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Research Article

INVESTIGATION ON THE INFLUENCE OF SPHERICAL TEXTURES ON THE PERFORMANCE CHARACTERISTICS OF POROUS JOURNAL BEARING

***K. Sharma**
Department of Mechanical Engineering, Arni University – Kathgarh, Indora, Kangra (H.P.)
**Author for Correspondence*

ABSTRACT
In the present study, the spherical dimple type texture is taken on the bearing surface for improving the performance characteristics of finite porous journal bearing. It is observed that the effect of surface textures on the prescribed location on the bearing performance is highly appreciated. The fluid film pressures build up inside the bearing becomes higher with inclusion of textures while compared with smooth bearing case. The location of dimples in the particular location has been suggested by with reference to the work of previous researchers. The modified Reynolds equation is solved numerically through finite difference approach for analysis and Simpson's 1/3rd method and over relaxation method are used in computing the various bearing characteristics by changing various bearing parameters such as eccentricity ratio, shaft speed, dimple depth, permeability parameter and lubricant viscosity.

Keywords: *Porous Journal Bearing; Surface Texture; Finite Difference Approach; Spherical Dimples*

INTRODUCTION
The journal bearing has been used extensively during the past centuries to mount rotating machinery. Alongside a steady increase in application, knowledge about these machine elements also has grown gradually. More recently, the application of a special type of plain journal bearing, the porous journal bearing, has become popular due to its advantageous self-lubricating properties and low production costs.
With the development of modern machines, the use of various fluids as lubricants under various circumstances has been given much importance. Most bearings are normally used to support rotating shafts in machines. Appropriate bearing design can minimize friction and wear as well as early failure of machinery. The objectives of bearing design are to extend bearing life in machines, reduce friction energy losses and wear, and minimize maintenance expenses and downtime of machinery due to frequent bearing failure. In manufacturing plants, unexpected bearing failure often causes expensive loss of production. The classification of bearing includes the rolling element bearing, hydrostatic, hydrodynamic and magnetic bearing.
Hydrodynamic bearings are used in various machines ranging from small engines to large turbines or in turbo machinery and these are operated at very high loads and speeds. At these operating conditions, friction losses are more, it means lubricant and bearing temperature becomes too high which becomes a serious problem.
Normally, a hydrodynamic bearing refers to a sleeve bearing or an inclined thrust-slider where the sliding plane floats on a thin film of lubrication. The fluid film is maintained at a high pressure that supports the bearing load and completely separates the sliding surfaces. The lubricant can be fed into the bearing at atmospheric or higher pressure. The pressure wave in the lubrication film is generated by hydrodynamic action due to the rapid rotation of the journal. The fluid film acts like a viscous wedge and generates high pressure and load-carrying capacity. The sliding surface floats on the fluid film, and wear is prevented (Hori, 2006; Hamrock *et al.*, 2004; Stachowiak and Batchelor, 2005; Morgan and Cameron, 1957).
The theoretical study for porous journal bearings was further extended by the works of Rouleau and Steiner, (1974), Shir and Joseph (1966), Murti (1971, 1972, 1973), Jang and Chang (1988), Prakash and Tiwari (1982, 1983). All these studies were based on the Darcy model (DM), in which Darcy's equation was used to guide the oil motion through the porous medium, and the no-slip condition was assumed at the porous bearing/clear oil interface.

Research Article

A critical review on various types and aspects of porous metal bearings was made by Kumar (1980). Many researchers have worked in the field of plain journal and porous journal bearings. They have found the bearing performance parameters with both theoretical and experimental investigation by using some principles of lubrication and appropriate boundary conditions. In addition to this, authors have also found the effects of surface roughness on the performance of bearing parameters. In recent, there is also some work performed on the thermal investigations on the hydrodynamic lubrication of porous journal bearing (Kumar, 1980). A number of authors work on the texturing aspects of bearings (Chiang *et al*., 2004; Kango and Sharma, 2010; Kango *et al*., 2012; Kango *et al.*, 2014; Sharma *et al*., 2014; Sharma *et al*., 2014; Tala-Ighil *et al*., 2007; Papadopoulos *et al*., 2011). A comparative study has been reported by Kango and Sharma (2010) between three different roughnesses models using transverse and longitudinal both type of roughness with power law model for non-Newtonian lubricant.

They used sinusoidal wave equation for bearing surface while considering different configurations with different asperity amplitude and wavelength at various eccentricity ratios. They found that the load carrying capacity and friction force increases with increasing the flow behavior index whereas, friction coefficient decreases with increasing the flow behavior index. They concluded that the longitudinal sinusoidal roughness is best suited for decreasing the friction force.

Kango *et al.*, (2012) numerically investigated the micro cavities on journal bearing and found that the effects of texture are noticeable if the dimple depth is greater than minimum film thickness of the lubricant. Kango *et al.*, (2014) also investigated the microtextured journal bearing including non-Newtonian fluid effects and JFO (Jakobsson, Floberg and Olsson) boundary conditions. They also performed the thermal analysis in their study i.e. viscous heat dissipation to find the performance parameters. The authors found that the average temperature of the lubricant gets reduced in case of texturing surface in comparison to smooth surface/ without texturing. Kango *et al.*, (2014) again investigated on different type of textures, i.e. dimpled surface and grooved surface and gave a brief comparative study on the effect of these types of textured journal bearings. The numerical results for these types of textures suggest that the micro-grooving type of texture reduces the average temperature and friction coefficient in comparison with spherical texture. Sharma *et al.*, (2014) presented the influence of sinusoidal wave textures on three different locations of the surface of bearing and obtain the best configuration among all. They also gave a comparison for the performance of a textured porous bearing for different configurations with the combined effects of two different non-Newtonian fluid models.

et al., (2014) also considered the combined influence of surface texturing with couple stress fluids for a finite journal bearing with JFO boundary conditions and reported that load carrying capacity gets increased with couple stresses for smooth journal bearings at different eccentricity ratios. However, the increase in load carrying capacity with texture marks only at low eccentricity ratios. Moreover, at low eccentricity ratio and for low values of dimple depth, the combined effects of texturing with couple stress fluids improve the load capacity of journal bearing while it decreased the load capacity by about 20% in case of high values of dimple depth and couple stress parameter.

Tala-Ighil *et al.*, (2007) studied the effect of surface texture for hydrodynamic journal bearings. In case of investigations on journal bearing, the shaft has been assumed smooth and rigid as first case. However, in the second case, bearing surface has been textured with spherical dimples. The authors have reported that the film thickness, pressure distribution, side leakage, and frictional torque are significantly affected due to presence of surface texture.

It has also been reported that the attributes of dimples (size, depth, density, and orientation) affect the bearing characteristics significantly. The type of geometry of texture (spherical dimples) has been taken from the author's work. In the present investigation, spherical types of dimples are incorporated on the bearing surface on a particular location and performance is investigated.

Numerical Analysis

The Reynolds equation for an incompressible, Iso-viscous fluid rheology of the bearing system for a combination of flow in the bearing clearance and that within the porous wall is given by Cameron, (1983). Figure 1 shows the schematic diagram for a porous journal bearing.

The circumferential length in the x-direction is rθ, the porous bearing length in the axial direction is L and nominal film thickness in the radial direction is h. The origin is taken on the oil sinter interface. The sinter is of thickness H, extending down to y = -H, and has a permeability ∅. The journal moves at a surface velocity U and the oil film thickness can be given as:

$$h = C_r(1 + e\cos\theta)$$

The flow through the sinter was governed by Darcy's law which can be given mathematically as

$$w = -\frac{\partial p}{\partial y}\frac{\phi}{\eta}$$

There is a negative sign as the flow is in decreasing pressure. The equation of continuity of flow is given as.

$$\frac{\partial}{\partial x}\left(h^3\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial z}\left(h^3\frac{\partial p}{\partial z}\right) = 6\eta\left[U\frac{dh}{dx} - 2\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial z^2}\right)\frac{\phi H}{\eta}\right] \quad (1)$$

Equation (1) is the generalized Reynolds equation for porous journal bearing.
Figure 2 depicts the geometry for spherical dimple supposed on the bearing surface in the present work. The mathematical model for ellipsoidal texture is also adopted from the work of previous authors. The work of spherical texture incorporated on the bearing surface is adopted from Kango *et al.*, (2014).

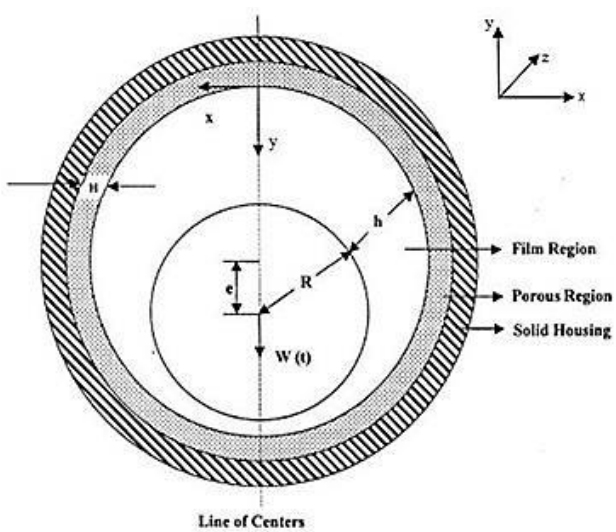

Figure 1: Schematic Diagram of a Porous Journal Bearing

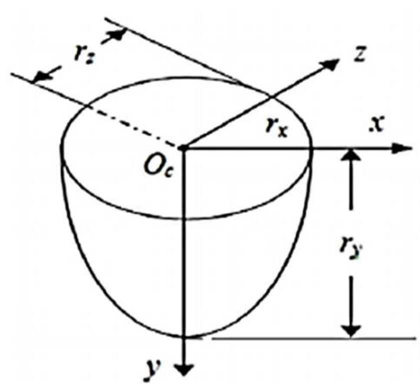

Figure 2: Geometry of Spherical Dimple

The three dimensional geometry of anspherical dimple is taken from Kango *et al.*, (2014) and as follows:

$$\left(\frac{(x-x_c)^2}{r_x^{\ 2}}+\frac{(y-y_c)}{r_y^{\ 2}}+\frac{(z-z_c)^2}{r_z^{\ 2}}\right)=1$$

r_x, r_y and r_z are the radii of the ellipsoidal dimples in the x, y and z directions respectively. The expressions for x, x_c and z_c are also adopted from Kango *et al.*, (2014).

$$x=R\theta,\ x_c=n_1a+\frac{(2n_1-1)L_x}{2},\quad z_c=n_1b+\frac{(2n_1-1)L_z}{2} \qquad (2)$$

where n_1 is the number of dimples and a and b are the distances.

From above equations,

$$\Delta h=r_y\times\sqrt{(1.0-r_y)} \qquad (3)$$

Where,

$$r_y=\left(\frac{(R\theta-x_c)^2}{r_x^{\ 2}}+\frac{(z-z_c)^2}{r_z^{\ 2}}\right)$$

If $r_x = r_z = r_{sph,}$ the film thickness expression will take the form of spherical dimple can be written as

$$\Delta h_{Sph}=\frac{r_y}{r_{Sph}}\sqrt{(r_{Sph})^2-(R\theta-x_c)^2-(z-z_c)^2} \qquad (4)$$

The film thickness equation for textured (spherical dimple) journal bearing is presented in equations as given below:

$$H_{texture}=C_r\ (1+\varepsilon\cos\theta)+\ \Delta\ h \qquad (5)$$

H_T is the film thickness for dimpled bearing, ε denotes the eccentricity ratio, Δh_{Sph} represents the dimensionless film thickness component which is the measure of spherical texture on the bearing surface.

Boundary Conditions

The boundary conditions for the Reynolds equation for the smooth and rough bearings are:

$$p=0\ \text{ At}\,\theta=0^0,360^0$$

$$p=0\ \text{ And }\ \frac{\partial p}{\partial\theta}=0\ \text{ at }\ \theta=\theta_c$$

Where, θc corresponds to initiation of cavitation. In this boundary condition, some positive pressure is considered in the divergent zone.

Bearing Performance Characteristics

Various Bearing Performance Characteristics for finite porous journal bearing are calculated which include the fluid film pressure (p), load carrying capacity (W). The total load supported by the bearing is calculated by integrating the pressure. Load is calculated from two components (W_1 and W_2) which act along the line of centers and perpendicular to the line of centers respectively. Simpson's 1/3rd rule is used for calculating the Load carrying capacity, friction force and other parameters.

$$W_1=\int_0^l\int_0^{2\pi} pr\cos\theta d\theta dz$$

$$W_2=\int_0^l\int_0^{2\pi} pr\sin\theta d\theta dz$$

$$W=\sqrt{W_1^{\ 2}+W_2^{\ 2}}$$

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The expressions used in calculating percentage change in load capacity can be given in the following equation as:

$$\% W = \frac{W_{textured} - W_{smooth}}{W_{smooth}} \times 100$$

The convergence criteria for the derived equations can be taken as given below:

$$\sum\sum \left| \frac{\left(P_{I,J} - P(I,J)_{K-1}\right)}{P(I,J)_{K}} \right| < 0.0001$$

Where *I*, *J* denotes the number of nodes and k denotes the number of iterations respectively. For this work, we used 150 nodes in x- direction and 48 nodes in z-direction. The pressure is computed iteratively through Gauss- Seidel method and over relaxation factor is used for finding solutions. In this program, the over relaxation factor is taken as 1.4-1.5. We also represent the algorithm and the flow chart for these numerical computations.

RESULTS AND DISCUSSION

The developed mathematical model is first validated with the previous models developed by the researchers. The present model is well validated with the work of Jang and Chang (1988), Papadopoulos *et al.*, (2011).

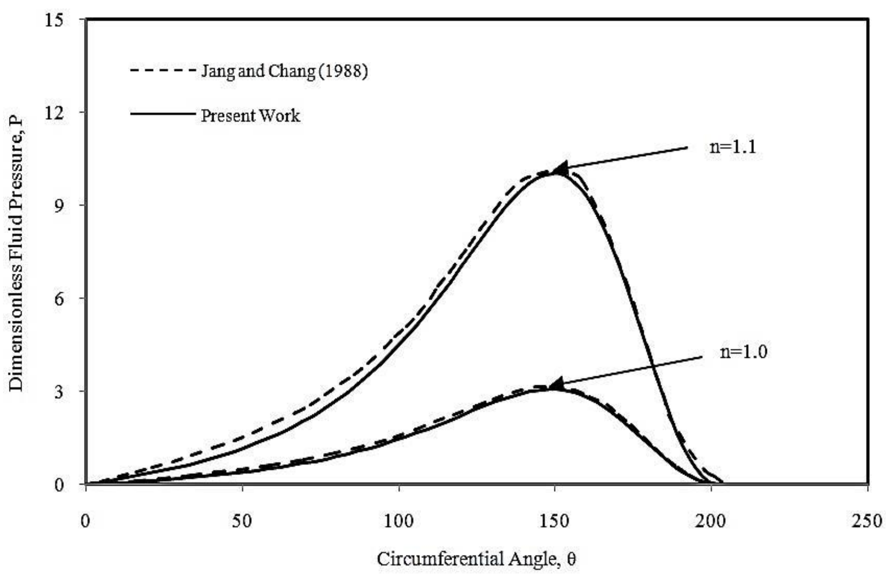

Figure 3: Validation of the Model for Pressure Distribution as a Function of Circumferential Angle with the Work of Jang and Chang (1988)

The results are calculated by varying different parameters such as eccentricity ratio, permeability parameters, shaft speed etc. to find the performance of the textured porous bearings. The performance of textured porous bearing is compared with smooth porous bearing and is shown graphically. The location of dimples and numbers and dimensions of the texture (ellipsoidal dimples) has been taken with reference to the work of Kango *et al.*, (2014). They have found that the optimized angular location for texture (ellipsoidal dimple) was from 0º to 128.5º. They have clearly found that partial texturing is fruitful as compared to full texturing and smooth surface i.e., without textures. Some results are also presented in the form of percentage to find the percentage change of performance characteristics between smooth and textured bearing surface.

Table 4.1: Input Data

Input	Numerical Value
Eccentricity ratio (ε)	0.1-0.5
Shaft speed (N), rpm	1000, 3000
Radial Clearance (C_r), m	50 x 10^{-6}
Shaft Radius (R), m	0.02
Bearing length (L), m	0.04
Consistency parameter at inlet temperature (m_0), Pa-s	0.08
Nodes in circumferential direction (N_θ)	150
Permeability parameter (ψ)	0, 0.005, 0.01, 0.05,0.1
Nodes in axial direction (N_z)	48
$d\theta$, m	0.000566
dz, m	0.000566
Dimple radius (r_s), m	0.003
Spherical radius (r_x and r_z), m	0.003 and 0.003
Dimple depth (r_y), µm	10, 20,30,40
L_x,m	0.0076
L_z, m	0.0076
a	0.001132
b	0.001689
Number of dimples in circumferential direction (N_{tx})	5
Number of dimples in axial direction (N_{tz})	4

Figure 3 shows the validation of present work with the work of Jang and Chang (1988) for pressure distribution as a function of circumferential angle and the trends clearly shows the equitably matching with the present model. The numerical results presented here are all dimensional. The validation for textured surface is also presented in Figure 4 with the work of Papadopoulos *et al.*, (2011).

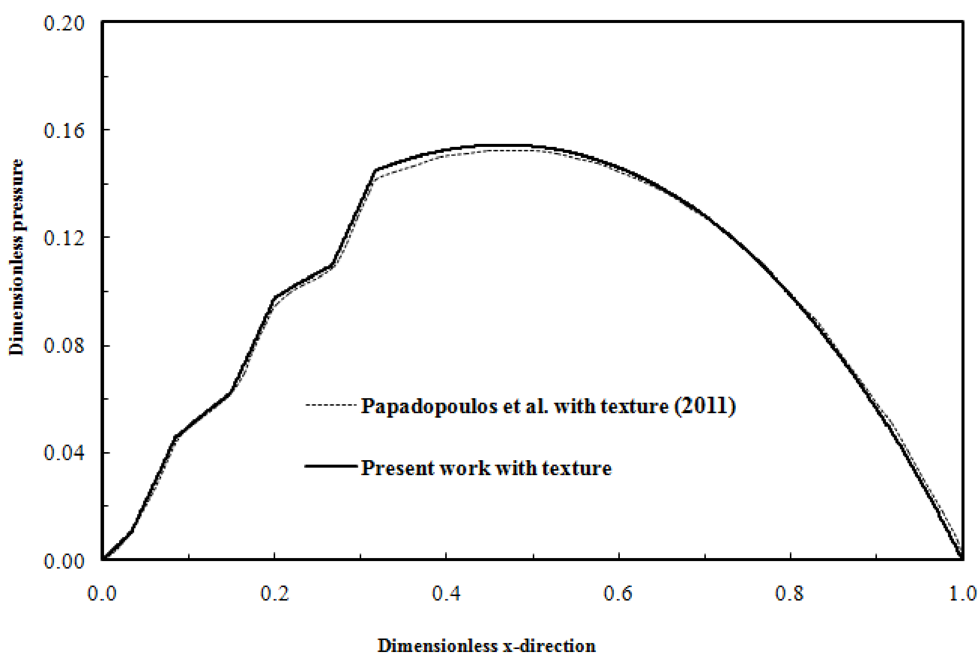

Figure 4: Validation of Dimensionless Pressure for Textured Journal Bearing with the Work of Papadopoulos *et al.*, (2011)

The improvement in bearing performance reveals in Figure 5 which shows a three dimensional representation of comparison between smooth and textured (spherical dimples) bearing for variation of fluid film pressures.

The fluid film pressures are significantly higher in textured case while compared with smooth case. The texturing enhances the bearing performance as clearly shown by results.

Figure 6 shows the effects of dimple depth on the load carrying capacity for the considered textures. The dimple depth is varied from 10 to 40 microns and load carrying capacity is calculated. It has been obtained that the load carrying capacity gets increased with increase in dimple depth. The results shown here are for low and high shaft speed (1000 rpm and 3000 rpm).

An increase of approximately 200 N in load carrying capacity is observed when the dimple depth is increased from 10 to 40 microns.

The results are also calculated for high shaft speed (3000 rpm) in which same trends are obtained; the larger the depth of dimple, the load carrying capacity is higher. At high shaft speed, an increase of approximately 400 N in load carrying capacity is observed when the dimple depth is increased from 10 to 40 microns.

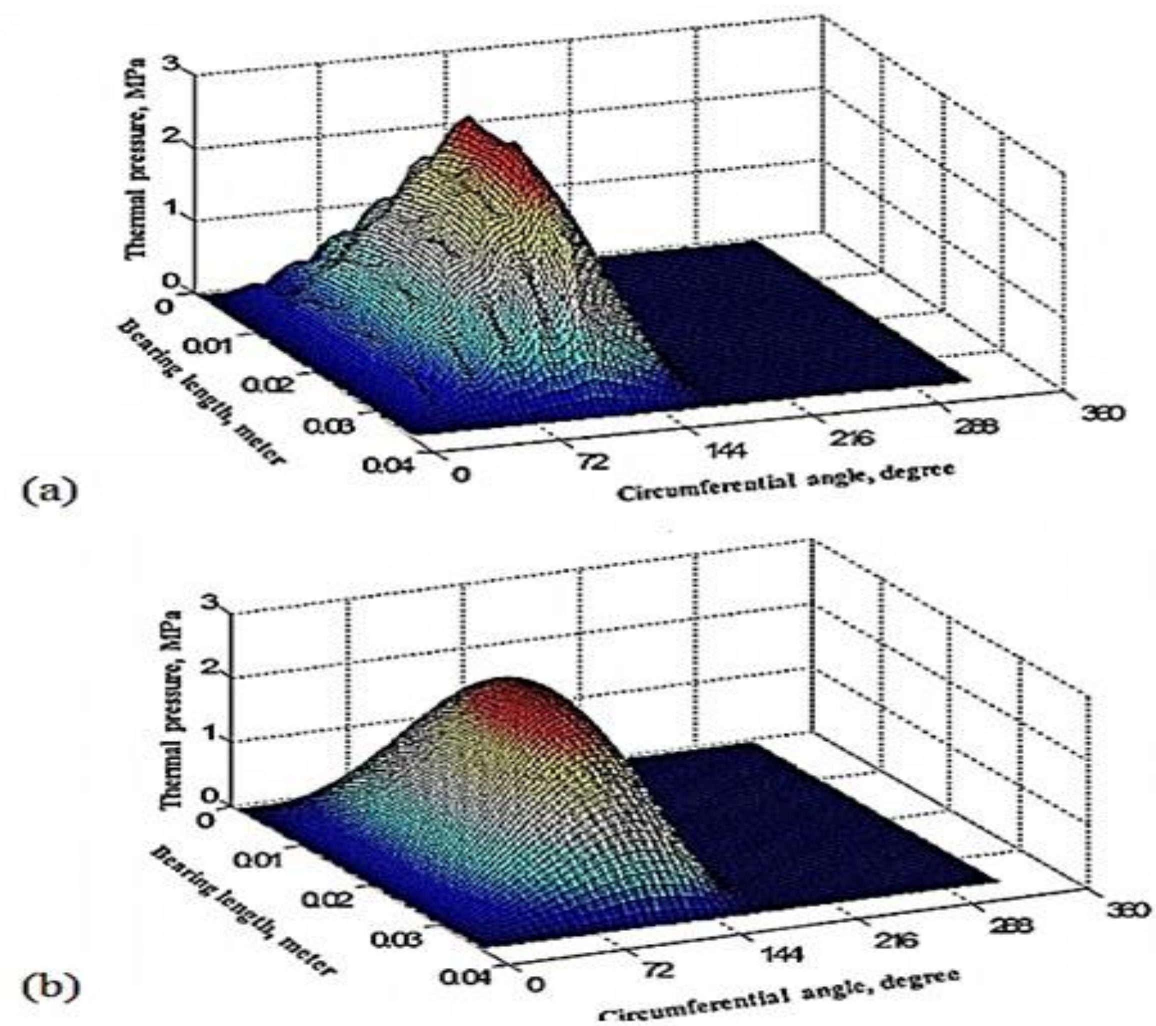

Figure 5: Three Dimensional Representations for Variation of Fluid Film Pressure in Case of (a) Spherical Dimple (Textured Surface) and (b) Smooth Surface

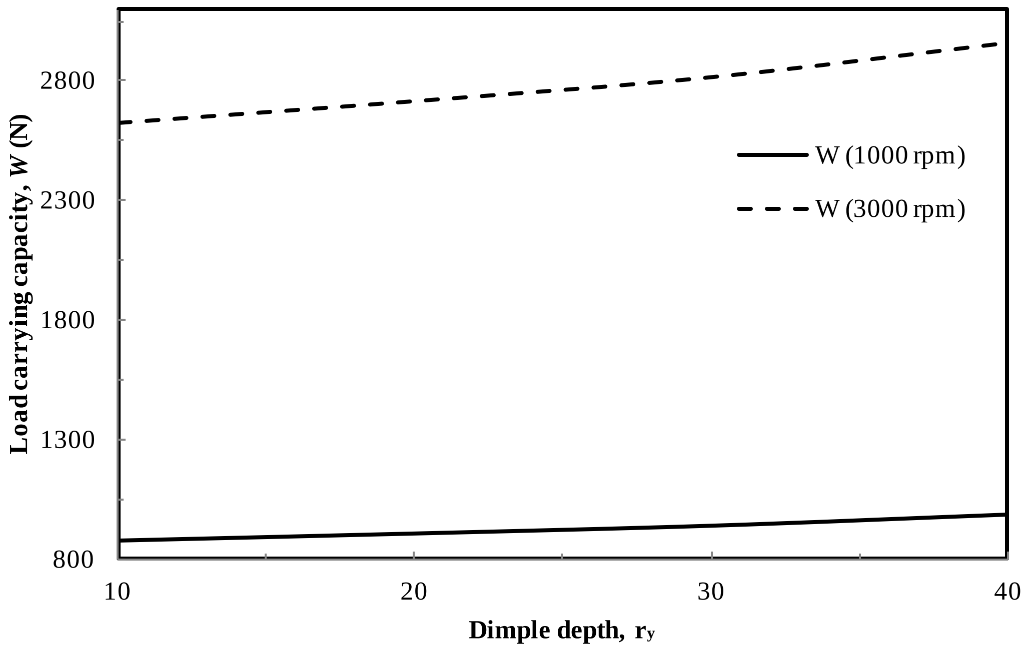

Figure 6: Effect of Dimple Depth on the Load Carrying Capacity of a Spherical Textured Porous Journal Bearing at High Shaft Speed (*N*= 3000 rpm, *ε*=0.3)

The results are also calculated in the form of percentage change as shown in Table 2 where percentage change in load carrying capacity is calculated. While compared with smooth case at high dimple depth such as at 30 microns, an improvement of around 12% has been observed and at 40 microns, around 18% enhancement in load carrying capacity has been observed. It has also been observed that the shaft speed does not influences the bearing performance as at low (1000 rpm) as well as high shaft speed (3000 rpm), the percentage increase in load carrying capacity is almost same. From previous results it has been revealed that large value of dimple depth and an intermediate eccentricity ratio with optimized shaft speed is advantageous for the better performance of porous journal bearing. Thus, the upcoming results are precisely taken on the basis of previously obtained results (*N*= 1000 rpm, *ε* = 0.3, c=0.00005 m).

Table 2: Percentage Change in Load Carrying Capacity (%W) with the Variation in Dimple Depth for Low (1000 rpm) and High Speed (3000 rpm)

Dimple Depth (r_y)	% Age Change in Load (1000 rpm) (%W)	% Age Change in Load (3000 rpm) (%W)
10	4.4457	4.4464
20	8.0726	8.07292
30	12.0608	12.0616
40	17.7719	17.7739

The study on the effect of permeability parameter is also an important aspect of porous bearing to be obtained. In the present work, the permeability parameter is varied from 0 to 0.1 and results are calculated. Figure 7 presents the influence of permeability parameter on the performance behaviour of porous journal bearing. The results have been calculated at high speed due to application of porous bearings i.e., low load and high speed applications. It has been observed that at high speed and at high value of dimple depth, the permeability parameter influences load carrying capacity as inclusion of texture enhances significantly. Moreover, the permeability parameter reduces the load carrying capacity in both cases. High value of permeability parameter reduces the load capacity at higher rate. So, an intermediate value of permeability parameter is taken (ψ=0.01) and load carrying capacity is calculated with variation of eccentricity ratio. As the applications of porous bearings are for low load and high speed equipments.

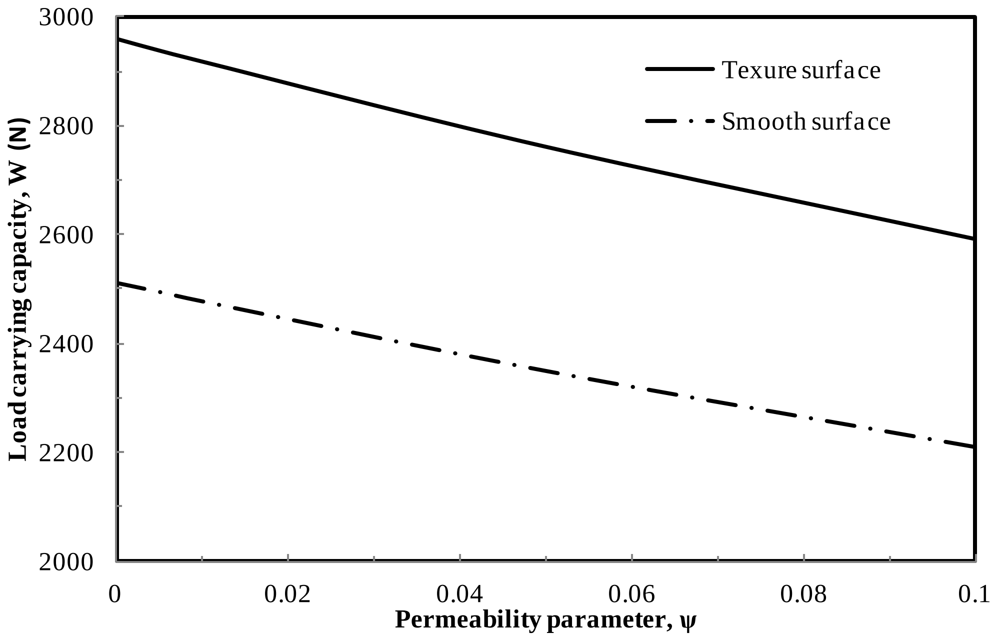

Figure 7: Effect of Permeability Parameters on the Load Carrying Capacity of a Textured and Smooth Bearing (r_y= 40 microns, *N*=3000 rpm, ε=0.3, *m*=0.08)

Conclusion

The results calculated in the previous section gives the following conclusions for various bearing performance characteristics such as fluid film pressures, load carrying capacity, percentage change in load carrying capacity for the effects of spherical type of textures incorporated on the bearing surface to investigate the performance of a finite porous journal bearing:

1. A maximum of around 18% improvement is observed in load capacity in case of textured surface for 40 microns dimple depth and 12% for 30 microns.
2. The load carrying capacity in cases of textured case gets improved with increase in dimple depth and decreased with increase in permeability parameter. Moreover, eccentricity ratio also improves the load carrying capacity with texture conditions.
3. The effect of permeability parameter is to decrease the load carrying capacityand the decrement is enlarged at high values of permeability parameters.
4. The location of texture is also an important parameter in improving the bearing performance as texture with fully pattern (0° to 360°) and in case of divergent zone does not give fruitful results. So, the best location observed for incorporating texture is in convergent zone (0° to 128.5°).

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