Review Article

Energy-Conserved Hydrodynamic Lubricated Components with Wall Slippage

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The hydrodynamic thrust slider and journal bearings as well as hydrodynamic lubricated gears with the merit of energy conservation by the wall slippage are reviewed. The principle for designing these hydrodynamic contacts is to artificially set the wall slippage on the stationary surface in the hydrodynamic inlet zone. To design the wall slippage on the moving surface in the hydrodynamic outlet zone can also give additional benefits. The technical merits of these mechanical components are the improved load-carrying capacity and the lowered friction coefficient, i.e., the energy conservation due to the wall slippage. Owing to the designed wall slippage, the carried load of the hydrodynamic step bearing can be increased by 200% ~ 400% while its friction coefficient can be reduced by 50% ~ 85%, and the load-carrying capacity of the hydrodynamic journal bearing can be increased by nearly 100% while at the same time, its friction coefficient can be reduced by more than 60%. For hydrodynamic lubricated gear contacts, by covering ultrahydrophobic or oilphobic coatings on the slower moving surface, the friction coefficient can be approaching to vanishing and the contact load-carrying capacity can be increased very significantly for large slide-roll ratios under medium or heavy loads.

1. Introduction

Energy conservation is a big issue in modern industry. It is mostly related to the frictional power encountered in mechanical transmission. To realize it by reducing friction is of vital value to modern industrial development [1]. Bronshetyn and Kreiner showed that significant energy savings in machines can be obtained by using the energy-efficient lubricants; the performance of which is dependent on the viscosity shear thinning and the viscosity-pressure index [2]. They described that adding the friction modifier into the oils can reduce the friction. Tung and Gao also showed that by adding molybdenum dithiocarbamate (MoDTC) (friction modifier) into the engine oil, the friction and wear on the piston ring had been effectively reduced [3]. The reductions of friction were also realized by adding micrometer-scale or nanometer-scale particles into the lubricating oils [4–7]. These include the biolubricants containing boron nitride nanoparticles [4], the lubricating water containing titanium dioxide nanoparticles [5], the olive oil containing nanoparticles [6], and the avocado and canola oil containing boron nitride nanoparticles [7]. Surface texturing was also found to be an effective way for bettering the hydrodynamic lubrication and reducing the friction in mechanical contacts [8–13]. Surface coatings like diamond-like carbon, titanium nitride, graphite-like carbon, tantalum, and Mo-Se-C coatings have been found to effectively reduce friction in the boundary lubricated contacts [14–17]. The oils with low viscosities have also been used to reduce the friction in hydrodynamic lubrication [18–22]. All the above-mentioned methods are the classical popular dints to reduce frictional energy loss in lubricated contacts. In recent decades occurred the new hydrodynamic lubrication technology by using the boundary slippage to improve the load-carrying capacity but reduce the friction coefficient of the hydrodynamic lubricated contacts [23–27]. It revises the moving velocities of the fluid film adjacent to a solid surface and changes the fluid flow rate through the contact. By
designing the boundary slippage on specific surfaces such as on the stationary surface in the inlet zone or on the moving surface in the outlet zone or both of them, the performance of a hydrodynamic lubrication including the friction reduction can indeed be very effectively improved.

Hydrodynamic lubricated bearings are the important apparatus to support the load and reduce the friction coefficient in rotating machinery. Their energy conservation is a critical subject both in the research and in the production development. The classical method for reducing the friction coefficient and improving the energy efficiency of these bearings is to use the low-viscosity lubricant and the lubricant additives [4–7, 18–22, 28]. However, for the condition of heavy loads and high sliding speeds, the technical benefits of these methods seem very limited. In contrary, the boundary slippage technology is particularly suitable for these operating conditions because of its generated large lubricant film load-carrying capacity.

The wall slippage was found to occur in a hydrodynamic journal bearing long time ago [29, 30]. It was interpreted as the result of the shear stress exceeding the capacity of the adhering layer-fluid interface in a normal hydrodynamic journal bearing and found to pronouncedly reduce the load-carrying capacity of the bearing [29–31]. On the other hand, the friction coefficient of the bearing is significantly increased [31, 32]. Thus, the interfacial slippage in a normal hydrodynamic bearing made of steel, which is oophilic, deteriorates the overall performance of the bearing.

The wall slippage was found to very easily occur in micro-/nanofluidics such as carbon nanotubes, which are hydrophobic [33–37]. With the reduction of the nanopore radius, the wall slippage more easily occurs [38]. By using the interfacial limiting shear strength model, Wang and Zhang satisfactorily explained this phenomenon [39]. The wall slippage can largely increase the water flow rate through carbon nanotubes [5–9]. In hydrophilic nanopores, the wall slippage was not detected, and the water flow rate through the nanopores is significantly reduced. These indicate that the wall surface property of a nanopore, which is hydrophobic or hydrophilic, can change the liquid flow rate in the nanopore. This indeed provides a strong indication for designing the hydrodynamic bearing by applying the wall slippage. Bronshteyn and Kreiner and Tung and Gao [2, 3] actually noticed the influence of the surface property on the carried load of a hydrodynamic journal bearing.

By using the slip length model, Salant and Fortier [40, 41] numerically showed that the wall slippage on the stationary surface in the bearing inlet zone can significantly increase the hydrodynamic pressure and carried load of a three-dimensional hydrodynamic journal bearing. The mechanism of this bearing performance improvement is that the flow rate into the bearing inlet zone is increased due to the occurring wall slippage, and for maintaining the flow continuity, the magnitudes of the pressure gradients as well as the pressures in the bearing must be increased. This also provides the indication that the wall slippage occurring on the moving surface in the bearing outlet zone can also pronouncedly increase the pressures and carried load of a hydrodynamic bearing, as it follows the same principle by reducing the flow rate out of the bearing outlet zone. The study by Zhang [42] on a hydrodynamic step bearing proves this wall slippage effect.

The wall slippage appears to be a promising technical dint for designing the energy-conserved hydrodynamic lubrication in the condition of heavy loads and high sliding speeds. The present paper reviews the impressive researches in recent years on hydrodynamic lubrication by applying the wall slippage to improve the bearing performance. This work can help to elucidate some critical points in the wall slippage, summarize the vital design principles for the bearings by applying the wall slippage, and give the direction in the future research in this area.

2. The Wall Slippage Model

In fluid mechanics, the flow velocity discontinuity on the solid surface indicates the occurrence of the wall slippage, and it shows the relative sliding between the adsorbed boundary layer and the solid surface. Consequently, the wall slippage is reasonably understood as the result of the shear stress exceeding the shear stress capacity of the adsorbed boundary layer-solid surface interface. The popularly used “slip length” is a fictitious concept and has no substantial physical meaning [43]. The slip length model was shown to be not reliable for evaluating the performance of a hydrodynamic bearing with interfacial slippage [44]. In contrast, the interfacial limiting shear strength model is physically reasonable for explaining the wall slippage, and it is expressed by

\[ u = u_{\text{solid}} \quad \text{for} \quad |r| < r_s, \]

\[ u \neq u_{\text{solid}} \quad \text{for} \quad |r| \geq r_s, \tag{1} \]

where \( u \) is the velocity of the adjacent layer on the solid
surface, $u_{solid}$ is the speed of the solid surface, $\tau$ is the shear stress, and $\tau_s$ is the maximum endurable shear stress, i.e., shear strength of the adsorbed boundary layer-solid surface interface.

In designing the hydrodynamic bearing, the hydrophobic or oilphobic coating needs to be covered on the stationary surface in the bearing inlet zone so that the slippage can very easily occur on this coating. In this case, the slippage occurs on the adsorbed boundary layer-bearing surface interface, not on the adsorbed boundary layer-fluid interface. If the bearing surface separation is no less than one hundred times of the thickness of the adsorbed boundary layer, the adsorbed boundary layer can be ignored, and the wall slippage can be considered as occurring on the fluid-bearing surface interface [45]. This is usually the case for the hydrodynamic bearing with the designed artificial wall slippage.

In a thrust slider bearing or a journal bearing, the hydrodynamic pressures are not so high so that slippage.

3. Hydrodynamic Bearings with the Designed Wall Slippage

3.1. Hydrodynamic Step Bearing. Figure 1 shows the hydrodynamic step bearing where the wall slippage is designed, respectively, on the stationary surface in the inlet zone and on the moving surface in the outlet zone. Principally, this step bearing is advantageous over the step bearing with the wall slippage only on the stationary surface in the inlet zone or only on the moving surface in the outlet zone. However, this mode of step bearing should satisfy the following conditions:

$$\lambda = \frac{2U - \tau_s}{r_h} < 1,$$

$$\lambda + G(\psi)(1 + \psi) < 1,$$

$$\phi_s > 1 + \frac{G(\psi)}{r_h} \left(1 + \frac{1}{\psi}\right),$$

where $\lambda = \frac{r_{in}}{r_{slip}}$, $U = \psi \eta / (r_{slip} h_s)$, $\psi = l_1 / l_2$, $r_h = h_s / h_b$, $\phi_s = \frac{r_{in}}{r_{slip}}$, and

$$G(\psi) = \frac{3(U - (\lambda_0 / 2))\psi r_h^2 - (3/2) r_h \psi}{(1 + \psi r_h^2)(1 + \psi)}.$$

Here, $u$ is the sliding speed; $\eta$ is the fluid bulk viscosity; $r_s$ is the shear strength of the fluid-stationary surface interface in the inlet zone; $r_{in}$ is the shear strength of the fluid-stationary surface interface in the outlet zone; $r_{slip}$ is the shear strength of the fluid-moving surface interface; $h_s$ and $h_b$ are the surface separations in the inlet and outlet zones, respectively; and $l_1$ and $l_2$ are the widths of the outlet and inlet zones, respectively. The results show that the increase of the load-carrying capacity of the step bearing by the designed wall slippage in Figure 1 can be realized in the condition of high sliding speeds and heavy loads. For achieving the most pronounced technical effect of the wall slippage, the value of $r_h$ may be as small as below 1.1 [42]. $\lambda$, $\phi_s$ must be less than unity. Both the reductions of $\lambda$ and $\phi_s$ strengthen the beneficial effect of the wall slippage. The stationary surface in the inlet zone should be as hydrophobic as possible. It can be realized by covering the most hydrophobic or oilphobic coating on the stationary surface in the inlet zone. Developing the ultrahydrophobic or oilphobic materials is of great importance to the energy conservation in the bearing, and it should be put as an important research task in the following time. Both the stationary surface in the outlet zone and the whole moving surface should be hydrophilic or oilphilic.

3.2. Hydrodynamic Journal Bearing. Figure 2 shows the energy-conserved hydrodynamic journal bearing where the wall slippage is designed on the stationary sleeve surface in the bearing inlet zone. The principle of the improvement of the performance of the hydrodynamic journal bearing by the wall slippage is the same with that of the thrust slider bearing. It should be satisfied that $\phi_s \leq \phi_0$, where $\phi_s$ is the envelope angle of the wall slippage zone and $\phi_0$ is the angular coordinate of the location where the maximum hydrodynamic pressure occurs as shown in Figure 2. It was found that this energy-conserved journal bearing is suitable for $\epsilon \leq 0.28$ [26]. As related to the eccentricity ratio, the optimum
The value of $\phi_{\text{slip}}$ for the strongest wall slippage effect was given as [27]

$$\phi_{\text{slip,opt}} = -540\varepsilon^2 + 410\varepsilon + 46,$$

where $\phi_{\text{slip,opt}}$ is in degree. If $\phi_{\text{slip}} < \phi_{\text{slip,opt}}$, both the hydrodynamic pressure and carried load of the bearing are increased with the increase of $\phi_{\text{slip}}$, while the value of the shear strength $\tau_{\text{sa}}$ of the fluid-sleeve surface interface in the inlet zone should be as lowest as possible. This relies on the application of the highly hydrophobic or oilphobic coating. The increase of the load-carrying capacity of the journal bearing in Figure 2 by the wall slippage can be nearly 100%, while at the same time, the reduction of the friction coefficient of the bearing by the wall slippage can be more than 60% [26]. The same amount is conserved for the frictional power in the bearing if the load is the same. This technical effect can be achieved when $\tau_{sl}$ is low. Although Zhang’s analytical derivation [26] is for the two-dimensional hydrodynamic journal bearing as shown in Figure 2, these obtained results can also be implemented to the three-dimensional journal bearing by incorporating the side leakage effect. The detailed condition for the formation of the energy-conserved hydrodynamic journal bearing in Figure 2 can be found from Ref. 26. It was shown that this energy-conserved journal bearing is easily realizable for the condition of high sliding speeds and heavy loads [26].

3.3. Hydrodynamic Line Contact. Figure 3 shows the energy-conserved hydrodynamic line contact where on the faster moving surface, there is no wall slippage while on the whole slower moving surface, there is the wall slippage with the low fluid-contact surface interfacial shear strength $\tau_{sb}$. This contact is subject to the condition $u_a > u_b$. If $\tau_{sl}$ approaches to zero, the dimensionless surface separation $H_x$ at the contact

\[ H_x = \frac{W}{5 \times 10^4} \]
center is solved from the following equation [27]:

\[
-0.2041 \left( \log \frac{W}{H_c} \right)^2 + 0.8876 \log \frac{W}{H_c} + \log \left( 6.0954G U_a \right) - 1.5 \log W - 1.2725 = 0,
\]

\[(7)\]

where \( H_c = h/R, W = \omega/(E' R), U_a = u_s \eta_f/(E' R), \) and \( G = \alpha E' \). Here, \( h \) is the dimensional surface separation at the contact center, \( R \) is the equivalent curvature radius of the two contact surfaces, \( \omega \) is the load per unit contact length, \( E' \) is the equivalent Young’s elastic modulus of the two contact surfaces, \( \eta_f \) is the circumferential speed of the faster moving surface, \( \eta_a \) is the fluid bulk viscosity in the ambient condition, and \( \alpha \) is the fluid viscosity-pressure index [27]. It was shown that when \( \tau_{sp} \) approaches to zero, the friction coefficients on both the two contact surfaces approach to vanishing [27]. The wall slippage effect on the friction reduction and energy conservation in this line contact is thus very significant. By covering an ultrahydrophobic or oilphobic coating on the slower moving surface, it can be realized that \( \tau_{sp} \) approaches to zero. Due to the wall slippage, the load-carrying capacity of this line contact is significantly increased for large slide-roll ratios and medium and heavy loads when \( \tau_{sp} \) is very low. It is more pronounced when \( U_a \) is higher. Figure 4 shows the comparison of the dimensionless surface separations at the contact center, respectively, for the present line contact and the conventional line contact (without any wall slippage) for the same loads. This energy-conserved hydrodynamic line contact can occur in gear contacts such as planet gear systems, where \( U_a = 0 \).

### 4. Surface Coatings for Setting the Wall Slippage

Preventing or designing the wall slippage on specific surfaces in the hydrodynamic lubricated area relies on the use of the hydro-/oilphilic coatings or the hydro-/oilphobic coatings. The more hydro-/oilphobic the covered surface coating, the more pronounced the wall slippage, and the more significant the improvement of the performance of hydrodynamic lubrication. In contrary, the more hydro-/oilphilic the surface coating, the more reliable the prevention of the wall slippage, which is also required in the design of hydrodynamic lubrication with wall slippage. Besides the well-known hydrophobic materials such as polytetrafluoroethylene (PTFE), carbon, and graphene, in recent decades, we noticed some impressive super hydro-/oilphobic coatings being used for enhancing the wall slippage such as octadecyltrichlorosilane [46], n-alkyl monolayers [46], silane [47], polydopamine coating [48], and fluoroalkylsilanes [49]. The hydro-/oilphilic materials like silica, silicon nitride, silicon carbonized, and \( \gamma \) alumina as well as steel can be used to prevent the wall slippage in a hydrodynamic lubrication. In the future, ultrahydro-/oilphobic coatings and ultrahydro-/ oilphilic coatings should be the development directions for manufacturing reliable hydrodynamic lubricated contacts with a good performance improved by the wall slippage.

### 5. Conclusions

Energy-conserved hydrodynamic thrust slider and journal bearings as well as energy-conserved hydrodynamic lubricated gears by applying the wall slippage are reviewed. Typically, the wall slippage is designed on the stationary or slower moving surface in the hydrodynamic inlet zone. The wall slippage on the moving surface in the hydrodynamic outlet zone can give additional beneficial effects. By the inlet wall slippage, the flow rate into the hydrodynamic contact is increased, or by the outlet wall slippage, the flow rate out of the hydrodynamic contact is reduced. For maintaining the flow continuity, the magnitudes of the pressure gradients as well as the hydrodynamic pressures must be increased in the whole hydrodynamic contact. Thus, the carried loads of the bearing or the gear contact are correspondingly increased. On the other hand, the wall slippage effect reduces the friction coefficient of the hydrodynamic contact. The designed bearing or gear contact with the wall slippage is therefore energy-conserved. Different from the classical energy conservation method such as using low-viscosity lubricants or lubricant additives, which are not very suitable for high speeds and heavy loads, the present mentioned energy-conserved bearings or gear contacts are realizable particularly for high sliding speeds and heavy loads.

The main technical issue and the future research task are to develop highly or ultrahydrophobic or oilphobic coatings which can be covered on the steel bearing or gear surfaces. In recent years, a few of such coatings have been developed, but their applications are still not seen. Besides these, the design principles of these bearings or gear contacts need to be further complemented by considering more realistic factors such as the thermal and surface roughness effects.

### Data Availability

The data reported in this paper will be available from the corresponding author with reasonable request.

### Conflicts of Interest

The authors declare that there is no conflict of interest with this research.

### References


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