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# A study of 2-lobe symmetric hole entry hybrid journal bearing operating with non-Newtonian lubricant considering thermal effects

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ABSTRACT

This paper presents the thermohydrostatic solution of 2-lobe symmetric hole entry hybrid journal bearing compensated with orifice restrictor and operating with cubic law lubricant. Simultaneous solutions of Reynold's, energy and conduction equations have been obtained by using finite element method and a suitable iterative scheme. The performance characteristics parameters of 2-lobe symmetric bearing system have been presented for various bearing geometries and nonlinearity factors. The numerically simulated results of the study indicates that the variation of viscosity of cubic law lubricant due to temperature rise and bearing geometry changes the bearing performance quite significantly.



## 1. Introduction

The cylindrical non-recessed hybrid journal bearings are used extensively in various engineering applications owing to their superior dynamic performance characteristics [1–4]. However, the critical requirements pertaining to operating conditions necessitates these bearings to be designed more accurately. The circular non-recessed bearings are prone to fluid induced instabilities such as oil whirl and whip. This has necessitated the development of multilobe journal bearing to prevail over the fluid induced instabilities. Recently, many studies related to multilobe journal bearings have been carried out and reported in the published literature [5–10].

Furthermore, a lubricant plays a great role on the overall performance of bearings. Lubricants with high molecular weight polymeric additives such as polyisobutylene and polymethacrylate are extensively being used these days. These lubricants exhibit non-Newtonian behavior wherein, a non-linear relationship is observed between shear stress and rate of shear. Therefore, the performance of bearing simulated using Newtonian behavior postulations may not provide a realistic bearing design data.

During the last few decades, many studies [11–19] have been carried out in the field of circular hydrostatic/hybrid bearings considering the non-Newtonian rheology of lubricants. Sinhasan and Sah [11] analytically investigated the influence of cubic law lubricant on the performance characteristics of circular hydrostatic journal bearing. The effect of nonlinear behavior of lubricant on flexible bearing system was carried out by Sharma et al. [12]. They reported that the nonlinear behavior of lubricant defined by a cubic shear stress law and a power law alters the dynamic response of a bearing system. Nagaraju et al. [14] studied the influence of roughness pattern on the performance of a hole entry hybrid journal bearing system lubricated with power law lubricant. They reported that the longitudinal surface pattern provides enhanced values of rotor dynamic coefficients for the value of power law index ($n=0.5$). Very recently, Kushare and Sharma [17,18] studied the influence of cubic law lubricant on the performance of two lobe worn hole entry journal bearing. They also presented the nonlinear transient stability response for the symmetric worn bearing configuration. It was reported that there is substantial reduction in the value of direct rotor dynamic coefficients of the order of 18–30% for worn bearing operated with cubic law lubricant.

Under the conditions of high speed and heavy operating load, temperature of lubricating fluid film and bearing surface increases. The rise in temperature changes the behavior of lubricant by reducing its viscosity. Further, as stated earlier, the addition of polymer additives changes the behavior of commercial lubricants to exhibit non-Newtonian behavior. Thus, the analysis based on the isothermal and isoviscous conditions of bearing operating with Newtonian lubricant may not provide realistic bearing performance. Therefore, to predict bearing performance characteristics

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**Nomenclature**

$a_b$ bearing land width, mm
$c$ radial clearance, mm
$e$ journal eccentricity, mm
$E$ Young's modulus of elasticity, N mm$^{-2}$
$F$ fluid film reaction $(\partial h/\partial t \neq 0)$, N
$F_x, F_z$ components of fluid film reactions in $X$ and $Z$ direction $(\partial h/\partial t \neq 0)$, N
$F_o$ fluid film reaction $(\partial h/\partial t = 0)$, N
$C_1$ clearance due to circumscribed circle on the bearing, mm
$C_2$ clearance due to inscribed circle on the bearing, mm
$g$ acceleration due to gravity, m s$^{-2}$
$h$ nominal fluid-film thickness, mm
$L$ bearing length, mm
$R_J, R_L, R_b$ radius of journal, lobe and bearing, mm
$d_o$ orifice diameter, mm
$p$ pressure, N mm$^{-2}$
$p_c$ pressure at hole, N mm$^{-2}$
$Q$ bearing flow, mm$^3$ s$^{-1}$
$S_{ij}$ stiffness coefficients $(i,j = 1,2)$, N mm$^{-1}$
$C_{ij}$ damping coefficients $(i,j = 1,2)$, N s mm$^{-1}$
$t$ time, s
$k$ thermal conductivity, W mm$^{-1}$ K$^{-1}$
$\omega_I$ $(g/c)^{1/2}$, rad s$^{-1}$
$\psi_d$ coefficient of discharge for orifice
$D$ journal diameter, mm
$W_o$ external load, N
$\Omega, \Gamma$ solution domains
$X, Y, Z$ cartesian coordinates
$X_J, Z_J$ coordinates of steady state equilibrium journal center from geometric center of bearing, mm

*Greek symbols*

$\lambda = L/D$ aspect ratio
$\phi$ altitude angle
$\mu$ dynamic viscosity of lubricant, N s m$^{-2}$
$\mu_r$ dynamic viscosity of lubricant at reference inlet temperature and ambient pressure, N s m$^{-2}$
$\rho$ density of the lubricant, kg mm$^{-3}$
$K$ nonlinearity factor for cubic shear law
$\tau$ shear stress in lubricant film, N mm$^{-2}$
$\dot{\gamma}$ shear strain rate, s$^{-1}$
$\mu_a$ apparent viscosity, N s m$^{-2}$
$O_j, O_{Li}$ journal center, Lobe center
$\omega_J$ journal rotational speed, rad s$^{-1}$
$\omega_{th}$ threshold speed, rad s$^{-1}$
$q$ heat flux, W m$^{-2}$
$p_s$ lubricant supply pressure, N mm$^{-2}$

*Non-dimensional parameters*

$\overline{a}_b = a_b/L$ land width ratio
$\beta^* = p^*/p_s$ concentric design pressure ratio
$\overline{C}_{S2} = \left(\pi d_o^2 \mu \psi_d / 4c^3\right)\left(2/\rho p_s\right)^{1/2}$ restrictor design parameter
$\overline{D}_e = \left(\frac{\mu_r}{\rho_f c_{pf}}\right)\left(\frac{c^2 p_s}{\mu_r R_J}\right)\frac{R_J}{c^2 T_r}$
$\overline{u}, \overline{v}$ $(u,v)\left(\frac{\mu_r R_J}{c^2 p_s}\right)$
. $\overline{C}_{ij} = C_{ij}\left(c^3/\mu R_J^4\right)$
. $(\overline{F}, \overline{F}_o) = (F, \overline{F}_o)/p_s R_J^2$
. $(\overline{h}) = (h)/c$; $\overline{\delta}_w = \delta_w/c$
. $\overline{p}, \overline{p}_c, \overline{p}_{max} = (p, p_c, p_{max})/p_s$
. $\overline{Q} = Q\left(\mu/c^3 p_s\right)$
. $\overline{T} = T/T_r$
. $\overline{\dot{\gamma}} = \left(\dot{\gamma}/(cp_s/\mu_r R_J)\right)$
. $\overline{t}_b = \frac{t_b}{R_J}$
. $\overline{K} = (cp_s/R_J)^2 K$
. $\overline{k} = k/k_r$
. $\overline{S}_{ij} = S_{ij}\left(c/p_s R_J^2\right)$
. $\overline{W}_o = W_o/p_s R_J^2$
. $(\overline{X}_J, \overline{Z}_J) = (X_J, Z_J)/c$
. $\tau = t\left(c^2 p_s/\mu R_J^2\right)$
. $\overline{X}^i{}_L, \overline{Z}^i{}_L = (X_L^i, Z_L^i)/c$
$\alpha, \beta = (X, Y)/R_J$ circumferential and axial coordinates
$\varepsilon = e/c$ eccentricity ratio
$\delta = C_1/C_2$ offset factor
. $\overline{\omega}_{th} = \omega_{th}/\omega_I$
$\Omega = \omega_J\left(\mu R_J^2/c^2 p_s\right)$ speed parameter

*Matrices*

$N_i, N_j =$ shape functions
$[\overline{F}]$ fluidity matrix
$\{\overline{p}\}$ nodal pressure vector
$\{\overline{Q}\}$ nodal flow vector
$\{\overline{R}_H\}$ vector due to hydrodynamic terms
$\{\overline{R}_{Xj}\}, \{\overline{R}_{Zj}\}$ right hand side vectors due to journal center velocities
$[\overline{K}_T]$ system thermal stiffness matrix for solid (bush) domain
$[\overline{K}_h]$ system thermal stiffness matrix due to convection term for solid (bush) domain
$\{\overline{H}_T\}$ nodal heat flow vector
$[\overline{A}_T]$ system thermal stiffness matrix for fluid domain
$[\overline{B}_T]$ nodal thermal load vector for fluid domain
$[\overline{C}_T]$ vector representing the interaction with the bush and journal
$\{\overline{T}_f\}$ nodal fluid-film temperature vector
$\{\overline{T}_b\}$ nodal bush temperature vector

*Subscripts and superscripts*

$b$ bearing
$R$ restrictor
$l$ lobe
min minimum
. first derivative w.r.t time
$*$ concentric operation
$J$ journal
$s$ supply
$i$ lobe number
max maximum
.. second derivative w.r.t time
- corresponding non-dimensional parameter
$r$ reference value

realistically, thermohydrostatic analysis with non-Newtonian lubricant must be considered.

In recent times researchers have given considerable attention to thermal effects. Many studies related to thermohydrodynamic/thermohydrostatic analyses pertaining to circular journal bearings have been reported in the literature [20–30]. Study pertaining to the influence of thermal effects on the performance of finite length journal bearing was carried out by Ferron et al. [21]. They obtained