4th International Conference on Mechanical Engineering, December 26-28, 2001, Dhaka, Bangladesh/pp. V 147-153

STATIC PERFORMANCE OF MISALIGNED HOLE-ENTRY HYBRID JOURNAL BEARING INCLUDING SURFACE ROUGHNESS EFFECTS

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Abstract The effect of surface roughness on the performance of a constant flow valve compensated misaligned hole-entry hybrid journal bearing system has been theoretically studied. The journal misalignment has been accounted by defining a pair of misalignment parameters φ and δ. The pressure and shear flow factors are used to modify the classical Reynolds equation for a rough surface journal bearing. The non-dimensional parameters Λ (surface roughness parameter) and γ (surface pattern parameter) have been defined to represent the magnitude of height distribution of surface roughness and their orientation respectively. The bearing performance has been studied for the isotropic surface patterns of the hole-entry hybrid journal bearing configuration. The study indicates that for prediction of realistic bearing characteristic data, the inclusion of surface roughness effects in the analysis is essential.

Keywords: Journal bearing, Hybrid, Misalignment, Roughness

NOMENCLATURE

$\bar{a}_b = a_b/L$, Bearing land width ratio,
$c, L =$ Radial clearance, Bearing length
$\bar{h}, \bar{h}_T = (h, h_T)/c$, Nominal, Average fluid-film thickness
$\bar{p} = p/p_s$, Pressure
$\tau = t\left(c^2 p_s / \mu R_J^2\right)$, Time
$(\bar{V}_{rj}, \bar{V}_{rb}) = \left((\sigma_j, \sigma_b)/\sigma\right)^2$, Variance ratios
$\bar{W}_o = W_o / p_s R_J^2$, External load
$\alpha, \beta = (X, Y)/R_J$, Circumferential and axial co-ordinates
$z = z_J + z_b$, Combined roughness height, $\bar{z} = z/c$
$erf(x) = 2/\pi \int_0^x \exp(-y^2)dy$, Error function
$\omega_J, \bar{\omega}_{th} =$ Journal rotational speed, Threshold speed
$\Omega = \omega_J \left(\mu R_J^2 / c^2 p_s\right)$, Speed parameter
$\varphi, \delta =$ Misalignment parameters
$\bar{\sigma} = \left(\sqrt{\sigma_J^2 + \sigma_b^2}\right)/c$, RMS value of combined roughness,
$\varphi, \delta =$ Misalignment parameters
$\bar{\sigma} = \left(\sqrt{\sigma_J^2 + \sigma_b^2}\right)/c$, RMS value of combined roughness,
$\Lambda = 1/\bar{\sigma}$, Surface roughness parameter
$\gamma = \frac{\lambda_{0.5x}}{\lambda_{0.5y}}$, Surface pattern parameter
$\lambda_{0.5x,y} =$ 0.5 correlation lengths of the x and y profile
$\lambda = L/D$, Aspect ratio

Subscript and Superscript

— Non-dimensional parameter
b Bearing
J Journal
o Steady state condition
s Supply pressure
. First derivatives w.r.t time

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INTRODUCTION

The last few decades have witnessed rapid technological advancements and the operating conditions of machines are becoming stringent, exact and more demanding. Thus, it becomes imperative that the bearings should be more reliable and their design should be based on more realistic bearing characteristic data. The majority of available studies in the literature concerning hole-entry journal bearings assume that both journal and bearing axes are properly aligned and journal and bearing surfaces are perfectly smooth. However, in actual practice, they may not be properly aligned and perfectly smooth. As a result of improper assembly, non-central load and shaft deflection due to elastic and thermal distortions etc, the journal and bearing gets misaligned. Further, due to the characteristic of machining process and its accompanying defects, the imperfections do exists on any finished surface and these usually takes the form of a succession of hills and valleys. Therefore, the analyses based on the assumption of aligned journal as well as smooth surface of bearing and journal may not give realistic bearing characteristics data. Some theoretical/experimental studies related to the recessed/non-recessed hybrid journal bearing system have been reported in the literature [Bou Said and Nicolas, 1992; Jain et al, 1997; Markho et al, 1979; San Andres, 1993 and Sato and Ogiso, 1983]. The previous work by the authors [Jain et al, 1997] indicate that the static and dynamic performance of a hole-entry hybrid journal bearing is affected due to journal misalignment.

The effect of surface roughness in the area of journal bearing problems is becoming an important research activity over the last few years. San Andres (1990) analysed the pocketed hybrid journal bearing by considering effect of surface roughness along with fluid inertia effect. More recently, Fayolle and Childs (1999) experimentally investigated the static and dynamic performance characteristics of a hybrid journal bearing by providing round-hole-pattern roughness on the lands. Hashimoto (1997), Li et al (1996) and Ramesh et al (1997) studied the effect of surface roughness on the performance of hydrodynamic journal bearing using flow factor method proposed by Patir and Cheng (1978,1979). Guha (2000) studied the combined effects of isotropic roughness and journal misalignment on steady state characteristics of hydrodynamic journal bearing.

The available studies in the case of hydrodynamic [Guha, 2000; Hashimoto, 1997; Li et al, 1996 and Ramesh et al, 1997] and hydrostatic [Fayolle and Childs, 1990 and San Andres, 1990] bearings demonstrate that their performance is significantly affected due to inclusion of surface roughness effects in the analysis. Among the available theoretical studies concerning the study of misaligned hole-entry hybrid journal bearings, the surface roughness effects have been neglected. The present work is, therefore, aimed to analyze the effects of surface roughness on the performance of constant flow valve compensated misaligned hole-entry hybrid journal bearing system. The effect of surface roughness in the analysis is considered by defining a non-dimensional surface roughness parameter Λ and a surface pattern parameter γ. The journal misalignment has been accounted by defining a pair of misalignment parameters φ and δ.

The static performance characteristics of a misaligned hole-entry journal bearing has been presented for the generally used representative values of roughness parameter (Λ) and for a set of representative values of journal misalignment parameters φ and δ for isotropic surface pattern. The results presented in this paper are expected to be quite useful to the bearing designers and the academic community.

ANALYSIS

1. *Average fluid-film thickness ($\bar{h}_T$)*

The geometry of the externally pressurized hole-entry journal bearing system along with rough surface and co-ordinate system is shown in Fig.1. Assuming Gaussian distribution of surface heights, the non-dimensional form of average fluid-film thickness $\bar{h}_T$ is written as [Hashimoto, 1997 and Ramesh et al, 1997]

$$\bar{h}_T = \frac{\bar{h}}{2}\left(1 + erf\left(\frac{\Lambda\bar{h}}{\sqrt{2}}\right)\right) + \frac{1}{\Lambda\sqrt{2\pi}}e^{-(\Lambda\bar{h})^2/2} \quad .... (1)$$

where $\bar{h}$ is the nominal fluid-film thickness. It is same as the fluid-film thickness obtained for a smooth surface journal bearing. For misaligned journal bearing $\bar{h}$ is expressed as [Jain et al, 1997]

$$\bar{h} = 1 - \bar{X}_J \cos\alpha - \bar{Z}_J \sin\alpha + \delta\frac{R_J}{c}\cos\alpha - \varphi\frac{R_J}{c}\sin\alpha \quad .... (2)$$

2. *Flow factors (ϕ_x, ϕ_y, ϕ_s)*

The pressure flow factors ϕ_x, ϕ_y are used to compare the average pressure flows (in axial and circumferential directions) in a rough journal bearing to that of smooth bearing and they are expressed in non-dimensional form as [Patir and Cheng, 1978]

$$\phi_x = 1 - Ce^{-r\Lambda\bar{h}} \text{ For } \gamma \le 1\,;\ \phi_x = 1 + C(\Lambda\bar{h})^{-r} \text{ For } \gamma > 1$$
$$\text{and } \phi_y(\Lambda\bar{h}, \gamma) = \phi_x(\Lambda\bar{h}, 1/\gamma) \quad .... (3a)$$

Similarly, the shear flow factor ϕ_s is used to represent the additional flow transport of lubricant in circumferential direction due to sliding of rough surface journal. Assuming both journal and bearing surfaces having same surface pattern (i.e. $\gamma_J = \gamma_b$), the shear flow factor in non-dimensional form is expressed as [Patir and Cheng, 1979]

$$\phi_s = (2\bar{V}_{rj} - 1)\Phi_s \quad \text{Since } \bar{V}_{rj} + \bar{V}_{rb} = 1 \quad .... (3b)$$

where Φ_s is a positive function of ($\Lambda.\bar{h}$) and the surface pattern parameter γ of a given surface and is given by

$\Phi_s = A_1(\Lambda\bar{h})^{\alpha_1} e^{-\alpha_2(\Lambda\bar{h})+\alpha_3(\Lambda\bar{h})^2}$ For $\Lambda\bar{h} \le 5$;

$\Phi_s = A_2 e^{-0.25(\Lambda\bar{h})}$ For $\Lambda\bar{h} > 5$ .... (3c)

where $C, r, A_1, A_2, \alpha_1, \alpha_2$ and α_3 appearing in Eqns. 3a and 3c are constants and γ is the surface pattern parameter.

3. *The average Reynold's equation*

The average Reynold's equation governing the laminar flow of lubricant in the clearance space between rough surfaces of journal and bearing in non-dimensional form is written [Patir and Cheng, 1978] as

$$\frac{\partial}{\partial\alpha}\left(\phi_x \frac{\bar{h}^3}{12}\frac{\partial\bar{p}}{\partial\alpha}\right)+\frac{\partial}{\partial\beta}\left(\phi_y \frac{\bar{h}^3}{12}\frac{\partial\bar{p}}{\partial\beta}\right)=\frac{\Omega}{2}\frac{\partial\bar{h}_T}{\partial\alpha} + \frac{\Omega}{2\Lambda}\frac{\partial\phi_s}{\partial\alpha}+\frac{\partial\bar{h}}{\partial\tau} \quad .... (4)$$

4. *Finite Element Formulation*

The lubricant flow field has been discretized using four-noded quadrilateral isoparametric elements. Using the Galerkin's techniques and orthogonality condition for Eqn. (4), the following system equations are derived [Sharma et al, 1993]

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

5. *Restrictor Flow Equation*

The equation of flow through the constant flow valve restrictor in non-dimensional form is expressed [Sharma et al, 2000] as

$\bar{Q}_R = \bar{Q}_c$, A constant .... (6)

SOLUTION PROCEDURE

The following numerical procedure is adopted for the computation of performance characteristics of misaligned hole-entry hybrid journal bearing including surface roughness effects. Initially for a specified external load $\bar{W}_o$, assuming steady state condition (i.e. $\dot{\bar{X}}_J = \dot{\bar{Z}}_J = 0$), the value of nominal fluid-film thickness $\bar{h}$, the average fluid-film thickness $\bar{h}_T$ and flow factors ϕ_x, ϕ_y and ϕ_s are computed for the tentative values of journal center position $\bar{X}_J$ and $\bar{Z}_J$ using Eqns.1-3 at all node points. The lubricant flow field system equation (Eqn.5), after adjustment for the flow through the constant flow valve restrictor (Eqn.6) and modification for proper boundary conditions is solved for the nodal fluid-film pressure distribution. Using the fluid-film pressure distribution, the journal center equilibrium position ($\bar{X}_J, \bar{Z}_J$) for the given vertical external load ($\bar{W}_o$) is established using a suitable iterative scheme. Once the equilibrium journal center position is established, the static performance characteristics are computed utilizing the relations published elsewhere by the authors [Jain et al, 1997].

RESULTS AND DISCUSSION

The static performance characteristics of a hole-entry hybrid journal bearing system including the effect of surface roughness have been obtained using the analysis and solution algorithm described in the previous sections. It is assumed that the journal and bearing surfaces have the same surface pattern parameter ($\gamma_J = \gamma_b = \gamma$). The results are presented for isotropic roughness pattern ($\gamma = 1$) with surface roughness parameter $\Lambda = 3$ and 5 for various values of restrictor design parameter $\bar{Q}_c = 0.03 - 0.07$ and for the values of external load $\bar{W}_o = 1.25$. The representative values of misalignment parameters used in the present study are $\varphi = \delta = 0.0000$ (for aligned bearing), $\varphi = 0.0002, \delta = 0.0000$ (for vertically misaligned bearing), $\varphi = 0.0000, \delta = 0.0002$ (for horizontally misaligned bearing) and $\varphi = 0.0002, \delta = 0.0002$.

Fig.2 shows the variation of maximum fluid-film pressure $\bar{p}_{\max}$ with isotropic roughness and journal misalignment. At a constant external load ($\bar{W}_o$) and for a chosen value of restrictor design parameter ($\bar{Q}_c$), the value of $\bar{p}_{\max}$ is found to increase due to journal misalignment during both hydrostatic ($\Omega = 0.0$) and hybrid ($\Omega \ne 0.0$) mode of operations. The value of $\bar{p}_{\max}$ is seen to increase further as surface roughness parameter Λ reduces (i.e. as surface roughness increases) during both hydrostatic/hybrid modes of operations of a bearing, Fig.2a and 2b. It may be noted that as the value of Λ decreases, the bearing surface becomes rougher.

Fig.3 shows the variation of nominal minimum fluid-film thickness $\bar{h}_{\min}$ with isotropic roughness and journal misalignment. At a constant external load ($\bar{W}_o$) and for a chosen value of restrictor design parameter ($\bar{Q}_c$), the value of $\bar{h}_{\min}$ reduces due to journal misalignment during both hydrostatic (Fig.3a) and hybrid (Fig.3b) modes of operation of bearing. However, the value of $\bar{h}_{\min}$ increases as surface roughness increases (as the value of Λ reduces) as compared to that of a corresponding smooth bearing with same type of misalignment. Further, the reduction in the value of $\bar{h}_{\min}$ is seen to be more when the journal is misaligned about both horizontal and vertical axes (i.e. for $\varphi = 0.0002, \delta = 0.0002$).

Figs.4 and 5 show the variation of misaligning moment $\overline{M}_x$ (i.e. moment about X-axis) and $\overline{M}_z$ (i.e. moment about Z-axis) respectively with surface roughness parameter (Λ) and journal misalignment. From these figures it may be observed that the values of $\overline{M}_x$ is positive (Fig.4a and 4b) and that of $\overline{M}_z$ is negative (Fig.5a and 5b) during both hydrostatic/hybrid modes of operations. It may be noted that in hydrostatic mode of operation, the value of $\overline{M}_x$ and $\overline{M}_z$ is zero for

CONCLUSIONS

On the basis of the results presented, the following conclusions have been drawn:

1. Inclusion of journal misalignment and surface roughness effects in the analysis affects the static performance characteristics of a constant flow valve compensated hole-entry hybrid journal bearing system appreciably. The combined influence of journal misalignment and surface roughness is to increase the values of maximum pressure $\overline{p}_{\max}$ and misalign moments $\overline{M}_x$ and $\overline{M}_z$.
2. At a constant external load ($\overline{W}_o$) and for a selected value of restrictor design parameter $\overline{Q}_c$, the value of minimum fluid-film thickness $\overline{h}_{\min}$ reduces due to journal misalignment. The inclusion of surface roughness in the misaligned hole-entry hybrid journal bearing enhances the value of $\overline{h}_{\min}$ as compared to corresponding smooth misaligned bearing.

3. The study undertaken in the present work amply demonstrates that, for a non-recessed hole-entry hydrostatic/hybrid journal bearing system, the inclusion of surface roughness effect in the analysis is more appropriate for a realistic prediction of bearing characteristics data.

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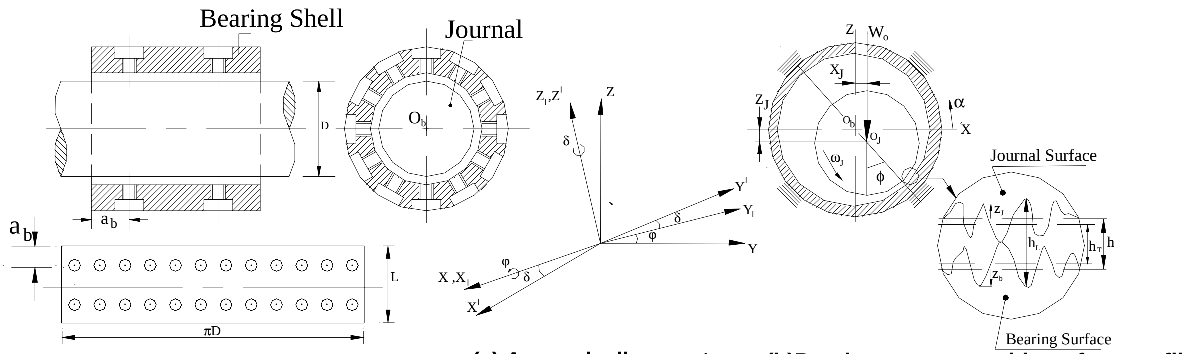

(a) Hole-entry bearing configuration **(c) Axes misalignment** **(b)Bearing geometry with surface profile**

Fig. 1 Hole-Entry Journal Bearing System

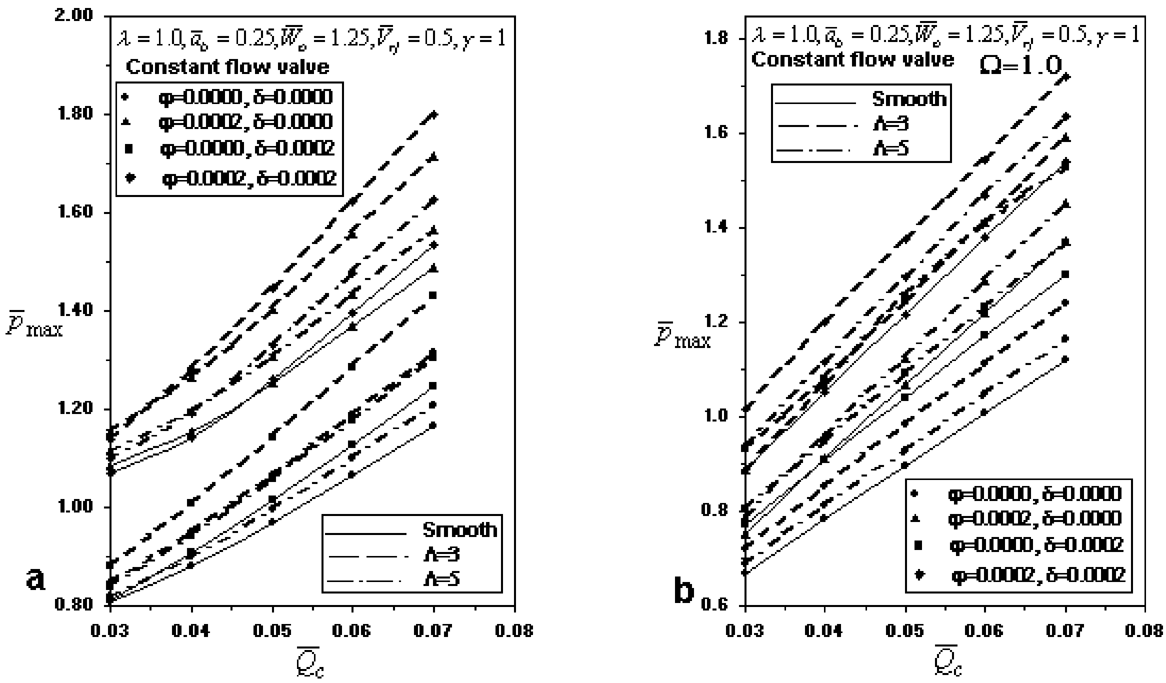

Fig. 2 Maximum fluid –film pressure ($\bar{p}_{max}$)

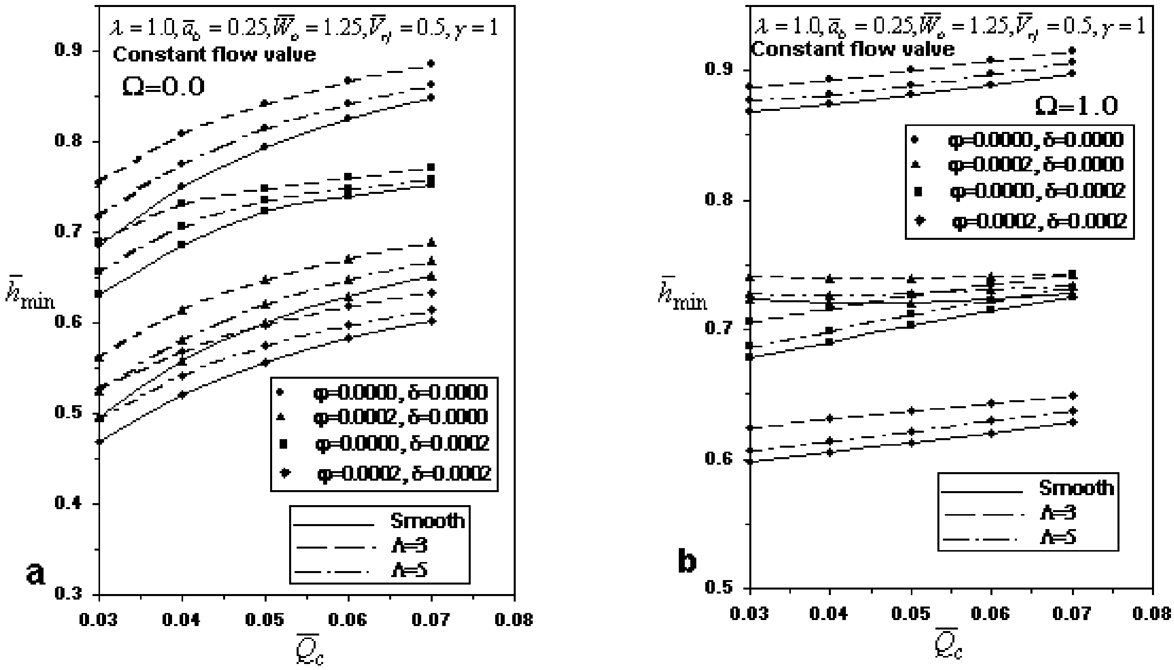

Fig. 3 Nominal minimum fluid –film thickness ($\bar{h}_{max}$)

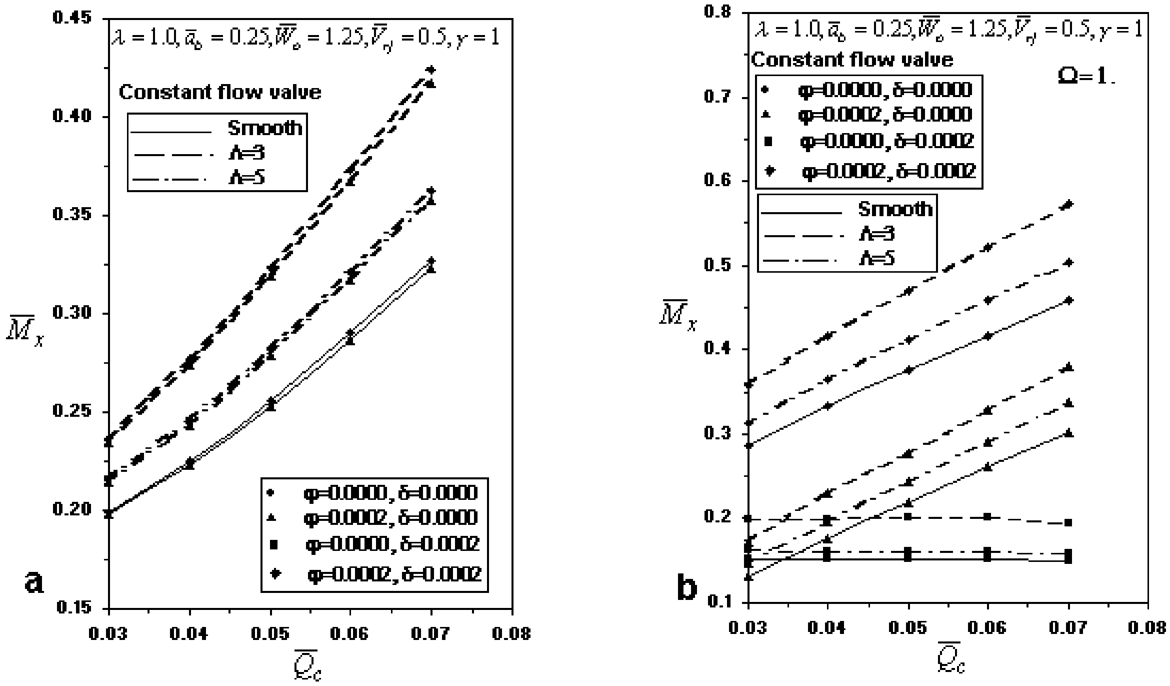

Fig. 4 Misaligning moment ($\overline{M}_{max}$)

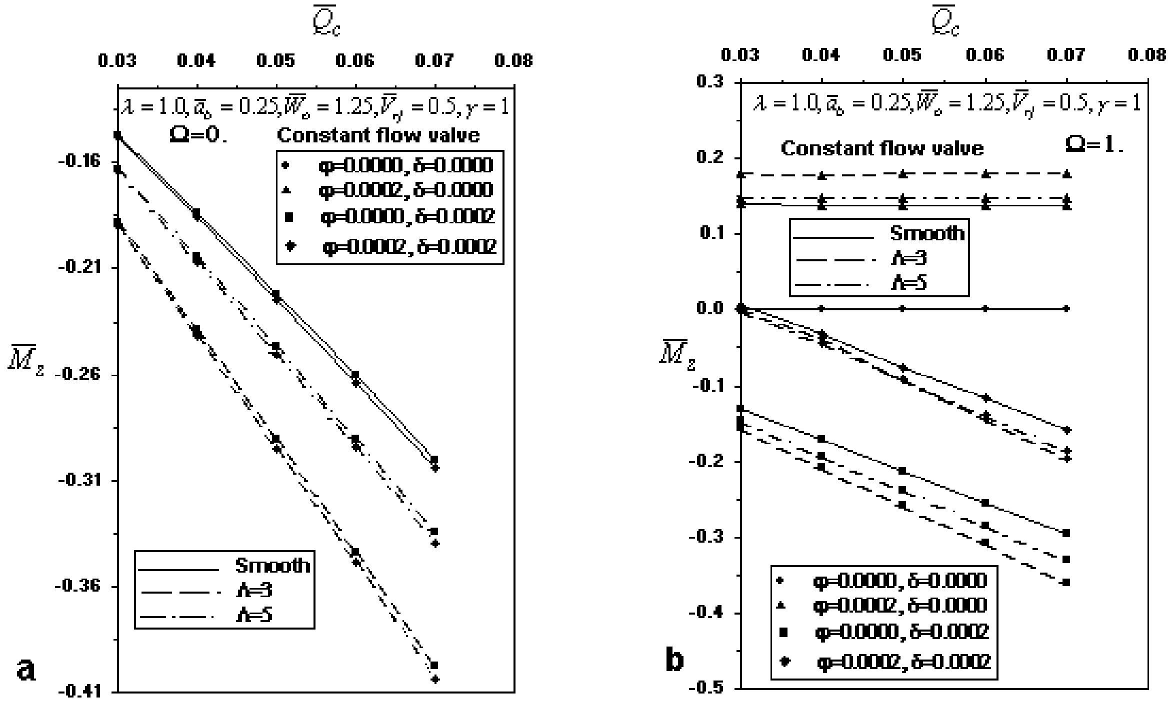

Fig. 5 Misaligning moment ($\overline{M}_{max}$)