Inertia Effect on the Cavitation Phenomena of Textured Bearing

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Abstract: For more than a century, with increasing the demand for energy-saving, there has been a growing application of surface texturing due to its good behaviour in enhancing the performances of tribological pairs. As is known, in textured surface the inertia as well as the cavitation has a major effect on the hydrodynamic pressure profile. The present paper examines the correlation between the cavitation and the inertia effects in textured lubricated contact using computational fluid dynamic (CFD) approach. The multi-phase cavitation model is adopted to obtain more realistic characteristic of the bearing. A quantitative analysis of inertia influences on cavitation zone is made in this paper. The existence of slip at the bearing pad is also particular interest. Based on the simulation results, it is found that increasing the inertia effect will trigger the presence of the cavitation phenomena. It is also equally shown that the wall slip condition appears to contribute to the reduced hydrodynamic lift. The present results illustrate a superior performance of bearing with low inertia pattern in comparison to other bearing types.

1 INTRODUCTION

Over the past years, extensive research acitivity has aimed at making machines more efficient by reducing the power losses found in bearings. Bearings are important components widely used in propulsion and industrial applicatons because of their efficiency, low cost, and simplicity.

Surface texturing as a tool for enhancing the tribological performance of mechanical components has been under intensive exploration over the last two decades. Within the broad area of tribology, the researches relating to the lubrication have paid much attention to surface texturing, as is reflected in many papers, for example (Tala-Ighil et al., 2011; Rao et al., 2012; Tauviqirrahman et al., 2014; Meng et al., 2015, Rahmani and Rahnejat, 2018). As mentioned in the literature, appropriate texturing has been found to increase hydrodynamic lift, reduce friction and the wear rate.

However, the available literature survey indicates that most of studies related to the texturing adopted Reynolds boundary condition for modeling the cavitation phenomena. As is known, the Reynolds approach as well as Sommerfeld theory or Half-Sommerfeld theory are often considered as a rough approximation, because it is not based on real physical phenomenon (Braun and Hannon, 2010). For this reason, in order to obtain more accurate result in solving the texturing problem in lubrication numerically and theoretically, for modelling cavitation tribologists have adopted either the mass-conservative approach (Dobrica et al., 2010, M. Tauviqirrahman, et al. 2016, Muchammad et al., 2017) or multi-phase model (Concli, 2016; Zhang et al., 2016, Lin et al., 2018). As a note, the lattest model provides a physical approach to introducing the influences of bubble dynamics.

Based on literatures ourvey, one can find that Reynolds equation is quite populer to use in solving the lubrication problem due to simplicity. However, the use of the Reynolds equation instead of Navier-Stokes equation in most published works limited the validity of the performance of the textured contact especially in explaining the inertia-related effect. Concerning the inertia influence, contradictory results among the published works were also obtained. For example, Arghir et al. (2003) postulated that the inertia could enhance the load carrying capacity in fully textured parallel sliders, while Dobrica and Fillon (2009) concluded the opposite result; inertia terms have, in general, a negative effect over the hydrodynamic performance. Therefore, what mechanism which leads to the

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generation of the enhanced lift hydrodynamic: inertia or cavitation is still unclear. In addition, the available references also indicate that the studies related to the correlation between cavitation and inertia are rather very limited.

In the application of lubricated contacts, in addition to texturing, the introduction of wall slip induced by hydrophobic coating has been subject to both analytical and experimental research recently. The use of wall slip has become popular since this type of surface enhancement would give a better tribological performance of the bearing significanlty, i.e. high load support but low friction (Rao et al., 2012, Tauviqirrahman et al., 2014, Tauviqirrahman et al., 2016, Senatore and Rao, 2018).

As an extended exploration of the simple textured bearing employed in the previously published studies, more work is required to provide the needful information for the inertia effect as well as the cavitation effect. The contribution of this paper is to explore the correlation between the cavitation and the inertia effect based on CFD (computational fluid dynamic) approach for two situations, i.e. no-slip and slip. Initially, for a reference design of textured bearing in conventional (no-slip) condition, the effects of inertia have been investigated. Finally, the effects of slip introduction of each inertia pattern of the textured bearing have been studied.

2 METHODOLOGY

2.1 Governing equations

In this work, a commercial CFD software based on finite volume method ANSYS FLUENT® is used. For all flows, ANSYS FLUENT® solves conservation equations for momentum and mass (Equations 1 and 2). The conservation equations for laminar flow (in inertial reference frame) is presented.

$$\rho\,(\mathbf{u}\bullet\nabla)\,\mathbf{u} = -\nabla p + \eta\nabla^2\,\mathbf{u} \tag{1}$$

$$\nabla\bullet\mathbf{u} = 0 \tag{2}$$

Once the film pressure is obtained through Equations 1 and 2, the load support of lubrication film on the bearing surface W can be calculated as:

$$W = \int p\,dx \tag{3}$$

The frictional force F acting on the stationary surface due to the viscosity shear force τ can be written as:

$$F = \int \tau\,dx \tag{4}$$

When the textured bearing operates, the cavitation of lubricant often exists. When the lubricant flow enters the texture cell, the hydrodynamic pressure might fall below the saturation lubricant vapor pressure, and the liquid would rupture and cavitation occurs.

In ANSYS FLUENT®, there are three available cavitation models: Singhal et al. model, Zwart-Gerber-Belamri model and Schnerr and Sauer model. However, in this study, the cavitation model of Zwart-Gelber-Belamri (Equations 5 and 6) is employed due to their capability (less sensitive to mesh density, robust and converge quickly. In cavitation, the liquid-vapor mass transfer (evaporation and condensation) is governed by the vapor transport equation (Zwart et al., 2004):

$$\frac{\partial}{\partial t}(\alpha_v\rho_v) + \nabla.(\alpha_v\rho_v \mathrm{v}) = R_g - R_c \tag{5}$$

where α_v is vapor volume fraction and ρ_v is vapor density. R_g and R_c account for the mass transfer between the liquid and vapor phases in cavitation.

If $p \le p_v$,

$$R_g = F_{evap}\frac{3\alpha_{\mathrm{nuc}}(1-\alpha_\upsilon)\rho_\upsilon}{R_{\mathrm{B}}}\sqrt{\frac{2}{3}\frac{\mathrm{P}_\upsilon - \mathrm{P}}{\rho_\ell}} \tag{6}$$

If $p \ge p_v$,

$$R_c = F_{cond}\frac{3\alpha_\upsilon\rho_\upsilon}{R_{\mathrm{B}}}\sqrt{\frac{2}{3}\frac{\mathrm{P} - \mathrm{P}_\upsilon}{\rho_\ell}} \tag{7}$$

where F_{evap} = evaporation coefficient = 50, F_{cond} = condensation coefficient = 0.01, R_B = bubble radius = 10^{-6} m, α_{nuc}= nucleation site volume fraction= $5\mathrm{x}10^{-4}$, ρ_l = liquid density and p_v = vapour pressure.

In the application of sliding surfaces in very narrow-gap conditions and the availability of hydrophobic coating materials, the lubricant can slip along a solid-liquid interface. In this way, the slip length b is generally used to address the relation between slip velocity and surface shear rate, that is,

$$u_s = b\left.\frac{\partial u}{\partial z}\right|_{\text{surface}} \tag{8}$$

where u_s indicates the slip velocity at the slip (hydrophobic) surface, b denotes the slip length, and $\partial u/\partial z|_{\text{surface}}$ is the surface shear rate.

As evident from the available literature, a large value of b was found to be crucial hypotheses to imply great slip and thus reduced friction (Choo et al., 2007). In the present study, the slip length induced by a hydrophobic surface is assumed as uniform in space and set to 10 µm based on the experimental work of Choo et al. (2007).

2.2 Simulation model

In this study, for modelling the textured bearing the shape of texture cell is chosen to be rectangular as this would be relatively easy to. Figure 1 shows a schematic of a textured lubricated contact with single texture cell. The texturing schematic studied here adopts the work of Dobrica and Filllon (2009). The flow is considered isothermal, steady and incompressible. One side of the film gap as well as the outlet is considered as periodic boundary condition to simplify the flow model and to reduce the computational cost. The operating pressure is set to 101 325 Pa. The lubricant properties at 20°C listed in Table 1 are employed.

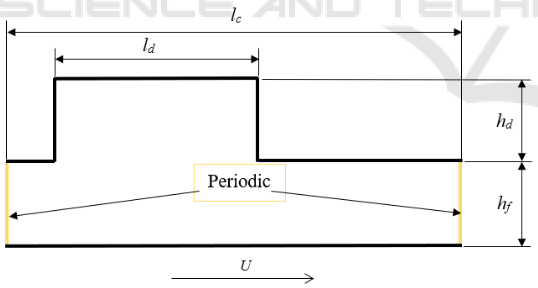


Figure 1: Schematic of a lubricated texture sliding contact with periodic boundary condition. (Note: h_d = dimple depth, h_f = land film thickness, l_d = dimple length, l_c = length of textured zone, U = sliding velocity).

In the present study, to explore the inertia effect, two patterns of the texture contact are adopted as shown in Figure 2, i.e. the pattern with high inertia effect (λ = 2, R_e = 57.3) and that with low inertia effect (λ = 20, R_e = 5.73). As a note, dimple aspect ratio λ is defined as the ratio between the dimple length l_D and the dimple depth h_d. For all following computations, texture density (defined as the ratio between the dimple length l_d and the texture cell length l_c) and relative dimple depth (defined as the ratio between the dimple depth h_D and the land film thickness h_F) are set to 0.5 and 1.0, respectively. In this paper, the variation of λ is performed by changing the value of h_D and keeping the l_d as constant.

Table 1: Lubricant properties at 20°C.

Saturation pressure of lubricant vapour	3,540 Pa
Saturation density of lubricant	860 kg/m^3
Saturation density of lubricant vapour	12.56 kg/m^3
Dynamic viscosity of lubricant	0.03 Pa.s

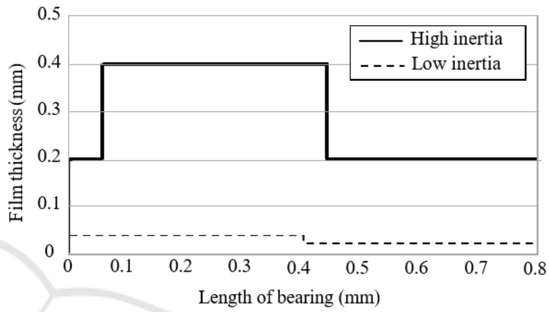


Figure 2: Comparison of two patterns of textured contact studied here (high inertia vs low inertia).

For modelling wall slip in ANSYS-FLUENT, an additional subroutine to enhance FLUENT's capability is made. This subroutine called as User-Defined-Function (UDF) is a function that allows a user to define the boundary conditions, material properties, and source terms for the flow regime, as well as specify customized model parameters. In this study, for the case analysis when the slip is considered, the slip is applied on the top surface while no-slip condition is employed on the bottom sliding surface.

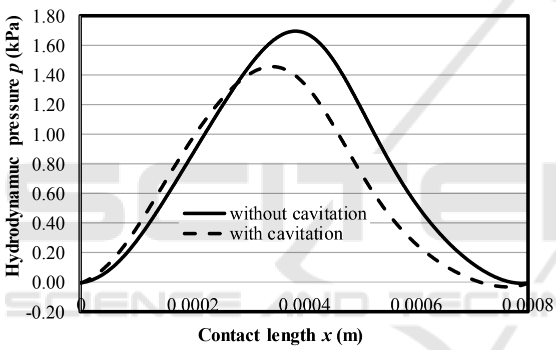
The generated grid for the simulations is composed of 169,960 and 98,879 quadrilateral elements for high inertia and low inertia pattern, respectively. Since cavitation may occur in the texture, mesh refinements are made inside the texture cell. In this work, for the numerical analysis in this research the pressure-based solver is adopted. The velocity-pressure coupling is treated using SIMPLE, while for spatial discretization of pressure, PRESTO is adopted.

3 RESULTS AND DISCUSSION

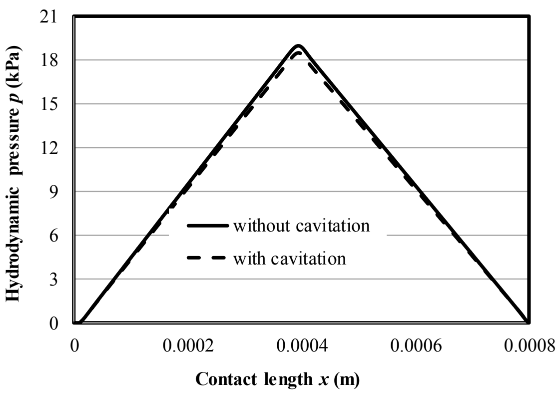
This section reports the results obtained for the periodic flow developed in one texture cell with periodic boundary condition, at two conditions, low inertia and high inertia effect.

3.1 No-slip condition

Figure 3 presents the hydrodynamic pressure along the contact evaluated by two approaches, i.e. "without cavitation modelling" versus "with cavitation modelling" for the case of high and low inertia effect, respectively. It can be seen that for the case of high inertia effect (Fig. 3 (a)), the maximum pressure is overestimated by about 15% when the cavitation model is not used. It appears that at the outlet edge of the contact, the deviation of the pressure profiles becomes larger. For the case of low inertia effect, it is evident that the prediction of two methods for the pressure profile nearly coincides. The discrepancy in the maximum pressure is just around 2%.



(a)



(b)

Figure 3: Hydrodynamic pressure with (a) high inertia (λ = 2, *Re* = 57.3), (b) low inertia effect (λ = 20, *Re* = 5.73).

Based on two cases studied here, it seems that the inertia effect has a strong correlation with the cavitation effect. When the inertia effect is low at the textured contact, the possibility of the occurrence of the cavitation will become small. Thus, it means that when the bearing is designed to operate in high inertia effect, one should take into account the cavitation model in the analysis.

In terms of load support, the discrepancy of the load support prediction between "with cavitation modelling" versus "without cavitation modelling" is shown in Figure 4. It can be observed that in the case of bearing with high inertia pattern, the discrepancy is up to 17 %, while for low inertia pattern, the discrepancy is just 3 %. This result strengthens the previous finding which highlighted that inertia can be a trigger to the occurrence of the cavitation.

The same trend is also observed with respect to the friction force as depicted in Figure 5. The inclusion of cavitation model in the analysis leads to the lower prediction of friction force compared to the analysis which ignores cavitation model. The most possible explanation is that based on physical point of view, there is a larger recirculation zone inside the texture cell in the case of high inertia pattern compared to that in low inertia case as seen in Figure 6. This recirculation may reduce the availability of the lubricant to generate more hydrodynamic lift and become a trigger to bring up the cavitation phenomena. It seems that in this case, the inertia has a negative effect in terms of load support as well as friction force. This finding matches well with the work of Dobrica and Fillon (2009).

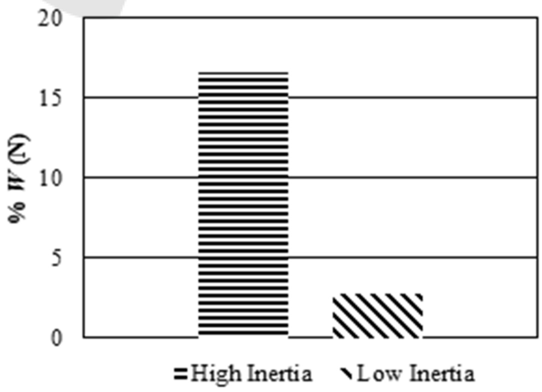


Figure 4: Discrepancy of predicted load support between cavitation model versus no-cavitation model for two inertia patterns.

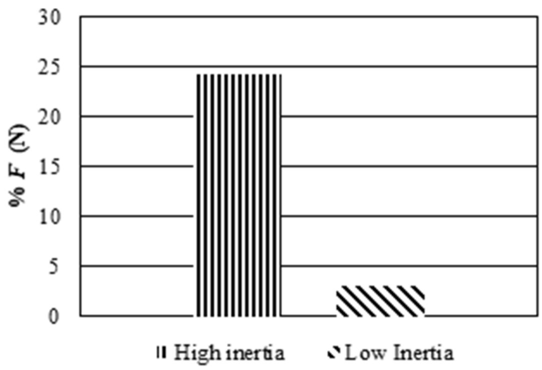
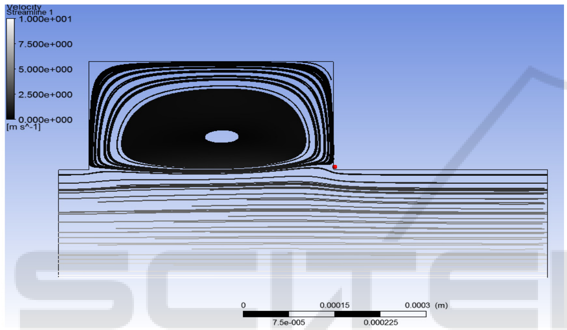
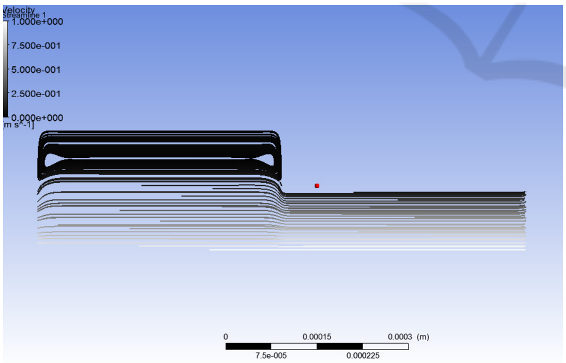


Figure 5: Discrepancy of predicted friction force between cavitation model versus no-cavitation model for two inertia patterns.



(a)



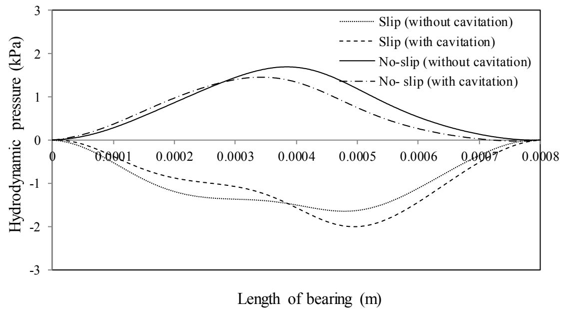
(b)

Figure 6: Stream function for different inertia patterns, (a) high inertia, (b) low inertia.

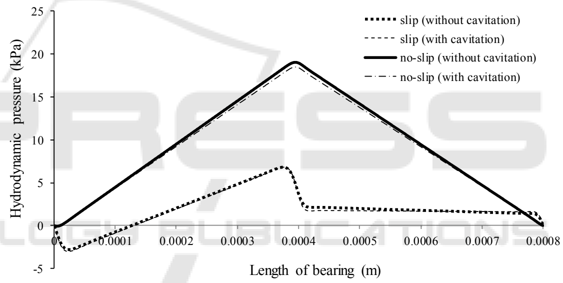
3.2 Slip condition

In this section, the surface of lubricated contact as reflected in Figure 2 is modified by introducing the wall slip boundary condition on top (stationary) surface. In real, the wall slip condition can be induced by giving the hydrophobic coating. In this way, the correlation between the inertia and cavitation effects in the presence of slip can be investigated in more deep way.

Figure 7 shows the hydrodynamic pressure profiles for various conditions (i.e., slip and no-slip, with cavitation modelling and without cavitation modelling). All results are evaluated for two bearings whose different inertia terms.



(a)



(b)

Figure 7: Hydrodynamic pressure for different conditions (slip and no-slip, with cavitation and without cavitation modelling) for the case of: (a) high inertia, (b) low inertia.

Three specific characteristics can be made based on Figure 7. Firstly, in the case of high inertia (Fig. 7 (a)), the slip-textured bearing shows the failure of lubrication mechanism. It seems that the slip boundary generates the large decrease in the pressure gradient especially inside texture cell both for the case of inclusion of cavitation modelling and for the case of exclusion of cavitation modelling. Secondly, in the case of the low inertia, unlike the case of high inertia, the load support is generated for the situation. It indicates that the slip has a more dominant role compared to inertia effect in altering the performance of bearing. The same trend of the pressure profile is also observed either when the cavitation modelling is considered or when ignoring the cavitation modelling. Other interesting finding is that the pressure generation by the presence of slip is much lower than that by neglecting the slip both for low inertia and high inertia pattern. In general, introducing the slip condition on top surface of the bearing is not recommended, because it leads to deterioration of the hydrodynamic pressure and thus the generated load support. Thirdly, the increase of the inertia effect by lowering λ and increasing R_e in this case is likely a trigger to bring up the occurrence of cavitation. Based on Figure 7 (a), it can be found that there is a deviation of the pressure profile between the case of "with cavitation" and "without cavitation modelling".

4 CONCLUSIONS

In this study, the correlation between the inertia effect and the cavitation effect on the texture lubricated contact in terms of pressure profile based on CFD (computational fluid dynamic) method was explored in detail. Two patterns of textured bearing, i.e. high inertia and low inertia were studied. The presence of the wall slip on the bearing was also of particular interest. From the CFD results, the main conclusion can be drawn, that is, the inertia term affects the occurrence of the cavitation strongly. Whether the slip is present or not in bearing, the impact of inertia forces on the occurrence of the cavitation phenomena is observable distinctly. This finding may guide a new way to improve the operation stability of the bearing by controlling the cavitation phenomena in order to enhance the life time of the system.

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