip /no-slip boundary condition. • Effect of slip boundary condition is more dominant at low convergence ratios. For high convergence ratios effect of slip is reduced. • Load carrying capacity increased by two times and friction force reduced by half as compared to conventional bearings.
Zhu et al (2019)	• Elastic deformation on surface. • Flow is steady. • Fluid is Newtonian. • Flow is laminar. • Flow is incompressible. • Inertial forces are neglected. • Heterogeneous slip/no-slip boundary condition on stationary surface. • No-slip boundary condition on moving surface. • Temperature condition is isothermal	• The elastic deformation of the surface tends to reduce the slip zone. • With heterogeneous slip/no-slip zone film thickness is increased. • Power loss is also reduced with slip boundary condition.

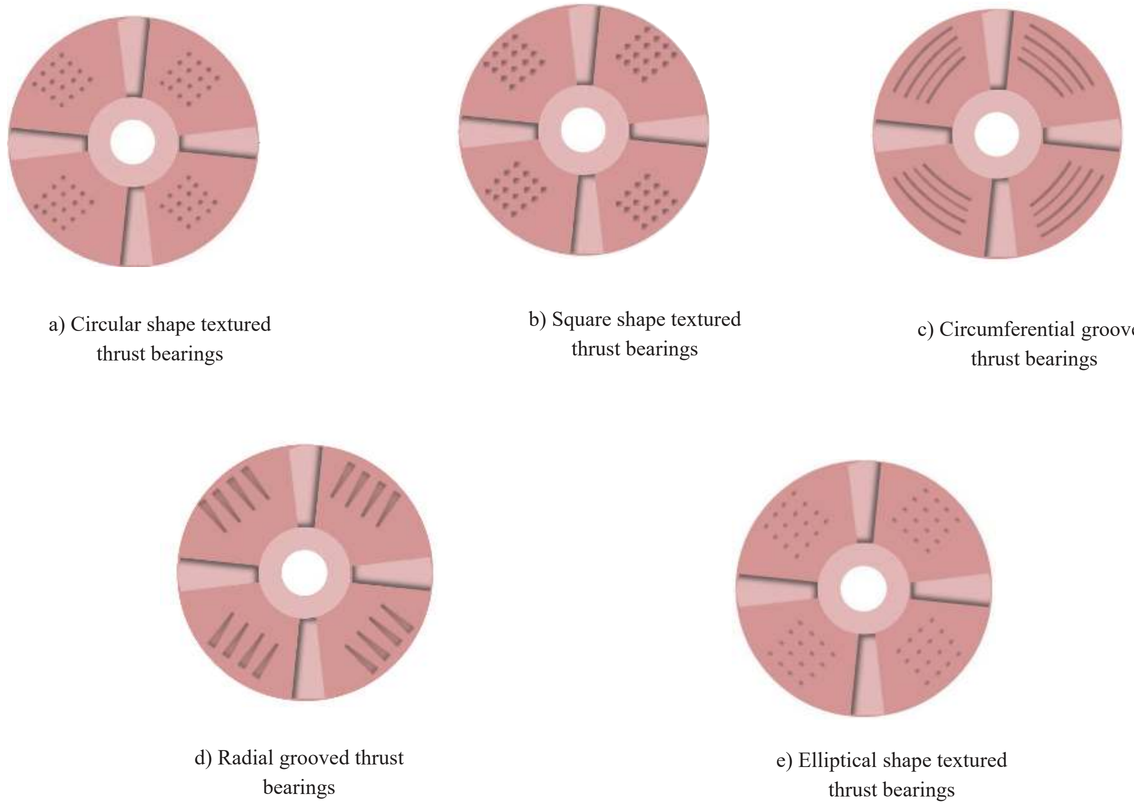


Fig. 7 Thrust bearing with different texture shapes

texture depth. The recirculation flow at the inlet is increased by increasing the texture depth over a certain limit. The increase in recirculation flow causes a reduction in overall pressure generation capacity of bearing [67]. Cupillard et al [68], Fouflias et al [69], Gropper [58], and Papadopoulos et al [70] observed the effect of micro dimpling on the thermal performance of thrust bearings. They observed that on texture thrust bearing overall temperature rise is reduced by a significant amount. Chalkiopoulos et al [133] consider the effect of thermal and mechanical deformation on the textured thrust bearing. Their study shows that thermal and mechanical deformation plays an important role in optimizing texture geometry for maximum performance of thrust bearings. Papadopoulos et al [71] and Qiu et al [72] examined the dynamic performance of textured thrust bearings. The following points highlight important observations regarding the effect on performance parameters with surface texturing on thrust bearings.

- Bearing performance is maximum when texture depth equal to film thickness [55].
- For texturing within the converging zone of bearing, increased number of textures are not beneficial in improving the bearing performance [56].
- For maximum performance length of texture should be equal to the gap between two textures [56].
- Effect of texturing is significant at low convergence ratios [65].
- Textured thrust bearing in diverging configuration able to generate a finite amount of load-carrying capacity [68].
- Texture zone extent up to ¾ of pad width and 2/3 of pad length is effective in decreasing friction force and in increasing load-carrying capacity [70].
- Cylindrical shape texture geometry gives better improvement as compared to other texture geometries [60].
- Textured thrust bearing shows a reduction in performance by considering thermal effect [54, 68, 69].
- Stiffness of textured bearing increases as compared to the smooth bearing surface [71].
- Damping of textured bearing decreases as compared to smooth bearing surfaces [71].
- Parallel textured thrust bearing gives an overall maximum performance as compared to the smooth bearing surface [54, 56, 59].
- Geometrical shape for maximizing bearing stiffness is different as compared to maximizing load-carrying capacity [71, 72].
- Textured with round edge and curved depth is better as compared to texture with straight edge and straight depth for improving both stiffness and friction force [55, 60].

2.1.3 Slider bearing with slip and surface texturing

It has been observed in many numerical studies that surface texturing and slip boundary condition are capable of improving the tribological performance of hydrodynamic thrust bearings [37, 45, 55, 56]. Rao et al [74] observed a combined effect of partial texturing and partial slip zone with zero critical shear stress on hydrodynamic slider bearings. They observed that with combined partial slip and partial texturing on slider bearing in parallel configuration give maximum enhancement in load-carrying capacity. Tauviqirrahman et al [75] optimized combined slip and texture zone profile for micro-scale short hydrodynamic slider bearings. They consider critical shear stress criteria while optimizing the combined slip-texture zone profile. Their study concluded that a partially textured surface combined with a partial slip zone is effective in generating higher load carrying capacity and a lower friction coefficient compared to bearings with the only surface textures. Slip zone profile with surface texturing on parallel surfaces give maximum tribological benefits for critical shear stress value close to zero [76]. Ismail and Sarangi [77] compared the effect of different texture shapes combined with heterogeneous slip/no-slip boundary condition on the friction force of parallel sliding contact. They observed that the performance of textured bearing with slip boundary condition is maximum at lower depth and lower aspect ratios. Table 4 shows the assumptions used and the input parameter taken for various performed numerical analysis on bearing with combined slip and textured. The following points highlight important observations regarding the effect of slip & texture on performance parameters of thrust bearings:

- Bearing with combined slip and texture region is beneficial in improving tribological performance at convergence ratio less than 0.3 [74].
- Load carrying capacity for bearing with combined slip & texture is not influenced by increasing the texture aspect ratio [75].
- Load carrying capacity for combined slip & texture bearing is decreased with an increase in the Reynolds number [76].
- Parallel sliding surface with combined slip & texture are efficient at higher slip length and lower critical shear stress values [77].

2.1.4 Journal bearing with slip

A journal bearing with a slip zone is as shown in Fig. 8 produce numerous advantages over the conventional journal bearing. The slip zone shape and size play an important role in improving the performance of bearings. Frontier & Salant [78] optimized the slip zone geometry for low-speed microscale

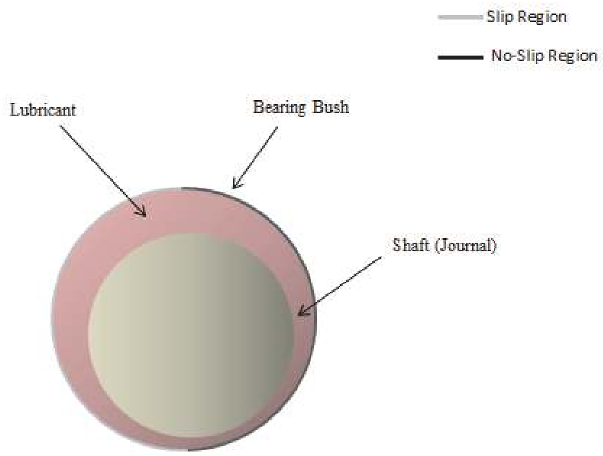


Fig. 8 Journal bearing with slip zone

Table 4 Hydrodynamic slider/thrust bearings with slip & texture

Author	Assumptions	Results
Tauviqirrahman et al. (2013, 2014)	• Temperature condition is isothermal. • Flow is steady and laminar. • No-slip condition on moving surface. • Slip condition on stationary surface. • Inertial force neglected. • Laminar flow.	• Texturing region has a huge impact on performance characteristics both for the combined textured/slippage pattern and the purely textured one. • With slip and texture predicted improvement in the load-carrying capacity is around 150–300%, While the reduction in the coefficient of friction is about 70–80%.
Ismail & Sarangi (2014)	• Fluid is incompressible. • Fluid is Newtonian. • Temperature condition is isothermal • Partial slip/no-slip condition on stationary surface. • No-slip condition on moving surface. • Inertial force neglected. • Laminar flow.	• With slip also sliding contacts can carry the load in a parallel configuration. • The fluid must have a slip length coefficient greater than 10.
Zouzoulas et al (2017)	• Fluid is Newtonian. • Effect of temperature on viscosity is considered. • Moving and stationary surfaces are in parallel configuration. • Fluid is incompressible. • Fluid is iso-viscous. • Fluid flow is laminar.	• Surface texture with slip boundary condition gives an overall reduction in friction force and maximum temperature rise. • Pocket bearing and bearing with circumferential groove performed better as compared to rectangular textured and radial groove bearings. • Film thickness is improved by 4-24%. • Overall temperature is reduced up to 7°C. • With the use of slip boundary condition load-carrying capacity improved by 62% and friction force reduced by 32%. • Slip boundary condition has great potential in improving the tribological performance of bearing.

hydrodynamic journal bearings. They observed that the rectangle shape slip zone profile within the convergent region is more efficient in maximizing the bearing performance. They also concluded that the effect of slip boundary condition is more significant for low eccentricity ratios while with increasing the eccentricity ratio the effect of slip boundary condition is reduced. Similarly, Cui et al [79] optimized the slip zone profile for high-speed journal bearings. They used varying slip length model to optimize the slip zone profile. They found that it is beneficial to extend the slip zone in the axial direction and the longitudinal length of the slip zone at the end of the slip zone must be greater than the starting length of the slip zone. The reduction of pressure in the diverging region is the most common problem in hydrodynamic journal bearings. This phenomenon of reduction of pressure is called cavitation. Bhattacharya et al [80] studied the effect of slip boundary condition on the cavitation region of hydrodynamic bearings. They showed that the multiple numbers of alternate slip/No-slip zones are effective in reducing the negative pressure area or cavitation area of the bearing. The optimized slip zone profiles with geometrical parameters are shown in Table 5.

Frontier & Salant [78] compared static performance characteristics of journal bearing with modified slip and conventional no-slip boundary condition. Rao [81] used a similar slip zone profile and observed dynamic characteristics of hydrodynamic journal bearings. Ma et al [135], Bhattacharya

Table 5 Optimized slip zone profiles for hydrodynamic journal bearings

<table>
<tr><th>Author & Year</th><th>Optimized Slip Zone Profile</th></tr>
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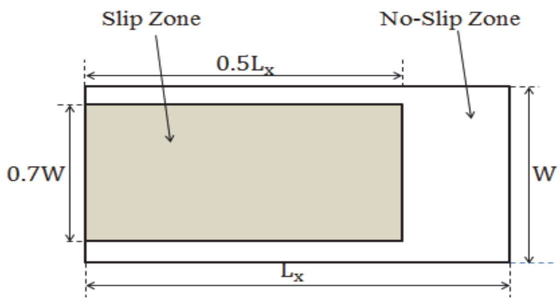
(2005)</td><td>
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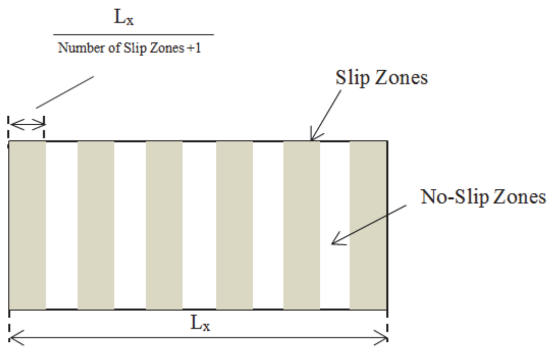
<tr><td>Bhattacharya et al. (2017)</td><td>
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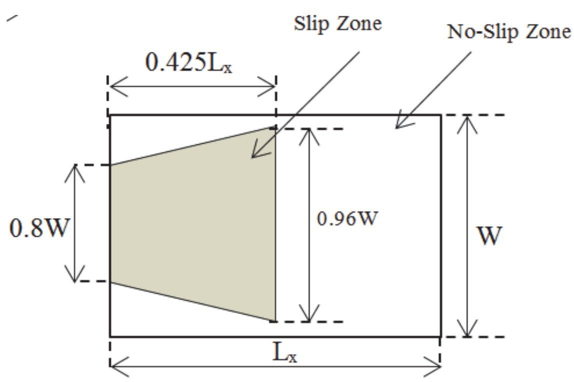
<tr><td>Cui et al. (2020)</td><td>
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et al [80] performed stability analysis with slip boundary condition for hydrodynamic journal bearing. Further study on the effect of slip boundary condition on static and dynamic characteristics of hydrodynamic journal bearings are listed in Table 6. For any performed numerical study assumption used and input parameters taken are very important. So, Table 6 also listed these important details. The following points highlight important observations regarding the effect on performance parameters with slip boundary condition on journal bearings.

- Journal bearing with slip is beneficial in improving bearing performance at low and medium eccentricity ratios [78].
- At high eccentricity ratios rectangular shape slip zone within the converging region of bearing give an improvement in friction force and load-carrying capacity [79].

Table 6 Hydrodynamic Journal Bearing with Slip

Author	Assumptions	Results
Fortier & Salant (2005)	• Temperature condition is isothermal. • Flow is steady and laminar. • No-slip condition on moving surface. • Heterogeneous slip/No-slip condition on stationary surface. • Inertial force neglected.	• Load carrying capacity increased by two times as compared to conventional bearings. • Friction force reduced by half as compared to conventional bearings. • At eccentricity ratio of above 0.92 slip boundary condition show little effect. • The side leakage rate is increased with slip boundary condition. • Slip coefficient value up to 10 significantly increased load-carrying capacity. • Slip coefficient value above 10 insensitive to load-carrying capacity. • Considering finite amount of critical shear stress is also helpful in improving bearing performance characteristics.
Rao (2009)	• Temperature condition is isothermal. • Flow is steady and laminar. • No-slip condition on moving surface. • Heterogeneous slip/No-slip condition on stationary surface. • Inertial force neglected.	• The large value of slip coefficient and the smaller dimension of the axial slip region improved threshold value. • At small eccentricity ratios variation of stiffness coefficients and damping coefficients are improved. • For high eccentricity ratios slip boundary condition insensitive to dynamic coefficients. • Slip zone extension in the axial direction up to 45^0 gives a maximum improvement in the threshold speed limit.
Wang et al. (2012)	• Fluid is incompressible. • Fluid is Newtonian. • Temperature condition is isothermal. • Partial slip/no-slip condition on stationary surface. • No-slip condition on moving surface. • Inertial force neglected. • Laminar flow.	• The oil film pressure, load carrying capacity, friction drag, and end leakage rate are larger with slip. • Temperature rise is lower and the oil film rupture delays with wall slip. • The wall slip and cavitation effect cannot change the trend of pressure distributions, with the change of eccentricity.
Zhang et al. (2014)	• Temperature condition is isothermal. • Flow is steady and laminar. • No-slip condition on moving surface. • Heterogeneous variable slip length boundary condition on stationary surface. • Inertial force neglected.	• Bearing with slip-on full surface significantly reduces friction coefficient at the cost of a reduction in load-carrying capacity. • For slip zone up to 140° bearing give maximum performance. • Cause of improvement in load-carrying capacity is the change in volumetric flow rate due to heterogeneous slip/no-slip boundary condition. • Slip length is increased with an increase in rotation speed. • At higher speed improvement in performance parameters are higher.

Bhattacharya et al. (2017)	• Flow is laminar. • Fluid is in-compressible. • Fluid is Newtonian. • Temperature change is considered. • 3D energy equation is solved. • Moving surface with no-slip boundary condition. • Stationary surface with slip and no-slip boundary condition.	• For short rotors, multiple slip/no-slip zones give better stability limit speed. • With multiple slip-no slip zone less improvement is observed for long rotors. • Journal bearing with 3, 4 & 5 pairs of slip/no-slip zones are best among purposed configuration. • Increasing the slip length to a very high value does not provide high slip velocity.
Cui et al. (2020)	• Flow is laminar. • Fluid is in-compressible. • Fluid is Newtonian. • Fluid is Iso-viscous. • Moving surface with no-slip boundary condition. • Stationary surface with slip and no-slip boundary condition.	• Better to enlarge the slip zone in the axial direction. • For high eccentricity ratio, slip zone location should be 0.9-1.0. • For high eccentricity ratio at certain regions slip velocity is opposite to the direction of rotation of the shaft. • Negative slip velocity weakens the performance of journal bearing. • It is better to locate the slip zone in the region $\theta = 0 \sim \pi + k\phi$. Where k- 0.5-0.9 and ϕ is the attitude angle.

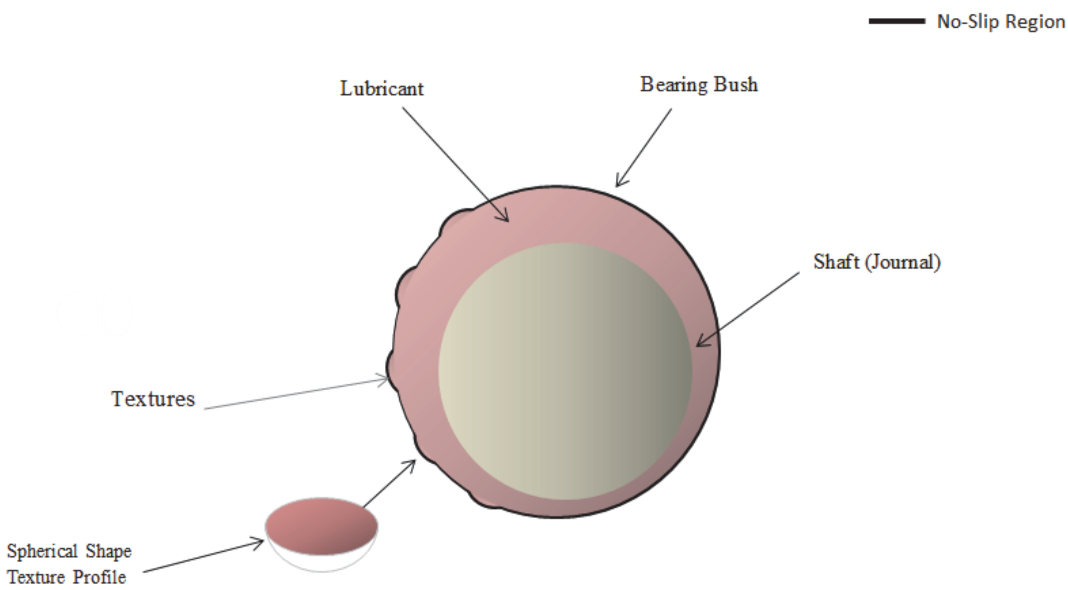

Fig. 9 Hydrodynamic journal bearing with surface texture

- Alternate slip/no-slip pairs are effective in reducing the cavitation area and improving the dynamic stability of journal bearings [80].
- Side leakage rate of lubricant is increased with slip boundary condition on journal bearing [78].
- At smaller value of slip zone extent up to 45° and the higher value of slip length stiffness coefficient and stability limit speed is improved [81].
- The load-carrying capacity reaches the maximum when the circumferential extent of the slip zone start at 0° and end at 180° [136].

2.1.5 Journal bearing with texture

A journal bearing with a random and deterministic microscale textures is as shown in Fig. 9 produced many different advantages over the journal bearing with a smooth surface. The geometrical parameters i.e. shape, size, and depth of the texture features play a vital role in enhancing the performance characteristics of bearings. Tala-Ighil et al [82, 83] optimized spherical and cylindrical shape texture geometry under steady loading condition for hydrodynamic journal bearings. They observed that texture on the declining part of the pressure field gives a significant improvement on performance parameters of journal bearings. Meng et al [84] investigate the effect of rectangular and spherical compound texture shape on the performance of journal bearings. Their study concluded that compound textures are more beneficial than simple textures in improving the tribological performance of hydrodynamic journal bearings. Similarly, many researchers like Hu et al [85], Kango et al [86, 87], Shinde & Pawar [88], and Sharma et al

[89] optimized different texture geometries for enhancing the tribological performance of journal bearings. Kango et al [90] performed the thermo-hydrodynamic analysis to consider the effect of spherical and elliptical surface texture on temperature rise with non-newtonian lubricants in the journal bearings. They observed that for both low and high eccentricity ratios overall temperature rise is reduced with surface texturing on journal bearings. Similarly, Tala-lghil & Fillon [91] and Wang et al [92] investigated the effect on overall temperature rise with different texture geometries on journal bearings. Wang et al [92], Manser et al [93], and Ramos et al [94] compared the static performance characteristics of textured journal bearing with smooth journal bearing surface. Similarly, Matele et al. [95], Jiang et al [96], and Jhoon et al [97] compared dynamic performance characteristics of textured journal bearing with smooth journal bearing surface. The important observations from the comparison study are discussed below:

- Maximum pressure is increased for texturing within the converging zone of bearing [82].
- Under steady-state condition minimum film thickness is increased for texturing in converging and diverging zone of journal bearing [83].
- Performance of textured bearing more influence by location of textures. Geometry shows very less influence on bearing performance [82, 83].
- Texturing effect is significant for low eccentricity ratio [86, 87].
- Partial texturing on bearing surface reduced overall cavitation area in the diverging zone [88, 89].
- Optimum texture profile depends on the operating conditions and geometrical parameters of bearings [84].
- Finite width journal bearing with texturing on the full surface reduce the attitude angle especially at low eccentricity ratios [97].
- Surface texturing reduced the overall temperature rise for both low and high eccentricity ratios [90-92].
- For power-law fluid textured journal bearing give maximum performance at flow behavior index 1.1 [90].
- Dynamic stability of textured bearing is improved as compared to smooth surface bearing [94].
- In textured bearing, the stiffness coefficient is increased for axial direction and decreases for radial direction [95].
- Damping coefficient is decreased for both axial and radial direction of texture journal bearing [96, 97].

2.1.6 Hydrodynamic journal bearing with slip and texture

From the above discussion, it is clear that surface texturing and slip boundary conditions are capable of improving the dynamic and static characteristics of hydrodynamic journal bearings. Many researchers performed a numerical study to observe the combined effect of slip and surface texturing as shown in Fig. 10 on hydrodynamic journal bearings [98-100]. Aurelian et al [98] performed the steady-state analysis to observe load carrying capacity and power loss for journal bearing with slip and surface texturing. Journal bearing with combined slip-texture zone gives enhancement in load carrying capacity and decrease in power loss. Random selection of the slip-texture zone profile gives performance loss as compared to textured bearing [98]. Slip boundary condition with surface texturing gives the increase in pressure near the minimum film thickness region and decrease in pressure at inlet region of bearing [99]. Kalavathi et al [100] considered the effect of slip boundary condition and random roughness on finite porous bearings. Their study shows that heterogeneous slip/no-slip region load carrying capacity and pressure distribution improve with the increase in roughness parameter. Rao et al [101] studied the variation of stiffness and damping coefficient for different slip-texture journal bearing profiles. They observed that stiffness and damping coefficient decrease with an increase in the eccentricity ratio. Further details on assumptions used and important observations on study related to slip-texture profiles are shown in Table 7. The following points highlight important observations regarding the effect on performance parameters with slip boundary condition on journal bearings.

- As compared to surface texturing, slip boundary condition gives more enhancement in journal bearing performance [98].

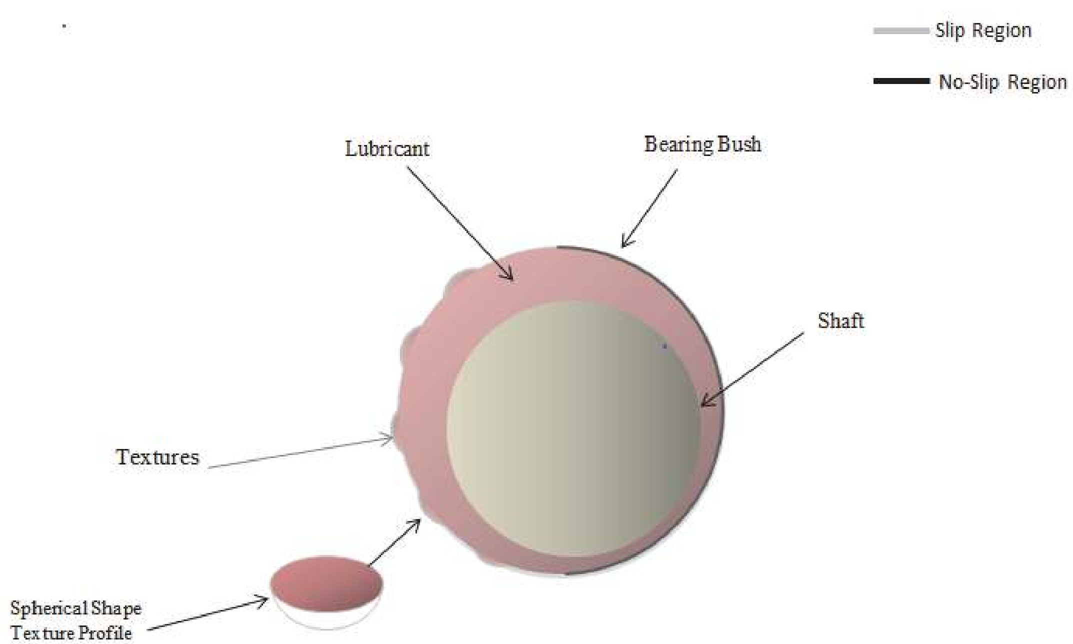

Fig. 10 Journal bearing with slip and surface texture

- Combine slip and texture region within the cavitation zone is not effecting the bearing performance [99].
- Journal bearing with slip boundary condition and random surface roughness give an improvement in load carrying capacity and maximum pressure [100].
- Partial slip and texture region significantly influence the dynamic stability of bearing [101].

2.2 Experimental study

In this section literature study related to experimental observations for the effect of slip, surface dimpling, and combine slip and surface texturing on the hydrodynamic bearing are presented.

2.2.1 Hydrodynamic thrust/slider bearing with slip

Choo et al [103, 104] measured friction reduction at low load and high speed with the use of homogeneous slip boundary condition. They used a tribometer for performing the experimental study. They suggested that with slip condition on the stationary surface and no-slip condition on moving surface lubricant film thickness is increased as compared to no-slip condition on both surfaces. Leong et al [105] mixed multiply alkylated cyclo-pentane (MAC) in hexadecane lubricant to generate a slip effect on the stationary surface of thrust pad bearings. The number of observations shows that slip effect produced due to mixing MAC in lubricant able to reduce friction force in comparison of the surface without slip.

Table 7 Hydrodynamic Journal Bearing with Surface Textures & Slip

Author	Assumptions	Results
Rao et al. (2019)	• Condition is in unsteady state. • Bearing is one dimensional and long. • Fluid is incompressible. • Temperature condition is isothermal. • Fluid is Newtonian. • Fluid is iso- viscous. • Inertia forces are neglected. • Fluid flow is laminar. • Slip /No-slip condition on stationary surface. • No-slip condition on moving surface.	• Heterogeneous slip/no-slip bearing surface can improve fluid-film bearing performance. • Bearing operating under slip has an advantage over a conventional bearing in terms of both load-carrying capacity and friction force.
Lin et al. (2015)	• Condition is in unsteady state. • Bearing is one dimensional and long. • Fluid is incompressible. • Temperature condition is isothermal. • Fluid is Newtonian. • Fluid is iso- viscous. • Inertia forces are neglected. • Fluid flow is laminar. • Slip /No-slip condition on stationary surface. • No-slip condition on moving surface.	• Texture/slip surface would not affect the pressure and load-carrying capacity when it locates at the cavitation zone. • The effect of texture/slip surface on load-carrying capacity would be beneficial if it locates at the pressure rise region, but its effect would be adverse if it locates at the pressure drop region. • Well-designed texture/slip surface can improve tribological performances. • Texture/slip surface would induce a high-pressure zone in the downstream direction and it would also make a pressure drop in the upstream direction. • The enhanced effect on load-carrying capacity is much higher if the texture/slip surface locates near the bearing center in an axial direction.
Kalavathi et al. (2016)	• Stationary surface is porous and rough. • Pores on surfaces are isotropic and homogeneous. • Flow is laminar. • Fluid is in-compressible. • Fluid is Newtonian • Temperature change is considered. • 3D energy equation is solved. • Moving surface with no-slip boundary condition. • Stationary surface with slip and no-slip boundary condition.	• With slip boundary condition increasing in surface roughness parameter gives an improvement in load-carrying capacity. • With slip boundary condition increasing in permeability gives a reduction in load-carrying capacity.

Kalin et al [106, 107] investigate the effect of slip condition on different lubrication regimes. They choose diamond-like carbon coating (DLC) as a non-wettable surface. Their observations showed that when both surfaces are non-wettable in nature, then in elasto-hydrodynamic lubrication regime friction force is reduced up to 20%. Moreover, in mixed lubrication regime friction force is reduced up to 9%. Jahanmir et al [47] studied the effect of a different combination of slip and no-slip surfaces on load-carrying capacity and friction force reduction of thrust bearings. They used hydrogenated diamond-like carbon coating as a slip surface. Wu et al [108] observed the effect of heterogeneous slip/no-slip surface on tribological behavior of parallel thrust bearings. They used a combination of low surface energy polytetrafluoroethylene (PTFE) and high surface energy polymethyl-methacrylat (PMMA) to prepare heterogeneous slip/no-slip surface. Liu et al [109] used fluorosilane as a low surface energy coating on steel and glass samples. They observed the effect of stepped wettability on friction and wear under limited lubricant supply condition. Their study concluded that in mixed lubrication regime stepped wettability produced high film thickness and give a reduction in friction coefficient.

2.2.2 Hydrodynamic slider/thrust bearing with texture

Etsion [110, 111] presented an experimental study on the tribological performance of micro-dimple surfaces in different mechanical components (piston rings. mechanical seals and thrust bearings). Each surface texture acts as a reservoir of lubricant and provides smooth operation during the mixed lubrication regime. Textured surfaces give enhancement in tribological performance. For laser textured parallel thrust bearings clearance increase by three times as compared to the thrust bearing with the smooth surface [111]. Similarly, Marian et al [57, 112] observed the effect of square and spherical shape partially textured thrust bearings. Qiu & Khonsari [113] investigated the tribological performance of circular and elliptical shape textured stainless steel rings. The textured surface showed a reduction in the coefficient of friction. The circumferential orientation of the elliptical shape texture gave a better performance as compared to other texture shapes. Scaraggi et al [114] plotted stribeck curve for texture surface. The comparison of data with smooth surfaces showed that textured surfaces allowed to reduce friction by 50% in the hydrodynamic regime. Zhang and Meng [115] observed that the prediction of cavitation zone by using mass conservation JFO Model [137] agree well with experimental results. Henry et al [116] performed an experimental study to investigate the influence of surface texturing on parallel thrust bearings. The texture thrust bearing performed better under light loading condition and for heavy loading condition performance is similar or poor then smooth bearing surfaces. The overall temperature rise is significantly reduced by high density textured bearing. In another experimental study, Henry et al [117] investigated the effect of surface texturing on starting and ending the working period of parallel and tilted pad thrust bearings. The friction torque during the startup period is decreased with surface texturing on the bearing pad. The transition time from mixed lubrication to hydrodynamic lubrication is increased with textured thrust bearings.

2.2.3 Hydrodynamic thrust bearing with slip and texture

The surface energy of any smooth non-wettable surface is further reduced by micro-scale random/regular surface texturing on that surface [118-120]. Ding et al [121] tested the effect of parallel groove on the wear rate of DLC coated stainless steel samples with water as a lubricating fluid. They found that the wear rate in the textured sample is less as compared to the untextured sample. Amanov et al [122] observed the tribological behavior of spherical texturing on the Si-DLC coated steel sample surface. They observed that the textured sample give a better tribological performance as compared to the untextured sample. Shum et al [118] and Arslan et al [123] optimized spherical texture geometry for DLC coated samples. Their finding shows that optimized texture geometry depends on the contact width. Koszela et al [124] prepared laser surface textured and low surface energy DLC coated internal combustion engine cylinder samples. Their investigation shows that as compared to un-textured samples for textured samples maximum power is increased by 5.8%.

2.2.4 Hydrodynamic journal bearing with slip

Bobzin & Brögelmann [125] performed experiments to study the influence of slip boundary condition on plain journal bearing of automobiles. They used DLC coating to produce slip effect on journal bearing. They observed that friction reduction of up to 25-36% for DLC coated bearing.

2.2.5 Hydrodynamic journal bearing with textures

Lu & Khonsari [126] plot stribeck curve for spherical and cylindrical textured journal bearing bush surfaces. They observed that with optimized texture geometry on the full surface of bearing friction force is reduced by a significant amount. Dadouche et al [127] compared the dynamic and static performance of textured bearing with plain journal bearing. Their study concluded that light and medium textured bearings are more stable then heavily textured bearing. They also observed about 6-8 degree increase in temperature for textured bearings. Lu et al [128] tested the effect of the bio-inspired textured pattern on friction characteristics of journal bearing. They show that friction behavior of textured bearing with the bio-inspired pattern is better as compared to simple pattern textured bearings. Yamada et al [129, 130] performed both experiment and numerical simulation to observe the effect of square texture geometry on static and dynamic characteristics of journal bearings. Vlădescu et al [131] performed an experimental study to investigate the effect of laser surface texturing on crankshaft bearing of IC engines. Galda et al [132] investigated the effect of texture on load-carrying capacity and friction force of hydrodynamic journal bearings.

3 Conclusion

The conclusions from the above literature survey are summarized below:

- The slip boundary condition on the full stationary surface reduces both friction force and load-carrying capacity.
- Suitable selection of slip and the no-slip zone is effective in increasing load-carrying capacity and intake rate of lubricant.
- An increase in side-leakage rate with the increase in slip length is the limitation of using a modified slip boundary condition.
- The slip boundary condition is more beneficial at low and medium eccentricity ratios.
- Microscale regular surface texture with optimized shape and size shows significant improvement in static and dynamic characteristics of hydrodynamic bearings.

- At low eccentricity ratios combined slip & texture is more efficient as compared to bearing with only slip boundary condition.

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