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RESEARCH

Comparative Performance of a Non-recessed Hole-entry Hybrid/Hydrostatic Conical Journal Bearing Compensated with Capillary and Orifice Restrictors

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A B S T R A C T

This research paper deals with the theoretical study of comparison of capillary and orifice compensated non-recess hole-entry hydrostatic/ hybrid conical journal bearing. Modified Reynolds equation governing the flow of lubricant in the clearance space of conical journal and bearing has been solved using FEM, Newton-Raphson method and Gauss elimination method. Spherical coordinate system has been employed to obtain the results. The results have been computed for uniform distribution of holes in the circumferential direction with the range of restrictor design parameter $\bar{C}_{s2}$ *= 0.02 - 0.1. The numerically simulated result shows, the use of orifice restrictor is to increase bearing stiffness, threshold speed and maximum pressure compared to capillary restrictor for applied radial load.*

1. INTRODUCTION

In today's modern world, human beings are much more dependent upon the mechanical machines for their daily needs. Since a mechanical machine, relative motion of machine element is observed while in operation. To take care of smooth operations of the relatively moving surfaces of the machine without wear and tear, another machine component called bearing is used, which is also called as the heart of every mechanical machine. Thus, different types of bearing have been used till date since it's inception. Further, the selection strategy of bearing types, fluid feeding devices, its configuration and bearing materials etc. have been demonstrated by Cheng and Rowe [1]. However, the industrial bearings are categorized as hydrodynamic, hydrostatic and hybrid bearing. Hydrodynamic bearing is a self pressure generating bearing, which uses wedge generation action due to journal rotation inside the bearing. In case of hydrostatic bearing, lubricant is supplied at high pressure in the bearing via a flow control device called as restrictor such as a constant flow valve, capillary and orifice restrictor. The hybrid type of bearing uses the combine mechanisms of both hydrostatic and hydrodynamic action. For a hybrid mode of recess bearing operating at high speed, sufficient hydrodynamic action is also not generated; hence, modification in design necessitates achieving maximum advantage of both hydrostatic and hydrodynamic action in a more efficient way. Thus, the nonrecessed bearing is proposed for hybrid operation. It is well known fact that nonrecessed circular and noncircular hybrid journal bearings are gaining tremendous popularity over the recessed bearing because of their enhanced performance characteristics. This implies that the holeentry hybrid journal bearings are widely used in many engineering applications [1–3]. Apart from this, bearing materials and its roughness, lubricant used and its viscosity also play an important role in providing enhanced bearing life. Baskar and Sriram [4] pointed out that the normal load and sliding velocity significantly affect the variation of friction. Therefore, they studied the friction and wear behavior of journal bearing material with the help of pin on disc wear tester for different lubricating oils. Further, they suggested that the chemically modified rapeseed oil (CMRO) is better oil as it was giving low friction. Further, Ayyappa et al. [5] investigated the combined influence of viscosity variation and surface roughness on the couple stress squeeze film for short journal bearing. They found that the transverse roughness pattern improved the squeeze film characteristics. However, the viscosity variation reduces the load carrying capacity and squeeze film time when compared with constant viscosity. P.C. Mishra [6] studied the performance characteristics of a roughen elliptic bore journal bearing to evaluate hydrodynamic pressure and oil temperature. Later, Bhagat and Roy [7] studied the thermo-hydrodynamic analysis of multi lobe oil and two axial groove journal bearing. They revealed that the threelobe journal bearing was giving high film temperature as compared to other bearings. Recently, Bompos and Nikolakopoulos [8] studied the surface texture magnetorheological fluid journal bearing under the influence of external magnetic field. They investigated that the lubricant is to alter its apparent viscosity for various kinds of surface textures. Singh et al. [9] investigated the dynamic stiffness and damping characteristics of a curved slider bearing using non-Newtonian Pseudoplastic and dilatant lubricant. They concluded that these characteristics alter significantly for non-Newtonian fluid. Patel and Deheri [10] studied the porous structure on the performance of magnetic fluid based rough short bearing, they analyzed the Kozeny-Carman and Irmay's model for roughness and magnetization effect on the bearing. They investigated that the Kozeny-Carman model is better for magnetization and porosity effect than the Irmay's model. Shenoy and Pai [11] studied the effect of misalignment on steady state characteristics of externally adjustable fluid film bearing. They calculated the static performance characteristics using finite difference method. They found that the static performance characteristics are higher for negative radial and tilt adjustments. Rac and Vencl [12] studied the tribological and design parameters of lubricated sliding bearing for high performance and longetivity. Their main focus was on load carrying capacity, bearing clearance and surface properties. Finally, at the end, they made some recommendations on tribological properties of bearing material, lubricant fluid, viscosity, etc. However, conical journal bearing more or less is also in the race of other types of bearing. The use of externally pressurized conical bearing in industrial application has improved machine performance beyond the capability of any other fluid film bearing. This is mainly due to their ability to carry both axial and radial load as well as the self-guiding nature of the conical surface. Thus, in the present work, the analysis dealing with the comparative study of the performance of non-recess hybrid conical journal bearing compensated with capillary and orifice restrictors for various semi cone angles is undertaken. The following paragraph details the investigational reviews of important studies relevant to the non-recess hole-entry journal bearing.

Now a day, non-recess hole-entry journal bearing configuration is in demand, as a consequence of this, many studies have been carried out and reported in the literature. Rowe et al. [3] extensively analyzed the performance of hole-entry journal bearing in 1982. They compared the performance characteristics of hole-entry bearing with that of slot-entry and recessed bearings for different power ratios. They found that the hole-entry bearings are especially effective for better load support and low energy consumption at hydrostatic and hybrid mode of operation. Nathi Ram and Sharma [13] studied the performance of orifice compensated non-recessed hole-entry hybrid journal bearing lubricated with micropolar lubricants in 2012. They investigated the correct combination of restrictor design parameter and lubricant micropolar parameters for obtaining optimum fluid film stiffness coefficients. Sharma and Kushare [14] studied the effect of two lobe symmetric hole-entry worn hybrid journal bearing nonlinear transient stability with non-Newtonian lubricant in 2014. Their result revealed that the non-Newtonian lubricant influences the journal trajectories and stability of a worn hybrid journal bearing. They [15] further studied the comparative study of two lobe non-recessed roughened hybrid journal bearing in 2015. In their study, they reported that the proper selection of roughness pattern parameters, offset factor and compensating device is essential to enhance the bearing performance. They [16] also demonstrated the effect of wear defect in the performance of two lobe hole entry hybrid bearing system compensated with orifice restrictor. Further, the following notable observations of the available studies indicate that they have been conducted in the case of central recess/pocket externally pressurized conical thrust bearings. In the year 1981, an annular recess conical thrust bearing has been studied by Prabhu and Ganesan [17] for both static and dynamic conditions, by considering the effect of rotational lubricant inertia for semi cone angles γ ($45^o \leq \gamma \leq 90^o$) compensated with capillary and orifice restrictors. Further, in 1983, they [18] theoretically studied the characteristics of multirecess conical hydrostatic thrust bearings, by taking into account the effect of rotational lubricant inertia. They computed stiffness and damping characteristics, bearing flow and load capacity for the actual useful of aspect and resistance ratios for capillary and orifice compensations. Further, in 2009 Guo Hong et al. [19] studied the dynamic performance of an externally pressurized deep/shallow pockets hybrid conical journal bearing compensated by flat capillary restrictors. Their result showed that the hybrid conical journal bearing has the advantages of high load carrying capability and high stability under small eccentricity. Very recently, Sharma et al. [20] studied Performance analysis of a multirecess capillary compensated conical hydrostatic journal bearing in 2011. Their result indicates that the lubricant flow rate is significantly reduces in case of conical journal bearing vis-à-vis the corresponding similar circular hydrostatic journal bearing. Further, in 2011, Sharma et al. [21] studied the orifice compensated influence of wear on the performance of a 4-pocket hybrid conical journal bearing. They suggested that the performance of the conical bearing is greatly affected by the wear defect. Sharma and Rajput [22] investigated the results for conical hydrostatic journal bearing lubricated with micropolar and Newtonian fluid for various semi cone angles. They revealed that the performance of micropolar fluid is superior as compared to Newtonian fluid. The static performance characteristics of plain hydrodynamic conical journal bearing, multiple wedge hydrodynamic conical journal bearing and hybrid conical journal bearing have been analyzed by Korneev [23] with turbine oil as lubricant and presented the formulas. He revealed that the load carrying capacity reduces as the semi cone angle is increased for Turbine oil lubricated conical bearing. However, the load carrying capacity increases as the radial eccentricity and speed is increased. Korneev [24] further studied the turbulence effect on static characteristics of water lubricated hydrodynamic and hydrostatic conical journal bearing. He formulated the design of journal bearing with turbulence and investigated that the turbulence increases the load carrying capacity. Further, much differentiating static characteristics is noted when turbulence is considered than the without consideration. Rana et al. [25] performed the theoretical analysis of a multi recess hydrostatic conical journal bearing compensated with constant flow valve using Finite element Method for micropolar fluid. They investigated that the bearing develops large pressure for the increase in radial load, constant flow valve parameter, characteristic length and semi cone angle. However, the increase in semi cone angle reduces the fluid film thickness of the bearing, thereby increasing the bearing stability. The influence of micropolar lubrication on the stability of multirecess conical hybrid journal bearing system compensated with constant flow valve has been studied by Rajput and Sharma [26] in 2014. They noted the stability threshold speed margin is increased substantially for micropolar fluid as compared to Newtonian fluid. Furthermore, under the influence of micropolar fluid, they also noted the increase in h_{min}, fluid-film stiffness and damping coefficients for semi cone angle γ=10° and γ=20°.

A thorough scan of the available literature, which actually deals with the studies related to externally pressurized bearing and their performances, in terms of various parameters, has been studied in depth. However, it has been observed that there is very limited information available on the conical types of bearing and no study is reported in the literature which throws light on the hole-entry conical bearing except Khakse et al. [27].

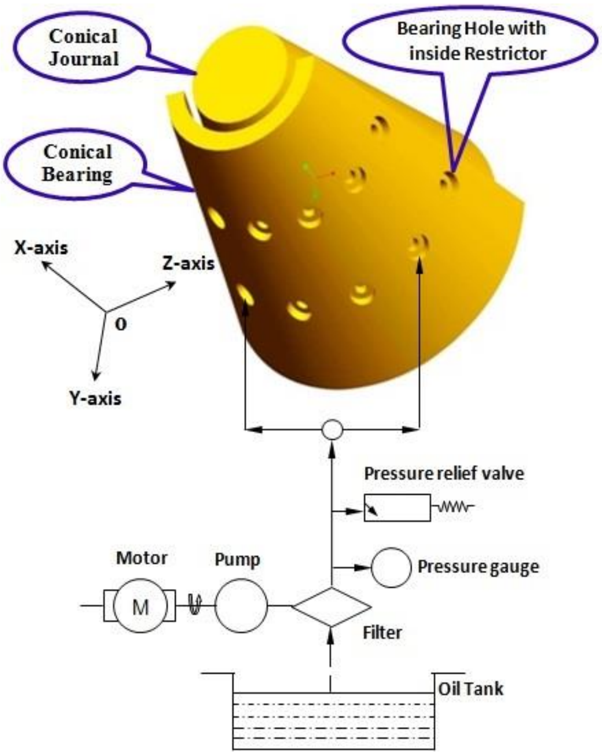


Fig. 1. Non-recess hole-entry conical hydrostatic/ hybrid journal bearing system.

A propose configuration as shown in Fig. 1 for a non-recess hole-entry conical hybrid/ hydrostatic journal bearing may have a significant role in the overall performance of the bearing. However, till date, no study has yet been reported concerning the comparative performance of a non-recess hole-entry hybrid/ hydrostatic conical journal bearing compensated with capillary and orifice restrictor. Therefore, the aim of this research is to compare the performance of a non-recess hole-entry hybrid/hydro-static conical journal bearing compensated with capillary and orifice restrictor and to bridge the gap in the literature.

2. MATHEMATICAL MODELLING

Generalized Reynolds equation governing the lubricant flow field in the clearance space of journal and bearing in spherical coordinate is as given below [20]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r}{12\mu}h^3\frac{\partial p}{\partial r}\right)+\frac{1}{\sin^2\gamma}\frac{\partial}{\partial\varphi}\left(\frac{h^3}{12\mu}\frac{1}{r^2}\frac{\partial p}{\partial\varphi}\right)=\frac{\omega_J}{2}\frac{\partial h}{\partial\varphi}+\frac{\partial h}{\partial t} \tag{1}$$

Converting the equation (1) into non-dimensional form using following:

$$\beta = r\sin\gamma/R_J;\ \bar{p}=\frac{p}{p_s};\ \bar{h}=\frac{h}{c};\ \bar{t}=\frac{t}{\left[\frac{\mu R_J^2}{c^2 p_s}\right]};\ (\alpha=\varphi)$$

coordinates are in non-dimensional parameter and angle in radian. The Non-dimensional form of modified Reynolds equation is given as [20]:

$$\frac{\partial}{\partial\alpha}\left[\left(\frac{1}{\beta}\right)\frac{\bar{h}^3}{12\bar{\mu}}\frac{\partial\bar{p}}{\partial\alpha}\right]+\frac{\partial}{\partial\beta}\left[\sin^2\gamma\,(\beta)\frac{\bar{h}^3}{12\bar{\mu}}\frac{\partial\bar{p}}{\partial\beta}\right]=\frac{\Omega}{2}\frac{\partial\bar{h}}{\partial\alpha}+\beta\frac{\partial\bar{h}}{\partial\bar{t}} \tag{2}$$

In a full lubricated region, lubricant fluid film of thickness (h) is present in between the conical journal and bearing and is expressed as [20]:

$$\bar{h}_0=\left(1-\bar{X}_J\cos\alpha-\bar{Z}_J\ sin\alpha\right)\cos\gamma \tag{3}$$

2.1 Restrictor flow equation

The flow through the orifice is proportional to the square root of the pressure difference across the orifice and is given as:

$$\bar{Q}_R=\bar{C}_{s2}\left(1-\bar{p}_c\right)^{1/2} \tag{4a}$$

The lubricant flow rate through the Capillary restrictor is expressed as:

$$\bar{Q}_R=\bar{C}_{s2}\left(1-\bar{p}_c\right) \tag{4b}$$

where, $\bar{p}_c$ = pressure at hole.

2.2 Finite element formation

Isoviscous incompressible lubricant flow field in the clearance space of hole-entry hybrid conical journal bearing has been discretized into four noded isoparametric elements. Elements are represented by the corresponding node number and are identified by the number at the centres of elements. The holes on the development of bearing surface are represented by the small circles. The mesh grid of the lubricant fluid flow field is divided into 60 nodes and 48 elements. However, any numbers of elements and nodes can be chosen for the finite element formulation. Applying the Lagrangian interpolation function to typical four noded isoparametric elements, the pressure at a point in the element is bilinearly distributed and is represented approximately as:

$$\bar{p} = \sum_{j=1}^{4} N_j \, \bar{p}_j \tag{5}$$

Introducing the approximate value of pressure ($\overline{p}$), equation (2) can be expressed as:

$$\frac{\partial}{\partial \alpha}\left[\left(\frac{1}{\beta}\right)\frac{\bar{h}^3}{12\bar{\mu}}\frac{\partial}{\partial \alpha}\sum_{j=1}^{4} N_j \, \bar{p}_j\right] + \frac{\partial}{\partial \beta}\left[\sin^2\gamma\,(\beta)\frac{\bar{h}^3}{12\bar{\mu}}\frac{\partial}{\partial \beta}\sum_{j=1}^{4} N_j \, \bar{p}_j\right] - \frac{\Omega}{2}\frac{\partial \bar{h}}{\partial \alpha} - \beta\frac{\partial \bar{h}}{\partial \bar{t}} = R^e \tag{6}$$

Where " R^e " is called as Residue.

Galerkin's technique is used to minimize the residue by orthogonality condition along with interpolation function and the element matrices are assembled to get a global matrix and are represented as [19]:

$$[\overline{F}]\{\overline{p}\} = [\overline{Q}] + \Omega\{\overline{R}_H\} + \dot{\overline{X}}_J\{\overline{R}_{Xj}\} + \dot{\overline{Z}}_J\{\overline{R}_{Zj}\} \tag{7}$$

Above two dimensional fluid flows field matrix can be elaborated as follows:

$$\begin{Bmatrix} \overline{F}_{11} & \overline{F}_{1i} & \overline{F}_{1j} & \overline{F}_{1n} \\ \overline{F}_{i1} & \overline{F}_{ii} & \overline{F}_{ij} & \overline{F}_{in} \\ \overline{F}_{j1} & \overline{F}_{ji} & \overline{F}_{jj} & \overline{F}_{jn} \\ \overline{F}_{n1} & \overline{F}_{ni} & \overline{F}_{nj} & \overline{F}_{nn} \end{Bmatrix} \begin{Bmatrix} \bar{p}_1 \\ \bar{p}_i \\ \bar{p}_j \\ \bar{p}_n \end{Bmatrix} = \begin{Bmatrix} \overline{Q}_1 \\ \overline{Q}_i \\ \overline{Q}_j \\ \overline{Q}_n \end{Bmatrix} + \mathbf{\Omega} \begin{Bmatrix} \overline{R}_{H1} \\ \overline{R}_{Hi} \\ \overline{R}_{Hj} \\ \overline{R}_{Hn} \end{Bmatrix} + \dot{\bar{x}} \begin{Bmatrix} \overline{R}_{x1} \\ \overline{R}_{xi} \\ \overline{R}_{xj} \\ \overline{R}_{xn} \end{Bmatrix} + \dot{\bar{z}} \begin{Bmatrix} \overline{R}_{z1} \\ \overline{R}_{zi} \\ \overline{R}_{zj} \\ \overline{R}_{zn} \end{Bmatrix} \tag{8}$$

where, $[\overline{Q}], \{\overline{R}_H\}, \{\overline{R}_{Xj}\}, \{\overline{R}_{Zj}\}$ are column vectors and $\{\overline{F}_{ij}\}$ matrix vector.

The hole-entry conical hybrid journal bearing compensated with capillary and orifice restrictor requires continuity of flow from restrictor to bearing clearance space; the expressions for capillary and orifice restrictor are as given in (4a) and (4b), where equation (4a) is a non-linear equation hence Newton-Raphson method is used and equation (4b) is a linear equation, hence Gauss elimination method is used to solve the system global equation. Let j^{th} node is lying on hole, then the term $\overline{Q}_j$ on right hand side can be replaced with $\overline{Q}_R$ which represent the flow through the hole having restrictor. Thus, after modification and necessary boundary conditions, the solution of system equation (8) gives hole/nodal fluid film pressure.

2.3 Boundary condition

Following boundary conditions are used in the present study [13].

1) Flow of lubricant through the restrictor is equal to the bearing input flow at hole.
2) The nodal flows are zero at internal nodes except those situated on holes and external boundaries.
3) Nodes situated on external boundary of the conical bearing have zero relative pressure with respect to atmospheric pressure, i.e. $\overline{p}|_{\beta=\pm1.0} = 0.0$
4) At the trailing edge of the positive region, $\bar{p} = \frac{\partial \bar{p}}{\partial \alpha} = 0.0$ is also called as Reynolds boundary condition.

2.4 Fluid film stiffness and damping coefficient

The fluid-film stiffness coefficient is defined as:

$$\bar{S}_{ij} = -\frac{\partial \bar{F}_i}{\partial \bar{q}_j}, (i = X, Z) \tag{9}$$

where,

i = direction of force or moment.

$\bar{q}_j$ = direction of journal center displacement $(\bar{q}_j = \bar{X}_J, \bar{Z}_J)$.

In matrix form:

$$\begin{bmatrix}\bar{S}_{XX} & \bar{S}_{XZ}\\ \bar{S}_{ZX} & \bar{S}_{ZZ}\end{bmatrix} = -\begin{bmatrix}\frac{\partial \bar{F}_X}{\partial \bar{X}_J} & \frac{\partial \bar{F}_X}{\partial \bar{Z}_J}\\ \frac{\partial \bar{F}_Z}{\partial \bar{X}_J} & \frac{\partial \bar{F}_Z}{\partial \bar{Z}_J}\end{bmatrix} \tag{10}$$

The fluid-film damping coefficient is defined as:

$$\bar{C}_{ij} = -\frac{\partial \bar{F}_i}{\partial \bar{\dot{q}}_j}, (i = x, z) \tag{11}$$

Here $\bar{\dot{q}}_j$ represents the velocity component of journal center $\left(\bar{\dot{q}}_j = \bar{\dot{X}}_J, \bar{\dot{Z}}_J\right)$.

In matrix form, the expressions for fluid-film damping coefficients may be express as:

$$\begin{bmatrix}\bar{C}_{XX} & C_{XZ}\\ \bar{C}_{ZX} & C_{ZZ}\end{bmatrix} = -\begin{bmatrix}\frac{\partial \bar{F}_X}{\partial \bar{\dot{X}}_J} & \frac{\partial \bar{F}_X}{\partial \bar{\dot{Z}}_J}\\ \frac{\partial \bar{F}_Z}{\partial \bar{\dot{X}}_J} & \frac{\partial \bar{F}_Z}{\partial \bar{\dot{Z}}_J}\end{bmatrix} \tag{12}$$

Thus, differentiating the global system equation (7) with respect to $\bar{\dot{q}}_j = \bar{\dot{X}}_J, \bar{\dot{Z}}_J$. Nodal pressures are obtained and then fluid film damping coefficient$\bar{C}_{ij}(i, j = \bar{\dot{X}}_J, \bar{\dot{Z}}_J)$.

3. SOLUTION PROCEDURE

Solution for the lubricant flow field for the capillary and orifice compensated non-recess hole-entry hybrid conical journal bearing is obtained using iterative scheme for vertical external load. Assuming, steady state condition ($\bar{\dot{X}}_J, \bar{\dot{Z}}_J = 0$) and constant viscosity, the equation (7) is solved for specified journal centre position ($\bar{X}_J, \bar{Z}_J$). Being capillary and orifice restrictor is used; the system equation becomes linear and non-linear respectively. Hence respective, Gauss eliminati-on and Newton-Raphson method is applied to solve these equations. Further, after adjustment for the flow through capillary and orifice restrictor with the necessary boundary conditions, one additional iterative loop is constructed for the equilibrium journal centre position using the equation as given below:

$$\overline{F}_X = 0 \text{ and } \overline{F}_Z - \overline{W}_r = 0 \tag{13}$$

The fluid film reaction term in equation (13) are expanded by Taylor's series about the i^{th} journal centre position and the increment ($\Delta\overline{X}_J^i, \Delta\overline{Z}_J^i$) on the journal coordinate are obtained as follows:

$$\Delta\overline{X}_J^i = -\frac{1}{D_J}\left[\left.\frac{\partial \overline{F}_z}{\partial \overline{Z}_J}\right|_i \; -\left.\frac{\partial \overline{F}_x}{\partial \overline{Z}_J}\right|_i\right]\begin{Bmatrix}\overline{F}_x^i\\ \overline{F}_z^i - \overline{W}_r\end{Bmatrix} \tag{14a}$$

$$\Delta\bar{Z}_J^i = -\frac{1}{D_J}\left[-\left.\frac{\partial \overline{F}_z}{\partial \overline{X}_J}\right|_i \; \left.\frac{\partial \overline{F}_x}{\partial \overline{X}_J}\right|_i\right]\begin{Bmatrix}\overline{F}_x^i\\ \overline{F}_z^i - \overline{W}_r\end{Bmatrix} \tag{14b}$$

where,

$$D_J = \left(\left.\frac{\partial \bar{F}_x}{\partial \bar{X}_J}\right|_i \cdot \left.\frac{\partial \bar{F}_z}{\partial \bar{Z}_J}\right|_i - \left.\frac{\partial \bar{F}_x}{\partial \bar{Z}_J}\right|_i \cdot \left.\frac{\partial \bar{F}_z}{\partial \bar{X}_J}\right|_i\right) \tag{14c}$$

The new journal centre position coordinate $\left(\overline{X}_j^{i+1}, \overline{Z}_j^{i+1}\right)$ are given as:

$$\overline{X}_J^{i+1} = \overline{X}_J^i + \Delta\overline{X}_J^i \tag{15a}$$

$$\overline{Z}_J^{i+1} = \overline{Z}_J^i + \Delta\overline{Z}_J^i \tag{15b}$$

Where $\overline{X}_J^i, \overline{Z}_J^i$ are the coordinate of the journal centre position.

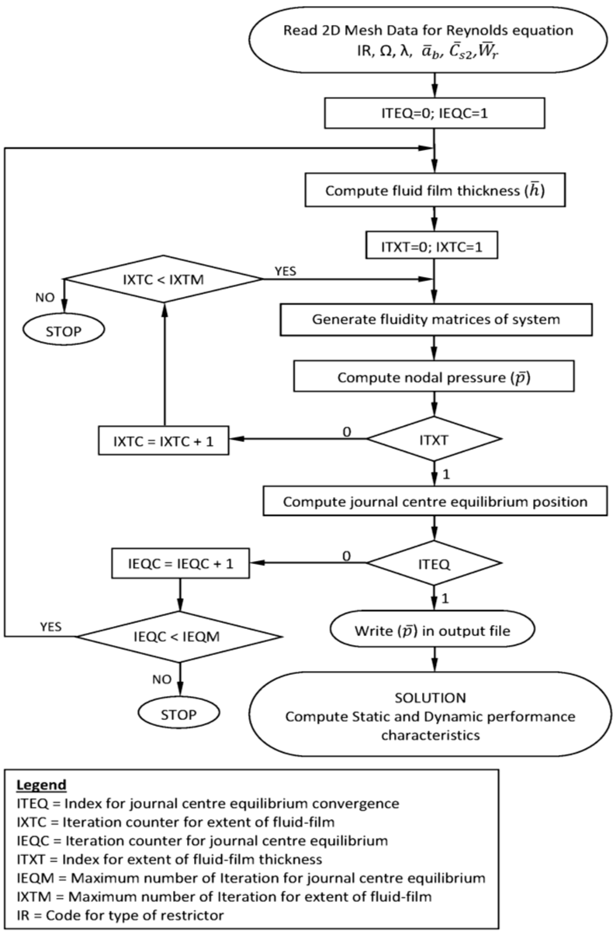


Fig. 2. Solution procedure flow chart.

Figure 2 shows the complete iterative solution, iterations are continued until the following convergence criterion is satisfied. Thus, the solution for the external vertical load is obtained.

$$\left[\frac{((\Delta \bar{X}_j^i)^2 + (\Delta \bar{Z}_j^i)^2)^{1/2}}{((\bar{X}_j^i)^2 + (\bar{Z}_j^i)^2)^{1/2}}\right] \times 100 < 0.001 \qquad (16)$$

4. RESULTS AND DISCUSSION

The performance characteristics for non-recess hybrid conical journal bearing, with two rows of symmetric hole configuration with 12 holes in each row are computed using Fortran 77 program. Since, non-availability of experimental results in the open published literature, for non-recess hole-entry hybrid/hydrostatic conical journal bearing compensated with capillary and orifice restrictor, the simulated results from the present study have been compared with the already published result of Stout and Rowe [2] as shown in Fig. 3, which shows the results are very much close and in good agreement.

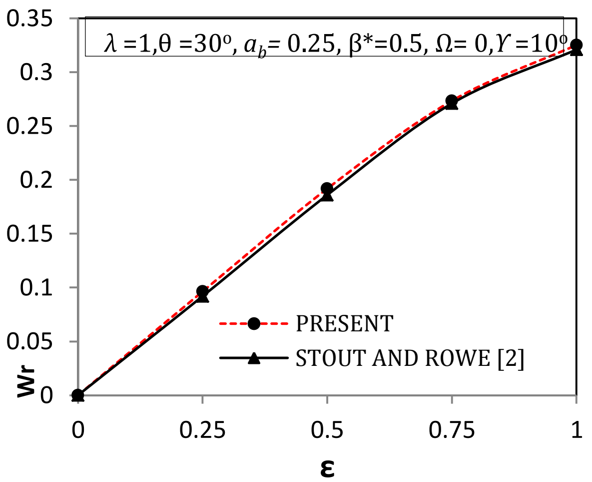
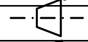
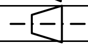


Fig. 3. Radial load 'Wr' versus eccentricity ratio ε.

In the present work, the simulated results are presented for the given bearing operating and geometric parameters as in Table. 1. Based on the available published literature [16], the values of the restrictor design parameter $\bar{C}_{s2}$=0.02-0.1 has been used in the present study.

The bearing performance characteristics parameters have been computed for the various semi cone angles (γ) = 5º, 10º, 20º and 30º. Further, results are presented for the percentage variation in orifice and capillary compensated hybrid/hydrostatic conical journal bearing.

Table 1. Bearing operating and geometric parameters.

Bearing parameter	Notation	Value
Bearing aspect ratio	λ	1.0
Restrictor design parameter	$\bar{C}_{s2}$	0.02 to 0.1
External radial load	$\bar{W}_r$	1
Speed parameter	Ω	1 = hybrid, 0 = hydrostatic
Number of holes	n	12
Number of row	—	2
Type of restrictor	Capillary and Orifice restrictor	
Different types of bearings under consideration with semi cone angle γ		
Bearing No.1		γ = 5º
Bearing No.2		γ = 10º
Bearing No.3		γ = 20º
Bearing No.4		γ = 30º

4.1. Variation of maximum pressure ($\bar{p}_{max}$) with ($\bar{C}_{s2}$)

Figure 4(a) shows the variation of maximum pressure ($\bar{p}_{max}$) with respect to restrictor design parameter ($\bar{C}_{s2}$) for non-recess hydrostatic/hybrid conical journal bearing compensated with capillary and orifice restrictor. It is observed from the Fig. 4(a) that, as the semi cone angle (γ) increases $\bar{p}_{max}$ also increases for both capillary and orifice restrictor.

As far as capillary compen-sated non-recess hybrid conical journal bearing is concerned, it shows poor performance as compared to capillary compensated non-recess hydrostatic conical journal bearing with the rise of semi cone angles. Similarly, it is also noted that orifice compensated non-recess hybrid conical journal bearing is showing enhanced performance as compared to capillary compensated non-recess hydrostatic conical journal bearing, but the same is poorer than orifice compensated non-recess hydrostatic conical journal bearing. Further, it is found that there is close rise of $\bar{p}_{max}$ for semi cone angle γ=5º and 10º throughout the range of restrictor design parameter for all capillary and orifice compensated hydrostatic and hybrid conical journal bearing. Whereas, semi cone angle γ=20º and 30º shows considerable enhancement in $\bar{p}_{max}$ for capillary and orifice compensated hydrostatic and hybrid conical journal bearing as compared to semi cone angle γ=5º and 10º. It is also be observed that the semi cone angle γ=5º shows higher pressure $\bar{p}_{max}$

than for γ=10º and it increases higher, as semi cone angle increases for orifice and capillary compensated non-recess hybrid conical journal bearing.

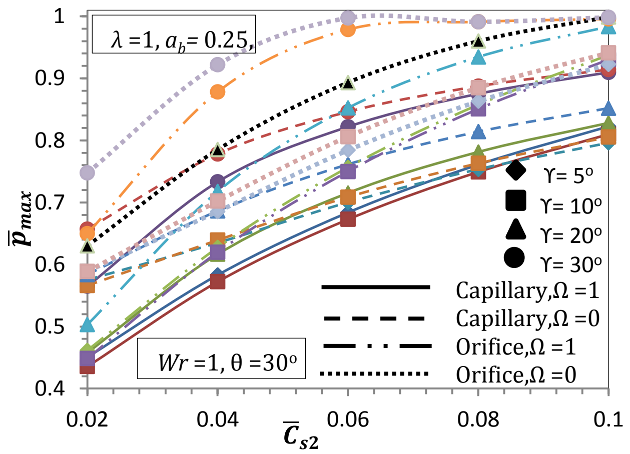


Fig. 4(a). Variation of $\bar{P}_{max}$ with $\bar{C}_{s2}$.

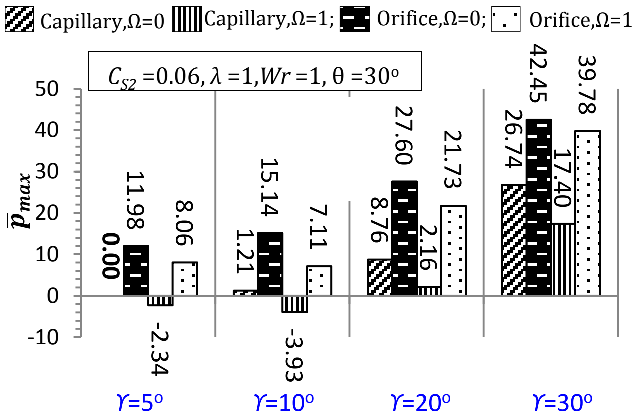


Fig. 4(b). % change of $\bar{P}_{max}$ with respect to base bearing.

However, it is not the case with the hydrostatic conical journal bearing. This indicates that the hydrodynamic action and semi cone angle affect the pressure rise or fall in hybrid mode. It is also seen from the Fig. 4(a) that the semi cone angle γ=30º orifice compensated hydrostatic and hybrid conical journal bearing shows increase in $\bar{p}_{max}$ up to $\bar{C}_{s2}$=0.07, after that it follows constant pressure pattern. Thus, it can be suggested from the Fig. 4(a) that the orifice compensated hydrostatic conical journal bearing with semi cone angle γ=30º gives higher performance as compared to other semi cone angle conical journal bearings. The percentage increase of orifice compensated non-recess hydrostatic conical journal bearing with respect to capillary compensated non-recess hydrostatic conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 11.98 %, 13.75 %, 17.32 % and 12.39 % for γ=5º, 10º, 20º and 30º respectively. Similarly, the percentage increase of orifice compensated non-recess hybrid conical journal bearing with respect to capillary compensated non-recess hybrid conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 10.64 %, 11.49 %, 19.15 % and 19.06 % for γ=5º, 10º, 20º and 30º respectively. It is to be noted from the Fig. 4(b) that the orifice compensated non-recess hydrostatic conical journal bearing gives maximum pressure for all semi cone angles γ=5º, 10º, 20º and 30º as far as overall scenario for percentage change of $\bar{p}_{max}$ with respect to γ=5º capillary compensated base bearing at $\bar{C}_{s2}$=0.06 is concerned.

4.2. Variation of minimum fluid film thickness ($\bar{h}_{min}$) with ($\bar{C}_{s2}$)

Figure 5(a) depicts the variation of minimum fluid film thickness ($\bar{h}_{min}$) with respect to restrictor design parameter ($\bar{C}_{s2}$) for capillary and orifice compensated non-recess hydrostatic and hybrid conical journal bearing. It is noted from the Fig. 5(a) that as the semi cone angle (γ) increases, $\bar{h}_{min}$ shows haphazard behaviour (independent of semi cone angle sequence) up to 20º for hydrostatic mode, then $\bar{h}_{min}$ decreasing for γ=30º. Similarly, $\bar{h}_{min}$ with respect to γ=5º increases up to γ=10º, then decreasing for γ=20º and 30º for hybrid mode. It is observed from the Fig. 5(a) that the $\bar{h}_{min}$ for semi cone angle γ=5º, 10º and 20º capillary and orifice compensated non-recess hydrostatic conical journal bearing shows steep increase up to $\bar{C}_{s2}$=0.04, there-after, it increases gradually till $\bar{C}_{s2}$=0.1. However, $\bar{h}_{min}$ initially increases for semi cone angle γ=30º and then it tends to decrease as the $\bar{C}_{s2}$ proceed.

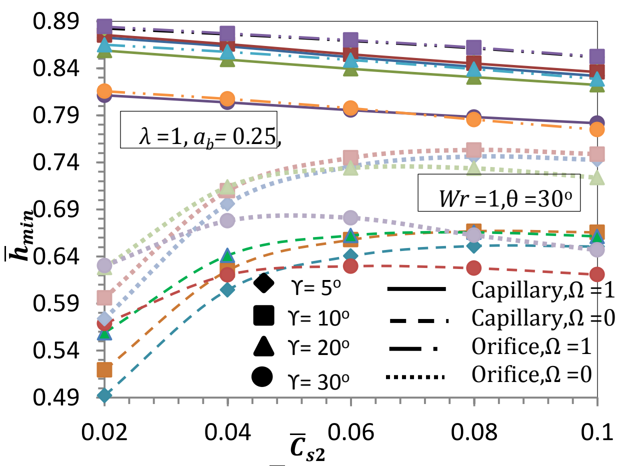


Fig. 5(a). Variation of $\bar{h}_{min}$ with $\bar{C}_{s2}$.

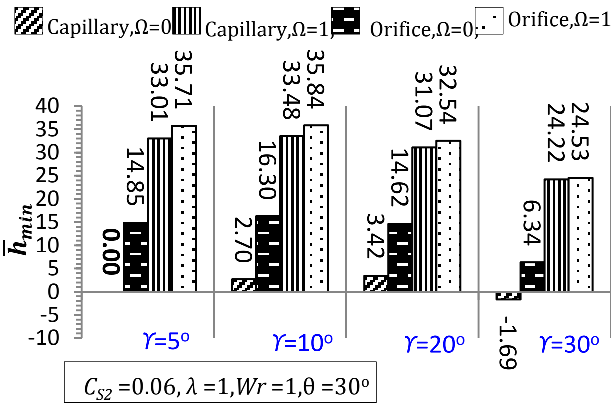


Fig. 5(b). % change of $\bar{h}_{min}$ with respect to base bearing.

Hence, from the Fig. 5(a), it is to be noted that the semi cone angle γ=30° orifice compensated non-recess hydrostatic conical journal bearing shows enhance performance for $\bar{h}_{min}$. There is gradual decrease in $\bar{h}_{min}$ for all semi cone angles when operating with capillary and orifice compensated non-recess hybrid conical journal bearing. However, increase/decrease in $\bar{h}_{min}$ occurs in the following sequence of semi cone angles γ=10°, 5°, 20° and 30° for both the restrictors. The γ=30° semi cone angle for capillary and orifice compensated hybrid conical bearing shows almost close and crossing path of $\bar{h}_{min}$, Hence, from the Fig. 5(a), it can be justified that overall orifice compensated non-recess hybrid conical journal bearing gives good performance than the capillary compensated. Thus, orifice compensated non-recess hybrid conical journal bearing may be recommended. The percentage decrease of capillary compensated non-recess hydrostatic conical journal with respect to orifice compensated non-recess hydrostatic conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 12.92 %, 11.69 %, 9.76 % and 7.54 % for γ=5°, 10°, 20° and 30° respectively. Similarly, the percentage decrease of capillary compensated non-recess hybrid conical journal with respect to orifice compensated non-recess hybrid conical journal bearing at $\bar{C}_{s2}$=0.06 is found to be of the order of 1.2 %, 1.73 %, 1.1 % and 0.25 % for semi cone angle γ=5°, 10°, 20° and 30° respectively. Moreover, It is also clear from the Fig. 5(b) that orifice compensated non-recess hybrid conical journal bearing is giving better performance among all the semi cone angles γ=5°, 10°, 20° and 30° when compared with the percentage change of $\bar{h}_{min}$ with respect to capillary hydrostatic conical base bearing γ=5°.

4.3. Variation of bearing flow ($\bar{Q}$) with ($\bar{C}_{s2}$)

Variation of bearing flow ($\bar{Q}$) for the various values of restrictor design parameter ($\bar{C}_{s2}$) varying from 0.02-0.1, for non-recess hybrid/hydrostatic conical journal bearing compensated with capillary and orifice restrictor have been shown in Fig. 6(a). The capillary and orifice compensated non-recess hybrid/hydrostatic conical journal bearing follows the same pattern of raising the bearing flow over the range of $\bar{C}_{s2}$. It is also evident from the Fig. 6(a) that as the semi cone angle (γ) increases from γ=5°, 10°, 20° and 30°, the bearing flow ($\bar{Q}$) decreases. The decrease in bearing flow ($\bar{Q}$) is more in case of γ=30° than the other semi cone angle for both capillary and orifice compensated non-recess hybrid/hydrostatic conical journal bearing. This decrease in bearing flow ($\bar{Q}$) may be because of increase of viscosity due to chunk of fluid at the conical angle. It is also observed from the Fig. 6(a) that capillary restrictor compensated non-recess conical bearing give more reduced flow than the orifice compensated for both hydrostatic and hybrid mode. Hence, γ=5° and 10° orifice compensated non-recess hydrostatic/hybrid conical journal bearing may be recommended for bearing design. It is also observed from the Fig. 6(a) that there is a slight wavy nature of bearing flow ($\bar{Q}$) in case of γ=30° orifice compensated non-recess hydrostatic conical journal bearing. The percentage decrease of bearing flow ($\bar{Q}$) for capillary compensated non-recess hydrostatic conical journal with respect to orifice compensated non-recess hydrostatic conical journal bearing at $\bar{C}_{s2}$=0.06 is found to be of the order of 17.11 %, 17.16 %, 17.04 % and 13.65 % for γ=5°, 10°, 20° and 30° respectively.

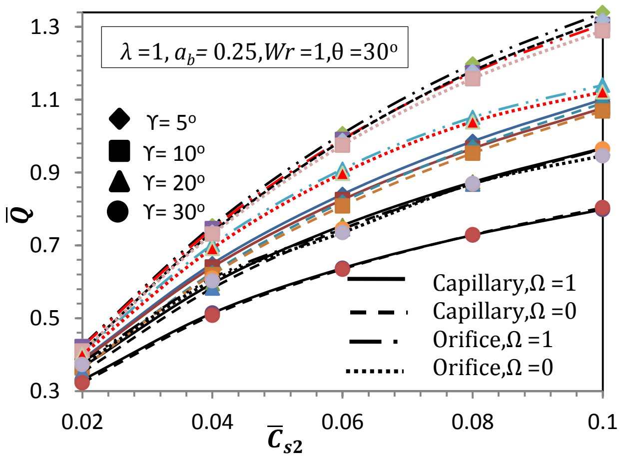


Fig. 6(a). Variation of $\bar{Q}$ with $\bar{C}_{s2}$.

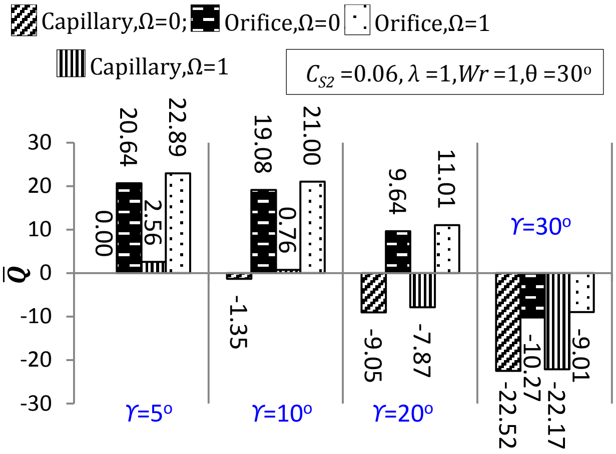


Fig. 6(b). % change of $\bar{Q}$ with respect to base bearing.

Similarly for percentage decrease of bearing flow ($\bar{Q}$) for capillary compensated non-recess hybrid conical journal with respect to orifice compensated non-recess hybrid conical journal bearing at $\bar{C}_{s2}$=0.06 is found to be of the order of 16.53 %, 16.72 %, 17.0 % and 14.50 % for semi cone angle γ=5°, 10°, 20° and 30° respectively. Furthermore, it is evident from the Fig. 6(b) that the orifice compensated non-recess hybrid conical journal gives the enhanced performance, when compared with the percentage change of bearing flow ($\bar{Q}$) with respect to the semi cone angle γ=5° capillary compensated non-recess hydrostatic conical journal base bearing at $\bar{C}_{s2}$=0.06.

4.4. Variation of direct fluid film stiffness coefficient $\bar{S}_{11}$ with ($\bar{C}_{s2}$)

Figure 7(a) indicate the variation of direct fluid film stiffness coefficient ($\bar{S}_{11}$) with respect to restrictor design parameter ($\bar{C}_{s2}$) for non-recess hybrid/hydrostatic conical journal bearing compensated with capillary and orifice restrictor. It is very much clear from the Fig. 7(a) that as $\bar{S}_{11}$ increases, the semi cone angle (γ) increases from γ=5° to 30° for hydrostatic and hybrid mode of operation. It is observed that the capillary hydrostatic conical bearing initially shows higher stiffness ($\bar{C}_{s2}$ between 0.04 to 0.06). Later, it takes over by capillary hybrid conical bearing. It means that the first half capillary hydrostatic bearing shows desired performance and in the later half capillary hybrid bearing shows good performance for all the semi cone angles (γ) varying from γ=5° to 30°. It is also to be noted that all capillary compensated hybrid and hydrostatic conical bearing initially show increase in $\bar{S}_{11}$. Later, it remains almost constant from $\bar{C}_{s2}$=0.06 till $\bar{C}_{s2}$=0.1.

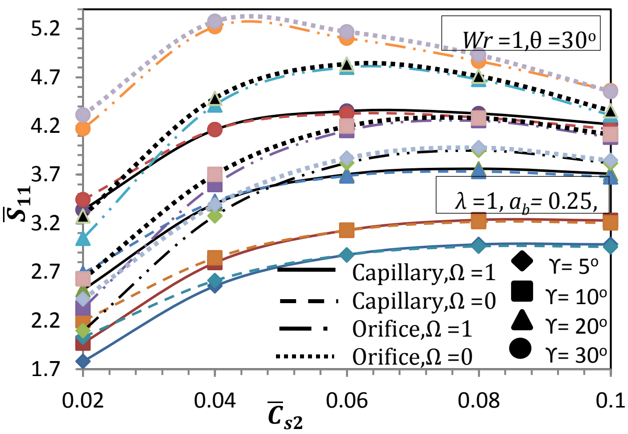


Fig. 7(a). Variation of $\bar{S}_{11}$ with $\bar{C}_{s2}$.

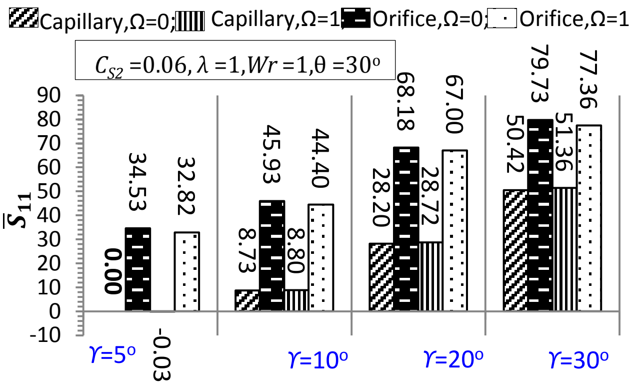


Fig. 7(b). % change of $\bar{S}_{11}$ with respect to base bearing.

The stiffness coefficient $\bar{S}_{11}$ for capillary and orifice compensated bearing is higher for hydrostatic mode than the hybrid mode. Similarly, in case of orifice compensated non-recess hydrostatic/hybrid conical journal bearing, the stiffness coefficient $\bar{S}_{11}$ continuously increases and then decreases. However, the maximum peak of increase is different for different semi cone angle (γ) bearing, but the stiffness of orifice compensated non-recess hydrostatic conical journal bearing is higher than the hybrid conical journal bearing throughout the operation. The percentage increase of orifice compensated non-recess hydrostatic conical journal bearing with respect to capillary compensated non-recess hydrostatic conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 34.52 %, 34.21 %, 31.19 % and 19.48 % for semi cone angle γ=5°, 10°, 20° and 30° respectively. Similarly, the percentage increase of orifice compensated non-recess hybrid conical journal with respect to capillary compensated non-recess hybrid conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 32.86 %, 32.72 %, 29.74 % and 17.18 % for γ=5°,10°, 20° and 30° respectively. Moreover, Fig. 7(b) also indicates that the performance of the orifice compensated hydrostatic conical journal bearing is superior among the other bearings when compared with the percentage change of $\bar{S}_{11}$ with respect to semi cone angle γ=5° capillary hydrostatic conical base bearing.

4.5. Variation of direct fluid film stiffness coefficient $\bar{S}_{22}$ with ($\bar{C}_{s2}$)

The variation of direct fluid film stiffness coefficient ($\bar{S}_{22}$) with respect to restrictor design parameter ($\bar{C}_{s2}$) for non-recess hydrostatic/hybrid conical journal bearing compensated with capillary and orifice restrictors have been shown in Fig. 8(a). It is observed from the Fig. 8(a) that, as the semi cone angles (γ) increases from γ=5° to 30°, the stiffness coefficients $\bar{S}_{22}$ increases over the range of $\bar{C}_{s2}$ for non-recess hydrostatic/hybrid conical journal bearing compensated with capillary and orifice restrictors. It can be seen that $\bar{S}_{22}$ for non-recess hybrid conical journal bearing compensated with capillary restrictor is better than hydrostatic conical journal bearing compensated with capillary restrictor. Similarly, $\bar{S}_{22}$ for non-recess hybrid conical journal bearing compensated with orifice restrictor is better than hydrostatic conical journal bearing compensated with orifice restrictor. It is also noted from the Fig. 8(a) that the semi cone angle γ=30° non-recess hybrid conical journal bearing compensated with orifice restrictor gives remarkable stiffness coefficient $\bar{S}_{22}$ than the other bearings. It can also be observed that up to $\bar{C}_{s2}$=0.045 various non-recess hydrostatic conical journal bearing compensated with capillary and orifice restrictor shows very good stiffness performance for all semi cone angles ranging from γ=5° to 30°. Later, hybrid mode prevails till $\bar{C}_{s2}$=0.1. In case of hybrid mode the bearing compensated with orifice and capillary restrictor, the stiffness of the bearing increases up to certain peak and then starts falling; this fall in $\bar{S}_{22}$ is not below the initial value of $\bar{S}_{22}$ except γ=30° non-recess hydrostatic conical journal bearing compensated with orifice restrictor. Hence, judicious selection of $\bar{C}_{s2}$ is necessary as per operational requirement.

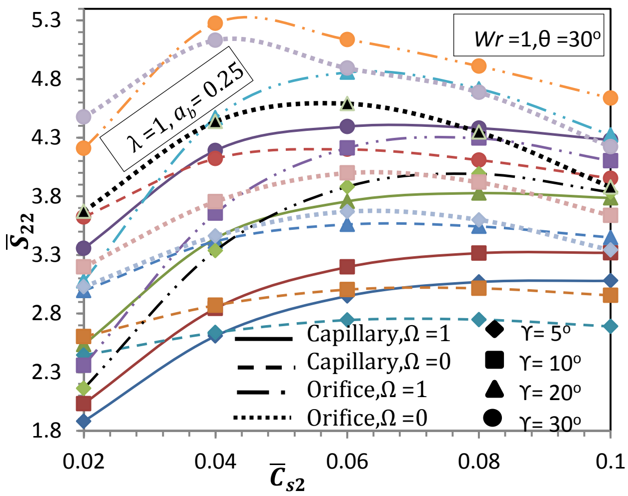


Fig. 8(a). Variation of $\bar{S}_{22}$ with $\bar{C}_{s2}$.

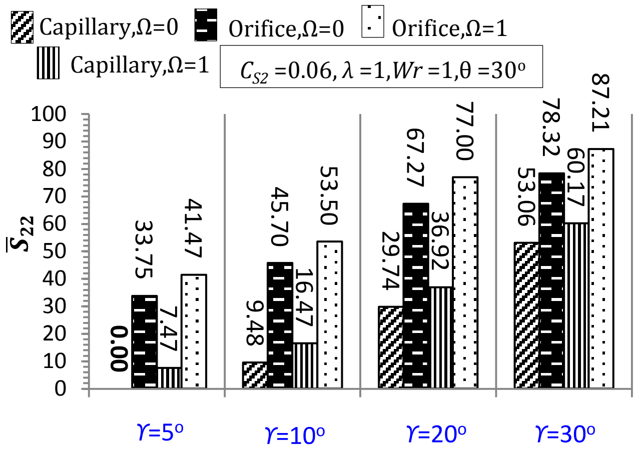


Fig. 8(b). % change of $\bar{S}_{22}$ with respect to base bearing.

The percentage increase of orifice compensated non-recess hybrid conical journal with respect to capillary compensated non-recess hybrid conical journal bearing at $\bar{C}_{s2}$=0.06 is found to be of the order of 31.63 %, 31.78 %, 29.27 % and 16.88 % for semi cone angle γ=5°, 10°, 20° and 30° respectively. Similarly, for percentage increase of orifice compensated non-recess hydrostatic conical journal bearing with respect to capillary compensated non-recess hydrostatic conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 33.74 %, 33.08 %, 28.93 % and 16.5 % for semi cone angle γ=5°, 10°, 20° and 30° respectively. Moreover, Fig. 8(b) shows the excellent performance of semi cone angle γ=30° orifice compensated hybrid conical journal bearing among the γ=5°, 10°, 20° and 30°, when evaluated for percentage change of $\bar{S}_{22}$ with respect to semi cone angle γ=5° capillary compensated hydrostatic conical journal base bearing at $\bar{C}_{s2}$=0.06.

4.6. Variation of direct fluid film damping coefficient $\bar{C}_{11}$ with ($\bar{C}_{s2}$)

The variation of direct fluid film damping coefficient ($\bar{C}_{11}$) with respect to restrictor design parameter ($\bar{C}_{s2}$) for non-recess hydrostatic/ hybrid conical journal bearing compensated with capillary and orifice restrictor is shown in Fig. 9(a). It is observed from the Fig. 9(a) that as the semi cone angle (γ) increases from γ=5° to 30°, damping coefficient $\bar{C}_{11}$ increases for all non-recess hybrid/hydrostatic conical journal bearing compensated with capillary and orifice restrictors.

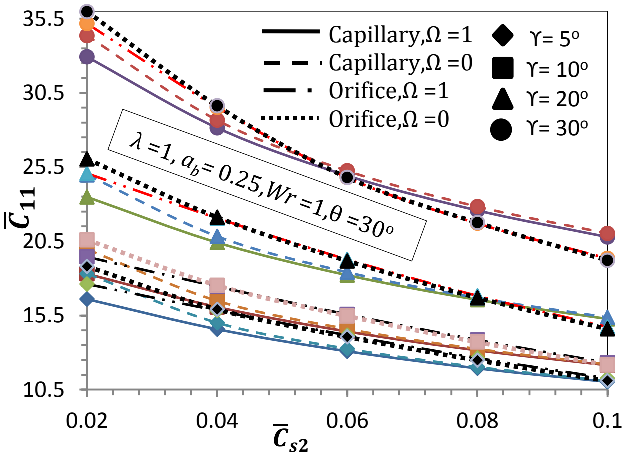


Fig. 9(a). Variation of $\bar{C}_{11}$ with $\bar{C}_{s2}$.

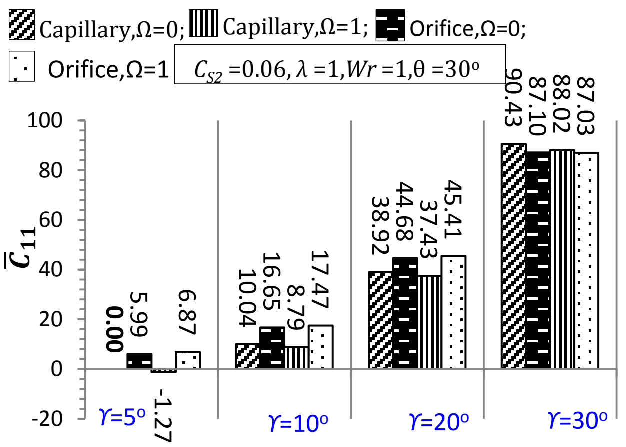


Fig. 9(b). % change of $\bar{C}_{11}$ with respect to base bearing.

The damping coefficient $\bar{C}_{11}$ is found to be at higher side for lower $\bar{C}_{s2}$. However, as the $\bar{C}_{s2}$ increases the damping coefficient $\bar{C}_{11}$ decreases. It is desirable to have high damping coefficient ($\bar{C}_{11}$) to maintain the journal stability. Moreover, it can be noted that the $\bar{C}_{s2}$ decreasing trend follow the same pattern for both hybrid and hydrostatic operation. Overall indication can be predicted for the semi cone angle γ = 30° that the orifice and capillary compensated non-recess hydrostatic conical journal bearing is favorable for higher damping coefficient ($\bar{C}_{11}$) from $\bar{C}_{s2}$=0.02 to 0.06 and $\bar{C}_{s2}$=0.06 onwards to 0.1 respectively. It may also be noted that, the critical value of $\bar{C}_{s2}$=0.055, 0.082, 0.1 and 0.1 where the damping coefficient $\bar{C}_{11}$ for orifice and capillary compensated conical journal bearing almost remain same for both the mode for semi cone angle γ=30°, 20°, 10° and 5° respectively. The percentage increase of orifice compensated non-recess hydrostatic conical journal bearing with respect to capillary compensated non-recess hydrostatic conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 5.99 %, 6.0 %, 4.14 % and -1.78 % for semi cone angle γ=5°, 10°, 20° and 30° respectively.

Similarly for percentage increase of orifice compensated non-recess hybrid conical journal with respect to capillary compensated non-recess hybrid conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 8.23 %, 7.97 %, 5.80 % and -0.52 % for γ=5°, 10°, 20° and 30° respectively. Also, from Fig. 9(b) it is clear that the damping coefficient $\bar{C}_{11}$ for orifice compensated hybrid/ hydrostatic conical bearing is higher for semi cone angle γ=5° to 20°. However, capillary compensated hydrostatic/hybrid conical bearing also shows better damping coefficient $\bar{C}_{11}$ for semi cone angle γ=30°.

4.7. Variation of direct fluid film damping coefficient $\bar{C}_{22}$ with ($\bar{C}_{s2}$)

The variation of direct fluid film damping coefficient ($\bar{C}_{22}$) with respect to restrictor design parameter ($\bar{C}_{s2}$) for non-recess hydrostatic/hybrid conical journal bearing compensated with capillary and orifice restrictor is as shown in Fig. 10 (a). It is observed that as the semi cone angle (γ) increases, the damping coefficient $\bar{C}_{22}$ increases for capillary and orifice compensated non-recess hybrid/hydrostatic conical journal bearing. It is evident from the Fig. 10(a) that both the capillary and orifice compensated non-recess hybrid conical journal bearing follows gradual reduction in damping coefficient $\bar{C}_{22}$ throughout the range of $\bar{C}_{s2}$ values for all semi cone angles. Whereas, capillary and orifice compensated non-recess hydrostatic conical journal bearing shows steep decrease of damping coefficient $\bar{C}_{22}$ up to $\bar{C}_{s2}$=0.04. Later, it decreases gradually till $\bar{C}_{s2}$=0.1.

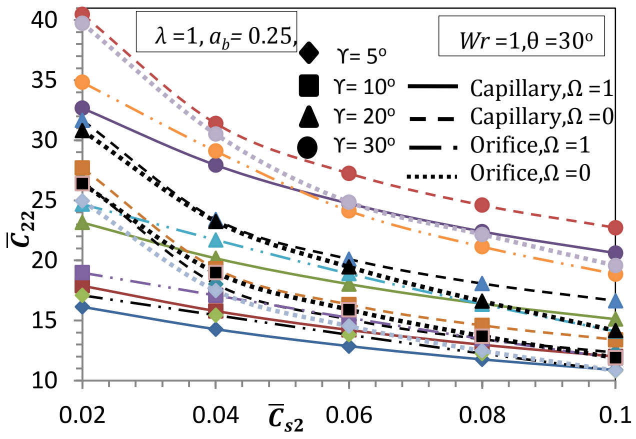


Fig. 10(a). Variation of $\bar{C}_{22}$ with $\bar{C}_{s2}$.

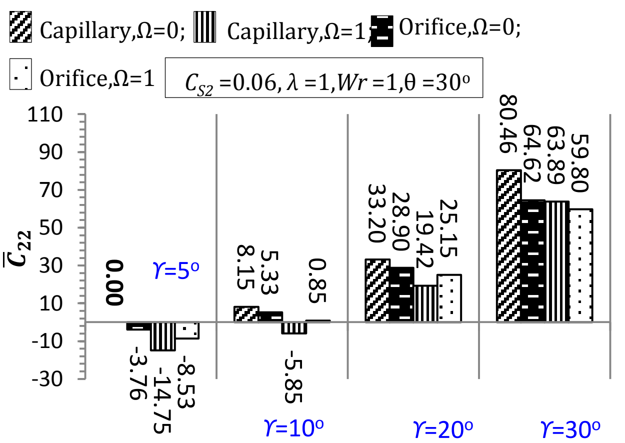


Fig. 10(b). % change of $\bar{C}_{22}$ with respect to base bearing.

In case of capillary and orifice compensated non-recess hybrid conical journal bearing, orifice compensated bearing shows better performance as compared to capillary compensated bearing for γ=5° and 10°. Whereas, semi cone angle γ=20° and 30° capillary compensated hybrid bearing takes over after some extent showing higher damping coefficient $\bar{C}_{22}$ than the orifice compensated bearing. It is also observed that all the semi cone angles γ=5°, 10°, 20° and 30° capillary compensated hydrostatic bearing shows superior damping coefficient $\bar{C}_{22}$ as compared to orifice compensated hydrostatic bearing. Further, it is also noted that γ = 30° non-recess hydrostatic conical journal bearing compensated with capillary restrictor gives highest damping coefficient $\bar{C}_{22}$ among the other bearings. The percentage increase of orifice compensated non-recess hybrid conical journal bearing with respect to capillary compensated non-recess hybrid conical journal bearing, at $\bar{C}_{s2}$=0.06, is found to be of the order of 7.30 %, 7.12 %, 4.79 % and -2.49 % for semi cone angle γ=5° ,10°, 20° and 30° respectively. The percentage increase of orifice compensated non-recess hybrid conical journal bearing with respect to capillary compensated non-recess hybrid conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 7.30 %, 7.12 %, 4.79 % and -2.49 % for semi cone angle γ=5°, 10°, 20° and 30° respectively. Similarly, the percentage increase of capillary compensated non-recess hydrostatic conical journal with respect to orifice compensated non-recess hydrostatic conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 3.91 %, 2.67 %, 3.33 % and 9.62 % for semi cone angle γ=5°, 10°, 20° and 30° respectively. Furthermore, Fig. 10(b) represents the percentage change of $\bar{C}_{22}$ with respect to semi cone angle γ=5° capillary compensated hydrostatic conical base bearing. The semi cone angle γ=10°, 20° and 30° capillary compensated hydrostatic conical journal bearing shows higher damping coefficient ($\bar{C}_{22}$) performance among the various considered bearings.

4.8. Variation of ($\bar{\omega}_{th}$) with ($\bar{C}_{s2}$)

Figure 11(a) depicts the variation of journal threshold speed ($\bar{\omega}_{th}$) with respect to the restrictor design parameter ($\bar{C}_{s2}$) for non-recess hybrid conical journal bearing compensated with capillary and orifice restrictor. It is observed from the Fig. 11(a) that as the semi cone angle (γ) increases from γ=5°, 10°, 20° and 30°, threshold speed $\bar{\omega}_{th}$ increases. Threshold speed $\bar{\omega}_{th}$ increases steeply for both capillary and orifice compensated non-recess hybrid conical journal bearing for all semi cone angle (γ) up to $\bar{C}_{s2}$=0.04, there after gradual increase in threshold speed $\bar{\omega}_{th}$ is observed. It is evident that 20° and 30° orifice compensated non-recess hybrid conical journal bearing shows better threshold speed $\bar{\omega}_{th}$ as compared to capillary compensated non-recess hybrid conical journal bearing. The percentage increase of orifice compensated non-recess hybrid conical journal bearing with respect to capillary compensated non-recess hybrid conical journal at $\bar{C}_{s2}$=0.06 is found to be of the order of 14.63 %, 14.66 %, 13.74 % and 9.74 % for semi cone angle γ=5°, 10°, 20° and 30° respectively.

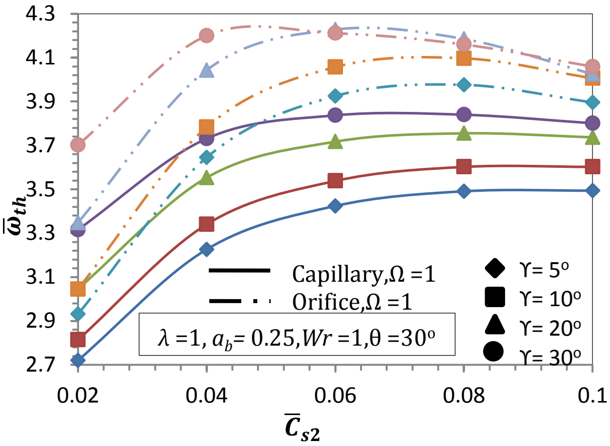


Fig. 11(a) Variation of $\bar{\omega}_{th}$ with $\bar{C}_{s2}$.

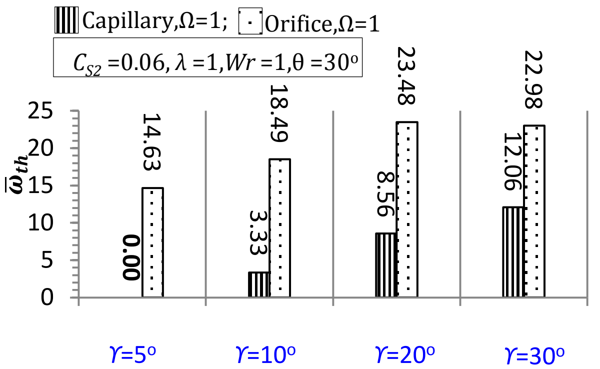


Fig. 11(b). % change of $\bar{\omega}_{th}$ with respect to base bearing.

Similarly, Fig. 11(b) shows the percentage change of $\bar{\omega}_{th}$ with respect to semi cone angle γ=5° capillary compensated hybrid conical base bearing, in which orifice compensated hybrid conical journal bearing depicts excellent threshold speed ($\bar{\omega}_{th}$) performance as compared to capillary compensated hybrid conical journal bearing for all semi cone angle γ=5°, 10°, 20° and 30° bearings.

5. CONCLUSION

Based on the simulations, the comparative static and dynamic performance characteristics of non-recess hole-entry hydrostatic/hybrid conical journal bearing compensated with orifice and capillary restrictors are computed using spherical coordinates in the present paper which leads to the following conclusions:

- For semi cone angle γ=20° onwards, non-recess orifice compensated conical bearing is better for maximum pressure ($\bar{P}_{max}$) than the capillary compensated restrictor. In general, orifice compensated non-recess conical journal bearing showed higher performance characteristics as compared to the counterpart bearing for the applied radial load.
- Minimum fluid film thickness ($\bar{h}_{min}$) is also prominent at γ=10° and 5° for orifice and capillary compensated hybrid conical journal bearing. Similarly, bearing flow ($\bar{Q}$) is prominent at γ=5° and 10° for non-recess orifice compensated hybrid/hydrostatic conical journal bearing.
- Direct fluid film stiffness coefficients ($\bar{S}_{11}$) and ($\bar{S}_{22}$) are found to be excellent for semi cone angle γ=20° onwards in case of orifice restrictor compensated non-recess hydrostatic/hybrid conical journal bearing. However, when radial load is applied, orifice compensated hybrid/hydrostatic conical journal bearing gives the overall enhanced stiffness performance for all semi cone angle.
- As the semi cone angle increases, orifice compensated hydrostatic conical journal bearing dampening ($\bar{C}_{11}$) prevails. However, the direct fluid film dampening ($\bar{C}_{11}$) effect ceases as the restriction increases. Similarly, orifice compensated bearing shows higher direct fluid film dampening results till semi cone angle γ=20°. Also, the capillary compensated bearing show enhanced direct fluid film dampening result for semi cone angle γ=30°. Moreover, normal to the direction of motion, the direct fluid damping coefficient ($\bar{C}_{22}$) shows higher damping performance for all semi cone angle for capillary compensated non-recess hydrostatic conical journal bearing.
- Threshold speed $\bar{\omega}_{th}$ for orifice compensated non-recess hybrid conical journal bearing is noticed to be higher, for all semi cone angles (γ) as compared to non-recess capillary compensated hybrid conical journal bearing.

NOMENCLATURE

a	radius of capillary, mm
a_b	axial bearing land width, mm
c	radial clearance, mm
C_{ij}	damping coefficient (*i,j*- 1,2), Ns/mm
d_c	diameter of capillary, mm
D_m	mean journal dia. of conical shaft, mm

e journal eccentricity, mm
F fluid film reaction, $\left(\frac{\partial \bar{h}}{\partial \bar{t}} \neq 0\right)$ N
F_o fluid film reaction, $\left(\frac{\partial \bar{h}}{\partial \bar{t}} = 0\right)$ N
h fluid film thickness, mm
J journal
l_c length of capillary, mm
L bearing length, mm
P pressure, N mm^{-2}
p_S lubricant supply pressure
Q bearing flow, mm^3 s^{-1}
r,θ,φ spherical coordinates ($\theta = \gamma$)
R_J mean radius of conical journal, mm
R_b radius of bearing, mm
R restrictor
S_{ij} fluid film stiffness coefficient (i,j=1,2), N/mm
T time, s
W_r radial load, N
W_a axial load, N
X,Y,Z cartesian coordinates
X_j,Z_j coordinates of steady state equilibrium journal center from geometric center of bearing, mm

Non-dimensional parameters

$\bar{C}_{ij}$ $C_{ij}(c^3/\mu R^4{}_J)$, damping coefficients
$\bar{C}_{S2}$ restrictor design parameter for Orifice restrictor $[1/12(3\pi a^4\mu_r \psi_d/c^3)](2/\rho\rho_s)^{1/2}$
$\bar{C}_{S2}$ restrictor design parameter for capillary restrictor $[3\pi a^4/12c^3 l_c]$
$\bar{F}$ $(F/p_s R^2{}_j)$
$\bar{F}_0$ $(F_o/p_s R^2{}_j)$
$\bar{h}$ h/c
$\bar{h}_{min}$ h_{min}/c
$\bar{p}$,$\bar{p}_{max}$ $(p, p_{max})/p_s)$
$\bar{Q}$ $Q\,(\mu/c^3 p_s)$
$\bar{S}_{ij}$ $S_{ij}\,(c/p_s R^2 j)$
$\bar{t}$ $(t(c^2\, p_s/\mu R^2{}_j)$
$\bar{W}_a$ $W_a/psR^2{}_j$
$\bar{W}_r$ $Wr/psR^2{}_j$
$\overline{XJ}$ X_J/c
$\dot{\bar{X}}_J, \dot{\bar{Z}}_J$ velocity components of journal centre
$\overline{ZJ}$ Z_J/c
α circumferential coordinate, (φ)
β axial coordinates, ($r \sin\gamma/R_J$)
ε eccentricity ratio, e/c
$\bar{\mu}$ μ/μ_r
Ω speed parameter, $\omega_J\,(\mu R^2{}_J/c^2 p_s)$

Greek symbols

γ semi cone angle
λ aspect ratio, L/D_m
μ dynamic viscosity of lubricant, Nsm^{-2}
μ_r dynamic viscosity of lubricant at reference inlet temperature and ambient pressure,Nsm^{-2}
ρ density of lubricant, kg mm^{-3}
ω_J journal rotational speed, rad s^{-1}
ω_{th} journal threshold speed

Matrices and vectors

N_i, N_j shape functions
$[\bar{F}]$ fluidity matrix
$\{\bar{Q}\}$ nodal flow vector
$\{\bar{R}_H\}$ vector due to hydrodynamic terms
$\{\bar{R}_{Xj}\}\{\bar{R}_{Zj}\}$ vector due to journal center velocities.
$\{\bar{p}\}$ nodal pressure vector

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