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Analysis of six-pocket hybrid misaligned irregular journal bearings operating with couple stress lubricant

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KEYWORDS

Couple stress lubricant
Finite Element Method
Geometrical irregularities
Six-pocket hybrid JBS
Misalignment
Orifice restrictor

ABSTRACT

The study aims to investigate the functioning of a six pockets hybrid geometrically irregular JBS (journal bearing system) under misaligned operation. Further, the study evaluates the comparative performance of the bearing system operated with CSL (Couple stress lubricant) vis-à-vis bearing system operated with Newtonian Lubricant. The flow action of a CSL in a bearing clearance space is developed by considering Stokes theory of couple stress fluid. To compute the solution of the governing equation, finite element method is used. The unknown pressure field in the system equation (non-linear) is computed by using Newton Raphson method. The computed results indicate that the misalignment and geometrical irregularities of journal may result in a noticeable drop in the bearing performance. Further, the use of CSL in JBS may noticeably recover the drop in the performance of JBS due to misalignment and irregularities of the journal.

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NOMENCLATURES

c	: Clearance, mm	$(\bar{a}_1, \bar{a}_2, \bar{a}_3) = (a_1, a_2, a_3)/c$
e	: Eccentricity of Journal, mm	$\bar{C}_{ij} = C_{ij}\left(\frac{c^3}{\mu R_J^4}\right)$
F_0	: Oil-film reaction (at $\frac{dh}{dt} = 0$), N	$\bar{h} = {}^{h}/_{c}$
p_c	: Pocket pressure, N/mm^2	$\bar{h}_{min} = \frac{h_{min}}{c}$
p_s	: Supply Pressure, N/mm^2	$\bar{p}, \bar{p}_c, \bar{p}_{max} = \frac{(p, p_c, p_{max})}{p_s}$
W_0	: External Load, N	$\bar{Q} = Q\left(\frac{\mu}{c^3 p_s}\right)$
X_J, Z_J	: Coordinates of journal centre	$\bar{S}_{ij} = S_{ij}\left(\frac{c}{p_s R_J^2}\right)$
η	: Constant Responsible for CSL	$\bar{T}_f = T_f\left(\frac{1}{p_s c R_J^2}\right)$
μ	: Dynamic Viscosity Coefficient, N.s/mm^2	$\bar{W}_0 = \frac{W_0}{p_s R_J^2}$
φ_c	: Function of CS	$\bar{X}_J \& \bar{Z}_J = \left(\frac{\bar{X}_J}{c} \& \frac{\bar{Z}_J}{c}\right)$
ρ	: Density of Lubricant, kg/mm^3	$(\alpha, \beta) = {}^{(x, y)}/_{R_J}$
ω_J	: Journal speed, rad/sec	$\bar{\mu} = {}^{\mu}/_{\mu_r}$
ω_{th}	: Threshold Speed, rad/sec	$\bar{\omega}_{th} = {}^{\omega_{th}}/_{\omega_I}$
ε	: Eccentricity Ratio, ${}^{e}/_{c}$	$\Omega = \left(\omega_j \Big/ \frac{c^2 p_s}{\mu R_J^2} \right)$
λ	: Aspect ratio, $\left(\frac{L}{D}\right)$	

Superscript

$-$	Non-dimensional Parameter
J	Journal

1.0 INTRODUCTION

Recent advancement in bearing technology visions to design the JBS for better efficiency and more durability. To enable the more durability to component, it becomes essential to analyze the primary causes of bearing's failures. The primary cause of the failure of a JBS is inadequate oil film profile during the operation of a journal bearing. Inadequate oil film profile may be confirmed caused by the irregular geometry of journal and bearing and the severe operational condition of bearing system.

Despite the availably of highly accurate manufacturing processes, it is a very challenging task to fabricate the journal and bearing with ideal dimensions. Many studies reported that various form of geometric irregularities viz. barrel, bell-mouth & undulated shape may exist in journal during its manufacturing. These geometric irregularities are of the order of micron i.e., order of oil film thickness. That is why these geometric irregularities of journals may result in a noticeable drop in the bearing performance. The many studies considered the effects of these irregularities of journal to predict the operation of 4-pocket hybrid JBS along with the effect of micropolar lubricant (Sharma and Rajput, 2013), power law lubricant (Jain and Sharma, 2015), effect of misalignment (Rajput et al. 2017) and turbulent effect (Singh and Sharma, 2020). The study (Sahu and Sharma, 2018) illustrated the functioning of slot-entry irregular JBS. These studies report that the geometrical errors of journal noticeably deteriorate the bearing performance from the view point of $\bar{p}_{max,}\bar{h}_{min,}\bar{T}_f,\bar{S}_{xx,}\bar{S}_{zz},\bar{C}_{xx,}\bar{C}_{zz}$ and $\bar{\omega}_{th}$. Now a days many researchers intestinally producing well defined micro-features in tribo-pairs for better performance (Gachot et al., 2017; Rosenkranz et al., 2019a Rosenkranz et al., 2019b). It is also found that these pattern under optimistic dimensions can noticeably improve the load supporting capacity and frictional behavior of different form of bearing viz. cylindrical roller thrust bearing (Gachot et al., 2016) and hybrid thrust bearing (Kumar et al., 2019).

Further, the journal's misalignment causes a severe effect on the functioning of bearing system as it disturbs the oil film profile in a JBS. The journal's misalignment may occur due to non-central loading, elastic deformation, thermal distortion and manufacturing errors etc. Many failures of journal bearing system were reported due to misalignment problem in JBS as it results in a significant decrease in minimum oil-film thickness. That's why many researchers considered the effects of misalignment in their studies of JBS. (Fisher A, 1922) firstly noticed that misalignment effect can considerably disturb the axial flow of oil and it may cause uneven temperature to rise in the bearing. (Mckee and Mckee, 1932) illustrated that journal misalignment noticeably affected the oil-film pressure profile. (Singh et al., 1973) illustrated that journal misalignment causes a noticeable down fall in the amount of oil-film pressure, load capacity and significant rise in friction coefficient. (Sato and Ogiso, 1983) indicated that misalignment causes a significantly decrease in the values of stiffness and load capacity of a hydrostatic recessed journal bearing. (Bou-Said and Nicolas, 1992) examined the influence of journal's misalignment to predict the performance of JBS operating under laminar & turbulent regimes. Their results illustrated that the misalignment results have more severe effect in case of laminar flow as compared to turbulent flow.

Arumugam et al. (1997) presented the influence of misaligned operation on the behavior of lobe JBS. The results reported that misalignment causes a significant reduction in bearing performance. In an experimental study of hydrodynamic JBS, (Bouyer and Fillon, 2002) noticed that misalignment causes a significant decrease in the values of maximum oil-film pressure. Further, (Bouyer and Fillon, 2003) examined the influence of journal's misalignment on the functioning of thermo-hydrodynamic JBS. The study (Baidya et al., 2019) presented the influences of misalignment on the porous JBS operated with micropolar lubricant. The results suggested that the misalignment of journal deteriorate the performance of bearing system.

Sharma et al. (1997) and Ram and Sharma (2012) illustrated the effect of misaligned operation on the characteristics of non-recessed JBS. The investigations were further extended to evaluate the effects of misaligned operation on multi-recessed JBS (Rajput et al., 2017). Their results indicated a noticeable reduction in the bearing performance due to the misaligned operation of a JBS.

The functioning of a JBS primarily depends on the characteristics of the lubricant. Lubricants used in oil-film bearings operating at high speed and high load are often blended with long chain additives to stabilize the viscosity variation with the temperatures. The mixing of these additives in oil changes the nature of lubrication from Newtonian to non-Newtonian. That is why the classical Newtonian theory cannot explain the behavior of polymer thickened lubricant. Stokes (Stokes, 1966) postulated that the size of additives noticeably influences the flow behavior of non-Newtonian lubricant, and the size of additives is comparable to the dimensions of oil-film thickness. Owing to a finite size, a fluid particle/additive interacts with neighboring fluid particle not only in term of force but also exerts a couple. This assumption induces the couple stress (CS) in the momentum conservation equation of the lubricant.

Later on, Stokes theory was used to predict the effects of CSL on the functioning of hydrodynamic JBS (Wang et al., 2002), two lobes hydrodynamic JBS (Crosby and Chhetti, 2009), two lobe hybrid JBS (Khatri and Sharma, 2016) and hole-entry hybrid JBS (Nathi R., 2017). The authors (Kumar and Sharma, 2017) analyzed the effects of CSL on the performance of bearing system along with different recess geometry and method of compensation. Further, the authors (Kumar et al., 2020) examined the effect of CSL on the performance of thrust bearing with elasticity effect. The studies reveal that the CSL significantly enhance the bearing performance from the viewpoint of pressure distribution, load capacity, frictional force, side flow, stiffness & damping coefficients and stability parameter.

The review of the concerning literature reveals that the journal's irregularities and misaligned operating condition noticeably deteriorate the performance of a JBS. Thus, it becomes quite essential to study these detrimental effects in the analysis of a JBS to suggests more accurate design data for the realistic and stringent geometric and operating conditions. Further, a JBS operated with CSL offers an improved performance than that of the Newtonian lubricated JBS. Therefore, CSL in bearing system may partially overcome the detrimental effect of misaligned operation and irregularities of journal in the JBS. Moreover, no study in literature addresses the effect of the CSL on the performance of misaligned hybrid geometric irregular JBS with orifice restrictor. Therefore, this work aims to suggests the influence of CSL on the functioning of orifice restricted six-pocket hybrid geometric irregular JBS under misaligned condition. Six-pocket JBS is chosen over the four pocket JBS as six-pocket JBS offers relatively better performance characteristics (Ho and Chen, 1984; Sharma et al., 1995).

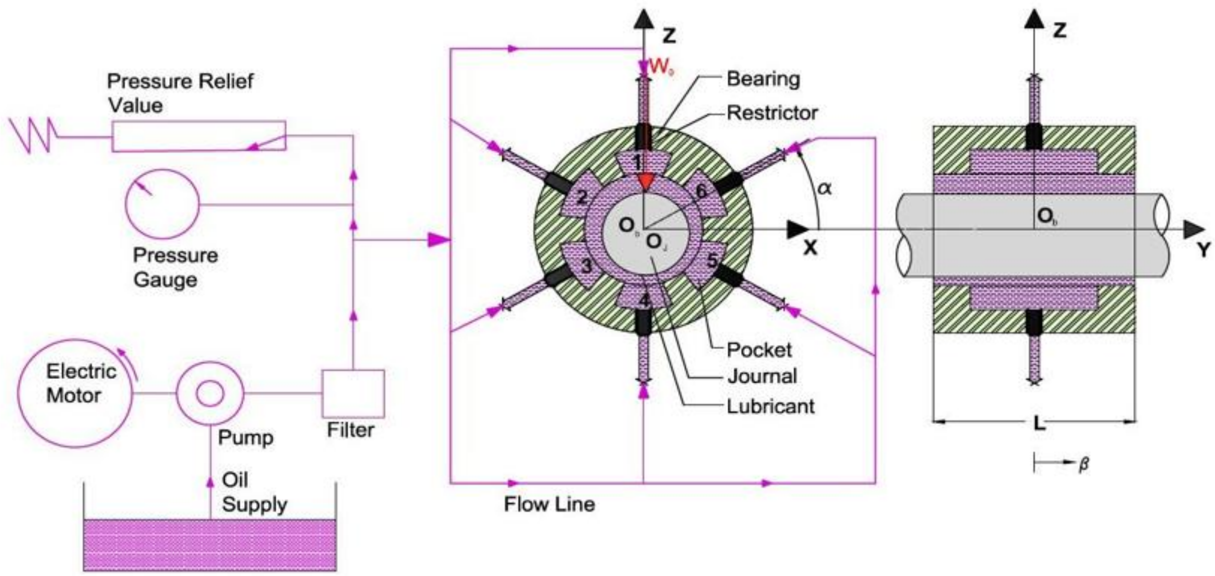

Figure 1: Schematic diagram of orifice compensated six-pocket hybrid JBS.

2.0 ANALYSIS

To govern the flow of the CS lubricant in a six-pocket hybrid JBS (as depicts in Figure 1), the governing Reynolds equation (non-dimensional) is indicated (Khatri and Sharma, 2016) as follows:

$$\frac{\partial}{\partial\alpha}\left(\frac{\bar{h}^3}{12\bar{\mu}}\bar{\varphi}_c\left(\bar{h},\bar{l}_c\right)\frac{\partial\bar{p}}{\partial\alpha}\right)+\frac{\partial}{\partial\beta}\left(\frac{\bar{h}^3}{12\bar{\mu}}\bar{\varphi}_c\left(\bar{h},\bar{l}_c\right)\frac{\partial\bar{p}}{\partial\beta}\right)=\frac{\Omega}{2}\frac{\partial\bar{h}}{\partial\alpha}+\frac{\partial\bar{h}}{\partial\bar{t}} \quad (1)$$

Where, $\bar{\varphi}_c\left(\bar{h},\bar{l}_c\right)=1-\frac{12\bar{l}_c^2}{\bar{h}^2}+\frac{24\bar{l}_c^3}{\bar{h}^3}tanh\left(\frac{\bar{h}}{2\bar{l}_c}\right)$, ($\bar{l}_c=0.0$ represents a Newtonian lubricant)

2.1 Oil-Film Thickness

For a misaligned hybrid geometric irregular JBS, the non-dimensional oil-film thickness ($\bar{h}$) is expressed as below (Rajput et al., 2017):

$$\bar{h}=1-\bar{X}_j\cos\alpha-\bar{Z}_j\sin\alpha+\bar{h}_{ir}+\bar{h}_{Mis} \quad (2)$$

Where, $\bar{h}_{ir}$ is the effect of journal's irregularity and $\bar{h}_{Mis}$ is the effect of misalignment on oil film thickness.

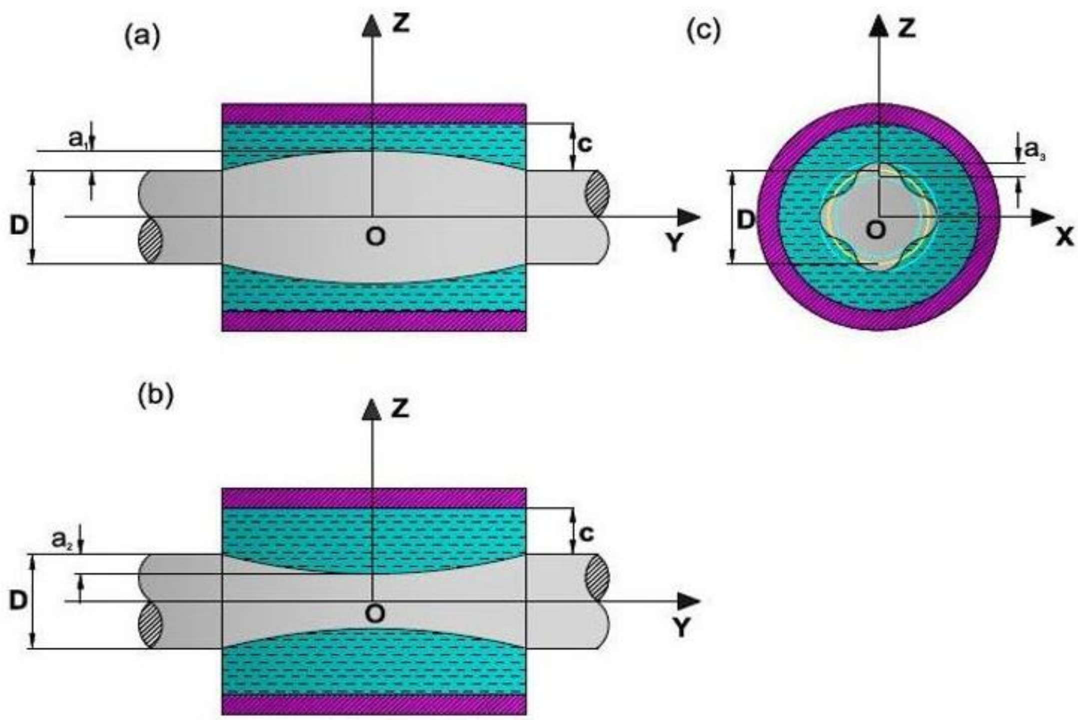

Figure 2: (a) Barrel shaped journal, (b) Bell-mouth shaped journal, (c) Undulations on journal.

For the geometric irregularities of journal shown in Figure 2 (a-c), the $\bar{h}_{ir}$ is expressed as follows:

$$\bar{h}_{ir} = \left\{ \begin{array}{ll} -\bar{a}_1 \sin\left(\frac{\pi\beta}{2\lambda}\right) & \text{barrel journal,} \\ \bar{a}_2 \sin\left(\frac{\pi\beta}{2\lambda}\right) & \text{bellmouth journal,} \\ 0.5\bar{a}_3 \sin(n\alpha + \xi) & \text{undulated journal} \end{array} \right\} \tag{2a}$$

As per the schematic of journal misalignment shown in Figure 3 (a-d), the $\bar{h}_{Mis}$ is given as follows:

$$\bar{h}_{Mis} = \beta\bar{\psi}\cos\alpha - \beta\bar{\varphi}\sin\alpha \tag{2b}$$

Where, $\bar{\varphi}$ and $\bar{\psi}$ are represents the misalignment parameter corresponding to X and Z axis sequentially.

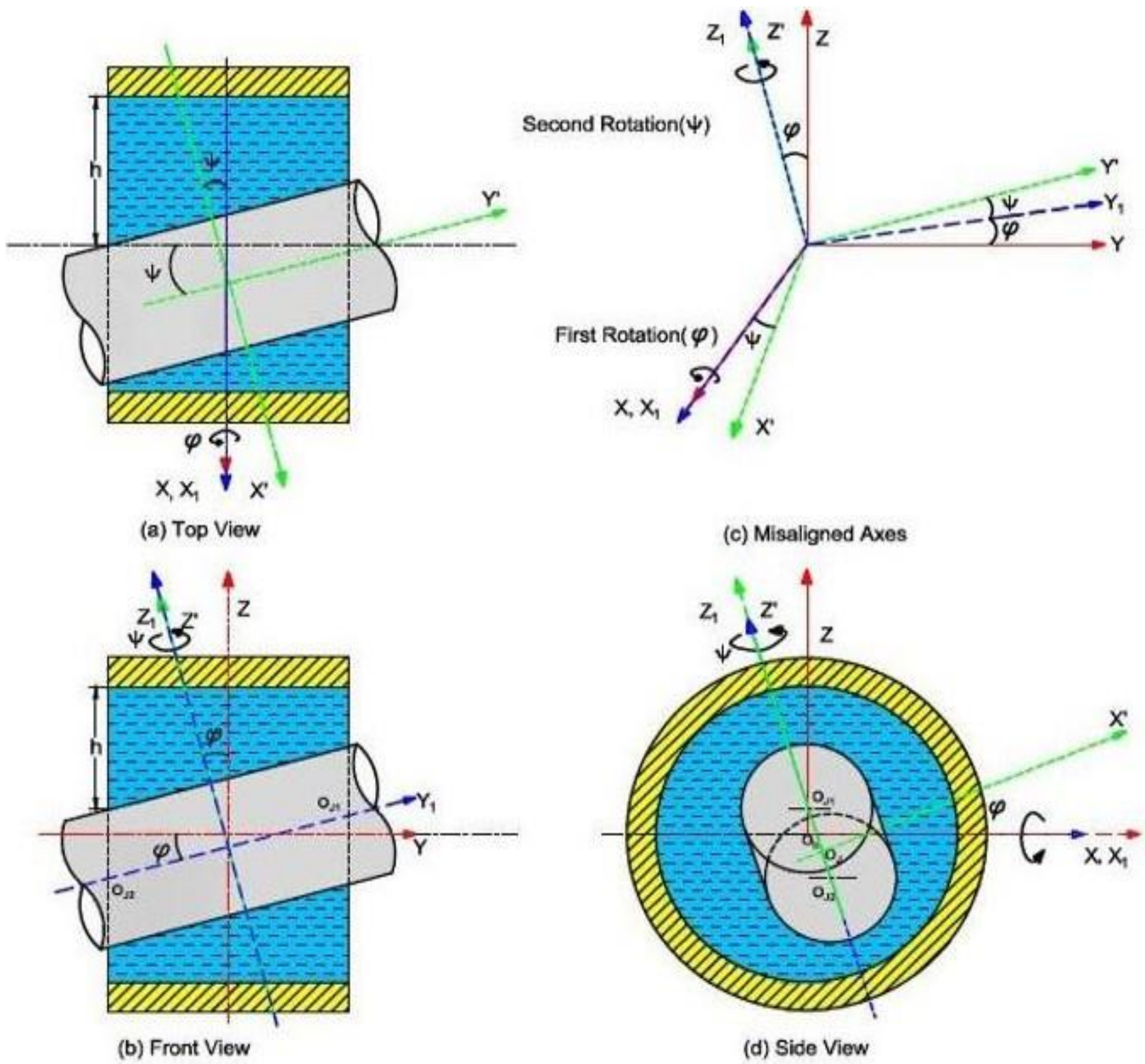

Figure 3(a-d): Schematic of misalignment of journal.

2.2 Finite Element Formulation

The pressure field {p} in the oil film domain is numerically computed by using finite element method. The oil-film pressure over a four noded quadrilateral isoparametric element is expressed (Garg, 2015; Tomar and Sharma, 2020) as follows:

$$\bar{p} = \sum_{j=1}^{n_l^e} \bar{p}_j N_j \quad (3)$$

The finite element formulation of the equation (1) is obtained by using Galerkin's method and yields the elemental equation (Rajput et al., 2017) as follows.

$$[\bar{F}]^e\{\bar{p}\}^e = \{\bar{Q}\}^e + \Omega\,\{\bar{R}_H\}^e + \dot{\bar{X}}_J\{\bar{R}_{X_J}\}^e + \dot{\bar{Z}}_J\{\bar{R}_{Z_J}\}^e + \dot{\bar{\varphi}}\{\bar{R}_{\varphi}\}^e - \dot{\bar{\psi}}\{\bar{R}_{\psi}\}^e \quad (4)$$

Where,

$$\bar{F}_{ij}^e = \iint_{A^e}\left[\frac{\bar{h}^3}{12\bar{\mu}}\bar{\varphi}_c(\bar{h},\bar{l}_c)\frac{\partial N_i}{\partial \alpha}\frac{\partial N_j}{\partial \alpha} + \frac{\bar{h}^3}{12\bar{\mu}}\bar{\varphi}_c(\bar{h},\bar{l}_c)\frac{\partial N_i}{\partial \beta}\frac{\partial N_j}{\partial \beta}\right] d\alpha\, d\beta \quad (4a)$$

$$\bar{Q}_i^e = \int_{\Gamma^e}\left\{\left(\frac{\bar{h}^3}{12\bar{\mu}}\bar{\varphi}_c(\bar{h},\bar{l}_c)\frac{\partial p}{\partial \alpha} - \frac{\Omega}{2}\bar{h}\right)n_\alpha + \left(\frac{\bar{h}^3}{12\bar{\mu}}\bar{\varphi}_c(\bar{h},\bar{l}_c)\frac{\partial p}{\partial \beta}\right)n_\beta\right\} N_i\, d\bar{\Gamma}^e \quad (4b)$$

$$\bar{R}_{H_i}^e = \frac{1}{2}\iint_{A^e}\bar{h}\frac{\partial N_i}{\partial \alpha}\, d\alpha\, d\beta \quad (4c)$$

$$\bar{R}_{X_{Ji}}^e = \iint_{A^e} N_i \cos\alpha\, d\alpha\, d\beta \quad (4d)$$

$$\bar{R}_{Z_{Ji}}^e = \iint_{A^e} N_i \sin\alpha\, d\alpha\, d\beta \quad (4e)$$

$$\bar{R}_{\varphi i}^e = \iint_{A^e} N_i\, \beta \sin\alpha\, d\alpha\, d\beta \quad (4f)$$

$$\bar{R}_{\psi i}^e = \iint_{A^e} N_i\, \beta \cos\alpha\, d\alpha\, d\beta \quad (4g)$$

Where n_α & n_β are represents direction cosines.

Based on the connectivity of the elements in the fluid film domain, the algebraic form of the system equation yields as follows:

$$[\bar{F}]\{\bar{p}\} = \{\bar{Q}\} + \Omega\{\bar{R}_H\} + \dot{\bar{X}}_J\{\bar{R}_{X_J}\} + \dot{\bar{Z}}_J\{\bar{R}_{Z_J}\} + \dot{\bar{\varphi}}\{\bar{R}_{\varphi}\} - \dot{\bar{\psi}}\{\bar{R}_{\psi}\} \quad (5)$$

2.3 Flow Through Orifice Restrictor

The oil flow rate through an orifice restrictor (Ghai, 1976) yields as follows:

$$\bar{Q}_R = \bar{C}_{S2}(1 - \bar{p}_c)^{1/2} \quad (6)$$

Where $\bar{C}_{S2}$ (Restrictor design parameter) $= \frac{1}{12}\left(\frac{3\pi d_0^2 \mu_r \psi_d}{c^3}\right)\left(\frac{2}{\rho p_s}\right)^{1/2}$

2.4 Boundary Conditions

To compute the numerical solution of unknown pressure field in equation (5), the various boundary conditions are applied as given in reference (Khatri and Sharma, 2016).

2.5 Bearing Characteristics Parameters

2.5.1 Frictional Torque

The frictional torque (non-dimensional) is indicated as follows.

$$\bar{T}_f = \int_{-\lambda}^{\lambda}\int_{0}^{2\pi}\left[\frac{\bar{h}}{2}\frac{\partial\bar{p}}{\partial\alpha}+\frac{\bar{\mu}}{\bar{h}}\Omega\right]\,d\alpha\,d\beta \tag{7}$$

2.5.2 Oil-Film Stiffness Coefficients

For a misaligned hybrid JBS, the oil-film stiffness coefficients are expressed as follows:

$$\bar{S}_{ij} = -\frac{\partial\bar{F}_i}{\partial\bar{q}_j}, \tag{8}$$

Where, i stands for direction of generalized force $(i = X, Z, \varphi, \psi)$ and $\bar{q}_j$ stands for generalized journal center displacement$\left(\bar{q}_j = \bar{X}_J, \bar{Z}_J, \bar{\varphi}, \bar{\psi}\right)$.
Oil-film stiffness coefficients may be represented in matrix form as follows.

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

Where, $\bar{F}_x = -\int_{-\lambda}^{+\lambda}\int_{0}^{2\pi}\bar{p}\cos\alpha\,d\alpha\,d\beta$

$$\bar{F}_z = -\int_{-\lambda}^{+\lambda}\int_{0}^{2\pi}\bar{p}\sin\alpha\,d\alpha\,d\beta$$

$$\bar{F}_\varphi = -\int_{-\lambda}^{\lambda}\int_{0}^{2\pi}\bar{p}\,\beta\sin\alpha\,d\alpha d\beta$$

$$\bar{F}_\psi = -\int_{-\lambda}^{\lambda}\int_{0}^{2\pi}\bar{p}\,\beta\cos\alpha\,d\alpha d\beta$$

The values of $\bar{S}_{ij}$ are computed by the integrating the pressure derivatives with respect to$(\bar{q}_j)$ over the domain.

2.5.3 Oil-Film Damping Coefficients

For a misaligned hybrid JBS, the oil-film damping coefficients are expressed as follows.

$$\bar{C}_{ij} = -\frac{\partial\bar{F}_i}{\partial\dot{\bar{q}}_j} \tag{9}$$

Where, $\bar{\dot{q}}_j$ stands for journal center velocity $\left(\bar{\dot{q}}_j = \bar{\dot{X}}_J, \bar{\dot{Z}}_J, \bar{\dot{\varphi}}, \bar{\dot{\psi}}\right)$. Similar to $\bar{S}_{ij}$, the oil film damping coefficients are computed by integrating the pressure derivatives with respect to $\bar{\dot{q}}_j$ over the domain.

2.5.4 Stability Threshold Speed Margin

The stability is the main priority for smooth functioning of a bearing system. Generally, the stability of a JBS is computed in terms of stability threshold speed margin ($\bar{\omega}_{th}$). The $\bar{\omega}_{th}$ is the function of direct and indirect oil film stiffness and damping coefficient. As the values of oil film stiffness and oil film damping coefficients noticeably gets influenced due to misalignment of journal. Therefore, it is expected that the values of $\bar{\omega}_{th}$ will be noticeably influenced due to misalignment of journal. Further, it may be practically seen that the JBS results in noiseless and smooth operation up to a certain value of rotational speed. Beyond that the stability of the system drop down and operation becomes noisy. The stability threshold speed margin is expressed as follows:

$$\bar{\omega}_{th} = \left[\frac{\bar{G}_1}{(\bar{G}_2 - \bar{G}_3)\bar{F}_0}\right]^{1/2} \tag{10}$$

Where,

$$\bar{G}_1 = [\bar{C}_{xx}\bar{C}_{zz} - \bar{C}_{zx}\bar{C}_{xz}],$$

$$\bar{G}_2 = \frac{[\bar{S}_{xx}\bar{S}_{zz} - \bar{S}_{zx}\bar{S}_{xz}][\bar{C}_{xx} + \bar{C}_{zz}]}{[\bar{S}_{xx}\bar{C}_{zz} + \bar{S}_{zz}\bar{C}_{xx} - \bar{S}_{xz}\bar{C}_{zx} - \bar{S}_{zx}\bar{C}_{xz}]}$$

$$\bar{G}_3 = \frac{[\bar{S}_{xx}\bar{C}_{xx} + \bar{S}_{zz}\bar{C}_{zz} + \bar{S}_{xz}\bar{C}_{zx} + \bar{S}_{zx}\bar{C}_{xz}]}{[\bar{C}_{xx} + \bar{C}_{zz}]}$$

3.0 SOLUTION METHODOLOGY

A repetitive solution methodology has been used to determine the unknown nodal oil film pressure and subsequently bearing characteristics parameters of JBS. Figure 4 shows the process diagram to describe the solution scheme. In first step, the geometric and operating parameters are input as depicted in block INGOP. In next step, the matrices as per FE formulation in equation (5) are computed and equation (5) is solved incorporating the boundary conditions in block OFP. Incorporation of continuity of flow condition results in a non-linear equation. To solve this non-linear equation for unknown oil film pressure $\{\bar{p}\}$, Newton Raphson method is used. Further, the corrections ($\Delta\bar{X}_J, \Delta\bar{Z}_J$) in the values of journal centre position are computed and checked against the convergence criterion given in equation (11) in block JEQL. Iterations are continued until the convergence is achieved. At convergence, the position of journal center is termed as equilibrium position of journal centre. The bearing characteristics parameters are computed for the equilibrium positions of journal centre in block BCP.

$$PERR = \left| \frac{\left[(\Delta \bar{X}_j^i)^2 + (\Delta \bar{Z}_j^i)^2 \right]^{1/2}}{\left[(\bar{X}_j^i)^2 + (\bar{Z}_j^i)^2 \right]^{1/2}} \right| \times 100 \leq 0.001 \tag{11}$$

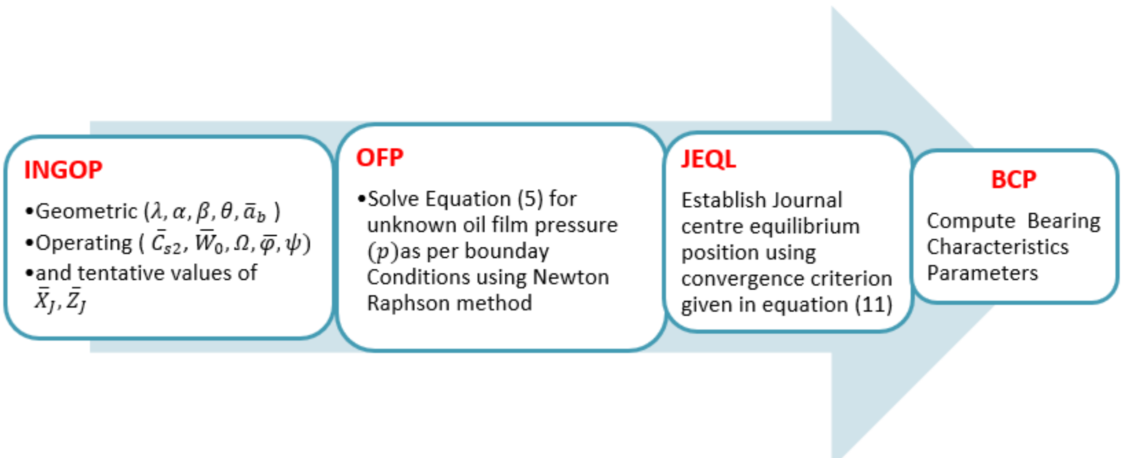

Figure 4: Process diagram illustrating solution methodology.

4.0 RESULTS AND DISCUSSION

To compute the unknown oil film pressure and subsequently bearing characteristics parameters, a MATLAB program is developed based on the mathematical formulation and methodology discussed in the prior section. To examine the authenticity of the developed program and methodology adopted, the computed results of the present code were matched up with previously published results of (Mokhaimar et al., 1999) and (Ghai, 1976). A good authentication among present results and previously published results can be noticed as indicated in Figure 5 (a-b).

The geometric and operating parameters of the multi-recessed misaligned hybrid geometric irregular JBS are judiciously taken from the available literature (Sharma et al., 1995; Rajput and Sharma, 2014, 2017) and indicated in Table 1. Bearing Characteristics parameters are computed for two misalignment conditions i.e., $\boldsymbol{M_X}$ ($\bar{\varphi} = 0.2, \bar{\psi} = 0.0$) and $\boldsymbol{M_{XZ}}$ ($\bar{\varphi} = 0.2, \bar{\psi} = 0.2$). In order to enumerate the influence of misalignment conditions, the % change in the values of characteristics parameters of the geometrical irregular JBS with respect to aligned operating condition is computed and depicted in Table 2. Furthermore, the effect of CSL on the characteristic parameters of regular and irregular journal bearing under aligned and misaligned condition with respect to Newtonian Lubricant is depicted in Table 3.

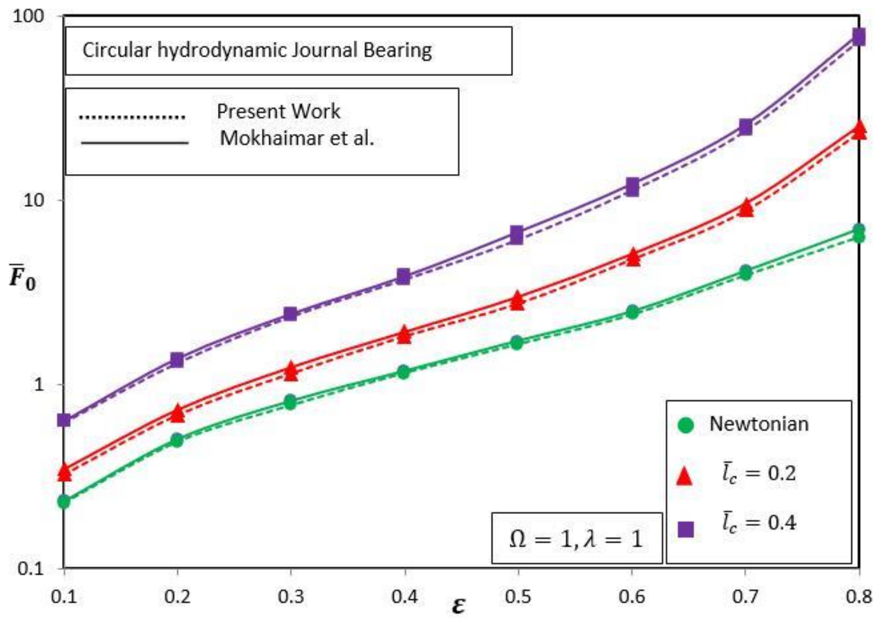

Figure 5 (a): Variation of $\bar{F}_0$versus eccentricity ratio (ε).

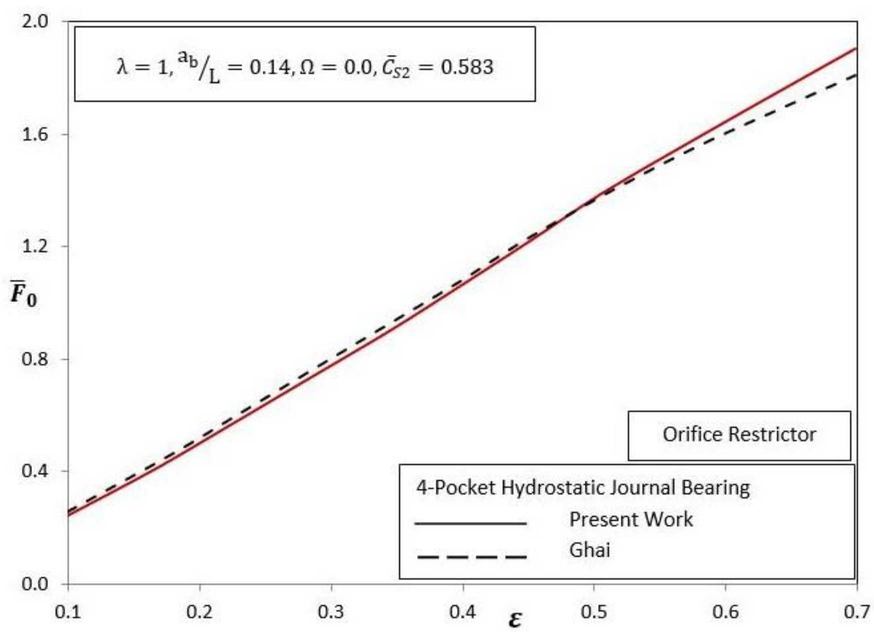

Figure 5 (b): Variation of $\bar{F}_0$versus eccentricity ratios(ε).

Table 1: Geometrical & operating parameters of JBS (Sharma et al., 1995; Sharma and Rajput, 2014, 2017).

Number of Pockets Considered	6	
Shape of recess	Rectangular	
Compensating device used	Orifice	
Inter recess angle	θ	12°
Aspect ratio	$\lambda = {}^{L}/_{D}$	1.0
Land width ratio	$\bar{a}_b$	0.14
External load	$\overline{W}_0$	1.0
Journal Speed parameter	Ω	0.25-1.5
Concentric design ratio	β^*	0.50
Barrel error ratio	$\bar{a}_1$	0.2
Bellmouth error ratio	$\bar{a}_2$	0.2
Undulated error ratio	$\bar{a}_3$	0.1
No. of waves in undulated shaped journal	n	10
Phase difference	ξ	0.0
Misalignment parameter (X-axis)	$\bar{\varphi}$	0.0, 0.20
Misalignment parameter (Z-axis)	$\bar{\psi}$	0.0, 0.20
Couple stress parameter	$\bar{l}_c$	0.0, 0.2

Furthermore, to get the collective effects of CSL and misaligned condition on the performance of six pocket irregular JBS, the bearing characteristics are computed for the specific external load $\overline{W}_0 = 1.00$ and for the journal velocity range (Ω =0.0-1.50) and are discussed in following subsection.

Table 2: Characteristic Parameters of six pocket misaligned hybrid irregular JBS with Newtonian lubricant.

Type of Journal	**Alignment Condition**	**Bearing Characteristic Parameters**							
		$\bar{h}_{min}$	$\bar{Q}$	$\bar{T}_f$	$\bar{S}_{xx}$	$\bar{S}_{zz}$	$\bar{C}_{xx}$	$\bar{C}_{zz}$	$\bar{\omega}_{th}$
Regular	$A(\bar{\varphi}=0.0, \bar{\psi}=0.0)$	0.7582	1.8514	13.1128	3.0262	2.8750	6.1818	5.839	3.4690
	$M_X(\bar{\varphi}=0.2, \bar{\psi}=0.0)$	0.5924	1.8769	13.2315	2.9215	2.8172	6.0848	5.8395	3.4266
	% Change	-21.87	+1.38	+0.91	-3.46	-2.00	-1.57	-0.92	-1.22
	$\boldsymbol{M_{XZ}}(\bar{\varphi}=0.2, \bar{\psi}=0.2)$	0.4685	1.9026	13.3987	2.8267	2.7619	6.0598	5.7757	3.3951
	% Change	-38.21	+2.77	+2.18	-6.59	-3.93	-1.97	-2.0	-2.13
Barrel	$\boldsymbol{A}(\bar{\varphi}=0.0, \bar{\psi}=0.0)$	0.6022	1.7602	15.0000	3.6486	3.4579	7.4487	7.0821	3.7983
	$\boldsymbol{M_X}(\bar{\varphi}=0.2, \bar{\psi}=0.0)$	0.5756	1.7904	15.1419	3.5085	3.3905	7.3087	7.0126	3.7497
	% Change	-4.42	+1.72	+0.95	-3.84	-1.95	-1.88	-0.98	-1.28
	$\boldsymbol{M_{XZ}}(\bar{\varphi}=0.2, \bar{\psi}=0.2)$	0.5050	1.8200	15.3359	3.3974	3.3229	7.2599	6.9282	3.7168
	% Change	-16.14	+3.39	+2.24	-6.88	-3.90	-2.53	-2.17	-2.15
Bellmouth	$\boldsymbol{A}(\bar{\varphi}=0.0, \bar{\psi}=0.0)$	0.7032	1.9316	11.8070	2.4524	2.3450	5.0905	4.8672	3.1410
	$\boldsymbol{M_X}(\bar{\varphi}=0.2, \bar{\psi}=0.0)$	0.5404	1.9533	11.9145	2.3776	2.3007	5.0328	4.8299	3.1062
	% Change	-23.14	+1.12	+0.91	-3.00	-1.89	-1.13	-0.77	-1.11
	$\boldsymbol{M_{XZ}}(\bar{\varphi}=0.2, \bar{\psi}=0.2)$	0.4127	1.9754	12.0735	2.2993	2.2649	5.0326	4.7949	3.0791
	% Change	-41.31	+2.27	+2.26	-6.20	-3.41	-1.14	-1.49	-1.97
Undulated	$\boldsymbol{A}(\bar{\varphi}=0.0, \bar{\psi}=0.0)$	0.7074	1.8521	13.1456	3.1891	2.7211	6.1035	5.9667	3.4666
	$\boldsymbol{M_X}(\bar{\varphi}=0.2, \bar{\psi}=0.0)$	0.5631	1.8809	13.2652	3.0723	2.6664	6.0107	5.9087	3.4204
	% Change	-20.39	+1.55	+0.91	-3.66	-2.00	-1.52	-0.97	-1.33
	$\boldsymbol{M_{XZ}}(\bar{\varphi}=0.2, \bar{\psi}=0.2)$	0.4184	1.9032	13.4352	2.9719	2.6233	5.9814	5.8475	3.3856
	% Change	-40.85	+2.74	+2.20	-6.81	-3.59	-2.0	-1.99	-2.33
$\lambda=1, \theta=12^{\circ}, \bar{a}_b=0.14, \beta^*=0.5, \Omega=1.0, \bar{W}_0=1.0, \bar{a}_1=\bar{a}_2=0.2, \bar{a}_3=0.1, \xi=0, n=10$									

Table 3: Characteristic Parameters of six pocket misaligned hybrid irregular JBS with CSL.

Type of Journal	Alignment condition	Lubricant type	Bearing Characteristic Parameters							
			$\bar{h}_{min}$	$\bar{Q}$	$\bar{T}_f$	$\bar{S}_{xx}$	$\bar{S}_{zz}$	$\bar{C}_{xx}$	$\bar{C}_{zz}$	$\bar{\omega}_{th}$
Regular	A	$\bar{l}_c = 0.0$	0.7582	1.8514	13.1128	3.0262	2.8750	6.1818	5.8939	3.4690
		$\bar{l}_c = 0.2$	0.8091	1.6227	12.9285	3.8163	3.5605	7.6121	7.1575	3.8611
	% Change		+6.71	-12.35	-1.41	+26.11	+23.84	+23.14	+21.44	+11.30
	M_X	$\bar{l}_c = 0.0$	0.5924	1.8769	13.2315	2.9215	2.8172	6.0848	5.8395	3.4266
		$\bar{l}_c = 0.2$	0.6416	1.6642	13.0344	3.6737	3.5003	7.5132	7.1191	3.8159
	% Change		+8.31	-11.33	-1.49	+25.75	+24.25	+23.47	+21.91	+11.36
	M_{XZ}	$\bar{l}_c = 0.0$	0.4685	1.9026	13.3987	2.8267	2.7619	6.0598	5.7757	3.3951
		$\bar{l}_c = 0.2$	0.5223	1.7042	13.1733	3.5560	3.4499	7.5012	7.1123	3.7898
	% Change		+11.48	-10.43	-1.68	+25.80	+24.91	+23.79	+23.14	+11.63
Barrel	A	$\bar{l}_c = 0.0$	0.6022	1.7602	15.0000	3.6486	3.4579	7.4487	7.0821	3.7983
		$\bar{l}_c = 0.2$	0.6402	1.4964	14.8330	4.4236	4.1021	9.0974	8.4623	4.1534
	% Change		+6.31	-14.99	-1.11	+21.24	+18.63	+22.13	+19.49	+9.35
	M_X	$\bar{l}_c = 0.0$	0.5756	1.7904	15.1419	3.5085	3.3905	7.3087	7.0126	3.7497
		$\bar{l}_c = 0.2$	0.6143	1.5452	14.9606	4.2648	4.0631	8.9886	8.4494	4.1149
	% Change		+6.72	-13.69	-1.19	+21.56	+19.84	+22.98	+20.49	+9.74
	M_{XZ}	$\bar{l}_c = 0.0$	0.5050	1.8200	15.3359	3.3974	3.3229	7.2599	6.7820	3.7168
		$\bar{l}_c = 0.2$	0.5471	1.5915	15.1231	4.1601	4.0386	8.9719	8.4921	4.1031
	% Change		+8.34	-12.55	-1.39	+22.45	+21.54	+23.58	+25.22	+7.97
Bellmouth	A	$\bar{l}_c = 0.0$	0.7032	1.9316	11.8070	2.4514	2.3450	5.0905	4.8672	3.1410
		$\bar{l}_c = 0.2$	0.7664	1.7330	11.5951	3.1347	2.9391	6.2048	5.8808	3.5093
	% Change		+8.99	-10.28	-1.79	+27.87	+25.33	+21.89	+20.83	+11.73
	M_X	$\bar{l}_c = 0.0$	0.5404	1.9533	11.9145	2.3776	2.3007	5.0328	4.8299	3.1062
		$\bar{l}_c = 0.2$	0.6026	1.7682	11.6893	3.0236	2.8809	6.1434	5.8462	3.4662
	% Change		+11.51	-9.48	-1.89	+27.17	+25.22	+22.07	+21.04	+11.94
	M_{XZ}	$\bar{l}_c = 0.0$	0.4127	1.9754	12.0735	2.2993	2.2649	5.0326	4.7949	3.0791
		$\bar{l}_c = 0.2$	0.4782	1.8027	11.8178	2.9110	2.8324	6.1545	5.8467	3.4342
	% Change		+15.87	-8.74	-2.12	+26.60	+25.06	+22.29	+21.94	+11.53
Undulated	A	$\bar{l}_c = 0.0$	0.7074	1.8521	13.1456	3.1891	2.7211	6.1035	5.9667	3.4666
		$\bar{l}_c = 0.2$	0.7593	1.6256	12.9662	4.0145	3.3799	7.4899	7.2728	3.8645
	% Change		+7.34	-12.23	-1.36	+25.88	+24.21	+22.71	+21.89	+11.48
	M_X	$\bar{l}_c = 0.0$	0.5631	1.8809	13.2652	3.0723	2.6664	6.0107	5.9087	3.4204
		$\bar{l}_c = 0.2$	0.6078	1.6676	13.737	3.8536	3.3211	7.4009	7.2262	3.8122
	% Change		+7.94	-11.34	-1.44	+25.43	+24.55	+23.13	+22.29	+11.45
	M_{XZ}	$\bar{l}_c = 0.0$	0.4184	1.9032	13.4352	2.9719	2.6233	5.9814	5.8475	3.3856
		$\bar{l}_c = 0.2$	0.4733	1.7076	13.2067	3.7288	3.2895	7.3821	7.2205	3.7807
	% Change		+13.12	-10.28	-1.70	+25.47	+25.39	+23.42	23.48	11.67
$\lambda = 1, \theta = 12^{\circ}, \bar{a}_b = 0.14, \beta^* = 0.5, \Omega = 1.0, \bar{W}_0 = 1.0, \bar{a}_1 = \bar{a}_2 = 0.2, \bar{a}_3 = 0.1, \xi = 0, n = 10$										

4.1 Effect on oil-film pressure ($\bar{p}$)

The nodal values of oil film pressure are computed and presented over the film domain to get the understanding of the physical behavior of JBS. The three-dimensional oil film pressure profiles for geometrically irregular JBS for three operating conditions (for sake of brevity) are depicted in Figure 6 viz. aligned Operation (A) with Newtonian lubricant, misaligned operation (M_{XZ}) with Newtonian lubricant and misaligned operation (M_{XZ}) with CSL. It may be noticed that for given operating conditions, the barrel type journal offers relatively higher value of oil film pressure than regular journal while other irregular journal results in lower values of oil-film pressure. Further, the misaligned operation results in the reduction in the oil film pressure for each shape of journal vis-a-vis align operating condition. The CSL operated JBS offers the noticeable enhancement in the values of the oil film pressure for regular as well as irregular journal. Therefore, the use of CSL may compensate the drop in oil film pressure caused by misaligned operation.

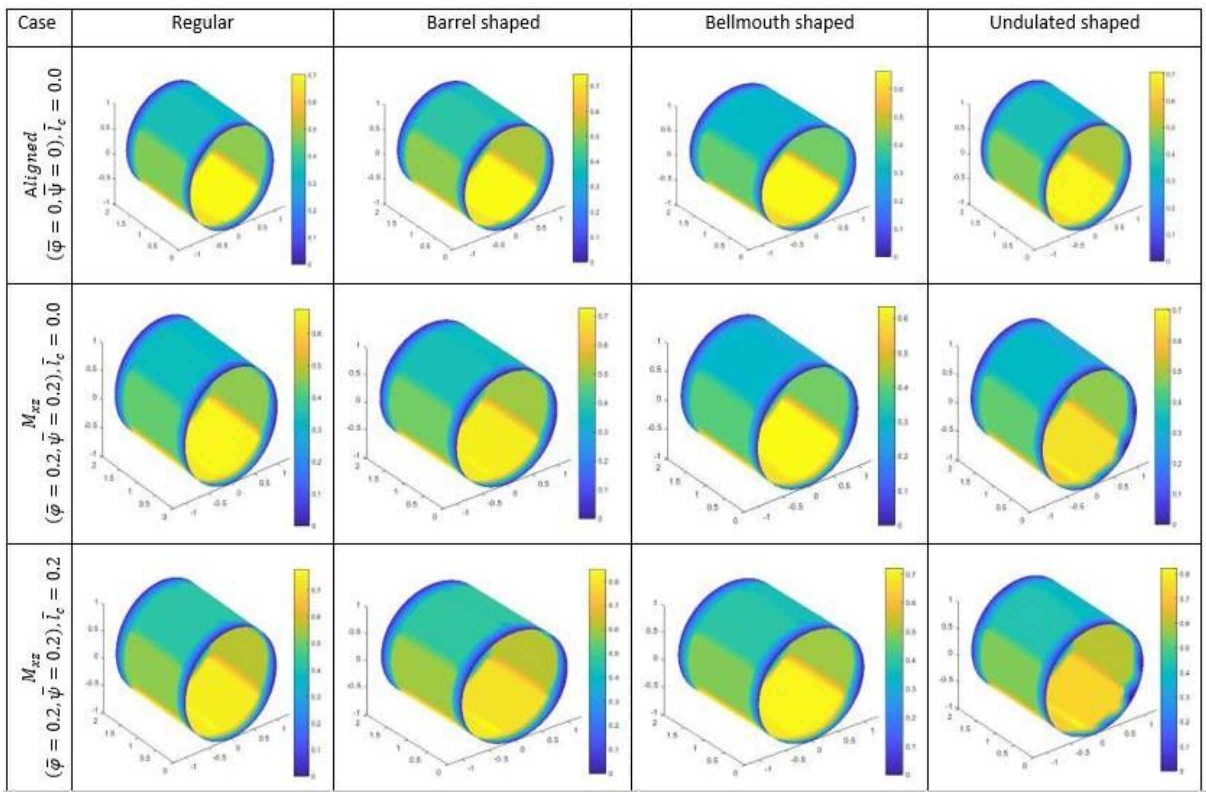

Figure 6: Distribution of oil film pressure over the bearing in six pocket hybrid JBS.

4.2 Effect on Oil-Film Thickness ($\bar{\mathbf{h}}$)

The formation of an oil film profile in a hybrid JBS essentially depends on the formation of oil film pressure in bearings. The geometric irregularities of journal under misaligned operation also affect the resultant oil film profile. In light of this, the three-dimensional oil film profile along the bearing dimensions ($\beta = 0.0 - 2.00, \alpha = 0 - 2\pi$) are illustrated for three cases (for the sake of brevity) in Figure 7 i.e., aligned condition (A) with Newtonian lubricant, Misaligned condition (M_{XZ}) with Newtonian Lubricant, Misaligned condition (M_{XZ}) with CSL. These images clearly serve to highlight actual appearance of misalignment and geometric irregularities of journal on the oil film profile. Further, for aligned condition, irregularities of journals result in a reduction in the $\bar{h}_{min}$with respect to the regular journal. However, for misaligned conditions, barrel journal may provide greater value of $\bar{h}_{min}$ than another journals. The CSL operated JBS provides noticeable increase in the value of oil film thickness.

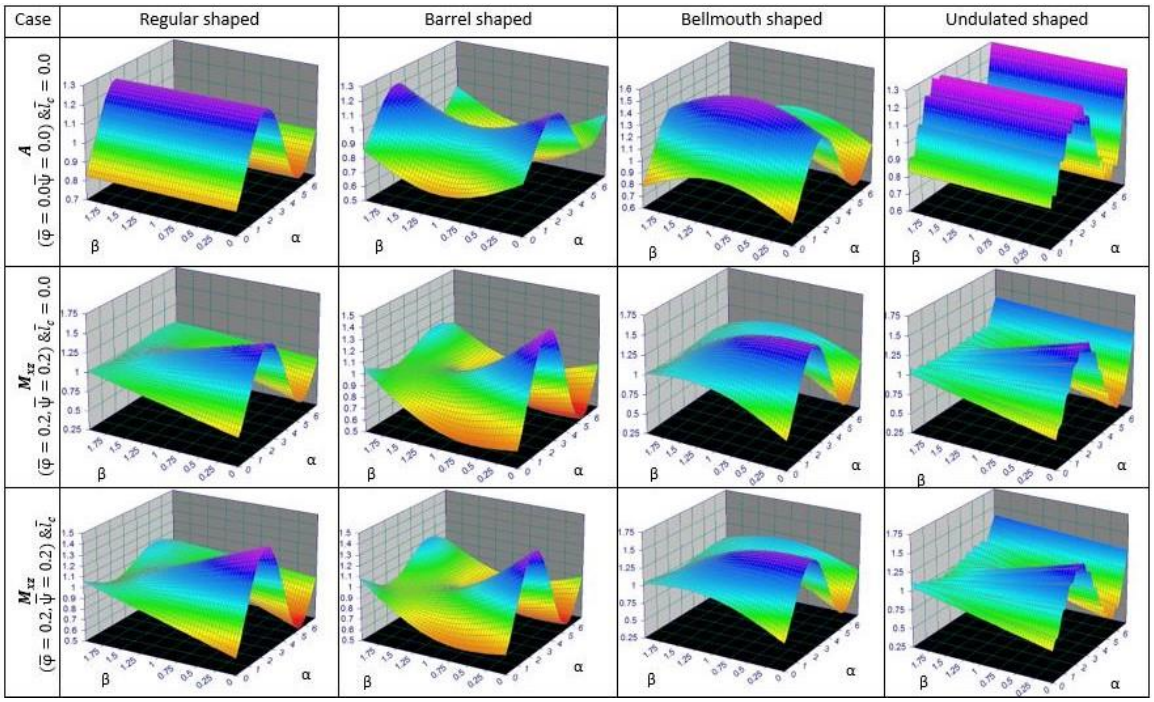

Figure 7: Distribution of Oil film profile over the bearing dimensions in six pocket hybrid JBS.

Figure 8 illustrates the variation in the value of $\bar{h}_{min}$ along with journal speed(Ω). The value of $\bar{h}_{min}$ rises with an increase in the value of Ω for each case studied as hydrodynamic pressure rises with Ω. Further, the value of $\bar{h}_{min}$ found lower due to journal's irregularities with reference to regular journal. The barrel shaped journal causes higher reduction in value of $\bar{h}_{min}$than other irregular journal for aligned operating condition. Further, it is noticeable that the journal's misalignment causes in substantially drops in the value of $\bar{h}_{min}$ for each case studied corresponding to align JBS. The journal misalignment (M_{XZ}) may provide a noticeable drop in the value of $\bar{h}_{min}$ for regular, barrel, bellmouth and undulated shaped journal by a factor of -38.21%, -16.14%, -41.31% & -40.85% respectively than that of aligned operation. The interesting observation is that for misaligned operation, the barrel journal offers a noticeable higher value of $\bar{h}_{min}$ than that of the regular journal. It can be attributed to the fact that oil film pressure is noticeably higher for barrel shaped journal for misaligned operation.

Furthermore, for misaligned operation, the CS lubricated regular and irregular JBS results a noticeable improvement in the value of $\bar{h}_{min}$ than Newtonian lubricated JBS. It may be noticed from the Table 3 that for misaligned operation (M_X, M_{XZ}), through use of CSL instead of Newtonian lubricant provide a substantial enhanced value of $\bar{h}_{min}$ for regular, barrel, bell-mouth and undulated shaped journal by a factor of (~8.31%, 11.48%), (~6.72%, 8.34%), (~11.51%, 15.87%) & (~7.94%, 13.12%) sequentially.

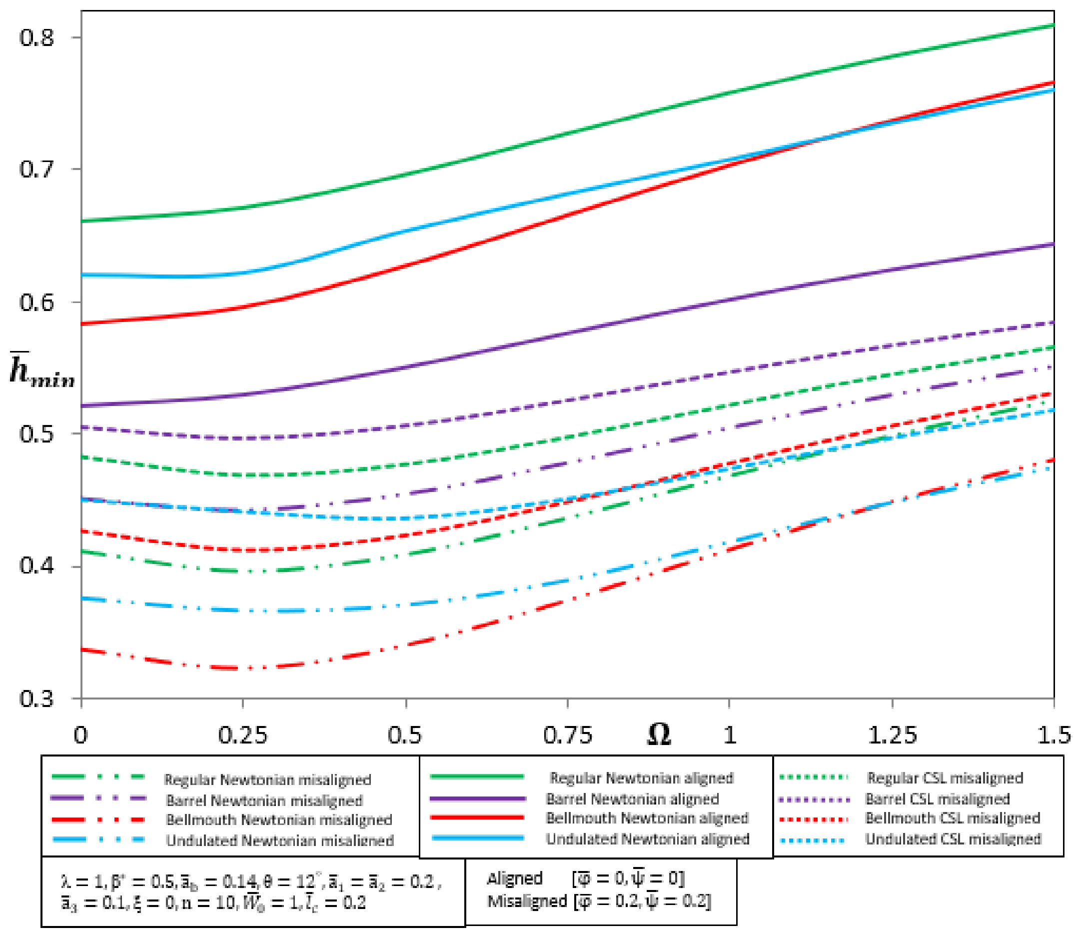

Figure 8: Variations in ($\bar{h}_{min}$) along with (Ω).

4.3 Oil-Film Rate ($\bar{\mathbf{Q}}$)

Figure 9 presents the variation in the value of $\bar{Q}$ along with journal speed (Ω). There is a slight variation in the value of $\bar{Q}$ with a rise in the value of (Ω) for irregular JBS under aligned and misaligned operation. Further, the requirement of $\bar{Q}$ is least for barrel shaped JBS and highest for bell-mouth shaped JBS due to respective clearance space. The journal misalignment causes a significant rise in the requirement of $\bar{Q}$ for regular and irregular JBS. The use of CSL instead of Newtonian results a considerable reduction in the value of $\bar{Q}$for regular and irregular JBS under misaligned operation. It may be noticed from Table 3 that the use of CSL provides a significant drop in the value of $\bar{Q}$ for regular, barrel, bellmouth and undulated shaped JBS under misaligned operations (M_X, M_{XZ}) by a factor of approximately (11.33%, 10.43%), (13.69%, 12.55%), (9.48%, 8.74%) & (11.34%, 10.28%) respectively with reference to Newtonian lubricant.

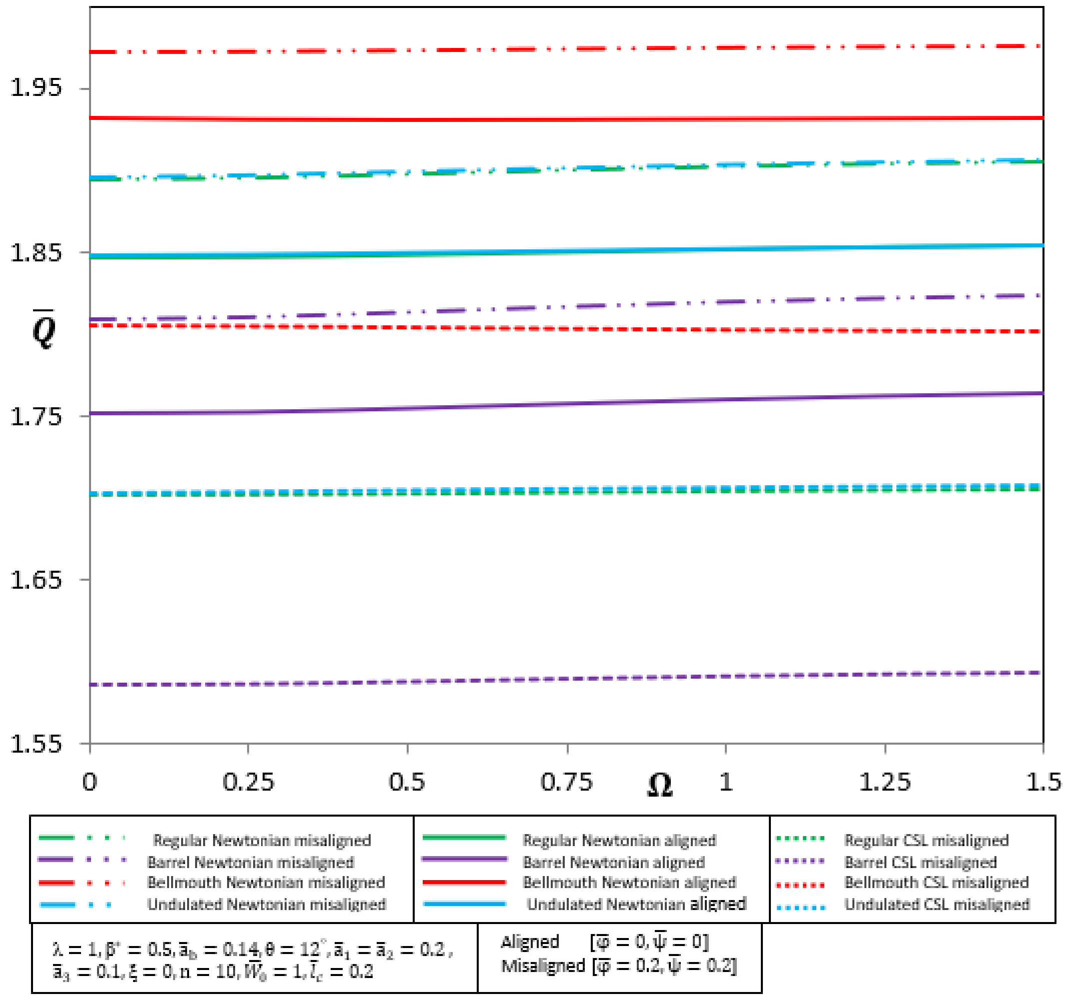

Figure 9: Variation in ($\bar{Q}$) along with (Ω).

4.4 Frictional Torque ($\bar{T}_f$)

Figure 10 presents the collective effects of CSL and misalignment of journal on the value of $\bar{T}_f$ along with journal speed (Ω)for regular and irregular shaped JBS. The results report that the value of $\bar{T}_f$ rises with a rise in Ω for regular and irregular JBS under aligned and misaligned operation. Further, the barrel shaped JBS offers the highest value of $\bar{T}_f$ and bellmouth shaped JBS provides least value of $\bar{T}_f$ under both aligned and misaligned operation. Therefore, the use of bellmouth journal in place of regular journal may be favorable in view of friction losses. Further, the effect of journal's misalignments(M_X, M_{XZ})on the value of $\bar{T}_f$ is relatively small (~1%, 2.25%) for each JBS studied vis-à-vis aligned condition. Furthermore, it is also observed that the CSL operated JBS under misaligned condition offer considerable reduction (~1.00-2.00%) in $\bar{T}_f$ than that of Newtonian lubricated JBS.

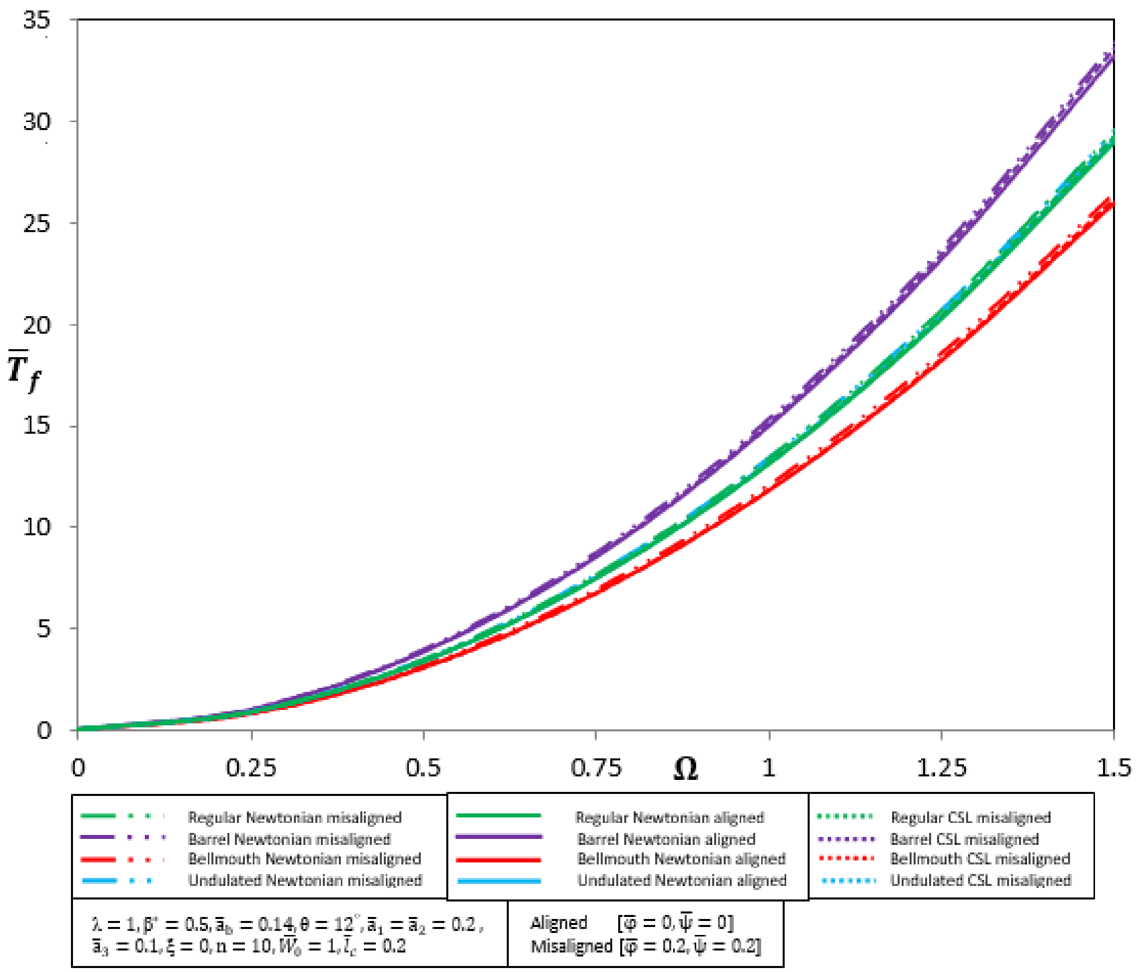

Figure 10: Variation in ($\bar{T}_f$) along with (Ω).

4.5 Oil-Film Stiffness Coefficients ($\bar{\mathbf{S}}_{\mathbf{xx}}$ & $\bar{\mathbf{S}}_{\mathbf{zz}}$)

Figures 11 (a-b) indicate the variation in the value of $\bar{S}_{xx}$&$\bar{S}_{zz}$ versus journal speed(Ω). It is noticed that the values of $\bar{S}_{xx}$ slightly changes with the value of (Ω) for regular, barrel and bellmouth shaped JBS. However, the variation in the $\bar{S}_{xx}$is significant for undulated shaped JBS as waviness in circumferential direction results in more stiffness with journal speed. Similarly, the value of $\bar{T}_f$, the barrel shaped JBS offers the highest value of $\bar{S}_{xx}$ and bell-mouth shaped JBS provides least value of $\bar{S}_{xx}$ as compared to regular JBS for both aligned and misaligned operation. Further, the misalignment (M_{XZ}) causes a noticeably reduction (~7.00%) in the value of $\bar{S}_{xx}$ for each case studied. From the results, it is also observed that the use of CSL substantially compensates the deterioration in the value of $\bar{S}_{xx}$caused by misaligned operation. For misaligned operation, the use of CSL ($\bar{l}_c = 0.2$) in place of Newtonian lubricant in geometric irregular JBS may offer the noticeably improvement (by a factor of ~18%-28%) in the value of $\bar{S}_{xx}$. Figure 11(b) depicts a minor reduction in the values of $\bar{S}_{zz}$ along with (Ω) for each JBS operating with Newtonian lubricant under in both aligned and misaligned operating condition. Barrel journal furnishes the maximum value of $\bar{S}_{zz}$ for align and misalign operation while bell-mouth journal furnishes the least value of $\bar{S}_{zz}$. The use of CSL ($\bar{l}_c = 0.2$) may refurbish ($by\sim$ 19%-25%) the deterioration in the value of $\bar{S}_{zz}$ caused by misalignment.

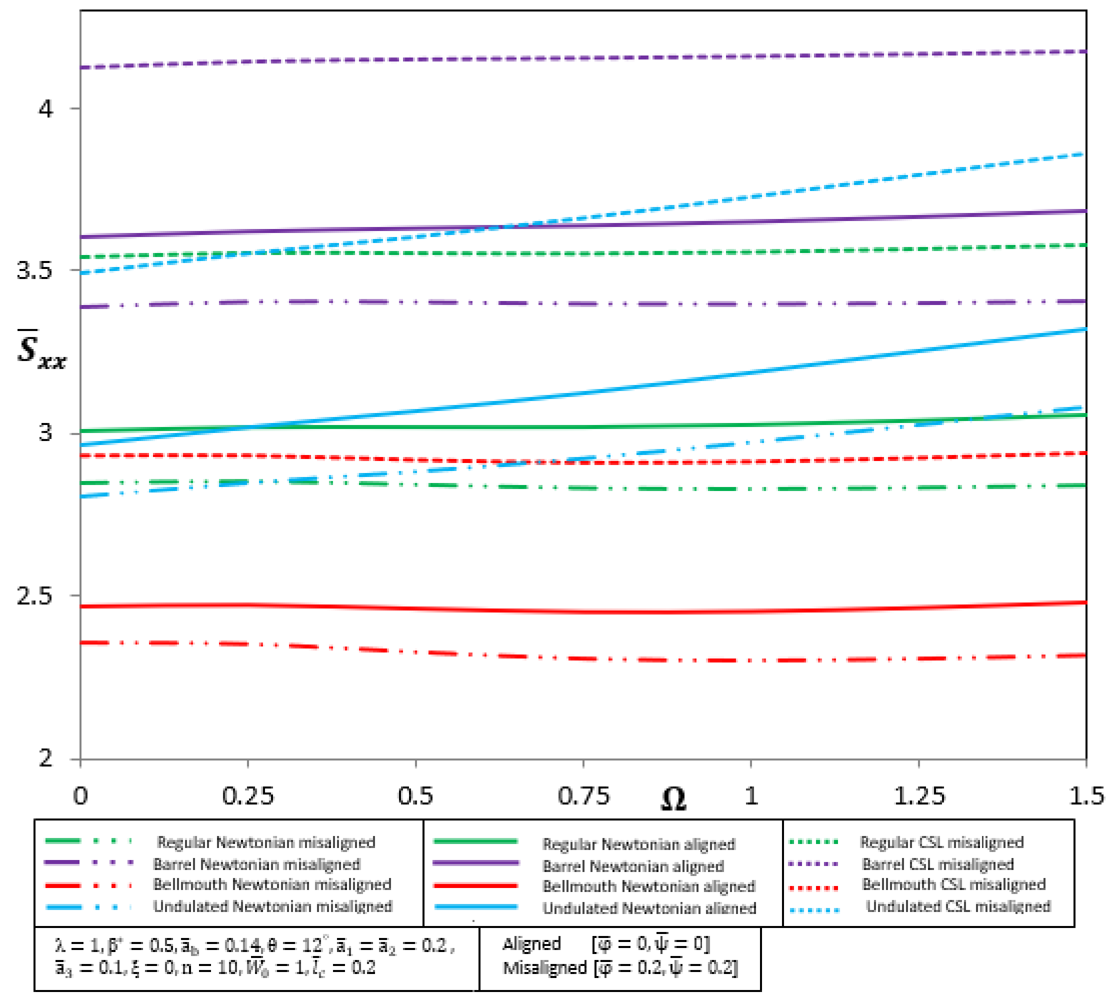

Figure 11 (a): Variation in ($\bar{S}_{xx}$) along with (Ω).

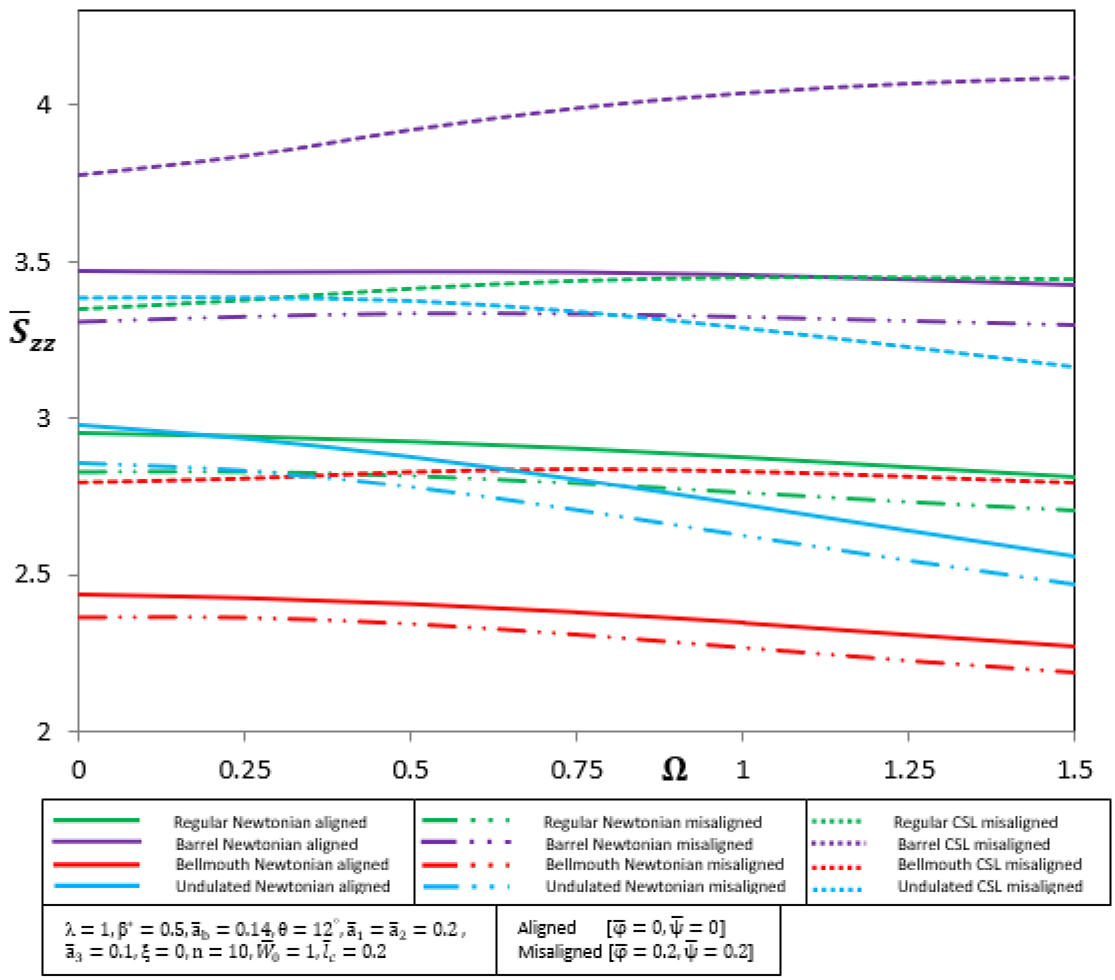

Figure 11 (b): Variation in ($\bar{S}_{zz}$) along with (Ω).

4.6 Oil-Film Damping Coefficients ($\bar{C}_{xx}$ & $\bar{C}_{zz}$)

Figures12 (a-b) presents the variation in the value of $\bar{C}_{xx}$ & $\bar{C}_{zz}$ along with Ω. A minute rise in the value of $\bar{C}_{xx}$with a rise in the value of Ω may be reported while the value of $\bar{C}_{zz}$ gets lowered with a rise in Ω. Likewise, to the oil film stiffness coefficients, the values of $\bar{C}_{xx}$ & $\bar{C}_{zz}$ gets also notably affected by numerous geometrical irregularities and misalignment of journal. Furthermore, the use of CSL offers substantially improvement (by ~22%-24% & 19%-25%) in the value of $\bar{C}_{xx}$ & $\bar{C}_{zz}$ of regular and irregular JBS under misaligned operation vis-à-vis Newtonian lubricant.

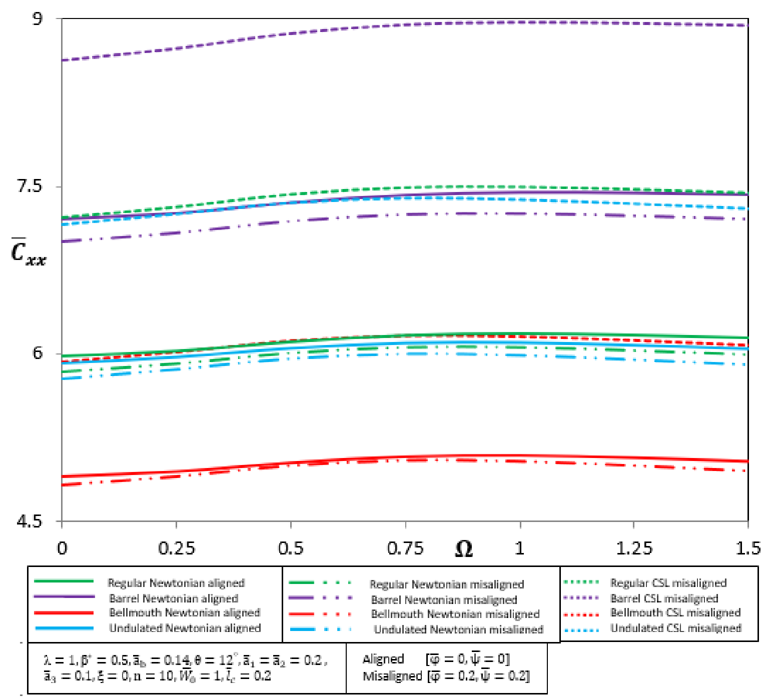

Figure 12 (a): Variation in ($\bar{C}_{xx}$) along with (Ω).

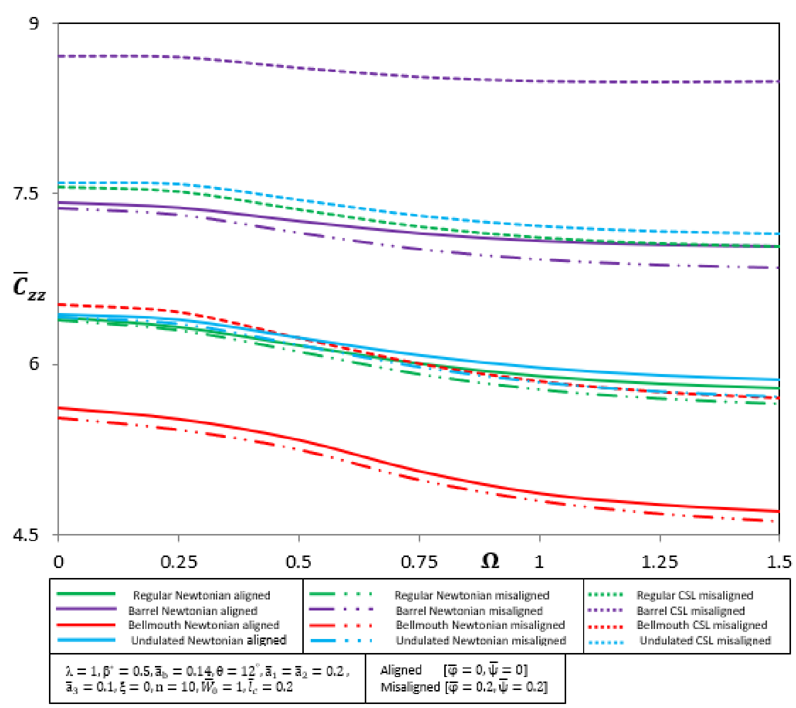

Figure 12 (b): Variation in ($\bar{C}_{zz}$) along with (Ω).

4.7 Stability Threshold Speed (ω_{th})

Figure 13 indicate the change in the value of ω_{th} along with journal speed(Ω). It has been reported that the value of $\boldsymbol{\omega_{th}}$ rises with journal speed up to Ω = 0.25 then start decreasing notably for regular and irregular JBS under both aligned and misaligned operation. Further, the barrel shaped and bellmouth shaped JBS offers the highest and least values of ω_{th} for both aligned and misaligned operation. This may be fact that ω_{th} is a function of oil film stiffness and damping coefficients. The misaligned condition(M_{XZ}) results a minute reduction in the value of ω_{th} for regular as well as irregular JBS. Moreover, through use of CSL may furnish a noticeable increase in the value of $\omega_{th}$by approximately 8%-12% for regular and irregular JBS under misaligned operation.

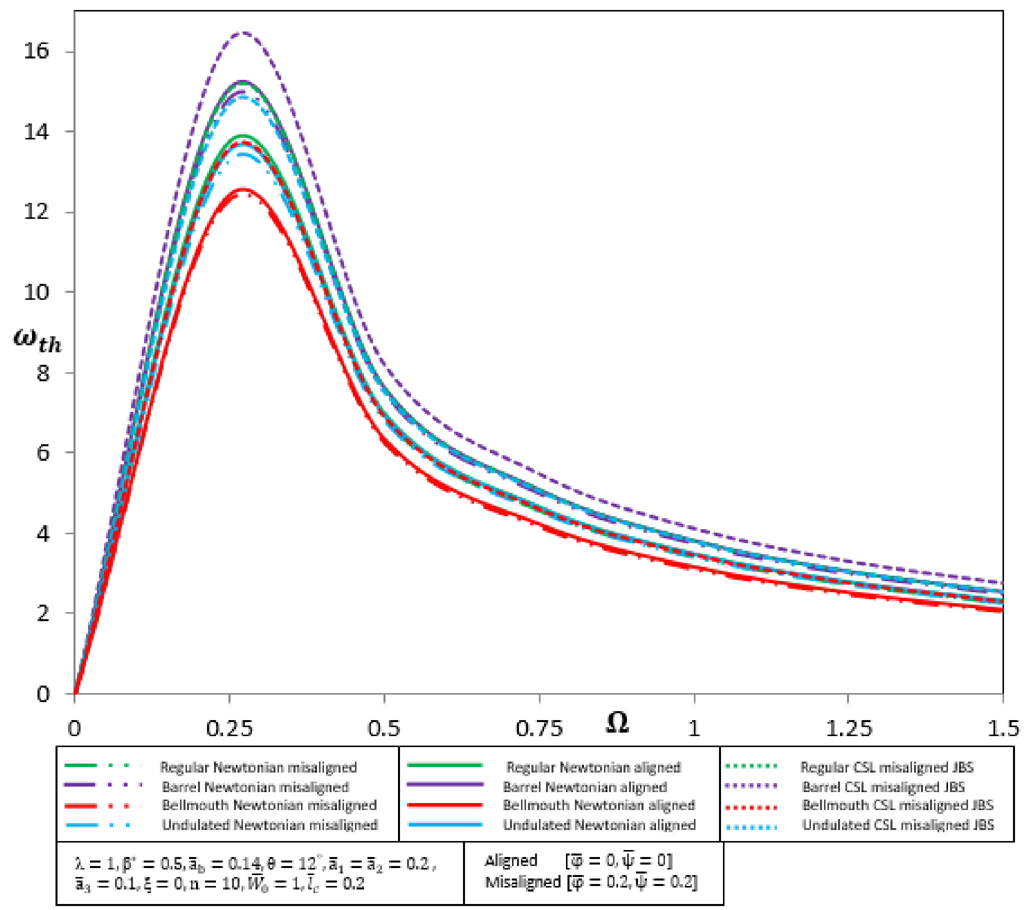

Figure 13: Variation in (ω_{th}) along with (Ω).

CONCLUSION

A computational investigation to analyze the effects of CSL on the functioning of six-pocket hybrid irregular JBS under misaligned condition has been performed. The simulated investigation may reveal that the different type of irregularities of journal notably reduces the value of $\bar{h}_{min}$ thereby other bearing characteristics parameters gets influenced. Further, the misaligned operation may cause a noticeable deterioration in the bearing performance. The misalignment M_{XZ} may results a maximum reduction in the values of characteristic parameters for each regular and irregular JBS i.e., the misalignment about both the axis causes the most adverse effect on the functioning of bearing operation. The journal's misalignment causes a significant reduction in the value of $\bar{h}_{min}$ for each case studied. It is interesting indication that the barrel shaped journal offers higher value of $\bar{h}_{min}$ than regular journal for misaligned operation. Furthermore, the barrel shaped journal requires least value of $\bar{Q}$ but causes the highest value of $\bar{T}_f$ and bellmouth shaped journal provides least value of $\bar{T}_f$ among other form of journal analyzed. Therefore, the misaligned and irregular journal collectively provides a detrimental effect on the bearing performance viz. $\bar{h}_{min}$, $\bar{Q}$, $\bar{T}_f$, $\bar{S}_{xx}$, $\bar{S}_{zz}$, $\bar{C}_{xx}$, $\bar{C}_{zz}$, & $\bar{\omega}_{th}$. Moreover, the use of CS lubricant in place of Newtonian lubricant may partially recover the detrimental effect caused by misalignment of journal and irregularities of journal on these bearing characteristics parameters.

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