1215

Characteristics of Dynamic Coefficients on Stability for Herringbone-Grooved Journal Bearings

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Abstract: This work proposes a novel approach to analyze the stability characteristics for the dynamic coefficients of a herringbone-grooved journal bearing. Based on the perturbation method at the equilibrium position of a journal bearing, this study expresses the variation of critical mass as the derivation of eight dynamic coefficients: four stiffness and four damping coefficients. Since the relationship between the critical mass and the eight dynamic coefficients is very complicated, it is difficult to judge the influence in previous studies of an individual dynamic coefficient on stability. The method presented in this paper can investigate quantitatively which dynamic coefficients dominate stability. The results show that the coefficients K_{xx} and K_{yx} increase and improve the stability as the eccentricity ratio increases. As the groove geometry changes, the coefficients governing stability depend on the parameters of groove geometry: groove depth, groove width, and groove angle. When the groove angle changes, variations in K_{xy} always exert negative influences on stability. When the groove depth or the groove width increases, the change in D_{yy} exerts a significant negative influence on stability. With an increase in the groove angle or groove pattern, the negative effect of D_{yy} on the bearing decreases. Accordingly, the influence of variations in the groove depth is similar to that of variations in the groove width.

Keywords: Herringbone-grooved journal bearing, stiffness, damping, stability, spectral element method

1. Introduction

Herringbone-grooved journal bearings (HGJBs) have been applied frequently in the computer information storage industry for high rotating speed performance, such as hard disk drives for computers and fans for mobiles. Moreover, employing herringbone grooves on the journal bearing increases spindle stiffness [1] and enhances the mechanical damping of a bearing system. The requirements for large-capacity data storage have increased markedly, making it essential to improve the stability characteristics of the bearing system when a magnetic head is reading or recording on a magnetic disk. Therefore, the effects of herringbone grooves on highly stable journal bearings warrant investigation.

The important dynamic characteristics of journal bearings can be broken down into the spring and damping properties. In general, the bearing's force-displacement relationship is collinear. Thus, a simple rotor bearing

system uses the isotropic force model to describe the bearing's force-deflection behavior. The displacement of a hydrodynamic journal bearing, however, is not linearly dependent on the hydrodynamic resistance force.

When a hydrodynamic journal bearing is displaced from its equilibrium position, the characteristics of the bearing's reaction can be represented by the means of four stiffness and four damping coefficients. Kirk [2] indicated that the cross-coupling terms K_{xy} and K_{yx} are the major sources of instability, while the cross-coupling damping terms D_{xy} and D_{yx} are the minor factors in determining stability. As shown in figure 1.1, cross-coupled stiffness produces a tangential force proportional to the shaft deflection [3]. When they considered journal bearing with herringbone grooves, Bonneau and Absi presented the stiffness coefficients associated with changes of the groove geometry and the eccentricity ratio [4]. However, their contributions are not applicable to investigate the relationship between dynamic coefficients and stability. In

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Refs. [2,5], the authors mentioned that the principal stiffness terms K_{xx} and K_{yy} exerted positive effects on stability. In addition, that literature pointed out that the cross-coupled stiffness influences stability: when K_{xy} is negative and opposite in sign to K_{yx}, that combination leads to instability. Therefore, the two coefficients K_{xy} and K_{yx} are the two dominant factors for instability. In addition, Ref. [6] mentioned that when the negative sign of K_{xy} turns positive, K_{xy} then contributes to the stability of the bearing. The methods described in the references described above determined the degree of influence on stability based on the value of the dynamic coefficients. Notably, the studies above discussed the dynamic coefficients of a plain journal bearing.
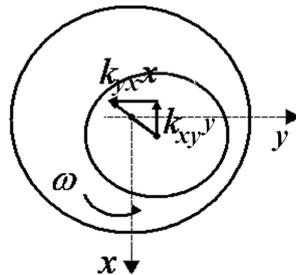
Figure 1.1 Cross-coupling stiffness in a journal bearing

In a study by Lund, he suggested that the dynamic coefficients are impractical for design purposes [7] and reviewed the stability criteria of the system associated with the concept of critical mass. Since the relationships between the critical mass and the eight dynamic coefficients are very complicated, it is difficult to judge the influence of an individual dynamic coefficient on stability.

To design the configuration of HGJBs, it is necessary first to understand the influence of groove parameters on stability. Zirkelback and San Andres [8] discussed the effects on the dynamic coefficients and the critical mass of HGJBs from changing the groove geometry. However, their contributions are not applicable to investigate the correlations between the coefficients and stability, nor the relationship between the groove angle and critical mass. Rao and Sawiski [9] clearly showed that HGJBs have a higher critical speed for concentric operation than plain journal bearings do, but how the shape of groove might affect the stability is still needed to be examined.

This paper analyzes the influences on critical mass of changing dynamic coefficients by altering the eccentricity ratio and the HGJB's groove parameters, and discusses the variations of the dynamic coefficients with the changes of critical mass. In order to calculate the pressure distribution of the fluid film, we solve the Reynolds equation by the spectral element method [10]. In addition, we use the perturbation method to work out the stability parameters of the bearings, i.e. the dynamic coefficients and the stability threshold. As the eccentricity ratio or the groove geometry changes, we analyze the variation in the critical mass through the changes of eight coefficients, conclude whether their contributions had a positive or negative influence on stability. Using the methods described, we analyze the consequence at the equilibrium position of changing the groove parameters, such as groove angle, groove depth, and groove width.

2. Analysis

Governing Equation Figure 2.1 displays the coordinate system and geometry of HGJBs. The curvature of the film in journal bearings is ignored. Since the film thickness h is relatively small, compared with the radius of the bearing r, the fluid film can be unwrapped into a plane. The Reynolds equation for the steady state, laminar, isothermal and incompressible flow is:

$$\frac{1}{r^2}\frac{\partial}{\partial \phi}\left[\frac{h^3}{12\mu}\frac{\partial p}{\partial \phi}\right] + \frac{\partial}{\partial z}\left[\frac{h^3}{12\mu}\frac{\partial p}{\partial z}\right] = \frac{\omega}{2}\frac{\partial h}{\partial \phi}, \quad (1)$$
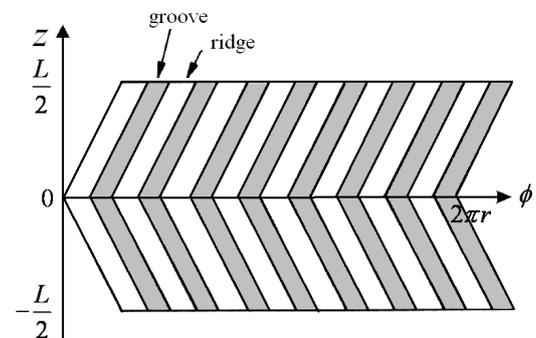
Figure 2.1 Geometry of herringbone grooved journal bearing

where the coordinate system (ϕ, z) is fixed to the bearing, p is the pressure in the fluid film, ω is the angular velocity, μ is the coefficient of viscosity. The fluid thickness h in the ridge and the groove regions, in terms of circumferential coordinates ϕ, are:

$$h = c(1 + \varepsilon \cos \phi) \quad (2)$$

in the ridge, and

$$h = c_g + c(1 + \varepsilon \cos \phi) \quad (3)$$

in the groove, with clearance c, groove depth c_g, and eccentricity ratio ε. The pressure field is continuous in the circumferential direction

$$p(\phi, z) = p(\phi + 2\pi, z), \quad (4)$$

and the pressure boundary conditions at bearing edges are

$$p(\phi, \frac{L}{2}) = p(\phi, -\frac{L}{2}) = 0 \qquad (5)$$

The cavitation algorithm is based on the Swift-Stieber condition [11].

$$p_{cav} = \left. \frac{\partial p}{\partial \theta} \right|_{cav} = 0 \qquad (6)$$

Once Eq. (1) is solved for the pressure in the equilibrium state, the radial and tangential loads can be obtained by integrating over the bearing area,

$$W_t = \int_A pr\sin(\pi - \phi)dzd\phi \qquad (7)$$

$$W_r = \int_A pr\cos(\pi - \phi)dzd\phi \qquad (8)$$

and the load can be expressed as

$$W = (W_t^2 + W_r^2)^{1/2} \qquad (9)$$

Perturbation method When the journal position changes slightly from the equilibrium state, the load also changes immediately; this may result in instability. Therefore, this paper uses the perturbation method [7] to study stability conditions. By assuming that a small reaction occurs about the equilibrium state, the pressure and the fluid film thickness displacement can be expressed as a first-order function of small perturbation

$$p_p = p_0 + p_x \Delta x + p_y \Delta y + p_{\dot{x}} \Delta \dot{x} + p_{\dot{y}} \Delta \dot{y} \qquad (10)$$

$$h_p = h_0 + \Delta x \cos\phi + \Delta y \cos\phi \qquad (11)$$

Substituting Eq. (10) and Eq. (11) into Eq. (1), the changes in the pressure of a journal near the equilibrium position can be calculated

$$\frac{1}{r^2}\frac{\partial}{\partial \phi}\left[\frac{h_p^3}{12\mu}\frac{\partial p_p}{\partial \phi}\right] + \frac{\partial}{\partial z}\left[\frac{h_p^3}{12\mu}\frac{\partial p_p}{\partial z}\right]$$
$$= \frac{\omega}{2}\frac{\partial h_p}{\partial \phi} + \Delta \dot{x}\cos\phi + \Delta \dot{y}\cos\phi \qquad (12)$$

Once the perturbation pressure is known, dynamic coefficients can be calculated by integration over the bearing area [12]. For example, the dimensionless coefficient K_{xx} can be obtained by

$$K_{xx} = \frac{c}{W}\int_y \int_\phi p_x \cos\phi \, rdzd\phi \,, \qquad (13)$$

and the pressure p_x is solved by collecting the terms of $O(\Delta x)$ in Eq. (12)

$$\frac{1}{r^2}\frac{\partial}{\partial \phi}\left[\frac{h_0^3}{12\mu}\frac{\partial p_x}{\partial \phi}\right] + \frac{\partial}{\partial z}\left[\frac{h_0^3}{12\mu}\frac{\partial p_x}{\partial z}\right]$$
$$= \frac{-\omega}{2}\left(\sin\phi + \frac{3\cos\phi}{h_0}\frac{\partial h_0}{\partial \phi}\right) - \frac{h_0^3}{4\mu r^2}\frac{\partial p_0}{\partial \phi}\frac{\partial}{\partial \phi}\left(\frac{\cos\phi}{h_0}\right) \qquad (14)$$

Note that the linear perturbed equation (12) is similar to Eq. (1), so the numerical code developed for the equilibrium state in the authors' previous study [10] can be applied directly. The dimensionless critical mass M_{cr} and whirl frequency ω_0 are [12]

$$M_{cr} = \frac{\kappa_0}{\omega_0^2} \qquad (15)$$

$$\omega_0^2 = \frac{(K_{xx} - \kappa_0)(K_{yy} - \kappa_0) - K_{xy}K_{yx}}{D_{xx}D_{yy} - D_{xy}D_{yx}} \qquad (16)$$

with

$$\kappa_0 = \frac{K_{xx}D_{yy} + K_{yy}D_{xx} - K_{xy}D_{yx} - K_{yx}D_{xy}}{D_{xx} + D_{yy}} \qquad (17)$$

Derivation of critical mass The dimensionless critical mass is a complicated function of eight dynamic coefficients. As the operation condition or the groove parameters, denoted by f, of the journal bearing change, the change of critical mass with the property f can be written as

$$\frac{dM_{cr}}{df} = \frac{\partial M_{cr}}{\partial K_{xx}}\frac{dK_{xx}}{df} + \frac{\partial M_{cr}}{\partial K_{xy}}\frac{dK_{xy}}{df} + \frac{\partial M_{cr}}{\partial K_{yx}}\frac{dK_{yx}}{df} + \frac{\partial M_{cr}}{\partial K_{yy}}\frac{dK_{yy}}{df}$$
$$+ \frac{\partial M_{cr}}{\partial B_{xx}}\frac{dD_{xx}}{df} + \frac{\partial M_{cr}}{\partial D_{xy}}\frac{dD_{xy}}{df} + \frac{\partial M_{cr}}{\partial D_{yx}}\frac{dD_{yx}}{df} + \frac{\partial M_{cr}}{\partial D_{yy}}\frac{dD_{yy}}{df} \qquad (18)$$

where f could be groove angle, groove depth, groove width, or any operating parameters of the hydrodynamic journal bearing. There are eight components on the right-hand side (RHS) of Eq. (18). Each component on the RHS of Eq. (18) can be considered as the contribution to the change of critical mass by an individual dynamic coefficient. For example, the first term, $\frac{\partial M_{cr}}{\partial K_{xx}}\frac{dK_{xx}}{df}$, is the contribution of dynamic coefficient K_{xx} to the critical mass as the property f changes slightly. If the value $\frac{\partial M_{cr}}{\partial K_{xx}}\frac{dK_{xx}}{df}$ is positive, that means that the contribution of dynamic coefficient K_{xx} to the stabilization of the system is positive. If the component of an individual dynamic coefficient is negative, that dynamic coefficient destabilizes the system. This work adopts a commercial code Mathematica for computation of partial derivatives of the critical mass with respect to an individual dynamic coefficient; i.e., the eight components on the RHS of Eq. (18).

3. Results and Discussion

We investigate the effects on stability of the variations in dynamic coefficients, based on the operating parameters that change as the critical mass changes. We also discuss how coefficients impact the critical mass by changing the operational features, such as the eccentricity ratio and the geometric shape of the grooves. The simulation for this paper is performed considering 17 circumferential elements and eight axial elements. Table 1 shows the geometrical parameters of HGJBs.

Table 1 Parameters of the HGJB

Clearance	6 [μm]
Radius	0.002 [m]
Length	0.004 [m]
Fluid viscosity	0.00124 [Pa-s]
Number of grooves	8
Groove angle	20-70 [deg]
Groove depth ratio	0.5-1.5
Groove width ratio	0.3-0.7
Ambient pressure	0 [N/m^2]

Figure 3.1 Comparison of load with the study [13]

Figure 3.2 Validation on critical mass with Hamrock [13]

In the following sections, we first discuss how variations in the operational conditions of the plain journal bearing affect stability. By changing some of the operational conditions of the journal bearing—namely, the eccentricity ratio and the length of the bearing—variations in critical mass can be observed. From these observations, we can infer the influence on stability of variations in the eccentricity ratio and the length of the bearing. Specifically, we can infer whether the bearing is more stable or unstable. Furthermore, when operational parameters change, we can observe variations with every dynamic coefficient. Thus, large variation is the coefficient that mainly affects critical mass and exerts a large influence on stability. In this approach, we can identify the main dynamic coefficient that affects stability.

In considering the stability of a plain journal bearing, we discuss the influence of changing the shape of the groove in the bearing to make it a herringbone groove. This study also discusses the main dynamic coefficient that affects stability—the relationship of groove shapes—as well as the contributions of the dynamic coefficients to determining critical masses. Furthermore, this paper compares the main coefficients that affect stability when changing the groove angle, the groove width, and the groove depth of a HGJB in order to determine the difference or similarity between the main coefficients that affect stability.

Validation The calculated numerical results are verified by comparison with experimental load and critical mass data. Figure 3.1 shows that the bearing load capacity agrees well with the experimental data from Hirs [13]. Figure 3.2 demonstrates that the critical mass of each different eccentricity ratio approaches the exact solution for a short bearing [13] as bearing length L decreases. Thus the numerical program developed for stability in an equilibrium state is accurate.

Effect on critical mass of changing the length of a plain journal bearing In this section, we explore how to determine the influences of the eccentricity ratio and the length of the bearing on the critical mass. The length of the bearing is changed to reduce the length-diameter ratio $1/\lambda$ to 1/16 from 1. As shown in figures 3.2 and 3.3, when the eccentricity ratio is greater than 0.5, increasing the eccentricity ratio increases the critical mass under every
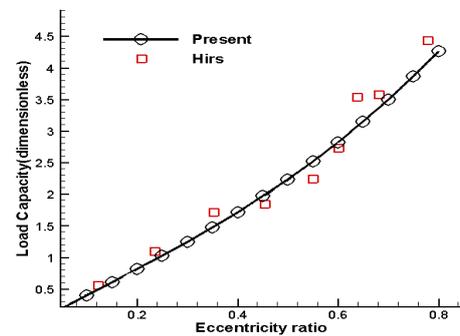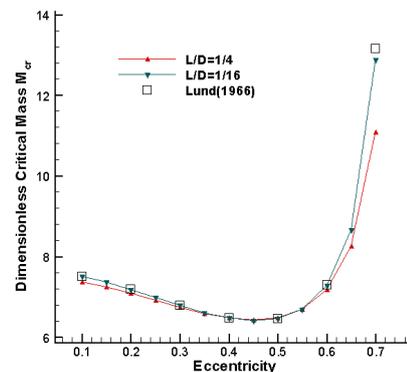
length-diameter ratios of the bearing. On the other hand, the critical mass at a length-diameter ratio of 1/4 is almost the same when the bearing has a length-diameter ratio of 1/16. As a result, for short bearings, the critical mass is insensitive to varying the length of the bearing.

When the eccentricity ratio is greater than 0.5, increasing the eccentricity ratio results in significantly increasing the critical mass. In next sections, this paper explore whether variations in groove appearances make a particular dynamic coefficient contribute more significantly to an increase or decrease of the critical mass.

Figure 3.4 shows the relationship between the variation in the coefficients and the variation in the critical mass. When the length-diameter ratio is 1 and the eccentricity ratio is greater than 0.5, the K_{xx} and K_{yx} components in Eq. (18) increase the critical mass significantly as the eccentricity ratio increases. As a result, when the eccentricity ratio is large, K_{xx} and K_{yx} are the dominant dynamic coefficients to promote stability.
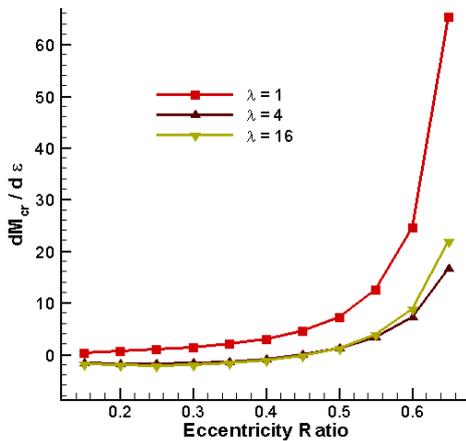
Figure 3.3 Critical mass at different groove diameter-length ratio
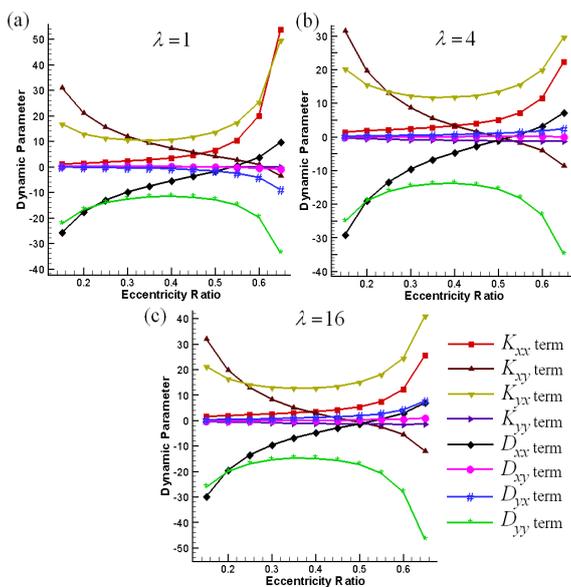
Figure 3.4 The variation of dynamic coefficients on critical mass at different length-diameter ratios

These dynamic coefficients benefiting stability are same as those obtained in the studies by Refs [2,5].

In a similar manner, this work also identifies the dynamic coefficients that affect stability negatively. Variation in D_{yy} reduces the critical mass when the eccentricity ratio is large, resulting in a negative effect on stability. In addition, we found that the effect on stability of some dynamic coefficients is not always positive or always negative. When the eccentricity ratio increases, variation in K_{xy} promotes stability, by affecting the critical mass when variation in K_{xy} is over zero, and

promotes instability when variation in K_{xy} is below zero. Therefore, K_{xy}'s influence on the critical mass reverses from positive to negative when the eccentricity ratio increases, while D_{xx}'s influence on the critical mass turns from negative to positive when the eccentricity ratio increases. Therefore, by observing the influence of the variations in dynamic coefficients on the critical mass, the method described in this paper provides a clearer perspective of the degree to which the variations of dynamic coefficients under different operating conditions influence stability. Notably, critical mass is a complicated parameter as shown in Eqs. (15)–(17). Accordingly, by applying the present method—the variable of each dynamic coefficient is partially differentiated with respect to the operational conditions—the values contributed by each dynamic coefficient can be compared. Observing the variation in the critical mass resulting from different operational conditions, we can find which dynamic coefficients contribute to the increase or decrease in the critical mass.

The following section discusses how adopting a herringbone pattern for the groove in the bearing affects the main dynamic coefficients that benefit or harm stability, and compares the result with that of plain journal bearing. Ultimately, we discuss whether adding the herringbone-pattern grooves changes the major dynamic coefficients that exert positive or negative influence on stability. In addition, employing the methodology in this study can understand the stability characteristics of journal bearings with other groove patterns [14–16].

Effect on the critical mass of changing the groove angle of HGJBs Table 1 presents the geometrical parameters of the HGJBs used in this study. The groove angle alters from 20 deg to 70 deg; other groove parameters remain unchanged. We discuss the influence of varying the groove angle and the eccentricity ratio on the critical mass, and then discuss the changes in the critical mass arising from the dynamic coefficients. Moreover, we can determine the degree of influence on the critical mass exerted by the dynamic coefficients.

a. Changing the eccentricity ratio while the groove angle remains fixed

As shown in figure 3.5, when the eccentricity ratio is in the range between 0.1 and 0.3, the critical mass differs only slightly under different groove angles. When the eccentricity ratio is greater than 0.3, peak value of the critical mass occurs at a groove angle 20 deg. On the other hand, when the groove angle is greater than 50 deg, the critical masses differ only slightly. After observing how variations in the dynamic coefficients influence stability, we find that changing the groove angle and the eccentricity ratio changes the influences. When the groove angle is less than 30 deg and the eccentricity ratio is greater than 0.5, increasing the eccentricity ratio increases the critical mass.

As shown in figure 3.6, dynamic coefficients that profit from the critical mass are contributed mainly by K_{xx} and K_{yx}. Furthermore, the smaller the groove angle is, the more
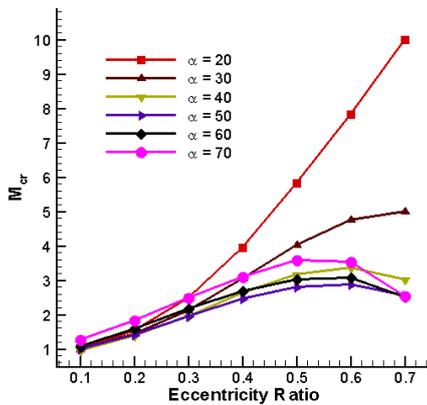
Figure 3.5 Critical mass of different groove angles α

Figure 3.6 The variation of dynamic coefficients on critical mass at different groove angles

these two coefficients contribute to increasing the critical mass.

As a result, increasing groove angle decreases the contribution of K_{xx} and K_{yx} to stability. By the same token, variation in D_{yy} should influence stability negatively. In addition, at different eccentricity ratios, the dynamic coefficients can produce both positive and negative influences on stability in HGJBs; this is also observed in plain journal bearings. For instance, when the eccentricity ratio increases, variation in K_{xy}, which determines the critical mass, promotes stability when it is above zero and destabilize the bearing when it is below zero. That is to say, the influence turns from positive to negative; and the influence of D_{xx} on the critical mass turns from negative to positive. Hence, when the eccentricity ratio changes for bearings with grooves, the main dynamic coefficients that promote negative and positive effects on stability at different groove angles stay the same as those of a plain journal bearing. However, the magnitude of variations in dynamic coefficients with changes in the eccentricity ratio is different under different groove angles. The sum of these differences is the discrepancy of the critical mass.

On the other hand, when the eccentricity ratio is fixed, this study determines the influence of the groove angle on stability by examining which dynamic coefficients are responsible for the change in the critical mass that accompanies the change in the groove angle.

b. Changing the groove angle while the eccentricity ratio is fixed

Examining the influence of dynamic coefficients on stability (figure 3.7), it is found that when the eccentricity ratio increases, the negative effect of K_{xy} on stability increases with an increase of the groove angle. Furthermore, K_{xy} exerts no positive influence on stability under any eccentricity ratio. In addition, under the same eccentricity ratio, dynamic coefficients of different groove angles could exert either positive or negative influence on stability. When the groove angle is small, D_{yx} exerts
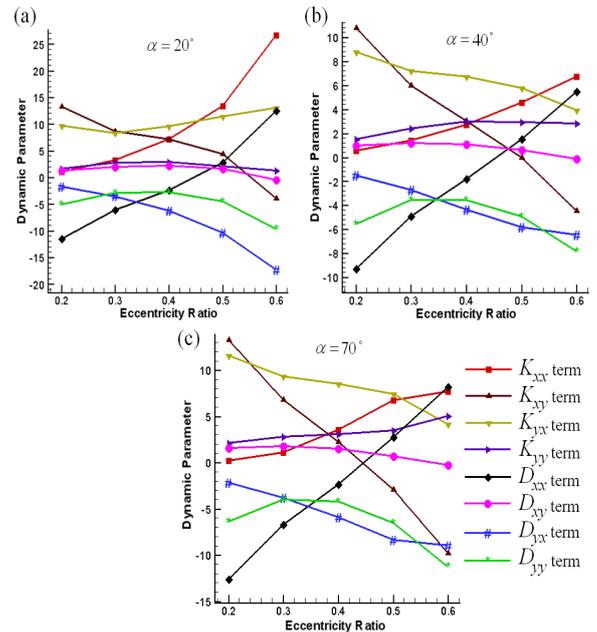
positive influence on stability, and this positive influence decreases as the groove angle increases. Contrariwise, when the groove angle is large, D_{yx} exerts negative influence on stability. Similarly, the influence of D_{yy}, on stability turns from negative to positive with as the groove angle increases.
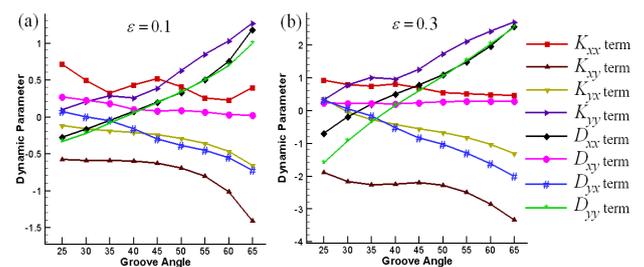
Figure 3.7 The variation of dynamic coefficients on critical mass at different eccentricity ratios ε when groove angle changes

From the comparisons in the preceding two sections, we conclude that when the eccentricity ratio is fixed while the groove angle changes, the main coefficients that affect the critical mass are different from those that affect the critical mass when the groove angle is fixed and the eccentricity ratio changes.

Effect on the critical mass of changes in the groove depth of HGJBs In this section, we discuss the influence

on the critical mass resulting from changing the groove depth ratio and the eccentricity ratio. The groove depth ratio changes from 0.5 to 1.5 while other groove parameters remain unchanged.

a. Changing the eccentricity ratio with fixed groove depth

When the depth ratio is less than 1 and the eccentricity ratio is greater than 0.5, the variation in K_{xx} and K_{yx} results in a significant increase in critical mass (figure 3.8). Therefore, the dynamic coefficients K_{xx} and K_{yx} are the dominant factors in promoting stability when the eccentricity ratio is large. By the same token, figure 3.8 shows that when the eccentricity ratio changes, the influence on stability of variation in D_{yy} is negative. With an increasing eccentricity ratio, the influence of K_{xy} on the critical mass changes from positive to negative, while the influence of D_{xx} on critical mass changes from negative to positive.

When the groove depth ratio is fixed and the eccentricity ratio changes, the main dynamic coefficients that promote negative and positive effects on stability are the same with those that affect the plain journal bearing: under different groove depths, main dynamic coefficients that promote negative and positive effects on stability will differ with changes in the eccentricity ratio. On the other hand, we can also determine the influences of the groove depth on stability by examining which dynamic coefficients are responsible for the change in the critical mass accompanying changes to the groove depth at a fixed eccentricity ratio.
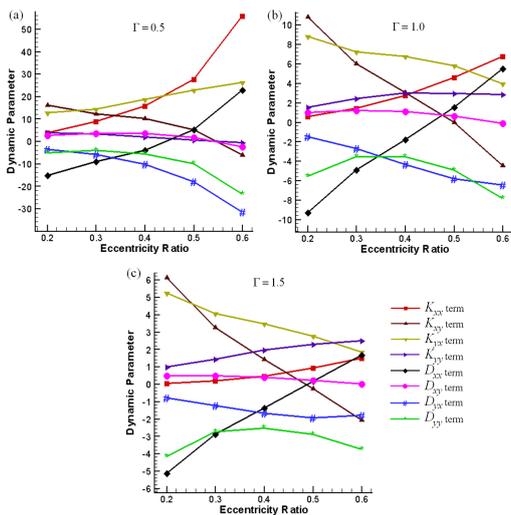
Figure 3.8 The variation of dynamic coefficients on critical mass at different depth ratios

b. Changing the groove depth with the eccentricity ratio fixed

When the eccentricity ratio is fixed and the groove depth is shallow, variation in D_{yx} exerts a significantly positive influence on stability (figure 3.9). However, as the groove depth increases, the positive effect on stability of D_{yx} decreases. That is, when the groove depth is small, D_{yx} is sensitive to changes in the groove depth. When the eccentricity ratio increases, the change in D_{yy} exerts significant negative influence on stability, but as the depth of the grooves increases, the negative effect on stability of D_{yy} decreases. Thus, D_{yy} is more sensitive to changes in the depth of the bearing when the groove depth is small.
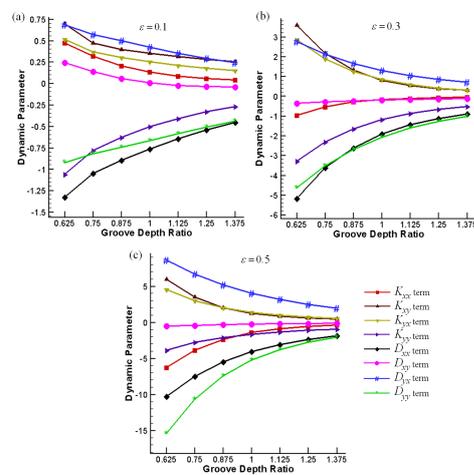
Figure 3.9 The variation of dynamic coefficients on critical mass at different eccentricity ratios when groove depth ratio changes

We conclude in previous section that even at a fixed eccentricity ratio, dynamic coefficients may exert opposite influence on stability for different groove angles. In contrast, as the groove depth changes, every dynamic coefficient consistently exerts either a positive or a negative influence on stability, which differs from the result when the groove angle changes.

Effect on critical mass of changing the width of grooves of HGJBs The following section will discuss the influence on the critical mass and dynamic coefficients resulting from changing the groove width ratio and the eccentricity ratio of HGJBs.

a. Changing the eccentricity ratio while the groove width remains fixed

Figure 3.10 indicates the magnitude of the contribution to stability made by varying the dynamic coefficients when the eccentricity ratio changes. When the groove width ratio is less than 0.5, changing the eccentricity ratio to above 0.5 will cause variations in K_{xx} and K_{yx}, resulting in a significant increase of the critical mass. Accordingly, when the eccentricity ratio is large, the dynamic coefficients of K_{xx} and K_{yx} are the dominant
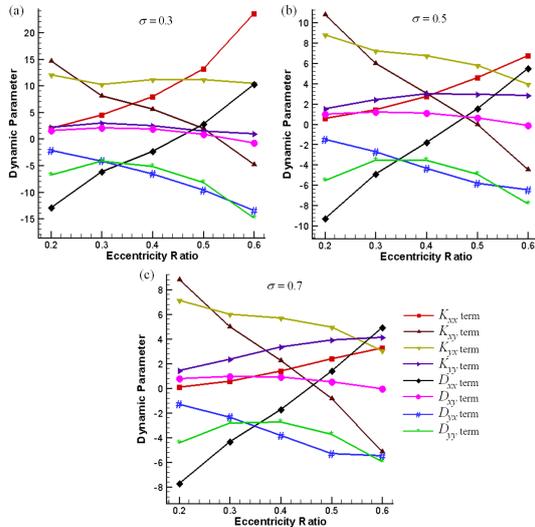
Figure 3.10 The variation of dynamic coefficients on critical mass at different width ratios σ

factors that promote stability. By the same token, when the eccentricity ratio changes, the variation in D_{yy} negatively affects stability. When the eccentricity ratio increases, the influence of K_{xy} on the critical mass turns from promoting stability when it is over zero, to causing instability when it is below zero. In contrast, the influence of D_{xx} on the critical mass changes from negative to positive. From the preceding result, we have shown that when the groove width ratio is fixed and the eccentricity ratio changes, the dynamic coefficients that mainly affect stability are the same as those determined in several previous sections.

b. Changing the groove width with a fixed eccentricity ratio

Figure 3.11 shows the influence of the variation in dynamic coefficients on the critical mass when the groove width changes while the eccentricity ratio remains fixed. When the eccentricity ratio is small, the critical masses under different groove widths are close to each other. Thus, the influence of dynamic coefficients on critical mass differs little under various groove widths.

After observing how variations in dynamic coefficients influence stability when the eccentricity ratio is large, we found that D_{yx} will exert a significant positive influence on stability when the groove width is small. However, increasing the width of the groove will decrease the positive effect on stability of D_{yx}. This means that under a fixed eccentricity ratio, D_{yx} is sensitive to changes in the bearing width when the groove width is small. The opposite phenomenon holds for D_{yy}: when the eccentricity ratio is high, D_{yy} will exert a significant negative influence on stability. With an increase in the width of the groove, the negative effect on stability of D_{yy}

will decrease. As a result, when the groove width is small, D_{yy} is sensitive to change in the groove width. In addition, every dynamic coefficient consistently exerts either positive or negative influence on stability when the groove width changes. This is the same as our finding when the groove depth changes. Thus, the result of changing the groove width is the similar to the effect on stability of HGJBs when the groove depth varies.
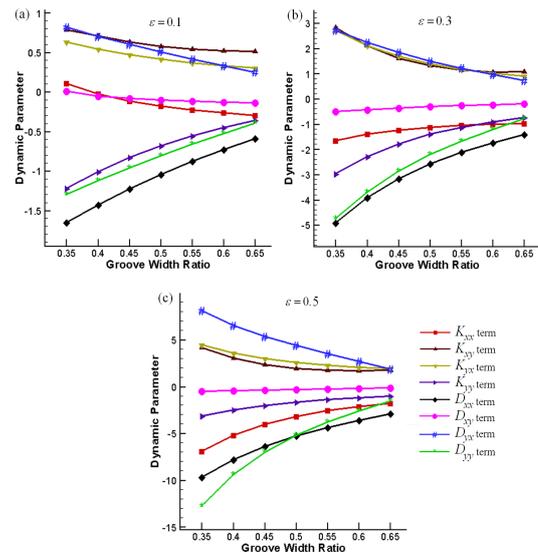
Figure 3.11 The variation of dynamic coefficients on critical mass at eccentricity ratio when groove width ratio σ changes

4. Conclusion

This paper investigates the characteristics of dynamic coefficients of HGJBs as they related to stability. Observing how variations in the dynamic coefficients affect the critical mass, this study determines which dynamic coefficients are the dominant factors in exerting positive and negative effects on stability, as follows:

1. When the eccentricity ratio is large, changes in that ratio will result in the increase of the dynamic coefficients K_{xx} and K_{yx} that exert significant positive influences on stability. On the contrary, variations in D_{yy} exert negative influence on stability. When the eccentricity ratio increases, the influence of K_{xy} on the critical mass changes from positive to negative, while the influence of D_{xx} changes from negative to positive.

2. The components of the dynamic coefficients in Eq. (18) that predominantly affect stability when the groove parameters change, under any fixed eccentricity ratio, are different from those under fixed groove parameters with a changing eccentricity ratio.

(1) When the groove angle changes, the component for K_{xy} of M_{cr} always exerts negative influences on stability. When the groove angle is small, D_{yx} exerts a positive influence on stability; however, with an increase in the angle, the positive effects of D_{yx} on stability decrease. Conversely, when the groove angle is large, variation in D_{yx} exhibits a negative influence on stability. In contrast, with an increase in the angle, the influence on stability of D_{yy} changes from negative to positive.

(2) When the groove depth or groove width changes, the dynamic coefficients will consistently exert a positive or negative influence on HGJBs. When the groove depth or width is small, D_{yx} exerts a significant positive influence on stability, but an increase in the groove depth or the groove width, will decrease the positive effects of D_{yx}. However, the opposite phenomenon occurs to D_{yy}. When the groove depth or the groove width increases, the change in D_{yy} exerts a significant negative influence on stability. With an increase in the groove depth or groove width, the negative effect of D_{yy} on the bearing decreases. Accordingly, the influence of variations in the groove depth is similar to that of the groove width. Therefore, the present approach clearly supplies the missing method to investigate the groove parameters of HGJBs that affect the critical mass.

Acknowledgement

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