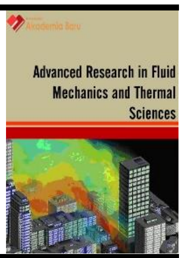
Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 71, Issue 2 (2020) 160-169

Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Numerical Optimization of Surface Texture for Hydrophobic Textured Slider Bearing

Open Access

Mohammad Tauviqirrahman[1,*], Toni Prahasto[1], Mohamad Lutfi Assaidiky[1], Muchammad[1,2]

[1] Laboratory for Engineering Design and Tribology, Mechanical Engineering Department, Engineering Faculty, Diponegoro University, Jl. Prof. H. Soedharto, Tembalang, Semarang, 50275, Indonesia
[2] Laboratory for Surface Technology and Tribology, Faculty of Engineering Technology, University of Twente, Drienerlolaan 5, Postbus 217, 7500 AE, Enschede, The Netherlands

ARTICLE INFO

Article history:
Received 13 January 2020
Received in revised form 6 April 2020
Accepted 10 April 2020
Available online 27 May 2020

Keywords:
Hydrophobic; optimization; slider bearing; texturing

ABSTRACT

To reduce a significant energy waste in industry due to the friction and wear in mechanical components, there is an increasing demand for durable thrust bearing under extreme operational conditions. Surface texturing, combined with the application of hydrophobic material, has been proven to be an effective and economical means to enhance the tribological lubrication performance of sliding surfaces. Therefore, in the present work, an exact optimization method is presented to optimize the surface texture in terms of the texture depth for enhancing the load-carrying capacity. Furthermore, the texture shapes, including ellipse and triangle, are investigated under different arrangements of hydrophobic materials. The lubrication characteristics are established by solving the modified Reynolds equation with means of finite volume method. For modeling the hydrophobic behavior, the critical shear stress model is employed to assure more real boundary conditions of bearing. The simulation results show that for any type of groove shape, the highest load-carrying capacity can be achieved under unique hydrophobic placement. The main interesting finding is the fact that the optimal texture with the groove shape of ellipse shows a better impact on the performance of slider bearing irrespective of the hydrophobic placements.

1. Introduction

In industries, the hydrodynamic thrust bearing is widely used to carry axial load. In order to improve the performance of bearing, many types of thrust bearings were analytically studied in the past centuries by researchers. However, in conventional lubrication theory, the slip boundary condition is often neglected. In fact, the assumption of no-slip was used. Recently, with the advance

* *Corresponding author.*
E-mail address: mtauviq99@lecturer.undip.ac.id (Mohammad Tauviqirrahman)

https://doi.org/10.37934/arfmts.71.2.160169

of micro-measurement, such assumption was no longer valid in particular when the hydrophobic material has been widely used in practical life.

The research on the hydrophobic coating inducing the slip boundary gained new momentum in 2003 when Spikes [1] published one interesting paper on the what-so-called "half-wetted" bearing. Employing such bearing, the combination of excellent load support with very low friction was highlighted. Later, numerous publications dealing with the use of the hydrophobic coating in lubrication have been published in recent years [2-6]. Overall, the vast majority of their findings led to the potential use of the hydrophobic material in widespread industrial rotating machinery.

Additionally, surface texturing has also been considered as a means for improving the lubrication performance. Recently, numerous studies on the effect of a textured surface on the tribological performance of thrust bearing have been reported with respect to the load-carrying capacity, film thickness, friction force, and side-leakage varying the shape, distribution, and size of textures. To find the optimal texturing parameters, many parametric optimization studies have also been conducted; for example, [7-11]. From these studies, promising results have been highlighted, as well as the algorithms to describe lubricant flow.

According to an intensive literature survey, very limited studies of optimization of surface texturing have been performed previously for the hydrophobic textured thrust bearing. Therefore, the present work is focused on optimizing groove depth for hydrophobic textured bearing and exploring its dependency on the objective function (i.e., load support maximization in this case). A mathematical optimization based on a modified Reynolds approach with slip is developed for the case of hydrophobic textured bearing with a double groove.

2. Analysis

2.1 Modified Reynolds Equation

Details of hydrophobic textured contact with the coordinate system are represented in Figure 1, while the geometrical parameter, as well as the physical parameter, studied here is shown in Table 1. For the textured pattern of bearing considered here, the hydrophobic coating is applied at the leading edge of the bearing with aiming to maximize the load-carrying capacity [4,12].

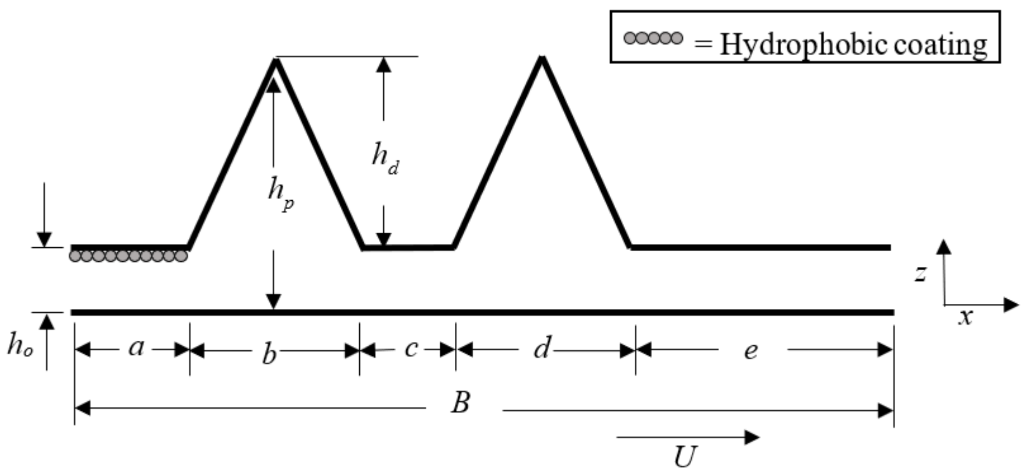


Fig. 1. Geometrical model of one-dimensional thrust bearing with double grooves. Note: Hydrophobic coating is employed at the inlet

Table 1
Fixed factor sets for analysis

Parameter	Value
Total length of bearing *B*	0.02 m
Inlet length *a*	0.003 m
First groove length *b*	0.0025 m
Valley length *c*	0.003 m
Second groove length *d*	0.0025 m
Sliding velocity *U*	1 m/s
Lubricant viscosity μ	0.01 Pa.s
Atmospheric pressure P_{atm}	100 kPa
Minimum film thickness h_o	1 µm
Groove depth h_d	3 µm
Critical shear stress, τ_c	0 Pa
Slip coefficient α	0.02

For solving the lubrication problem, some assumptions, such as constant viscosity, incompressible flow, and Newtonian behavior, have been made. Based on the critical shear stress model [3,4] and the above assumptions, the generalized Reynolds equation in cartesian coordinates is proposed as follows

$$\frac{\partial}{\partial x}\left(h^3\frac{h^2+4h\mu(\alpha_s+\alpha_m)+12\mu^2\alpha_s\alpha_m}{h\left(h+\mu(\alpha_s+\alpha_m)\right)}\frac{\partial p}{\partial x}\right)=6\mu U\frac{\partial}{\partial x}\left(\frac{h^2+2h\alpha_s\mu}{h+\mu(\alpha_s+\alpha_m)}\right)-6\mu\tau_{cs}\frac{\partial}{\partial x}\left(\frac{\alpha_s h(h+2\alpha_m\mu)}{h+\mu(\alpha_s+\alpha_m)}\right)+ 6\mu\tau_{cm}\frac{\partial}{\partial x}\left(\frac{\alpha_m h(h+2\alpha_s\mu)}{h+\mu(\alpha_s+\alpha_m)}\right)-12\mu U\frac{\alpha_s\mu}{h+\mu(\alpha_s+\alpha_m)}\frac{\partial h}{\partial x}+6h\frac{\partial p}{\partial x}\frac{\partial h}{\partial x}\frac{h\alpha_s\mu+2\alpha_s\alpha_m\mu^2}{h+\mu(\alpha_s+\alpha_m)}+12\mu\tau_{cs}\left(\frac{\alpha_s(h+\alpha_m\mu)}{h+\mu(\alpha_s+\alpha_m)}\frac{\partial h}{\partial x}\right)- 12\mu\tau_{cm}\left(\frac{\alpha_s\alpha_m\mu}{h+\mu(\alpha_s+\alpha_m)}\frac{\partial h}{\partial x}\right) \quad (1)$$

where *p* is the hydrodynamic pressure, *h* is the lubricant film thickness, *U* is sliding velocity, μ is the lubricant viscosity, α is the hydrophobic coefficient, τ_c is the critical shear stress, and subscript *s* and *m* refer to the stationary and moving surface, respectively. The lubrication performance parameter of load carrying capacity *W* is expressed as

$$W=\int_0^B p(x)dx \quad (2)$$

The load-carrying capacity *W* is defined as the integral of the hydrodynamic pressure across the entire computational domain.

2.2 Solution Procedure

To ensure accurate solutions, several mesh investigations are performed. The computations have been conducted for various meshes, from 30,000 to 70,000 nodes based on the predicted load-carrying capacity. The modified Reynolds equation is discretized by the finite volume method. Then, the discrete modified Reynolds equation is assembled and solved using the tridiagonal matrix algorithm.

In the present study, the exact optimization method is used due to rapid convergence capability. In detail, the solution parameters setting for optimization simulations are listed in Table 2.

Table 2
Parameter settings

Description	Optimization setting
Objective Function	Maximization of the load-carrying capacity
Design Variable	Groove depth Lower bond: 0.1 µm Upper bond: 10 µm
Constrain	Total bearing length

3. Results and Discussion

3.1 Case 1: Optimization Result

In this section, the optimization results in terms of film thickness profile, hydrodynamic pressure, and the load support are presented for the case of textured bearing with double grooves in which the hydrophobic coating is applied at the leading edge of the contact.

Figure 2 shows the film thickness profile of the lubricated contact for the initial solution and optimal solution. Based on Figure 2, it is clear that the optimization calculation gives the lower groove depth. The decrease in groove depth for the optimal solution is around up to 73% compared to that for the initial solution. Either for the first groove or the second one, the total predicted film thickness is the same, i.e., 2.3 µm. With these profiles, the distribution of the dimensionless hydrodynamic pressure for the case of initial bearing and optimized bearing configurations can be retrieved, as depicted in Figure 3. The numerical results illustrate that the hydrodynamic pressure for the optimized hydrophobic textured bearing is higher than that for the initial one. It can be observed that the pressure gradient at the textured area for the optimal solution is more significant than for the initial one. By optimization, for optimized textured bearing, the predicted dimensionless load carrying capacity is 0.1602 or just 3.55% higher than that for initial textured bearing. It indicates that the groove shape of triangular even under the optimal configuration is not able to enhance the performance very much.

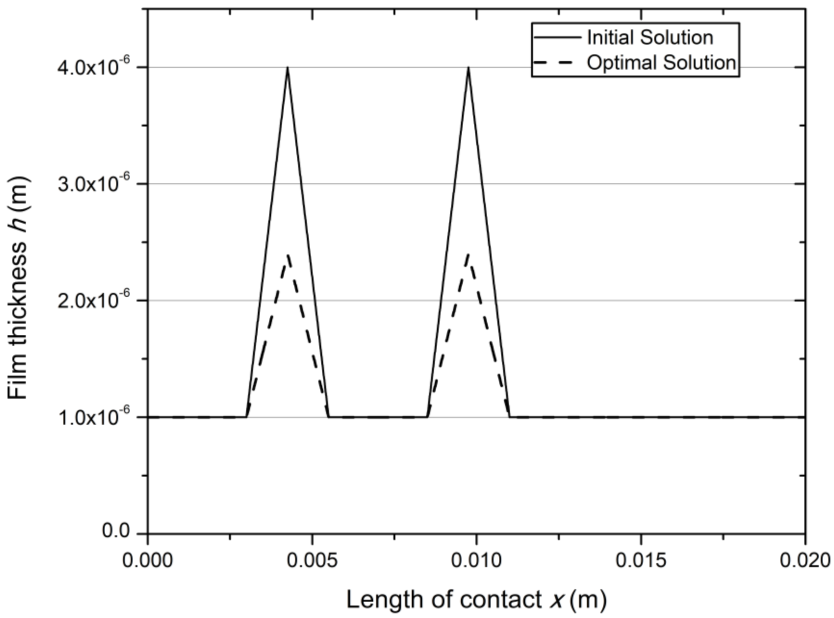


Fig. 2. Optimization result of double triangular grooves of textured bearing with hydrophobic coating in terms of film thickness profiles

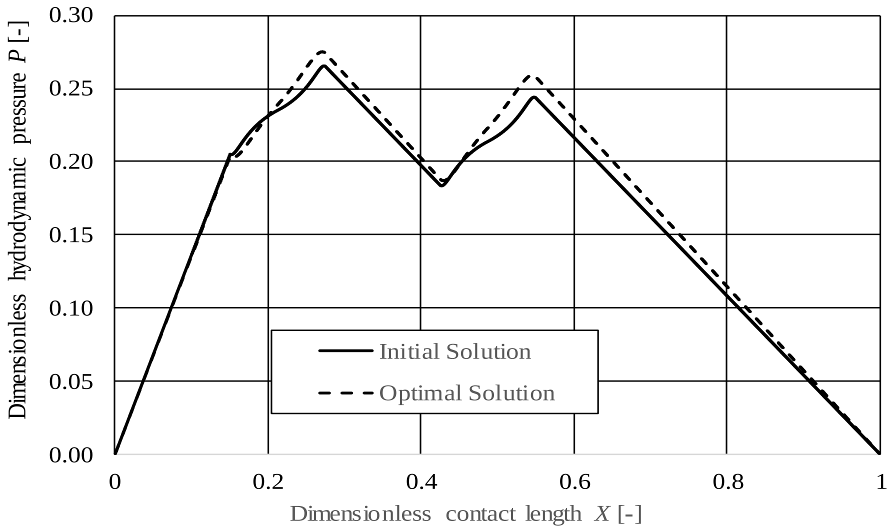


Fig. 3. Optimization result of double triangular grooves of textured bearing with hydrophobic coating in terms of dimensionless hydrodynamic pressures

3.2 Case: Effect of More Hydrophobic Coatings

To validate the above conclusion dealing with the less enhancement of load support by the optimal triangular shape of the groove, the computations have been conducted for the case of textured bearing with addition of a hydrophobic coating. In addition to the inlet of the contact, in the following analysis, the hydrophobic coating is also employed on the valley between two grooves of textured bearing, as indicated in Figure 4. It is hypothesized that more hydrophobic coating will make the resulted pressure larger with the same amount of the lubricant as discussed by [2,4].

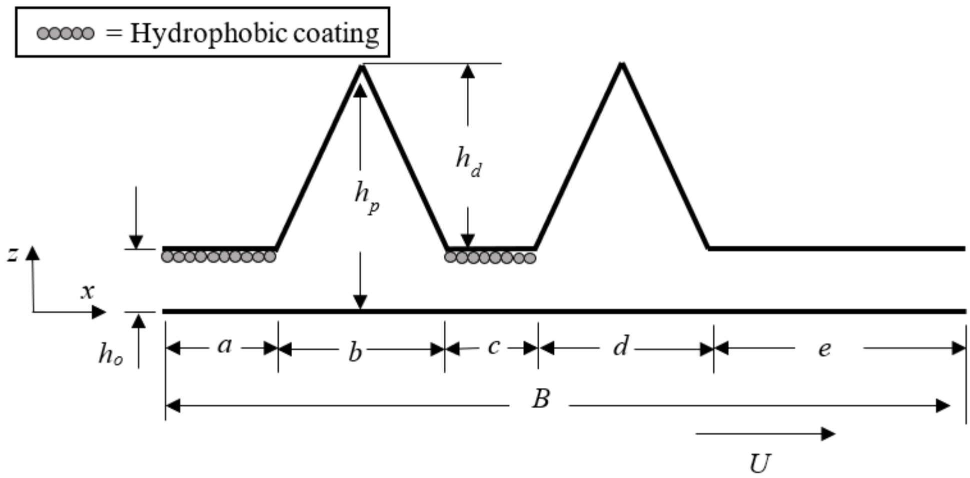


Fig. 4. Geometrical model of one-dimensional thrust bearing with double triangular grooves. Note: Hydrophobic coating is employed at the inlet and the valley between two grooves

Based on the optimization results, it is found that the optimal groove depth maximizing the load-carrying capacity is 1.8 µm or 120% smaller than the initial groove depth. As reflected in Figure 5, with respect to the land film thickness, the ratio of optimal the groove depth h_d over the land film thickness h_o is 1.8. Based on the mathematical point of view, it indicates that the optimization tends to lower the groove depth. This trend can be observed both for the case 1 (i.e., slip is only employed at the inlet of the contact, see Figure 1) and the case 2 (i.e., slip is applied at the inlet contact and the valley between two grooves, see Figure 4).

Comparing the hydrodynamic pressure result between the optimal bearing and the initial pattern, as shown in Figure 6, the optimal texture depth increases the improvement of the load-carrying capacity of about 1 %. No significance of the load-carrying capacity, as highlighted in this case, justifies that the groove shape should be well-chosen to enhance the tribological performance.

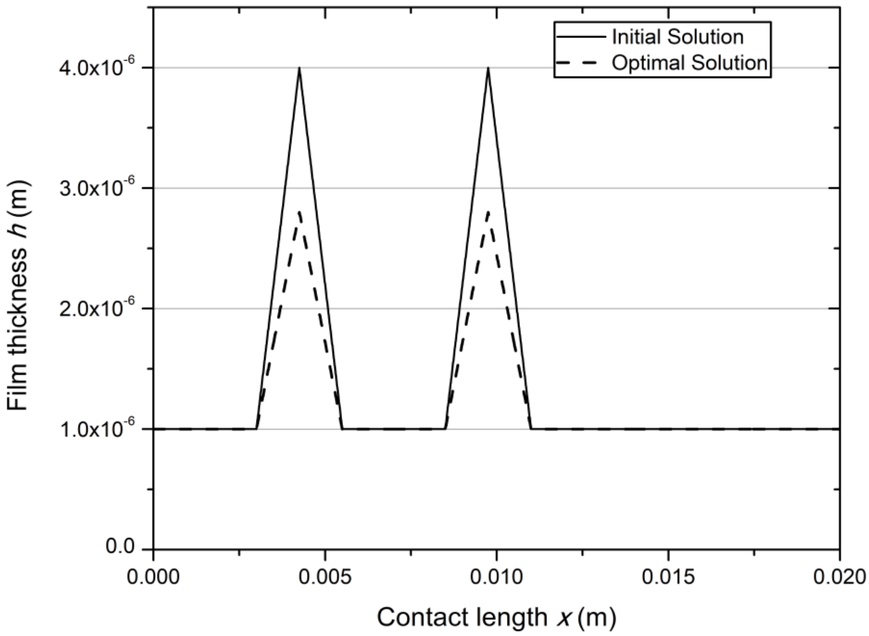


Fig. 5. Optimization result of double triangular grooves of textured bearing with more hydrophobic coating in terms of the film thickness profile

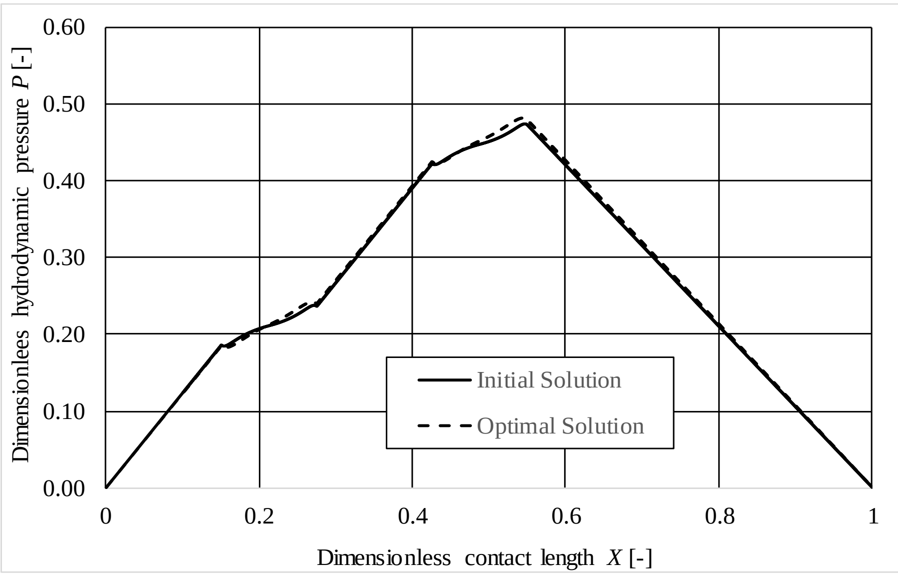


Fig. 6. Optimization result of double triangular grooves of textured bearing with more hydrophobic coating in terms of hydrodynamic pressure

The presence of a more hydrophobic coating on the textured bearing is not able to improve the load-carrying capacity significantly. Based on the physical point of view, it indicates that physical geometry has a more dominant role compared to the chemical role in altering the tribological performance. This finding matches well with the analytical result of Muchammad *et al.,* [12] and the numerical solution of Tauviqirrahman *et al.,* [13]. It should be noted that in the present study, the hydrophobic effect is modeled with the critical shear stress model by modifying the Navier-slip model, which means that physically the assumption of the full slip was adopted. According to Sharafatmandjoor [14], the slip length value can increase with increasing the volume flow rate. However, such an increase was not considered in this study.

3.3 Case 3: Elliptical Shape of Groove

In this section, in order to examine how significant can the groove shape affects the performance, the calculations have also been performed for the case of slip-textured bearing with double elliptical grooves, as depicted in Figure 7. In this way, it is hypothesized that the elliptical shape has better performance than a triangular shape. This is because the elliptical groove has more space to contain the lubricant compared to the triangular groove. As a note, the bearing geometry with elliptical grooves studied here is similar to that with triangular grooves, as indicated in Table 1. The ellipse geometry for initial bearing has a major radius of 1.25 mm (i.e., half of the groove length *b*), while for minor radius, it reads 3 µm which is the groove depth h_d (i.e., $h_d = h_p - h_o$). As shown in Figure 7, for the analysis, the slip is applied at the leading edge of the contact and the valley between two grooves.

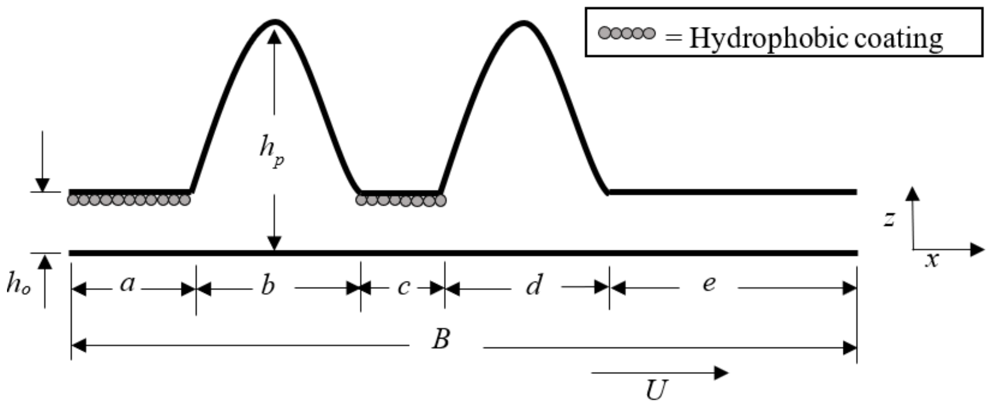


Fig. 7. Geometrical model of one-dimensional thrust bearing with double elliptical grooves. Note: Hydrophobic coating is employed at the inlet and the valley between two grooves

Figure 8 and 9 show the results of the optimization procedure in terms of hydrodynamic pressure and load support, respectively. Based on Figure 8, it can be revealed that the higher hydrodynamic pressure resulted from the case of the optimized pattern is observed. However, concerning the load-carrying capacity *W*, similar to the case of optimal textured pattern with a double triangular design, the increase in the value of *W* is not so high; it is just around 4%, as reflected in Figure 9. This finding strengthens the fact that the texturing can improve the performance of the rotary micro/macro machine, as shown in the literature [4,7-13,15].

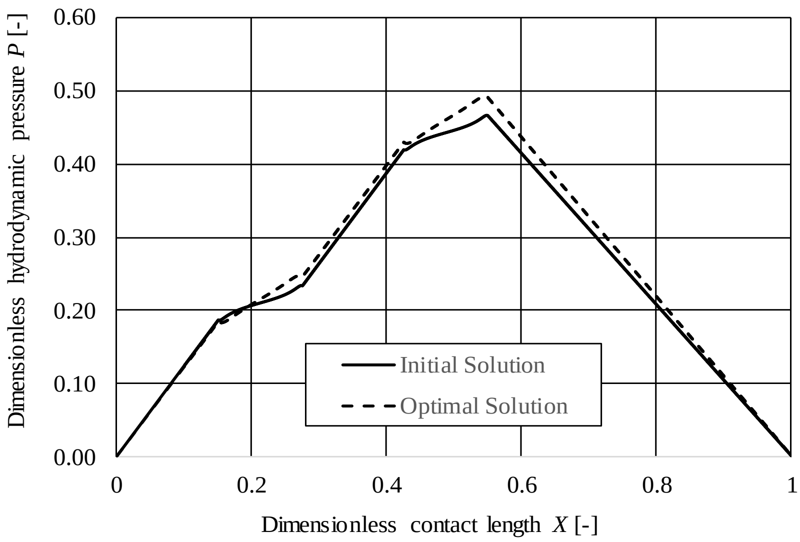


Fig. 8. Hydrodynamic pressure profile of double elliptical grooves of the slip-textured bearing

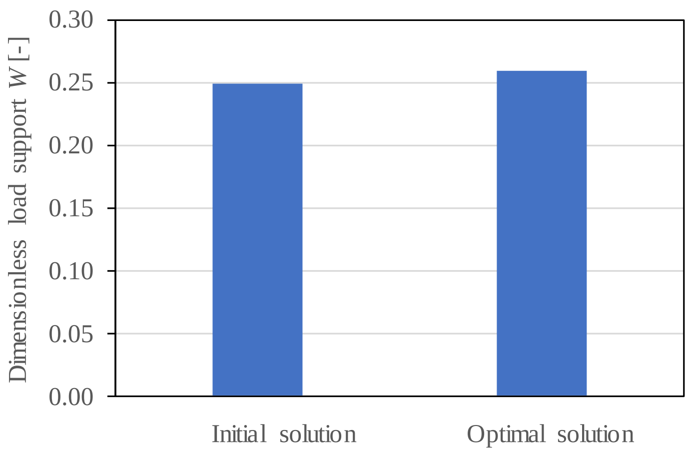


Fig. 9. The predicted load support for initial and optimal solutions

4. Concluding Remarks

In the present work, a numerical optimization procedure in relation to the lubrication model was established in order to optimize the groove depth for generating the maximum load-carrying capacity. Two shapes of grooves, i.e., triangular and elliptic, were of particular interest. Based on the numerical solution results, the conclusions can be drawn. The optimization results show that the optimum groove depth depends significantly on the operating conditions of the bearing but is mostly independent of the groove shape. It is noticed the optimal textured bearing can generate the lower film thickness but slightly higher load support. The reduced film thickness leads to decreased lubricant supply during the bearing operation. Consequently, based on the environmental sustainability point of view, the present finding will assure energy-saving globally.

The most outcome of the current work is that the effect of the application of more hydrophobic coating applied on the optimal textured area on the performance is not so significant. The geometrical texture has a more dominant role in influencing the performance. In other words, in the case of double textured bearing, the hydrophobic coating inducing the slip boundary should be employed at the leading edge of the contact, and it is not necessary to apply to the other area. Regarding the groove shape, based on the simulation results, it is found that the optimal texture with the groove shape of ellipse shows a better impact on the performance of slider bearing in comparison with the triangular shape irrespective of the hydrophobic placements.

To obtain the complete result, for future work, the design variables of the optimization procedure should be extended, not only focusing on the groove depth but also other texturing parameters such as groove length, number of grooves, etc. Also, the objective function of the friction force minimization should become the next issue by employing the multi-objective function approach.

Acknowledgment

This research was financially supported by The Faculty of Engineering, Diponegoro University, Indonesia, through Strategic Research Grant 2019.

References

[1] Spikes, Hugh A. "The half-wetted bearing. Part 1: extended Reynolds equation." *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* 217, no. 1 (2003): 1-14. https://doi.org/10.1243/135065003321164758

[2] Wu, C. W., G. J. Ma, Ping Zhou, and C. D. Wu. "Low friction and high load support capacity of slider bearing with a mixed slip surface." (2006): 904-907. https://doi.org/10.1115/1.2345419

[3] Aurelian, Fatu, Maspeyrot Patrick, and Hajjam Mohamed. "Wall slip effects in (elasto) hydrodynamic journal bearings." *Tribology International* 44, no. 7-8 (2011): 868-877. https://doi.org/10.1016/j.triboint.2011.03.003

[4] Tauviqirrahman, Mohammad, Rifky Ismail, Jamari Jamari, and Dirk J. Schipper. "Combined effect of texturing and boundary slippage in lubricated sliding contacts." *Tribology international* 66 (2013): 274-281. https://doi.org/10.1016/j.triboint.2013.05.014

[5] Lin, Qiyin, Zhengying Wei, Yubin Zhang, and Ning Wang. "Effects of the slip surface on the tribological performances of high-speed hybrid journal bearings." *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology* 230, no. 9 (2016): 1149-1156. https://doi.org/10.1177/1350650116630202

[6] Rao, T. V. V. L. N., A. M. A. Rani, M. Awang, and F. M. Hashim. "Stability evaluation of three-layered journal bearing with slip/partial slip." *Industrial Lubrication and Tribology* 69, no. 3 (2017): 334–341. https://doi.org/10.1108/ILT-08-2016-0184

[7] Buscaglia, Gustavo C., Ionel Ciuperca, and Mohammed Jai. "On the optimization of surface textures for lubricated contacts." *Journal of mathematical analysis and applications* 335, no. 2 (2007): 1309-1327. https://doi.org/10.1016/j.jmaa.2007.02.051

[8] Scaraggi, Michele, Francesco P. Mezzapesa, Giuseppe Carbone, Antonio Ancona, Donato Sorgente, and Pietro Mario Lugarà. "Minimize friction of lubricated laser-microtextured-surfaces by tuning microholes depth." *Tribology International* 75 (2014): 123-127. https://doi.org/10.1016/j.triboint.2014.03.014

[9] Uddin, M. S., and Yi Wei Liu. "Design and optimization of a new geometric texture shape for the enhancement of hydrodynamic lubrication performance of parallel slider surfaces." *Biosurface and Biotribology* 2, no. 2 (2016): 59-69. https://doi.org/10.1016/j.bsbt.2016.05.002

[10] Zhang, Hui, Meng Hua, Guo-zhong Dong, Dong-ya Zhang, Wang-jian Chen, and Guang-neng Dong. "Optimization of texture shape based on Genetic Algorithm under unidirectional sliding." *Tribology International* 115 (2017): 222-232. https://doi.org/10.1016/j.triboint.2017.05.017

[11] Wang, Wei, Yongyong He, Jun Zhao, Yang Li, and Jianbin Luo. "Numerical optimization of the groove texture bottom profile for thrust bearings." *Tribology International* 109 (2017): 69-77. https://doi.org/10.1016/j.triboint.2016.12.006

[12] Muchammad, Muchammad, Mohammad Tauviqirrahman, J. Jamari, and Dirk Jan Schipper. "An analytical approach on the tribological behaviour of pocketed slider bearings with boundary slip including cavitation." *Lubrication science* 29, no. 3 (2017): 133-152.

https://doi.org/10.1002/ls.1361

[13] Tauviqirrahman, M., and A. Pratama. "Hydrodynamic Lubrication of Textured Journal Bearing Considering Slippage: Two-dimensional CFD Analysis Using Multiphase Cavitation Model." *Tribology in Industry* 41, no. 3 (2019). https://doi.org/10.24874/ti.2019.41.03.10

[14] Sharafatmandjoor, S. "Review of the 'Flow through a Circular Tube with a Permeable Navier Slip Boundary'; the Double-Slip Challenge." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 10, no. 1 (2015): 1-4. http://www.akademiabaru.com/doc/ARFMTSV10_N1_P1_4.pdf

[15] Shirly Empaling, Ahmad Zahran Md Khudzari, Muhammad Rashidi Abdul Kadir, Kahar Osman, Akmal Hakim Mohamad Hudzari, Mohammad Hasbullah Padzillah, Ishkrizat Abdul Talib, Mohamed Ezani Abdul Taib, and Aizai Azan Abdul Rahim."Spiral Groove Bearing Geometry Variation Effect on Left Ventricular Assist Device Impeller Performance." *CFD Letters* 11, no. 1 (2019): 86-101. http://www.akademiabaru.com/doc/CFDLV11_N1_P86_101.pdf