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Analysis of non-Newtonian lubricated textured contact for mixed slip/no-slip configuration considering cavitation

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Abstract. The increasing use of non-Newtonian fluids as lubricants has received much attention due to their high shear. The present study explores a lubrication mechanism in lubricated textured contact for mixed slip/no-slip pattern considering cavitation. The effect of texturing depth on the bearing performance is also investigated. The numerical method based on commercial CFD (computational fluid dynamic) software is carried out to analyze the tribological characteristics (i.e., hydrodynamic pressure distribution) of lubricated textured contact. To model slip, the enhanced user-defined-function (UDF) in the FLUENT® package is developed. The analysis results show that giving textures as well as a slip to one of the parallel sliding surfaces can generate significant hydrodynamic pressure to affect the load support. The increase in the load support is also indicated by increasing the streamline recirculating flow. Besides, numerical results suggest that cavitation modeling has a significant effect on performance. Ignoring cavitation leads to less accurate results.

1. Introduction

The bearing has offered technological advances and has played an essential role in many relevant fields. However, the main problem limiting the development of the bearing extensively is friction and wear. To solve this problem, the use of artificial texture and slip is important in lubricated devices because of the benefits associated with load support and friction [1-2]. As a consequence of the development of modern machines, improved lubricant characteristics have received great attention. The researchers found the desired oil by adding some polymers to the Newtonian fluid, which in turn causes the fluid properties to be non-Newtonian. Experimental studies suggested that non-Newtonian fluids can improve lubrication performance in hydrodynamic bearing systems [3-4].

Recently, research on adding texture and slip on the bearings have been conducted by researchers [5-8]. Many researchers have also introduced an experimental work for the analysis of textured bearings with non-Newtonian lubricants [9-10]. In most existing studies, it is known that the width and/or height of texture and slip can increase the load and reduce friction. However, the consequence of growing load support causes changes in film thickness, causing changes in pressure on



the bearing surface. If this pressure changes significantly, it generates cavitation and affects the lubrication performance of the bearing [11]. Cavitation on textured bearing was paid much attention by researchers [12-13]. From these studies, it was known that cavitation occurs due to the presence of texture on the significant bearing effect on the performance of lubrication in the bearings. Besides, the optimal form of composition was highlighted. However, the result of slip was not modeled in their analysis.

Generally, research on cavitation and/or slip is done separately. In this work, the lubrication mechanisms on lubricant parallel texture contacts for mixed slip / no-slip patterns including the cavitation effect will be studied. The impact of texturing depth on the performance is also investigated. The numerical method based on commercial CFD (computational fluid dynamic) software is carried out to analyze the tribological characteristic (i.e., hydrodynamic pressure distribution) of lubricated textured contact. To model slippage, the enhanced user-defined-function (UDF) in the FLUENT® package is developed.

2. Methods

In this research, commercial CFD codes based on the Navier-Stokes equation are applied. CFD has more advantages over Reynolds approaches when simulating hydrodynamically lubricated contacts because they are capable of solving contact problems lubricated on complex geometries. The sliding contact is modeled on a slider bearing. The bearing width is assumed to be infinite, so the fluid pressure gradient velocity only affects the x-direction.

The Navier-Stokes Equation is settled over the domain using the finite-volume method the FLUENT® commercial CFD software package. The equations are steady and solved in the x - and z -directions only. The comparisons are applied with constant density and viscosity, without body force. Refer to this property, the Navier–Stokes and continuity equations can be expressed, respectively:

$$\rho(u \bullet \nabla)u = -\nabla p + \eta \nabla^2 u \quad (1)$$

$$\nabla \bullet u = 0 \quad (2)$$

The stress-strain relationship of the lubricant was modeled with a power-law fluid model scheme applied in this study. This means that the shear stress τ is a function of some power of shear strain rate $\dot{\gamma}$ and its mathematical expression reads [8]:

$$\tau = m (\dot{\gamma})^n \quad (3)$$

Refer to the above equation, m is consistency index, and n is flow behavior index. The turbulent model of Realizable k- ϵ is used with standard wall functions as near-wall treatment, to present more realistic bearing characteristics. In the case of textured bearings, when pressure drops below atmospheric pressure due to changes in texture geometry, the air's ability to dissolve in the fluid is reduced, so that air appears in the fluid layer and forms cavitation. In FLUENT®, there are three available cavitation models: Schneer and Sauer model, Zwart-Gelber-Belamri model and Sigal et al. model. In this study, the Zwart-Gelber-Belamri is employed due to their capability (less sensitive to mesh density, robust and converge quickly). In cavitation analysis, the liquid-vapor mass transfer (evaporation and condensation) is governed by the vapor transport equation. For Zwart-Gelber-Belamri model, the final form of the cavitation is as follow:

If $P \leq P_v$

$$R = F_{vap} \frac{3\alpha_{nuc}(1-\alpha_v)\rho_v}{\Re_B} \sqrt{\frac{2}{3} \frac{P_v - P}{\rho_\ell}} \quad (4)$$

If $P \geq P_v$

$$R = F_{cond} \frac{3\alpha_v \rho_v}{\Re_B} \sqrt{\frac{2}{3} \frac{P - P_v}{\rho_\ell}} \quad (5)$$

The schematic of the lubricated sliding contact is presented in Figure 1. The textured surface of the bearing is assumed as the stationary wall, and the upper surface of the bearing is set as a moving wall. The enhanced user-defined-function (UDF) in the FLUENT® package is developed to model hydrophobicity, i.e., slippage. The analysis will be regarded as isothermal; therefore, the energy conservation equation is not included. The volume-based technique is employed as the control to solve the Navier-Stokes equation numerically. At the inlet and outlet of the domain, the pressure was set to atmospheric. For the solution, the assumption of a non-Newtonian laminar flow model is implemented.

In this simulation, there are two variations of the texturing geometry. The texturing depth, H_d variations are 0.1 and 0.75 by varying slip and no-slip on each geometry. The geometry used in this modeling is a textured bearing reference to Cupilard et al. [14]. In the CFD simulation, the mesh will be used consisting of a block with a uniform grid. The number of grid points in the longitudinal direction (N_x) and transverse (N_z) is 900 x 50. The mesh configuration is reflected in Figure 2. The lubricated contact simulation presents the characteristics as shown in Table 1.

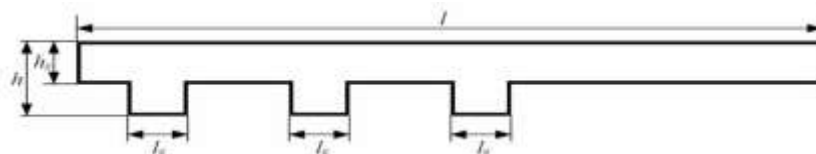


Figure-1. Schematic of a textured slider bearing

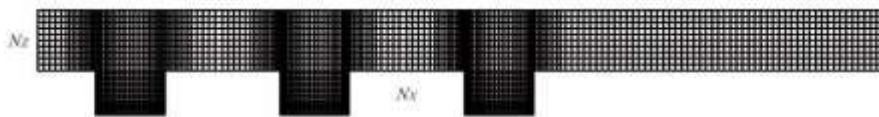


Figure-2. The mesh structure on the domain of textured slider bearing

Table- 1. Main characteristics of the bearing analyzed

Parameter	Value
Velocity U	2 m/s
Lubricant density (liquid) ρ_ℓ	1000 kg/m ³
Consistency index k	0.044 kg·s ⁻ⁿ⁻² /m
Power-law index n	0.75
Dynamic viscosity (minimum) η_{min}	0.001 kg/m·s
Dynamic viscosity (maximum) η_{max}	1000 kg/m·s
Inlet pressure P_{inlet}	1 atm
Outlet pressure P_{outlet}	1 atm

3. Result and discussion

3.1. Effect of the slip

Figure 3 presents a scheme of textured slider bearings including slips. Hydrodynamic pressure distribution results by varying slip / no-slip configurations for both texturing depth, $H_d = 0.1$ and $H_d = 0.75$ are reflected in Figures 4 and 5. It can be seen that simulation results for no-slip configurations produce lower pressure profiles than slip configurations, for both $H_d = 0.1$ and $H_d = 0.75$. This means that providing slip to one of the parallel sliding surfaces can produce significant hydrodynamic pressure to influence load support (tribological performance).

Figure 6 shows that the streamline recirculating flow for slip model is higher than the no-slip model. The streamline recirculating flow can also indicate the increase of the load support. It can be observed that the slip affects to generate more vortex compared to the no-slip pattern, which leads to the occurrence of the inertia. Therefore, the slip configurations give more hydrodynamic pressure.

The detail simulation results for the load support and the friction forces are presented in table 2. For the texturing depth, $H_d = 0.1$, the slip can improve the load support 88.6 % and reduce the friction force 18.3 %. The slip also increases the load support 78.1 % and decreases the friction force 7.7 %, for the texturing depth, $H_d = 0.75$.

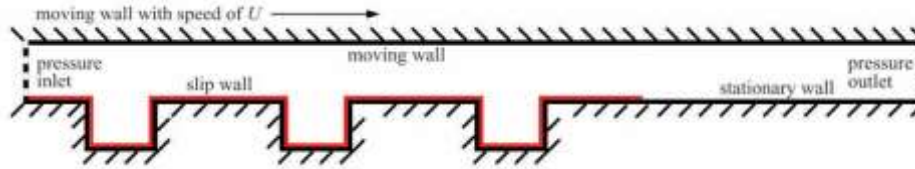


Figure-3. Schematic of textured slider bearing including slip boundary

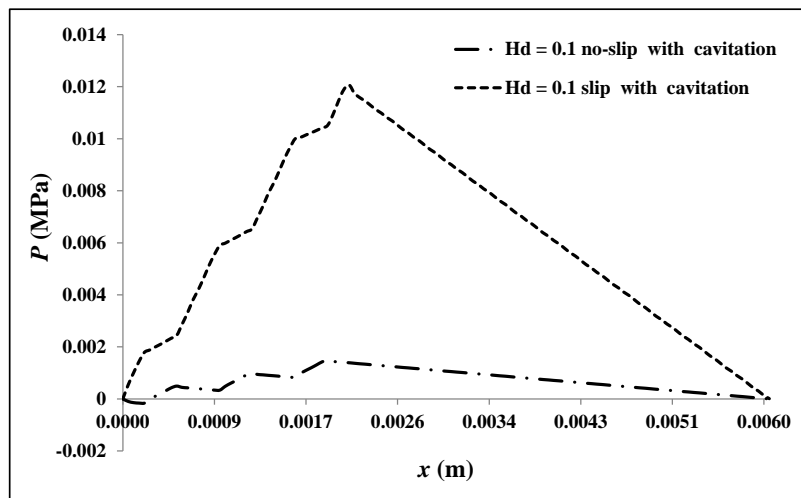


Figure-4. The results of the pressure distribution on the textured slider bearing for $H_d = 0.1$ with slip boundary and no-slip boundary both with cavitation

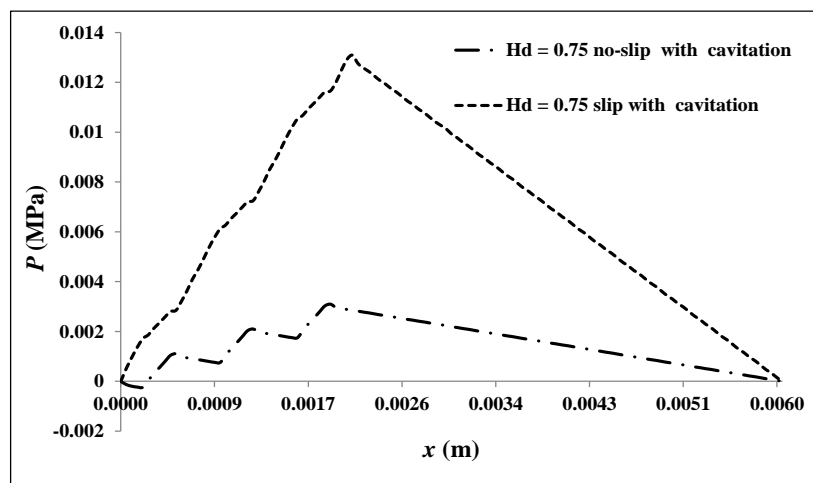


Figure-5. The results of the pressure distribution on the textured slider bearing for $H_d = 0.75$ with slip boundary and no-slip boundary both with cavitation

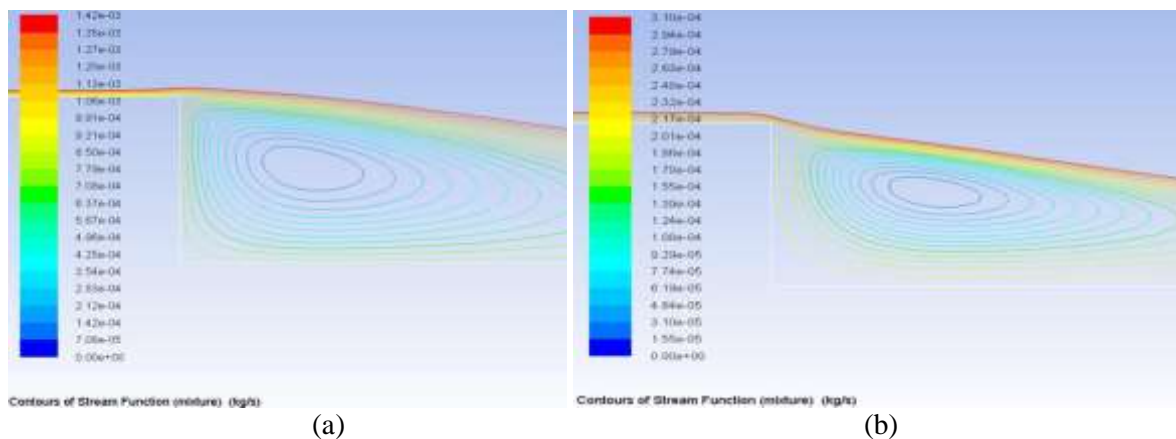


Figure-6. The results of the streamline recirculating flow on the first texturing for $H_d = 0.75$, (a) slip, (b) no-slip both with cavitation

Table- 2. The simulation results of the load support and friction on the textured slider bearing

Cavitation	$H_d = 0.1$		$H_d = 0.75$	
	Load Support, W (N)	Friction Force, F (N)	Load Support, W (N)	Friction Force, F (N)
Slip	36.23	0.98	39.29	1.07
no-slip	4.10	1.16	8.58	1.16
Δ (%)	88.6	18.3	78.1	7.7

3.2. Effect of the texturing depth ($H_d = 0.1$ and $H_d = 0.75$) and cavitation

The effect of texturing depth on the bearing performance is also investigated in this study. Figure 7 depicts the comparison of the pressure distributions on the textured slider bearing by varying the texturing depth ($H_d = 0.1$ and $H_d = 0.75$) both for the slip and no-slip boundary including cavitation. It can be seen that the simulation results for $H_d = 0.75$ effect a higher pressure profile compared to $H_d = 0.1$. It indicates that the texturing depth geometry influences to the bearing lubrication performances. The texturing depth, $H_d = 0.75$ is more recommended to be applied on the textured slider bearing. Figure 7 also reflects the comparison between the hydrodynamic pressure distribution with cavitation and that without cavitation. It can be seen that the simulation results for the cavitation model predict lower pressure profile compared to that without cavitation. Therefore, Neglecting the cavitation leads to the less accurate result.

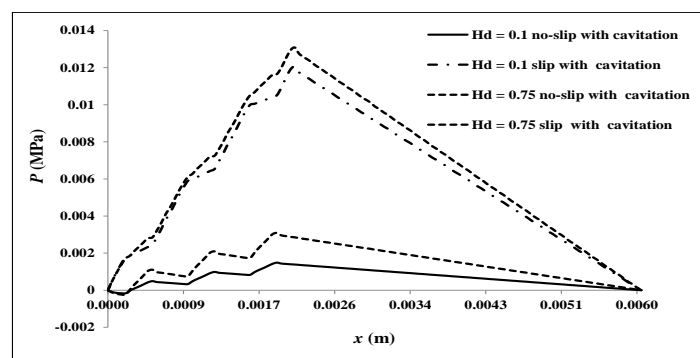


Figure-7. The comparison of the pressure distributions on the pocketed slider bearing by varying the texturing depth ($H_d = 0.1$ and $H_d = 0.75$) with cavitation

4. Conclusion

In this paper, based on CFD approach, the non-Newtonian lubricant was investigated for analyzing the textured bearing with slip. The cavitation model was also of particular interest. Based on the explanation discussed earlier, it was concluded that the textures, as well as slip, produce a significant effect on the hydrodynamic pressure and the load support. Besides, the cavitation modeling has great significance in altering the hydrodynamic performance.

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