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Numerical optimization of texture shape for parallel surfaces under unidirectional and bidirectional sliding

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ABSTRACT

A numerical optimization approach based on the sequential quadratic programming (SQP) algorithm is used to determine the optimum texture shape for generating the highest load-carrying capacity (LCC). A benchmark problem is first solved to validate this optimization method. Then the novel texture shapes which produce the maximum LCC for both unidirectional and bidirectional sliding motion are proposed and analyzed. For unidirectional sliding the optimum textures have chevron-type shapes with flat fronts and for bidirectional sliding they consist of pairs of the trapezoid-like shapes. Finally, the performances of optimum shapes are compared with those of regular shapes using a mass-conservative algorithm.

1. Introduction

The study of enhancement of tribological performance via surface texturing has received an explosion of interest in recent years. The benefits of applying surface texturing include increasing load-carrying capacity [1], reducing friction force and wear [2,3], expanding the range of hydrodynamic lubrication [4], and improving seizure resistance [5]. In order to maximize the effect of surface texturing, many theoretical and experimental studies have been carried out to optimize the geometrical parameters of textures by varying dimple size, depth and area density [6–15]. One of the often cited literatures on the subject is the work of Etsion et al. [6] who investigated the effects of geometric parameters on the performance of spherical shape dimples. They found that the ratio of the dimple's depth over the diameter is the most important design parameter and that there exists an optimum value of this parameter which maximize the average pressure. Wang et al. [1] experimentally investigated the performance of dimpled SiC thrust bearings under water lubrication and reported the optimum values of diameter, depth and area ratio of the dimples that maximize the load-carrying capacity (LCC). These studies mainly focus on the performance of circular dimples.

Since the dimple's shape, itself, is another important factor for the design of surface textures, a few studies have compared the tribological performances of different texture shapes and investigated the shape and orientation effect both experimentally and numerically. Wang and Hsu [16] investigated the effects of texture shape and orientation on the frictional behavior using a pin-on-disk tribometer. They compared textures with three shapes (circular, elliptical and triangular) and two orientations (parallel and perpendicular to the sliding direction). Their test results showed that texture shape and orientation have an influence on the friction and that the elliptical dimples with major axis placed perpendicular to the sliding direction exhibited the highest friction reduction. Later, Yu et al. [10] developed a numerical model on a single dimple to computationally simulate the results of their experiments. They compared the average pressures of different textures and reported that the elliptical dimple with major axis perpendicular to the sliding direction generates the highest average pressure, which agrees with the previous experimental results.

Lu and Khonsari [17] compared the effects of circular and elliptical dimples on the Stribeck curve of journal bearing. They found that the bushing with elliptical dimples has a lower friction coefficient under mixed lubrication. Galda et al. [9] studied the dimple shape and distribution effect on the characteristics of Stribeck curve with a block-on-ring test rig. Ring specimens with dimples of spherical, long-drop and short-drop shapes were tested. Their results demonstrated that dimples of spherical and long-drop shapes perform better than the short-drop shape in terms of friction coefficient. In a recent paper, Qiu et al. [18] optimized the geometries and densities of six different texture shapes in terms of LCC under air lubrication. Then, the performance of each dimple shape with optimal geometry was compared. They concluded that ellipsoidal dimple provides the maximum LCC.

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Nomenclature

g	Switch Function
h	Local film thickness (m)
h_0	Minimum film thickness (m)
h_g	Texture depth (m)
$\bar{h}$	Dimensionless local film thickness, h/h_0
L	Unit cell length (m)
p	Local Pressure (Pa)
p_0	Ambient pressure (Pa)
p_c	Cavitation Pressure (Pa)
$\bar{p}$	Dimensionless pressure, p/p_0
U	Sliding speed (m/s)
$\overline{W}$	Dimensionless load-carrying capacity
β	Bulk modulus of the lubricant (Pa)
φ	Film content parameter
μ	Lubricant viscosity (Pa.s)
λ	Characteristic number, $6\,\mu LU/\beta h_0^2$
ρ	Local fluid density (kg/m^3)

The above-mentioned works show that, indeed, the tribological performance of textured surfaces is sensitive to the shape of the texture. And some dimple shapes, like ellipse or long-drop shape, perform better than others in terms of lowering the friction coefficient or increasing the LCC. However, most of these studies have concentrated on ordinary geometric shapes, and the global-optimum texture shapes for parallel flat surfaces are still unclear.

The aim of the present study is to identify optimal texture shapes for parallel flat surfaces with a mathematical optimization method. The optimization algorithm is based on the sequential quadratic programming (SQP) method due to its superior performance. Starting from an arbitrary texture shape, the optimum texture geometries for both unidirectional and bidirectional sliding are obtained by an optimization process which changes the design variables of texture shape to maximize the LCC. Furthermore, the performances of optimum texture shapes are compared with those of ordinary shapes under different operating conditions.

2. Problem formulation

2.1. Computational domain and design variables

Fig. 1(a) shows the distribution of patterns on a typical textured surface. The micro-dimples are uniformly distributed on the surface with a constant depth h_g. For theoretical study, usually, a square unit cell containing one texture pattern is considered as the computational domain and periodic boundary conditions are applied in the sliding direction (X) to account for the interaction between textures. Assuming that the interactions in the other direction (Y) are negligible, the boundaries in this direction are kept at ambient pressure. The textured surface is stationary and the runner surface moves with a velocity U along the X-axis. The objective is to maximize the LCC of textured surface by determining the optimum texture shape within a unit cell.

As shown in Fig. 1(b), a series of horizontal lines evenly divide an arbitrary texture geometry in the Y direction. With the lengths and center locations of these lines known, the texture shape can be formed by connecting the adjacent horizontal lines. Therefore, the design variables for the texture shape are simply the lengths (L_1, L_2,…, L_n) and corresponding center locations (X_1, X_2,…, X_n) of the horizontal lines. The texture depth (h_g) is assumed to be constant and its value is also optimized as a design variable. In this study, the unit cell is divided to six sections, which results in 15 design variables. The LCC of an arbitrary texture shape can be calculated by solving the Reynolds equation to determine the hydrodynamic pressure and integrating the result to obtain the total load. Then the optimization algorithm adjusts the values of these design variables to find the texture shape with maximum LCC. This method is similar to the one used in Ref. [19], which optimized the groove shapes for flat thrust bearings.

2.2. Governing equation and objective function

The Reynolds equation is employed to analyze the pressure distribution $p(x, y)$ within the unit cell. Assuming the lubricant is Newtonian and incompressible, the steady-state Reynolds equation [20] can be expressed as

$$\frac{\partial}{\partial x}\left(h^3\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(h^3\frac{\partial p}{\partial y}\right)=6\mu U\frac{\partial h}{\partial x} \tag{1}$$

where h is the local film thickness and μ is fluid viscosity.

To non-dimensionalize Eq. (1), the following dimensionless terms are defined:

$$\bar{x}=\frac{x}{L},\ \bar{y}=\frac{y}{L},\ \bar{h}=\frac{h}{h_0},\ \bar{p}=\frac{p}{p_0},\ \Lambda=\frac{6\mu UL}{p_0 h_0^2} \tag{2}$$

where L is the length of the square cell, h_0 is the minimum film thickness and p_0 is the ambient pressure. Substituting Eq. (2) in Eq. (1) yields the dimensionless form of the Reynolds equation:

$$\frac{\partial}{\partial \bar{x}}\left(\bar{h}^3\frac{\partial \bar{p}}{\partial \bar{x}}\right)+\frac{\partial}{\partial \bar{y}}\left(\bar{h}^3\frac{\partial \bar{p}}{\partial \bar{y}}\right)=\Lambda\frac{\partial \bar{h}}{\partial \bar{x}} \tag{3}$$

The finite difference formulation was applied to discretize Eq. (3), which leads to a set of linear algebraic equations. These equations were then solved by a fast direct solver based on LU decomposition [21]. Once Eq. (3) is solved based on the given film profile and boundary conditions, the pressure distribution is determined. The negative pressure in the solution is set to zero to account for cavitation, which is equivalent to the half-Sommerfeld boundary condition. The non-dimensional LCC is used as the objective function in the optimization, and its value can be obtained by integrating the dimensionless pressure over the entire domain:

$$\overline{W}=\int_0^1\int_0^1 \bar{p}\,d\bar{x}\,d\bar{y} \tag{4}$$

The optimization problem can now be stated in dimensionless form as follows: Find $\overline{X}_1$, $\overline{L}_1$,…$\overline{X}_n$, $\overline{L}_n$, $\overline{h}_g$ that maximize the objective function $\overline{W}$ subject to the constraint that the entire texture shape is within the domain.

3. Solution method

Since the optimization problem in this study is nonlinear and constrained, the sequential quadratic programming (SQP) method is applied to determine the optimum texture shape. This method is considered to be more efficient and accurate than other nonlinear programming methods when solving problems of small to medium size [22], and it has been successfully applied in the shape optimization of bearing designs [23–25]. The basic idea of SQP method is as follows: it begins with an initial guess of the design variables and evaluates the objective function at the starting point. Next, it solves the quadratic programming sub-problems to obtain