Influence of Texture Orientation on the Hydrodynamic Lubrication

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***Abstract*— Surface texturing is a prominent method to improve the hydrodynamic lubrication performance. The numerical work is carried out to study the effect of orientation of textures on the performance characteristics like load support, end flow and friction parameter of parallel sliding contacts. The parameters used in the analysis to investigate the effect of orientation are size and height of surface texture. The governing pressure equation is solved using Finite difference method with Gauss-Seidel iterative relaxation scheme. The result shows that orientation of texture shows significant effect on the performance characteristics. Moreover, texture size and its height also play a vital role on the performance of parallel sliding contacts.**

Keywords—lubrication; parallel sliding contact; surface texture

I. INTRODUCTION

The fluid film between parallel surfaces does not support any load until there is a change in the surface geometry of parallel surface. The change in surface geometry is obtained by providing surface textures which is one of the reliable method to generate hydrodynamic pressure in the fluid film of parallel surfaces. Surface textures are having pre-determined size, shape, distribution and orientation which can alter the hydrodynamic lubrication characteristics significantly. Sarang et al., [1] explained the manufacturing process of positive and negative textures using UV Photolithography process. Yu et al., [2] theoretically investigated the effect of different negative texture shapes and its orientation on the hydrodynamic pressure generated between conformal contacting surfaces. The results indicated that shape and orientation has substantial effect on load carrying capacity of contacting surfaces. Arghir et al., [3] utilized numerical technique to explore the lift-off force due to pressure generation in different macro-roughness textured surfaces.

Siripuram and Stephens [4] numerically studied various types of deterministic positive and negative asperities on the surface of parallel slider. Their analysis is carried out at constant texture height and their results indicated that friction coefficient is insensitive to asperity / cavity shape but quite sensitive to size of cross-section. Yu et al., [5] numerically and experimentally investigated the effect of dimple shape on the performance of parallel sliding contacts. They found that suitable dimple area ratio and dimple depth is helpful to get better friction reduction. They have also noticed that load support and friction reduction are sensitive with dimple shapes. The pressure build-up in case of a textured surface could be due to local cavitation at the diverging gap. Therefore, care must be taken while dealing with cavitation and boundary condition at the diverging gap. The different theories related to the cavitation model are studied by Qiu and Khonsari [6]. A thermohydrodynamic analysis of 3D textured slider is studied by Cupillard et al., [7] using CFD. They observed that in the presence of thermal effect, dimples placed at the slider inlet shows positive influence on the load support. Whereas, effect of asymmetric micro-dimples on the hydrodynamic lubrication is studied by Han et al., [8]. They noticed that asymmetric shape of textures gives better load carrying capacity in comparison of symmetric shape of textures. For the optimization of one-dimensional texture shape on parallel thrust bearing Guzek et al., [9] developed unified computational approach to produce a maximum load support or minimum frictional coefficient.

From the experimental results, Wang et al., [10] observed substantial increase of load carrying capacity around 2.5 times with dimples on the surface of Sic thrust bearing where water is used as a lubricant. The effect of hemispherical dimples on hydrostatic mechanical face seal is studied experimentally and analytically by Etsion and Halperin, [11]. Their result depicts better frictional torque reduction as compared to standard face seals. Pettersson and Jacobson, [12] performed laboratory tests on textured and untextured samples modelling the situation of start and stop in radial piston hydraulic motor. They found that untextured sample shows higher friction as compared to all textured samples. The effect of partial texturing of square dimples on load carrying capacity of thrust pad bearing is investigated experimentally and theoretically by Marian et al., [13] and they found that higher load carrying capacity is obtained using partial texturing and moreover, good correlation is obtained between experimental and theoretical results. Antoszewski [14], carried out experimental work by making pores in square array distribution using laser micromachining and their finding depicts that textured surface possess very less friction as compared to smooth surface at different speeds. The effect of surface textures on gas seals are studied by Kligerman and Etsion, [15] using FEM modelling. They noticed that spherical dimples have significant effect on the hydrodynamic performance of gas seal. Brizmer et al., [16] observed that partial surface texturing exhibit better result as compared to full texturing for higher values of slider length to width ratio. Whereas, Etsion et al., [17] experimentally analyze the model explained by Brizmer et al., [16] and found good correlation. For partially textured surfaces increasing the number of dimples would not help in improving load capacity or friction coefficient in pure hydrodynamic mode [18].

Tala-Ighil et al., [19] numerically analysed the texture effect on journal bearing characteristics under steady state condition. They examined two surfaces, one is smooth and other is numerically textured surface with spherical dimples and the results showed better performance with textured surface. Cupillard et al., [20] analysed the effect of dimple depth on bearing friction and load carrying capacity of textured conformal contact (journal bearing) using computational fluid dynamics. They observed that deep dimples located in maximum pressure region at high eccentricity ratio and shallow dimples located just downstream of maximum pressure at low eccentricity ratio reduces the friction coefficient. Tala-Ighil et al., [21] studied the optimum arrangement of textured area on the journal bearing to get larger load support.

A considerable work is done on circular dimple / negative shape of textures and little attention is paid on the positive texture shapes and its orientations. Therefore, in the present work, a theoretical model is developed to study the effect of orientation for two types of texture shapes (Triangular and Elliptical) on the hydrodynamic performance of parallel sliding contacts.

II. THEORY

The present analysis is carried out on a unit cell having texture at the centre and by keeping appropriate boundary conditions along the edges of unit cell. It has assumed that textures are provided on the stationary surface in square array distribution, while sliding surface is smooth and having sliding velocity 'U' along the *x*-direction. In most of the referred available literature, Reynolds equation is used to study the effect of surface texture on hydrodynamic performance of bearings. Dobrica and Fillon [22] studied the suitability of Reynolds equation in Rayleigh step bearing by considering step height as 50% of the film thickness. They found that for thin films, ≤ 200 μm, Reynolds equation show good results regardless some of the assumptions being violated nearby area of discontinuity. Scaraggi [23] mentioned that Reynolds equation is applicable when the ratio of maximum film thickness C to lattice length of unit cell L_X is less than 10^{-2}. Moreover, Dobrica and Fillon [24] observed that Reynolds equation is applicable when texture length to depth ratio is higher and Reynolds number is lower. Therefore, in the present analysis fluid is assumed as Newtonian and incompressible, whereas, flow is considered to be laminar. The iso-thermal, iso-viscous, steady-state Reynolds equation can be written as,

$$\frac{\partial}{\partial x}\left(\frac{h^3}{12\eta}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{h^3}{12\eta}\frac{\partial p}{\partial z}\right)=U\frac{\partial h}{\partial x} \tag{1}$$

with film thickness, for positive texture

$$h=\begin{cases} C-h_g & \text{above the protrusion} \\ C & \text{elsewhere} \end{cases} \tag{2}$$

and for negative texture

$$h=\begin{cases} C+h_g & \text{above the recess} \\ C & \text{elsewhere} \end{cases} \tag{3}$$

where, C is the total gap between parallel surfaces and h_g is the height of surface textures.

The non-dimensional quantities used to non-dimensionalize the (1), (2) and (3) are

$$\bar{p}=\frac{pC^2}{\eta U L_X},\ \bar{x}=\frac{x}{L_X},\ \bar{z}=\frac{z}{L_Z},\ \bar{h}=\frac{h}{C},\ k=\frac{L_X}{L_Z},\ \bar{H}=\frac{h_g}{C}$$

The non-dimensional form of Reynolds equation and film thickness is

$$\frac{\partial}{\partial \bar{x}}\left(\bar{h}^3\frac{\partial \bar{p}}{\partial \bar{x}}\right)+k^2\frac{\partial}{\partial \bar{z}}\left(\bar{h}^3\frac{\partial \bar{p}}{\partial \bar{z}}\right)=6\frac{\partial \bar{h}}{\partial \bar{x}} \tag{4}$$

for positive textures

$$\bar{h}=\begin{cases} 1-\bar{H} & \text{above the protrusion} \\ 1 & \text{elsewhere} \end{cases} \tag{5}$$

for negative textures

$$\bar{h}=\begin{cases} 1+\bar{H} & \text{above the recess} \\ 1 & \text{elsewhere} \end{cases} \tag{6}$$

On account of equally distributed textures on the stationary surface, it is assumed that pressure distribution is periodic in *x*-direction with a period equal to unit cell size L_X, whereas, an ambient pressure condition is used in *z*-direction. The non-dimensional form of boundary conditions used are

in *z*-direction

$$\bar{p}(\bar{x},\bar{z}=0)=0,\ \bar{p}(\bar{x},\bar{z}=1)=0 \tag{7}$$

and in *x*-direction

$$\bar{p}(\bar{x}=0,\bar{z})=\bar{p}(\bar{x}=1,\bar{z});\ \frac{\partial \bar{p}}{\partial \bar{x}}(\bar{x}=0,\bar{z})=\frac{\partial \bar{p}}{\partial \bar{x}}(\bar{x}=1,\bar{z}) \tag{8}$$

At the cavitation boundary, Reynolds boundary condition is used which implies that the pressure at each node and the pressure gradient with respect to direction normal to the boundary is zero i.e.

$$\bar{p}=0 \text{ and } \frac{\partial \bar{p}}{\partial \bar{x}}=0 \quad \text{when } \bar{p}<0 \tag{9}$$

An iterative procedure has been employed to evaluate the solution of equation (4). The numerical method of finite difference has been used to solve the equation. This leads to set of algebraic equations which can be solved using Gauss-Seidel iterative scheme by satisfying boundary and cavitation conditions (7) - (9). Once pressure at each node is calculated in the fluid film region, load support, end flow and friction parameter are evaluated using the known pressure value. The equations of load support, end flow and friction parameter in non-dimensional terms are

$$\overline{\mathrm{w}} = \int_0^1\int_0^1 \bar{p}\, d\bar{x}\, d\bar{z} \tag{10}$$

$$\overline{\mathrm{Q}} = \int_0^1 \left(-\frac{k\bar{h}^3}{12}\frac{\partial \bar{p}}{\partial \bar{z}}\right) d\bar{x} \tag{11}$$

$$\mu\left(L_X/C\right) = \frac{\bar{F}}{\bar{W}} \tag{12}$$

where,

$$\bar{F}\left(\text{Friction Force}\right) = \int_0^1\int_0^1 \left(\pm\frac{1}{2}\bar{h}\frac{\partial \bar{p}_0}{\partial \bar{x}} + \frac{1}{\bar{h}}\right) d\bar{x}\, d\bar{z} \tag{13}$$

III. Results And Discussion

In order to justify the accuracy of developed programme, obtained results are validated with previously available results [4] or well known analytical results. The Rayleigh step bearing as shown in Fig. 1 was solved analytically and their result is compared with the numerical solution of parallel sliding contacts having square shape texture at the centre and by keeping infinitely long condition in transverse direction. Non-dimensional peak pressure of both cases are shown in Fig. 2 where good correlation is obtained between them and slight difference may be due to numerical error.

The numerical analysis is carried out to study the effect of texture orientations on the hydrodynamic performance parameters of parallel sliding contacts by varying two parameters namely, aspect ratio and texture height ratio. The maximum value of aspect ratio will be depends on the shape of textures considered in the analysis. The two type of textures namely, Triangular and Elliptical, are used in the analysis and their maximum value of aspect ratios are 0.3 and 0.38 respectively. Texture height ratio should not be high because if texture height is larger than minimum fluid film thickness, calculation of 2D pressure is not accurate. Therefore, maximum texture height ratio is considered as 0.6. The orientation angles considered for triangular and elliptical textures are shown in the Fig. 3. In this present analysis, major axis to minor axis ratio of elliptical texture is considered as 2 and fluid flow is along longitudinal direction.

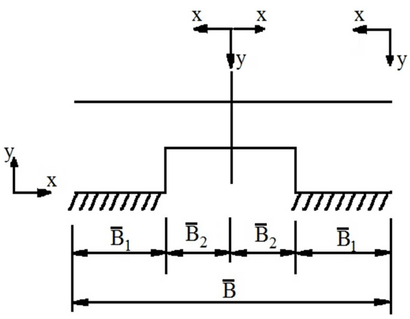


Fig 1. Rayleigh step bearing

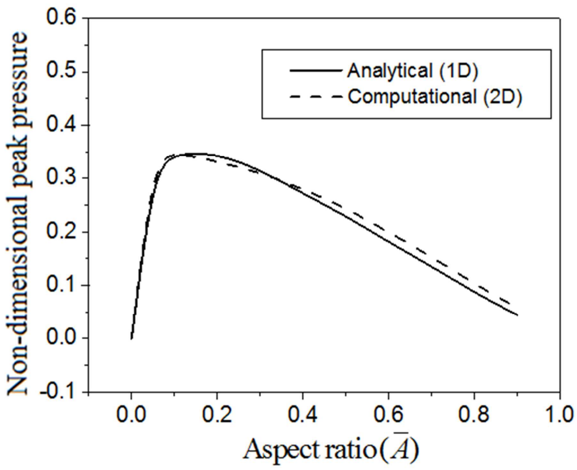


Fig. 2 comparison of the non-dimensional peak pressure

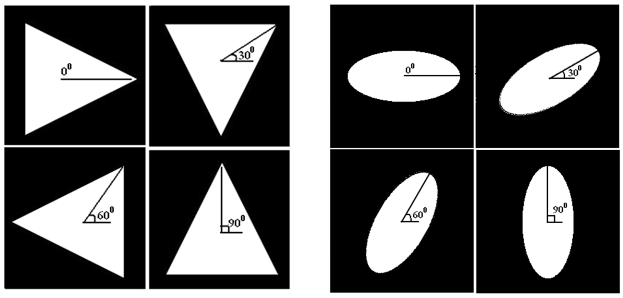
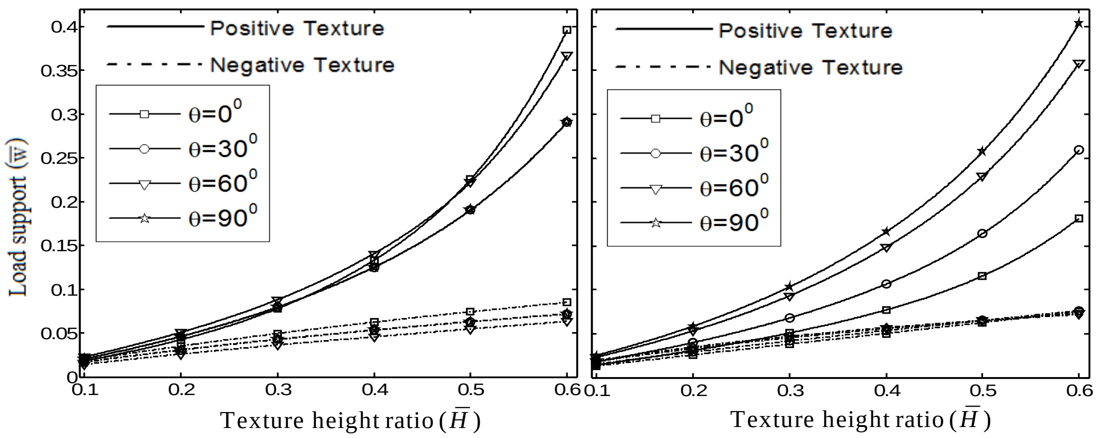


Fig. 3 Orientation angle of Triangular and Elliptical texture

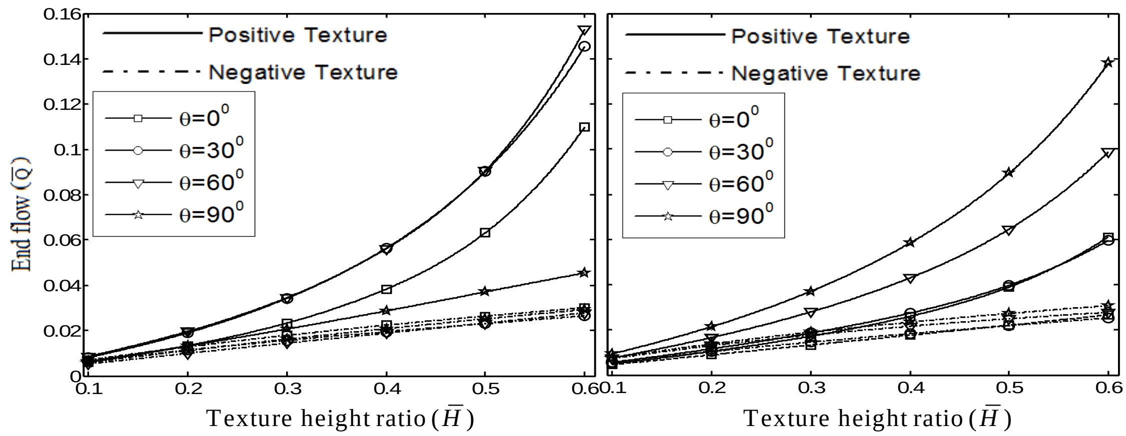
A. *Effect of Angular Orientation with Varying Texture Height Ratio*

Fig. 4 shows the orientation effect on load support with varying texture height ratio at a particular value of $\bar{A} = 0.2$. The positive texture shows higher load support as compared to negative textures which is evident from the Fig. 4. This is because more amount of fluid flow is obstructed by positive textures leading to higher pressure build-up. In case of negative textures, steady and low pressure will build up since the fluid gets trapped in the recess, generally, negative textures will acts as a reservoir. For positive textures, as the texture height increases, higher hydrodynamic pressure builds-up that gives higher load support. Furthermore, the load support increases exponentially for a higher value of texture height ratio, where fluid film becomes thinner. In case of triangular texture, 60^0 orientation of positive texture shows higher load support with increasing texture height ratio up to 0.5, and then 0^0 orientation shows higher load support as compared to other orientations. Whereas, in case of elliptical texture, 90^0 orientation exhibits higher load support with increasing texture height ratio as compared to other orientations. However, in negative texture of elliptical shape, orientation effect is negligible on load support. Similar variations are also observed in Fig. 5 for end flow, which shows a direct proportionality with load support, increases with texture height ratio.



(a) Triangular (b) Elliptical

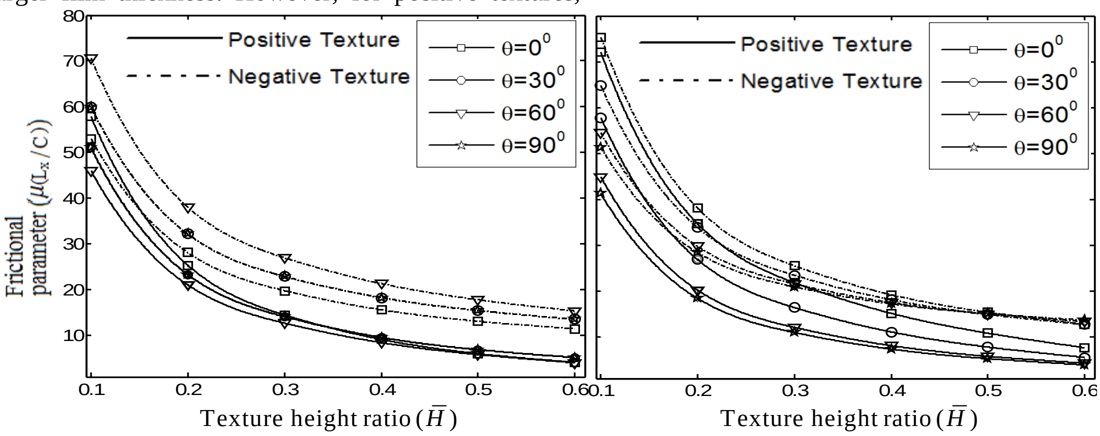
Fig. 4 Effect of orientation on load support with varying texture height ratio



(a) Triangular (b) Elliptical

Fig. 5 Effect of orientation on end flow with varying texture height ratio

On the other hand, friction parameter is inversely related to load support as shown in Fig. 6. The 60^0 triangular orientation and 90^0 elliptical orientation of positive textures exhibits lower friction parameter as compared to other orientations. For the case of negative textures, friction parameter decreases with increasing texture height ratio because friction force may reduce due to larger film thickness. However, for positive textures, friction force increases with increasing texture height ratio. Although, friction force increases, the friction parameter reduces because rate of increase of load support is higher as compared to the rate of increase of friction force and friction parameter is inversely related to the load support. This may be the reason that positive textures show reduction in friction parameter with increasing texture height ratio.



(a) Triangular (b) Elliptical

Fig. 6 Effect of orientation on friction parameter with varying texture height ratio

B. *Effect of Angular Orientation with Varying Aspect Ratio*

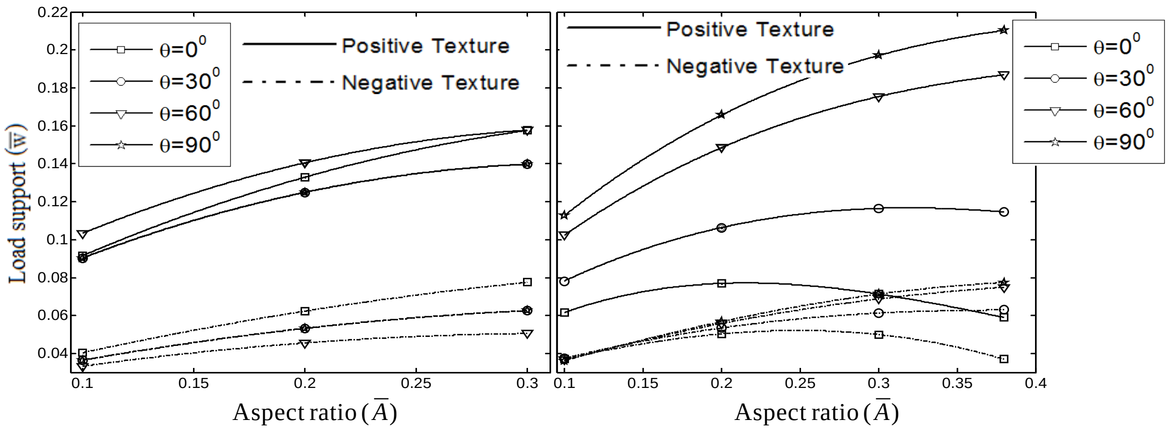
Effect of orientation on the load support with varying aspect ratio for both texture shapes are shown in the Fig. 7 at a particular value of $\bar{H}=0.4$. It can be observed from the Fig. 7(a) that positive triangular texture shows higher load support as compared to negative texture. The 60^0 triangular orientation of positive texture shows higher load support as compared to other orientations. Because of its orientation angle, more amount of fluid is obstructed leading to higher pressure development which enhances load support. However, for all angular orientations, load support is increasing with increasing aspect ratio. The 30^0 and 90^0 triangular orientations exhibit similar result in case of both positive and negative textures because area resisting to the fluid flow is same for both orientations (see Fig. 3). It is evident from the Fig. 7 (a) that 0^0 triangular orientation of negative texture shows better result as compared to other angular orientations. This means, angular orientation shows negative effect on load support.

Figure 7 (b) shows the effect of elliptical orientation on load support for the case of both positive and negative textures, where it can be observed that effect of orientation is significant on load support in case of positive textures as compared to negative textures. For 0^0 elliptical orientation, load support increases with increasing aspect ratio up to 0.2, and then decreases with further increase in aspect ratio, whereas, other two orientations shows higher load support with increasing aspect ratio. As a whole, 90^0 elliptical orientation shows higher load support as compared to other orientations.

The effect of orientation on end flow with varying aspect ratio for positive and negative textures of triangular and elliptical shapes is shown in the Fig. 8. For both positive and negative textures of triangular and elliptical shapes, end flow increases with increasing aspect ratio. However, for the case of positive triangular textures, 60^0 triangular orientation shows higher end flow with increasing aspect ratio up to 0.19, and then 30^0 triangular orientation shows better result with further increase in aspect ratio. Whereas in case of negative textures, 0^0 triangular orientation shows higher end flow with increasing aspect ratio. This indicated that angular orientation shows negative effect on end flow. Figure 8 (b) shows the effect of elliptical orientation with varying aspect ratio and result shows similar variations as load support which was shown in the Fig. 7 (b).

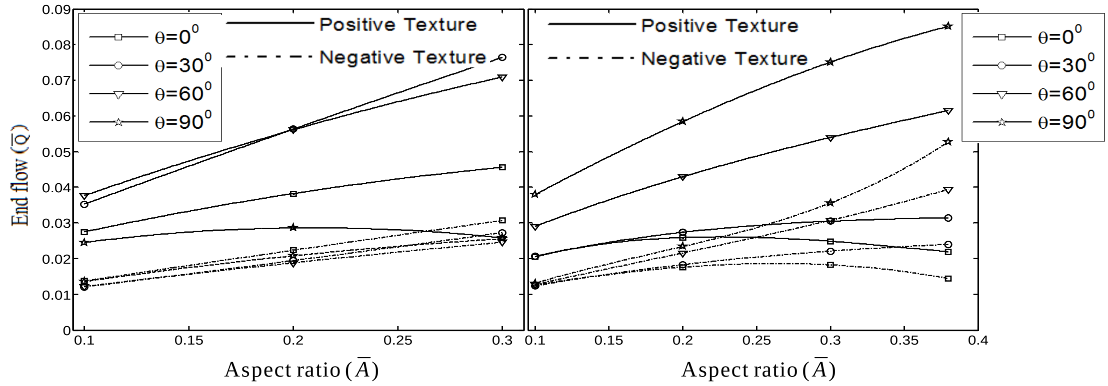
The effect of angular orientation on friction parameter is shown in the Fig. 9. For the case of triangular texture, negative texture shows larger reduction of friction parameter with increasing aspect ratio as compared to positive textures. For the case of elliptical shape, angular orientation gives lower friction parameter with increasing aspect ratio except 0^0 orientation of both positive and negative textures, whose values are increasing with the aspect ratio after 0.2 and 0.25 respectively. However, 60^0 positive triangular texture and 90^0 positive elliptical texture depicts lower fiction parameter as compared to other orientations of both positive and negative textures.

As a whole, angular orientation shows significant effect on the performance parameters especially in positive textures, whereas, in negative textures, angular orientation of triangular shape shows negative effect. Therefore, it can be concluded that in case of negative textures, angular orientation may show positive / negative effect on the performance parameters depending on texture shape. However, in case of positive textures, angular orientation shows significant effect on the performance parameters.



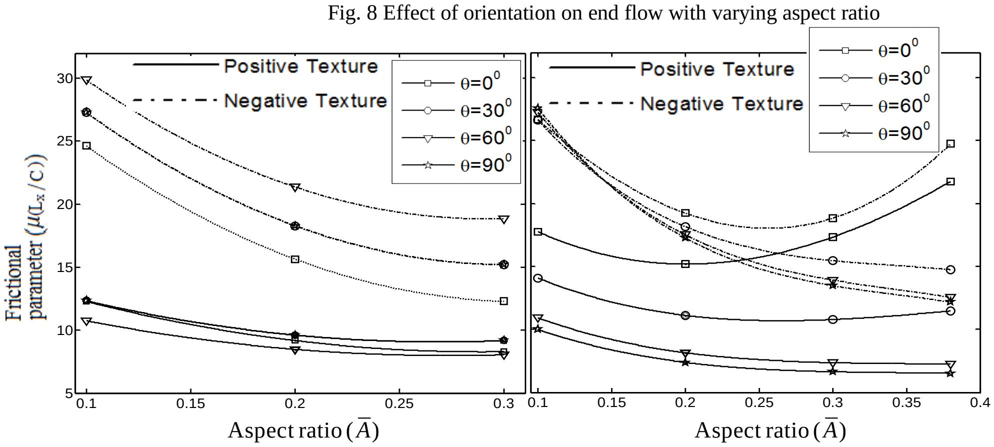
(a) Triangular (b) Elliptical

Fig. 7 Effect of orientation on load support with varying aspect ratio



(a) Triangular (b) Elliptical

Fig. 8 Effect of orientation on end flow with varying aspect ratio



(a) Triangular (b) Elliptical

Fig. 9 Effect of orientation on friction parameter with varying aspect ratio

IV. CONCLUSION

The numerical analysis is carried out to investigate the effect of texture angular orientation on the performance parameters of parallel sliding contacts for the case of both positive and negative textures of triangular and elliptical shapes. From the results it can be concluded that

- Positive texture shape exhibits improved performance parameters of parallel sliding contacts as compared to negative textures.
- For the case of negative textures, angular orientation may show positive / negative effect on hydrodynamic performance depending on texture shapes.
- Orientation effect in positive textures exhibit considerable effect on the hydrodynamic performance of parallel sliding contact.
- The 60^0 triangular orientation and 90^0 elliptical orientation of positive textures shows better performance parameters as compared to other orientations.

NOMENCLATURE

$\bar{A}$	= aspect ratio (area of textured surface/area of unit cell)
C	= maximum clearance between the parallel surfaces
$\bar{F}$	= non-dimensional friction force
h	= film thickness of the lubricant
$\bar{h}$	= non-dimensional film thickness
h_g	= height of the protrusion or recess
$\bar{H}$	= texture height ratio
k	= ratio of the imaginary cell lengths (L_X/L_Z)
L_X	= length of the imaginary cell in *x*-direction
L_Z	= length of the imaginary cell in *z*-direction
p	= pressure of the lubricant film
$\bar{p}$	= non-dimensional pressure of lubricant film
$\bar{Q}$	= non-dimensional end flow
U	= maximum velocity in *x-z* plane
$\bar{w}$	= non-dimensional load carrying capacity
$\bar{x}, \bar{y}, \bar{z}$	= non-dimensional co-ordinates ($\bar{y}$ is across the film)
$\mu(L_X/C)$	= non-dimensional friction parameter
η	= dynamic viscosity of the lubricant
ρ	= density of the lubricant

REFERENCES

[1] K.N. Sarang, S. Lyndon, H.C. Philip, and R.B. Siripuram, “Manufacturing of Micro asperities on Thrust Surfaces using Ultraviolet Photolithography”, APSE Winter Topical Meeting, vol. 28, pp. 148-153, 2003.

[2] Haiwu. Yu, Xiaolei. Wang, and Fei. Zhou, “Geometric shape effects of surface texture on the generation of hydro dynamic pressure between conformal contacting surfaces”, Tribology Letters, vol. 37, pp. 123-130, 2009.

[3] Mihai. Arghir, Nicolos. Raucou, Mathieu. Helene, and Jean. Frene, “Theoretical analysis of the incompressible laminar flow in a macro-roughness cell”, ASME J. Tribology, vol. 125, pp 309-318, 2002.

[4] R.B. Siripuram, and L.S. Stephens, “Effect of deterministic asperity geometry on Hydrodynamic Lubrication”, Journal of Tribology, Transactions of ASME, vol. 126, iss. 3, pp 527-534, 2004.

[5] H. Yu, H. Deng, W. Huang, and X. Wang, “The effect of dimple shapes on friction of parallel surfaces”, Proc. ImechE, Part J: J. Engineering Tribology, vol. 225, pp. 693-703, 2013.

[6] Y. Qiu, and M.M. Khonsari, “On the prediction of cavitation in dimples using mass-conservative algorithm”, ASME J. Tribology, 131, pp. 041702-1-041702-11, 2009.

[7] S. Cupillard, S. Glavatskih, and M.J. Cervantes, “Computational fluid dynamics analysis of a journal bearing with surface texturing”, Proc. IMechE, Part J: J. Engineering Tribology, vol. 222, pp. 97-107, 2007.

[8] J. Han, L. Fang, J. Sun, Y. Wang, S. Ge, and H. Zhu, “Hydrodynamic lubrication of surfaces with asymmetric microdimple”, Tribology Transactions, vol. 54, pp. 607-615, 2011.

[9] Agata. Guzek, Pawel. Podsiadlo, and Gwidon W. Stachowiak, “A unified computational approach to the optimization of surface textures:One dimensional hydrodynamic bearings”, Tribology online, vol. 5, iss. 3, 50-160, 2010.

[10] X. Wang, K. Kato, K. Adachi, and K. Aizawa, “Loads carrying capacity map for the surface texture design of SiC thrust bearing sliding in water”, Tribology international, vol. 36, pp. 189-197, 2003.

[11] I. Etsion, and G. Halperin, “A laser surface textured hydrostatic mechanical seal”, Tribology Transactions, vol. 45, iss. 3, pp. 430-434, 2002.

[12] U. Pettersson, and S. Jacobson, “Textured surfaces for improved lubrication at high pressure and low sliding speed of roller/piston in hydraulic motors”, Tribology International, vol. 40, iss. 2, pp. 355-359, 2007.

[13] V.G. Marain, M. Kilian, and W. Scholz, “Theoretical and experimental analysis of a partially textured thrust bearing with square dimples”, Proc. IMechE, Part J: J. Engineering Tribology, vol. 221, pp. 771-778, 2007.

[14] B. Antoszewski, “Formation of sliding surface with texture by laser micromachining”, Przeglad Elektrotechniczny (Electrical review), ISSN 0033-2097, R. 87, pp. 6-8, 2011.

[15] Y. Kligerman, and I. Etsion, “Analysis of the hydrodynamic effects in a surface textured circumferential gas seal”, Tribology Transactions, vol. 44, iss. 3, pp. 472-478, 2001.

[16] V. Brizmer, Y. Kligerman, and I. Etsion, “A laser surface textured parallel thrust bearing”, Tribology Transactions, vol. 46, iss. 3, pp. 397-403, 2003.

[17] I. Etsion, “Improving tribological performance of mechanical components by laser surface texturing”, Tribology Letters, vol. 17, iss. 4, pp. 733-737, 2004.

[18] Ramin. Rahmani, Ayoub. Shirvani, and Hassan. Shirvani, “Optimization of partially textured thrust bearings with square-shaped micro-dimples”, Tribology Transactions, vol. 50, pp 401-406, 2007.

[19] N. Tala-Ighil, P. Maspeyrot, M. Fillon, and A. Bounif, “Effect of surface texture on journal bearing characteristics under steady state operating conditions”, Proc. IMechE, Part J: J. Engineering Tribology, vol. 221, pp. 623-633, 2007.

[20] S. Cupillard, S. Glavatskih, and M.J. Cervantes, “Computational fluid dynamics analysis of a journal bearing with surface texturing”, Proc. IMechE, Part J: J. Engineering Tribology, vol. 222, pp. 97-107, 2007.

[21] N. Tala-Ighil, M. Fillon, and P. Maspeyrot, “Effect of textured area on the performance of a hydrodynamc journal bearing”, Tribology International, vol. 44, pp. 211-219, 2010.

[22] M. Dobrica, and M. Fillon, “Reynolds’ model suitability in simulating Rayleigh step bearing thermo hydrodynamic problems”, Tribology Transactions, vol. 48, pp. 522-530, 2005.

[23] M. Scaraggi, “Textured surface hydrodynamic lubrication: Discussion”, Tribology Letters, vol. 48, iss. 3, pp. 375-391, 2012.

[24] M.B. Dobrica, and M. Fillon, “About the validity of Reynolds equation and inertia effects in textured sliders of infinite width”, Proceedings of IMechE Part J: Journal of Engineering Tribology, vol. 223, pp. 69-78, 2009.