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Characteristics of lubrication at nano scale on the performance of transversely rough slider bearing

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1. Introduction

The squeeze film slider bearings are used in frictional devices such as clutch plates, automobile transmission and domestic appliances. Many investigators (Bhat [1], Bhat and Patel [2], Prakash and Viz [3]) dealt with the problem of squeeze film porous slider bearing. Slider bearings have been studied for several film shapes (Bagci and Singh [4], Hamrock [5], Pinkus and Sternlitcht [6]) because slider bearings are often used for supporting transverse load.

During these last few years a considerable amount of progress has been made in the research for thin film lubrication. Thin film lubrication has been well studied as a new lubrication regime since 1990s. A rheological model was developed by Tichy [7] and applied to thin film lubrication. The associated Reynolds' equation was solved to show that the effect of increasing the layer thickness parameter and surface layer viscosity is to increase the load carrying capacity and reduce the friction. In fact, thin film lubrication is a transition lubrication regime between elastohydrodynamic lubrication and boundary lubrication, which has specific lubrication features. Luo et al. [8-13] investigated the transition from elastohydrodynamic lubrication to thin film lubrication, the transition from thin film lubrication to boundary lubrication, failure of liquid film at nano scale, the properties of fluid film at nano scale and the mechanism of thin film lubrication. Shen et al. [14] discussed the effect of liquid crystal additives in the construction of thin film. Homala et al. [15] studied the relation between coherence force and friction force of the molecular thin liquid films. Tichy [16-18] proposed three physical models (director vector, viscosity model, porous surface model and layer model). Here it was observed that the lubricant exhibited nearly solid like behavior near the surfaces and nearly all sliding takes place across a thin shear layer. Mitsuya et al. [19] introduced the modified Reynolds' equation of porous media model considering the effect of the shear thinning. The lubrication characteristics of thin film lubrication are indeed, determined by the combination of viscosity and properties of the surfaces and the lubricant. Here, thin film lubrication is defined as a condition in which the combination of the properties of solid surfaces and the lubricant molecules and the viscosity of the lubricant determined the lubricating features between two surfaces in relative motion. Numbers of examples have been reported about the use of nano particles to improve the performance of thin film lubrication. The micro continuum mechanism of the fluid accounting for the intrinsic motion of material constituents other than the classical continuum mechanism must be used in these conditions. The derivation of a specialized theory for fluid micro continua known as couple stress theory of fluids and presented by Stokes [20], defines the rotation field in terms of velocity field. Das [21] considered the theoretical values of the central film thickness within the elastic context in line contact model. Zhang et al. [22] investigated the lubrication characteristics of thin film lubrication in two phase fluid. Here, it was shown that the existence of couple stress improved the load carrying capacity.

Most of the theoretical investigations of bearing lubrication more or less explicitly assumed that the bearing surfaces can be represented by the smooth mathematical planes. However, it has been recognized that this might be an unrealistic assumption especially, in bearings working with small film thickness. Various methods such as postulating a sinusoidal variation in film thickness (Burton [23]) has been introduced in order to seek a more realistic representation of engineering rubbing surfaces. But this method is perhaps more appropriate in an analysis of the influence of waviness rather than roughness. Very often the surface is made up of hills and valleys of different lateral and vertical sizes and is distributed randomly over the surface. The randomness suggests that one must resort to statistical methods of roughness characterization. It is also important to note that because of the involvement of so many length scales on roughness the characterization techniques must be independent of any length scale. One of the characteristic of a rough surface is the probability distribution (Bharat Bhushan [24]). Tzeng and Saibel [25, 26] introduced stochastic concept and succeeded in carrying out an analysis of a two dimensional inclined slider bearing with one dimensional roughness in the direction transverse to the sliding direction. However, bearing surfaces having received some run-in and wear seldom exhibit a type of roughness approximated by this type of mathematical modeling. With this end in view Christensen and Tonder [27-29] developed and modified the approach of Tzeng and Saibel [25-26] and proposed a comprehensive general analysis for the surface roughness (both transverse as well as longitudinal) based on a general probability density function. Subsequently, this approach of Christensen and Tonder [27-29] was used to study the effect of surface roughness on the performance of bearing systems in a good number of investigations (Ting [30], Prakash and Tiwari [31], Prajapati [32], Guha [33] and Gupta and Deheri [34]). Andharia et al. [35, 36] proposed to study and analyze the effect of surface roughness on the performance of squeeze film bearing using general stochastic analysis and here it was concluded that from life period point of view the roughness must be accounted for while designing the bearing system.

An important aspect of lubrication with very thin films, in the presence of roughness is the possible breakdown of Reynolds' equation. The Reynolds' equation cannot be employed if the roughness slope is too large and oblique or the wave length is too short compared to the film thickness, because one of the important assumptions behind the Reynolds' equation is the near parallelism of the surfaces. The validity of the Reynolds' equation is based on the ratio of fluid film thickness to the composite standard deviation of surface heights. Keeping this in view Bharat Bhushan [37] theoretically proved that the flow factor approach is also valid for compressible lubrication. Lendraitis, Snitka and Mizarienė [38] dealt with the possibility of applying Si membranes for nanopositioning of micro objects where in finite element method was used. Fnides, Yallese, Mabrouki, and Rigal [39] conducted experimental study is conducted to determine statistical models of surface roughness criteria. Mathematical models were devised by the software Minitab in order to express the influence degree of each cutting regime element on surface roughness.

Here it has been sought to study and analyze the characteristics of lubrication at nano scale on the performance of transversely rough slider bearing.

2. Analysis

The configuration of the bearing which is infinite in the Y direction is presented in Fig. 1. The slider moves with the uniform velocity U in the X direction. The length of the bearing is L while h_0 and h_1 being the minimum and maximum film thickness.

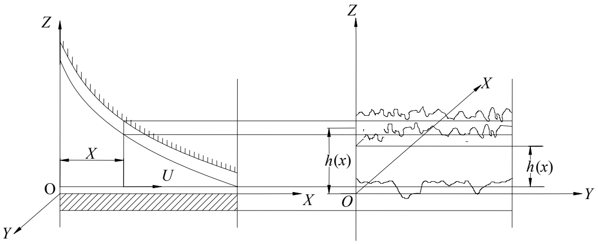

Fig. 1 Configuration of the problem

The bearing surfaces are assumed to be transversely rough. The thickness $h(x)$ of the lubricant film is

$$h(x) = \bar{h}(x) + h_s \tag{1}$$

where $\bar{h}(x)$ is the mean film thickness and h_s is the deviation from the mean film thickness characterizing the random roughness of the bearing surfaces. h_s is considered to be stochastic in nature and governed by probability density function $f(h_s)$, $-l \le h_s \le l$, where l is the maximum deviation from the mean film thickness. The mean $\bar{\alpha}$, the standard deviation $\bar{\sigma}$ and the parameter $\bar{\varepsilon}$ which are the measure of symmetry of the random variable h_s are defined by the relationships

$$\bar{\alpha} = E(h_s) \tag{2}$$

$$\bar{\sigma}^2 = E\left((h_s - \alpha)^2\right) \tag{3}$$

and

$$\bar{\varepsilon} = E\left((h_s - \alpha)^3\right) \tag{4}$$

where E denotes the expected value defined by

$$E(R) = \int_{-c}^{c} R\, f(h_s)\, dh_s \quad (R \text{ is a variable}) \tag{5}$$

and

$$f(h_s) = \begin{cases} \dfrac{35}{32\, l^7}\left(l^2 - h_s^{\,2}\right)^3 & -l \le h_s \le l \\ 0 & else\,where \end{cases} \tag{6}$$

It is easily observed that $\bar{\alpha}$, $\bar{\sigma}$ and $\bar{\varepsilon}$ are all independent of x while $\bar{\alpha}$ and $\bar{\varepsilon}$ can assume both the positive and negative values, $\bar{\sigma}$ is always positive.

In polar mechanics the mechanical action is assumed to be equivalent to a force and moment distribution which results in couple stresses. The state of stress is measured by stress tensor and a couple stress tensors. Neither of the second order tensor is symmetric in general. Accordingly, the state of stress at a point is measured by several independent components.

With the usual assumptions of hydrodynamic lubrication the modified Reynolds' equation with couple stress effect assumes the form (Deheri, Andharia and Patel [37], Zhang, Wen and Luo [22], Luo, Huang, Wen [12]).

$$\frac{d}{dx}\left(g(h)\phi(\gamma)\frac{dp}{dx}\right) = 6\mu U \frac{dh}{dx} \tag{7}$$

where c is the characteristic length (which contributes to the couple stress effect), μ is the viscosity of the lubricant and η is the material constant responsible for couple stress parameter while

$$c = \sqrt{\eta}/\mu \tag{8}$$

$$\gamma = h/c \tag{9}$$

$$\phi(\gamma) = 1 - \frac{12}{\gamma^2} + \frac{44}{\gamma^3} \tag{10}$$

and

$$g(h) = h^3 + 3h^2\bar{\alpha} + 3h\bar{\alpha}^2 + 3\bar{\sigma}^2 h + 3\bar{\sigma}^2\bar{\alpha} + \bar{\alpha}^3 + \bar{\varepsilon} \tag{11}$$

Integration of this equation leads to

$$\frac{dp}{dx} = \frac{6\mu U(h - h_m)}{g(h)\phi(\gamma)} \tag{12}$$

where h_m is the film thickness at maximum pressure. Introducing the dimensionless quantities

$$H = \frac{h}{\Delta h},\ H_m = \frac{h_m}{\Delta h},\ X = \frac{x}{L},\ G(H) = \frac{g(h)}{(\Delta h)^3},$$

$$\alpha = \frac{\bar{\alpha}}{\Delta h},\ \sigma = \frac{\bar{\sigma}}{\Delta h},\ \varepsilon = \frac{\bar{\varepsilon}}{\Delta h},\ P = \frac{p(\Delta h)^2}{\mu U L}$$

the equation (12) reduces to

$$\frac{dP}{dX}=\frac{6(H-H_m)}{G(H)\phi(\gamma)} \tag{13}$$

where

$$G(H)=H^3+3H^2\alpha+3H\alpha^2+3\sigma^2H+3\sigma^2\alpha+\alpha^3+\varepsilon \tag{14}$$

In view of the boundary conditions

$P=0$ at $X=0$ and $X=1$

we obtain the nondimensional pressure distribution in the form of

$$P=6\int_0^1\frac{H-H_m}{G(H)\phi(\gamma)}dX \tag{15}$$

The dimensionless load carrying capacity per unit width is given by

$$W=\frac{w(\Delta h)^2}{\mu UL^2}=\int_0^1 P\,dX\,. \tag{16}$$

3. Results and discussion

It is clearly seen that the pressure distribution is determined by Eq. 15, while Eq. 16 present the distribution of load carrying capacity. These performance characteristic depend on various parameters such as film thickness parameter H_m, standard deviation σ, variance α, skewness ε and characteristic length γ. For smooth surfaces this investigation reduces to the study conducted by Zhang et al. [22].

In order to study the quantitative effect of surface roughness of the bearing on its performance characteristics we prefer to opt for the plane slider

$$H=H_0+a(1-X)$$

so that the couple stress effect is more clearly seen where a is film shape parameter in dimensionless form.

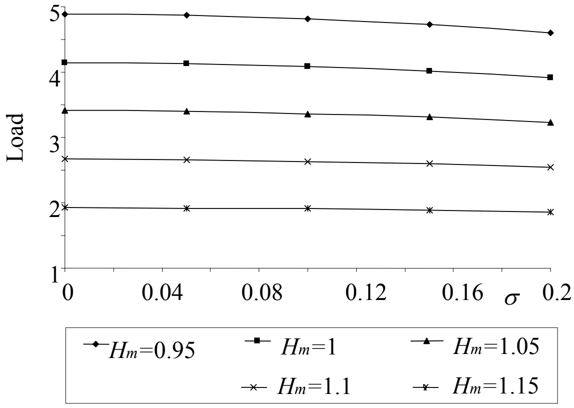

Fig. 2 Variation of load carrying capacity with respect to σ and H_m

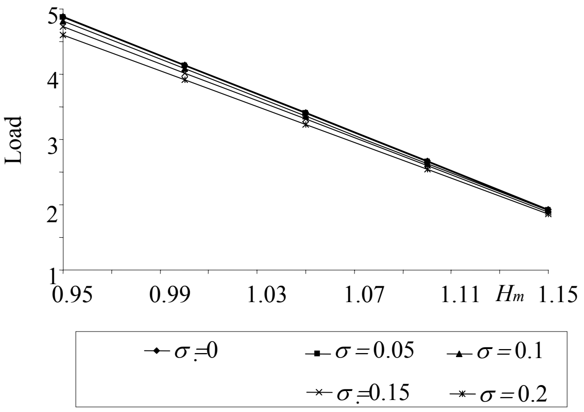

Fig. 3 Variation of load carrying capacity with respect to H_m and σ

In Figs. 2 and 3 we have the variation of load carrying capacity with respect to standard deviation for various values of H_m. It is clearly visible that for the lower and moderate values of H_m the load carrying capacity decreases due to standard deviation. However, for higher values of H_m the effect of standard deviation is almost negligible.

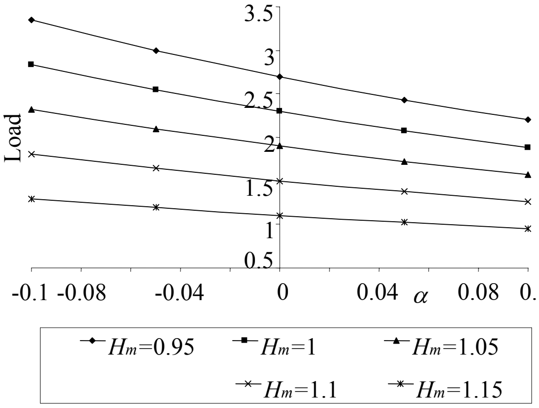

Fig. 4 Variation of load carrying capacity with respect to α and H_m

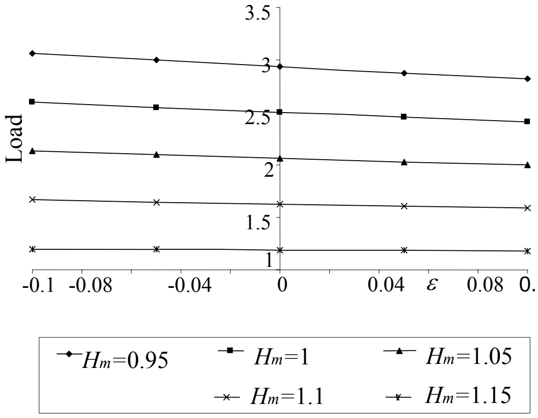

Fig. 5 Variation of load carrying capacity with respect to ε and H_m

The effect of variance and skewness on the distribution of load carrying capacity due to H_m is shown in

Figs. 4 and 5. These two figures suggest that the negatively skewed roughness and negative variance tend to increase the load carrying capacity for lower and moderate values of H_m. It is also noticed that ε (+ve) and α (+ve) decrease the load carrying capacity for lower and moderate values of H_m. Further, the rate of increase in the load carrying capacity due to negatively skewed roughness and negative variance decreases for higher values of H_m while the rate of decrease in the load carrying capacity due to positively skewed roughness and variance (+ve) decreases for higher values of H_m. It is observed that the load carrying capacity decreases substantially even for higher values of H_m with respect to the variance.

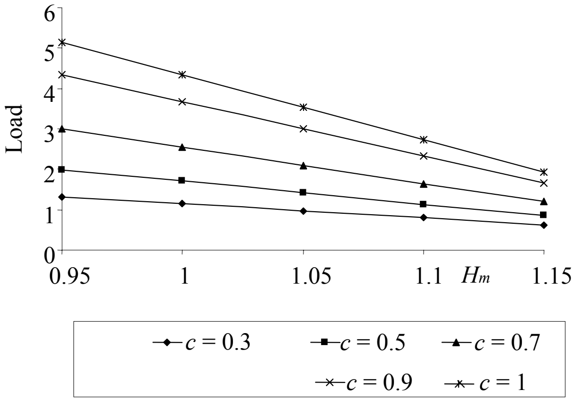

Fig. 6 Variation of load carrying capacity with respect to c and H_m

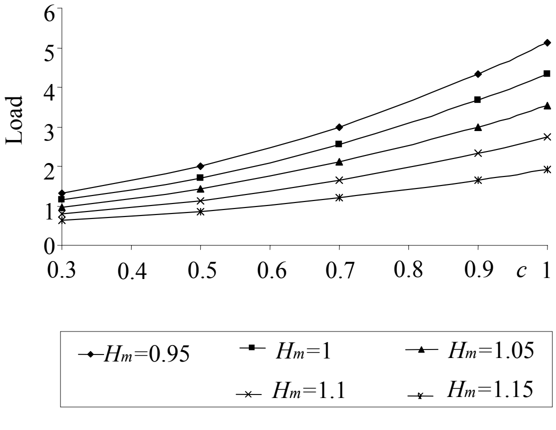

Fig. 7 Variation of load carrying capacity with respect to c and H_m

Figs. 6 and 7 tend to indicate that the dimensionless load carrying capacity significantly increases due to the characteristic length while H_m decreases the load carrying capacity substantially.

Figs. 8 and 9 suggest that standard deviation decreases the load carrying capacity with respect to the variance and skewness. However, this decrease in the load carrying capacity is comparatively more in the case of skewness.

In addition, from Figs. 8 - 10 one can easily visualize that the effect of negative variance is significantly positive in the case of negatively skewed roughness while equally adverse is the combined effect of positively skewed roughness and variance positive.

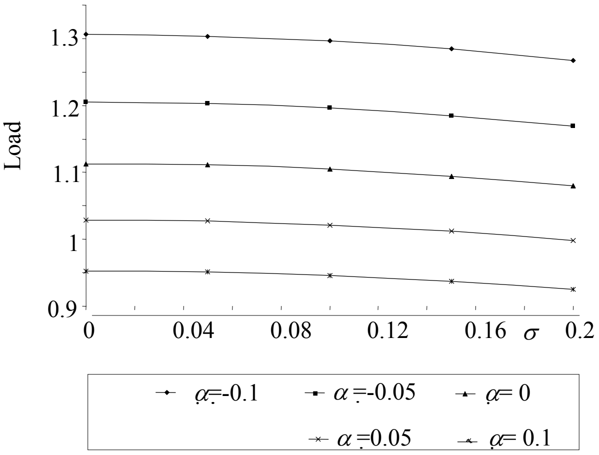

Fig. 8 Variation of load carrying capacity with respect to σ and α

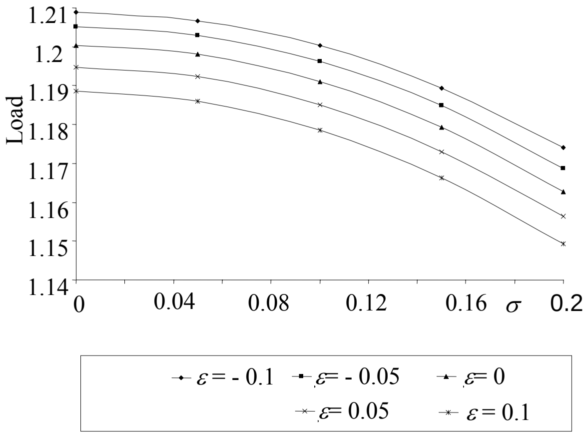

Fig. 9 Variation of load carrying capacity with respect to σ and ε

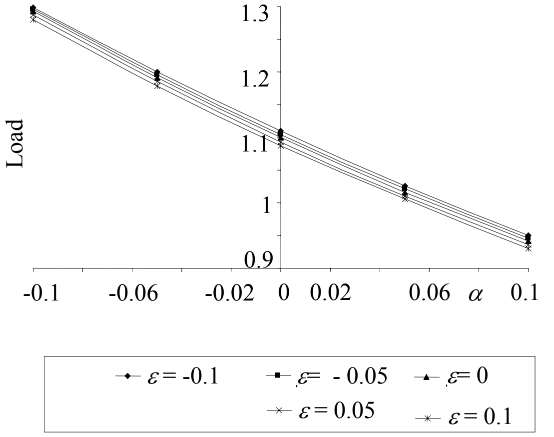

Fig. 10 Variation of load carrying capacity with respect to α and ε

The effect of standard deviation is presented with respect to the characteristic length in Fig. 11. Surprisingly, here the standard deviation has a nominal adverse effect.

It is noted from Figs. 12, a and b that the positive variance has an adverse effect in general when considered with the characteristic length. The increase in the load carrying capacity due to negative variance decreases with respect to the characteristic length.

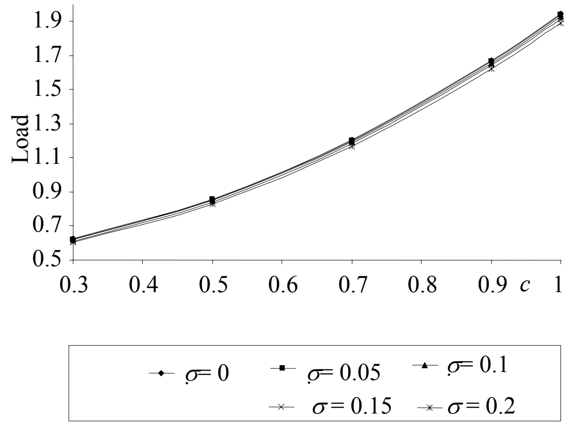

Fig. 11 Variation of load carrying capacity with respect to σ and c

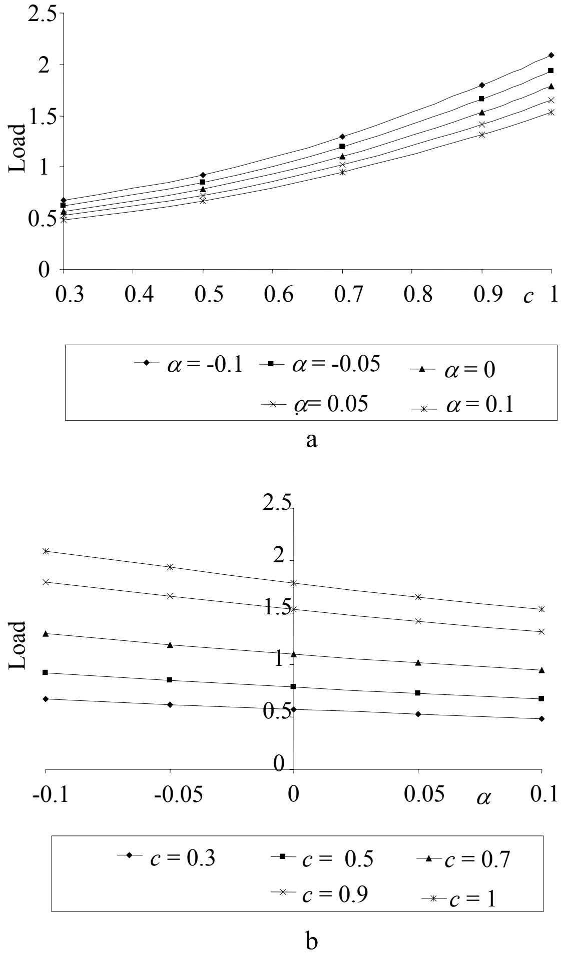

Fig. 12 a - variation of load carrying capacity with respect to c and α ; b - variation of load carrying capacity with respect to α and c

In Fig. 13 we have the effect of characteristic length on the distribution of load carrying capacity for various values of skewness. It is clear from this figure that there is a negligible effect of skewness when considered with the characteristic length.

Figs. 14 and 15 present the profile for friction. It is seen that friction decreases substantially with respect to the characteristic length.

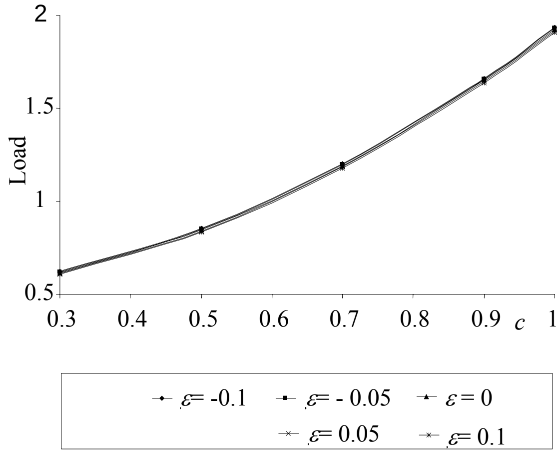

Fig. 13 Variation of load carrying capacity with respect to c and ε

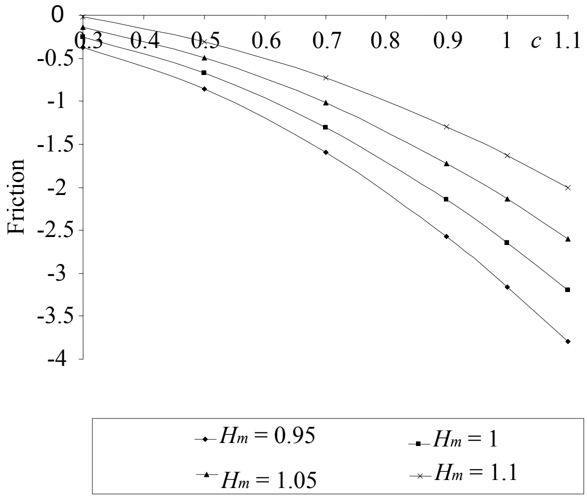

Fig. 14 Variation of friction with respect to c and H_m

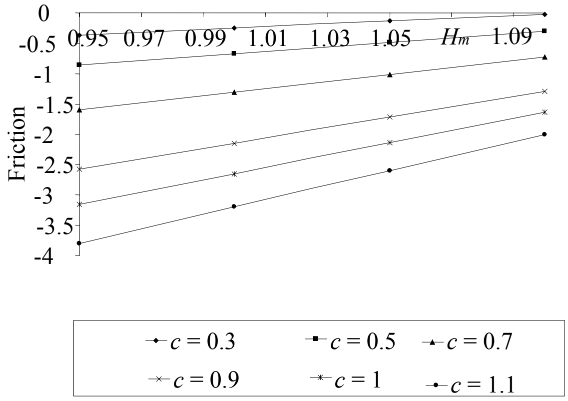

Fig. 15 Variation of friction with respect to c and H_m

Finally, Fig. 16 makes it clear that the negatively skewed roughness reduces the friction considerably. Same is the case of negative variance. It is clearly noticed that the negative variance reduces the friction relatively more as compared to that of negatively skewed roughness.

From this study it is indicated that the increased load carrying capacity due to negatively skewed roughness further increases owing to the negative variance for all most all values of H_m. Besides, the prominent role of thickness at maximum film pressure is emphasized here which becomes all the more evident while dealing with roughness for the thin film lubrication at nano scale.

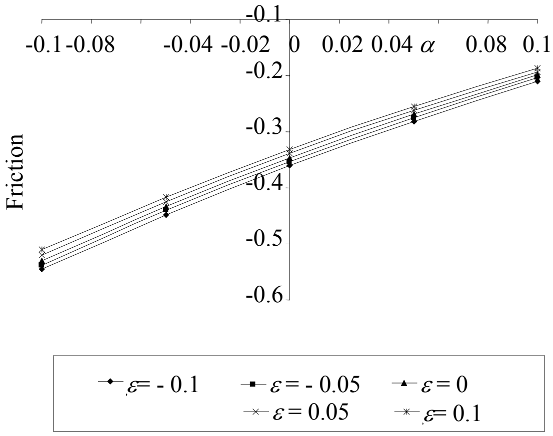

Fig. 16 Variation of friction with respect to α and ε

In fact the effect of couple stress is equivalent to improving the effective viscosity which increases the load carrying capacity of fluid film to some extent. As the characteristic length increases this influence become more significant.

This article establishes that the existence of couple stress improves the performance of bearing systems which gets further increased when the thin film lubrication is considered at the nano scale. Although, the bearing suffers in general, there exist ample scopes for improving the performance of the bearing systems in the case of negatively skewed roughness especially, when negative variance is involved. The negative effect induced by the standard deviation associated with roughness can be compensated to a large extent by the positive effect of the thin film lubrication at nano scale in the case of negatively skewed roughness. This compensation further increases due to couple stress effect.

4. Conclusion

The findings incorporated here make an interesting reading as thin film lubrication is a lubrication regime where the ordering of the molecules plays a dominant role during lubricating process. A close scrutiny of the results presented here indicates that the conclusions drawn here are in good agreement with the conclusions drawn by some of the experimental based models known earlier. This investigation suggests that the roughness must be given due consideration while designing the rough bearing system dealing with the thin film lubrication at nano scale. This article also underlines the importance of the thin film lubrication at nano scale and couple stress effect while dealing with the lubrication of a rough slider bearing, from life period point of view.

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TEPIMO CHARAKTERISTIKOS NANO SRITYJE EKSPLOATUOJANT SKERSINIO ŠIURKŠTUMO SLYDIMO GUOLĮ

Reziumė

Analizuojama paviršiaus skersinio šiurkštumo įtaka plonasluoksniam hidrodinaminiam slydimo guolio tepimui nano srityje. Dviejų vienas kito atžvilgiu judančių paviršių plonasluoksnį hidrodinaminį tepimą daugiausia lemia paviršiaus savybės, tepalas ir jo klampumas. Paviršiaus šiurkštumo ir šlyties įtempių sukurtas efektas negali būti ignoruojamas, kai skystyje vyrauja taisyklingai išsidėsčiusios molekulės. Paviršiaus šiurkštumas apibūdinamas atsitiktine sklaida su nenuliniais vidurkiu, dispersija ir asimetrijos koeficientu. Apibendrinta Reinoldso lygybė yra stochastiškai suvidurkinta ir išspręsta esant atitinkamoms ribinėms sąlygoms; gautas slėgio pasiskirstymas, pagal kurį apskaičiuojama laikomoji galia. Pastebėta, kad skersinis šiurkštumas apskritai yra žalingas. Tačiau šis neigiamas efektas yra santykinai mažesnis už nustatytą plonasluoksniam hidrodinaminiam tepimui esant mažesniems ir vidutiniams sluoksnio storiams ir maksimaliam slėgiui. Neigiamas šiurkštumo asimetrijos koeficientas gerokai padidina laikomąją galią, kuri dar labiau padidėja esant neigiamai dispersijai. Nustatyta, kad laikomoji galia didėja priklausomai nuo plonasluoksnio hidrodinaminio tepimo nano skalėje. Be to, laikomąją galią ypač padidina būdingasis ilgis, turintis įtakos šlyties įtempiams dėl trinties sumažėjimo. Nustatyta, kad tepimo, esant šlyties įtempiams metu atsirandantis mastelio efektas yra tuo didesnis, kuo plonesnis tepalo sluoksnis.

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CHARACTERISTICS OF LUBRICATION AT NANO SCALE ON THE PERFORMANCE OF TRANSVERSELY ROUGH SLIDER BEARING

Summary

Efforts have been made to study and analyze the effect of transverse surface roughness on the behavior of thin film lubrication at nano scale of a slider bearing. Basically, the combination of the properties of surfaces, the lubricant and viscosity of the lubricant are responsible for thin film lubrication between two surfaces in relative motion. The effects induced by the surface roughness and couple stress cannot be disregarded in this regime where the ordered molecule dominate the fluid field. The roughness of the surfaces is characterized by a random variable with non zero mean, variance and skewness. The associated Reynolds' equation is then stochastically averaged and solved with suitable boundary conditions to get the pressure distributions which in turn, lead to the calculation of load carrying capacity. It is observed that the effect of transverse roughness is adverse in general. However, this negative effect is relatively less when considered with thin film lubrication for lower and moderate values of film thickness at maximum film pressure. The negatively skewed roughness increases the load carrying capacity substantially, which gets further increased in the case of negative variance. It is established that load carrying capacity increases due to the thin film lubrication at nano scale. The existence of couple stress enhances the load carrying capacity. Besides, the characteristic length contributing to the couple stress increases the load carrying capacity considerably while the friction decreases. Size dependent effects are observed in the lubrication with couple stress and the thinner the lubrication film is the more obvious becomes the effect.

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ХАРАКТЕРИСТИКИ СМАЗКИ В НАНО ОБЛАСТИ ПРИ ЭКСПЛУАТАЦИИ ПОДШИПНИКА СКОЛЬЖЕНИЯ С ПОПЕРЕЧНОЙ ШЕРОХОВАТОСТЬЮ

Резюме

В статье рассмотрено валяние поперечной шероховатости поверхности на тонкую гидродинамическую смазку подшипника скольжения в нано области. В основном свойства поверхности, смазка и ее вязкость ответственны за тонкую гидродинамическую смазку между двумя относительно передвигающимися поверхностями. Шероховатость поверхности и эффект напряжении сдвига нельзя игнорировать, если в жидкости доминируют упорядоченные молекулы. Шероховатость поверхности характеризуется случайным распределением с ненулевым средним, дисперсией и коэффициентом асимметрии. Стохастически усреднена и решена с соответствующими граничными условиями обобщенная зависимость Рейнольдса применяется для расчета распределения давления, при помощи которого определяется несущая способность. Установлено, что поперечная шероховатость является неблагоприятным. Однако ее отрицательный эффект относительно меньше полученного для тонкой гидродинамической смазки при низких и средних толщинах слоя и максимальном давлении. Отрицательный коэффициент шероховатости существенно повышает несущую способность, которая еще больше повышается при отрицательной дисперсии. Определено, что несущую способность в нано области повышает тонкая гидродинамическая смазка. Кроме того, характеристическая длина, влияющая на напряжения сдвига существенно повышает несущую способность из за уменьшения трения. При смазке с напряжениями сдвига замечен масштабный эффект, который усиливается с уменьшением толщины смазочного слоя.

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