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Design of Dimensionless Parameters of a Parallel Combination of Capillary restrictor and Membrane type restrictor in single-pad hydrostatic bearing set-up to achieve high static stiffness

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Abstract

Hydrostatic bearings have been frequently used in high-precision machine tools at the present time for their ability to perform accurately with durability. One of the key characteristic of hydrostatic system is the stiffness of the bearing and it is generally true to design a hydrostatic bearing with a higher stiffness, such that the variation of the deflection due to load variation is limited. For a single pad hydrostatic bearing set-up with membrane type restrictor, the bearing stiffness will tend to infinite at a dimensionless load capacity of 0.33. The corresponding design restriction ratio and dimensionless bearing stiffness are 0.25 and 1.33 respectively. The current research explains that with the use of a hybrid restrictor set-up i.e. parallel combination of a membrane type restrictor and fixed capillary restrictor, the bearing stiffness will tend to infinity at relatively higher dimensionless load capacity. A major finding of the research work is that a high static stiffness of the hydrostatic bearing can be obtained over a higher value of load capacity controlling three major design parameters and they are dimensionless capillary ratio(β_c), dimensionless membrane stiffness(K_r^*) and the design restriction ratio(λ) of the membrane restrictor system. Target of current research was to derive the relation between K_r^*, λ and β_c. It has been derived that K_r^* and λ are the function of β_c only. In the parallel combination of capillary restrictor and membrane type restrictor, capillary restrictor acts as a bypass restrictor and hence the above design may be adopted to delay the flow minimizing the clogging effect of membrane-type restrictor at starting.

Introduction

Hydrostatic bearings are fluid film bearings that rely on a film of lubricant to create a clearance between the fixed and moving part of the system. As pressurised high-pressure fluid is used to maintain the clearance, the clearance can be created at the stationary condition of rotor-bearings system. The performance of hydrostatic bearing typically depends upon the type of compensation mechanism used. Generally there are two types of compensation. One is passive compensation e.g. capillary and orifice restrictors [1]. The other is active compensation which include spools, membranes, and constant flow valves (Fig.1). The passive compensation restrictors generally offer a fixed resistance as it does not undergo any shape or configurational change with the change in load capacity. However actively compensated restrictors varies its resistance by changing the configuration and shape with the change in load capacity. The performance characteristics of an actively compensated restrictor is better than a passively compensated restrictor. In 1962, Mohsin [3] proposed various methods to improve the hydrostatic bearing stiffness. One of the effective method is to reduce the nominal clearance of the bearing. Another method is the use of opposed-pad bearing set up to improve the bearing stiffness for a higher load range. But these two ways have certain disadvantages. With decrease in nominal clearance, the viscosity friction increases, in results the losses goes on increasing. The opposed pad configuration design and manufacturing is very much complex. Lin SC [2] derived the optimized design parameters for a membrane-type restrictor which will lead to an infinite static stiffness condition for a hydrostatic bearing set up. He found that the bearing will attain a high static stiffness in a certain load range if the dimensionless membrane stiffness and design restriction ratio are taken 1.33 and 0.25 respectively. Bassani and Piccigallo (1992) [1] have provided the equations for flow rate, static load, and static stiffness for almost all type of compensation devices. Yuan Kang [4] showed that with the use of a pre-restrictor before the membrane-type restrictor the load capacity range decreases. Because of power consumption and environmental pollution issues, Gohara et al. [5] researched about the water-lubricated hydrostatic bearing with membrane-type restrictor to lower the power consumption of the system at relatively high working speed. The numerical and experimental results proved that the water lubricated hydrostatic bearing still

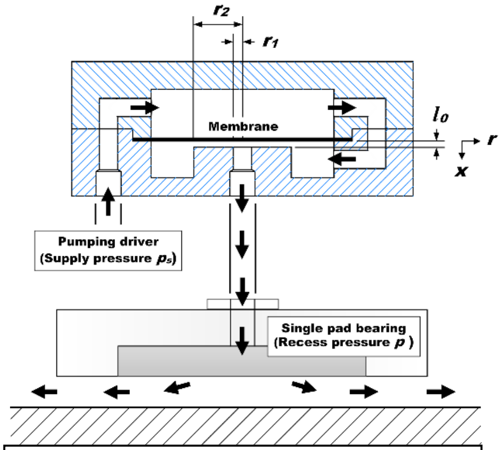

Fig. 1: A sketch plot for the full circuit diagram of membrane restrictor and bearing.

function with very high static stiffness even if the viscosity of lubricant is very small. Design of variable restrictors are much complicated than the design of fixed flow restrictors. Many design processes had been derived, but there is no general rule to be available for use by industry users and designers. In this paper the effect of a combination of capillary restrictor and membrane-type restrictor in a hydrostatic bearing set-up are studied. The dimensionless parameters are optimized for high static stiffness of the bearing. It is hoped to find the key values of the design parameters before following up particular references for more detailed design on a combination of capillary restrictor and membrane-type restrictor.

Mathematical Formulations

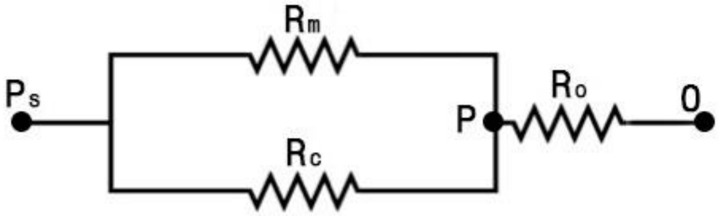

Fig.2: Equivalent circuit diagram of the proposed restrictor and bearing set-up

The equivalent restrictor resistance between the supply pressure and recess pressure is given by,

$$R_r = \frac{R_m R_c}{R_m + R_c} \tag{1}$$

The recess pressure in terms of supply pressure and dimensionless parameters are given by,

$$P = \frac{P_s}{1+\frac{1}{\frac{(1-\xi)^3}{\lambda}+\frac{1}{\beta_c}}} \tag{2}$$

The dimensionless membrane stiffness in terms of dimensionless parameters are given by,

$$K_r^* = \frac{3}{\lambda^{\frac{1}{3}}}\left(\frac{1}{\frac{P_s}{P}-1} - \frac{1}{\beta_c}\right)^2 \left(1 - \frac{P}{P_s}\right)^2 \tag{3}$$

The deformation ratio in terms of dimensionless parameters are given by,

$$\xi = 1 - \left(\frac{\lambda}{\frac{P_s}{P}-1} - \frac{\lambda}{\beta_c}\right)^{\frac{1}{3}} \tag{4}$$

The ideal deformation ratio in terms of dimensionless membrane stiffness is given by,

$$K_r^* \xi = 1 - \frac{P}{P_s} \tag{5}$$

When there is a good match between the ideal and real deformation ratio curves, the bearing stiffness should theoretically approach to infinity in that particular loading region which is shown in Fig.4.a, Fig.4.b and Fig.4.c. To have a good match, the practical dimensionless membrane stiffness should be approximately equal to the theoretical one [2].

The dimensionless clearance ratio in terms of load capacity is given by [1]

$$\frac{h}{h_0} = \left(\frac{R_0}{R_r}\frac{1-\frac{\beta W}{W_0}}{\frac{\beta W}{W_0}}\right)^{\frac{1}{3}} \tag{5}$$

Where $\frac{\beta W}{W_0}$ the dimensionless load capacity and R_r is the effective resistance between the parallel combination of capillary restrictor and membrane-type restrictor.

The bearing stiffness is given by [1]

$$K = 3\frac{W}{h}\frac{1}{\frac{1}{1-\frac{\beta W}{W_0}}+\frac{W\,dR_r}{R_r\,dW}} \tag{6}$$

Results and Discussion

The dimensionless membrane stiffness and the deformation ratio are computed for the following dimensionless parameters of the hydrostatic bearing

β_c = 1, 50, 100 and λ = 0.2, 0.4, 0.6, 0.8, 1

The dimensionless clearance ratio and the dimensionless bearing stiffness are computed for the following dimensionless parameters of the hydrostatic bearing

β_c = 1, 5, 20, 50, 100 and $\lambda = \lambda_{optimum} = \frac{1}{4}\left(\frac{\beta_c}{1+\beta_c}\right)$

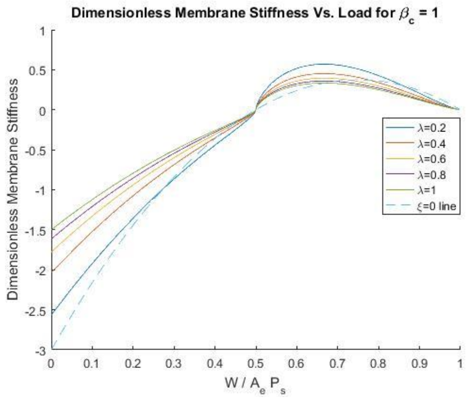

Fig.3.a: Dimensionless membrane stiffness variation for β_c = 1

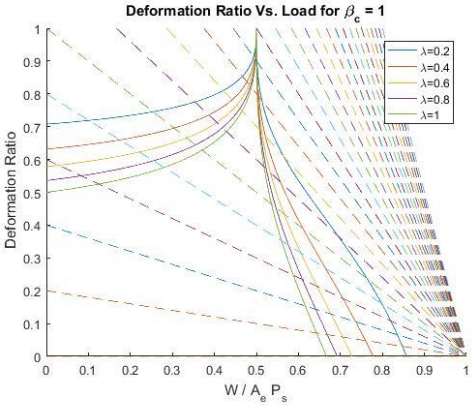

Fig.4.a: Deformation Ratio variation for β_c = 1

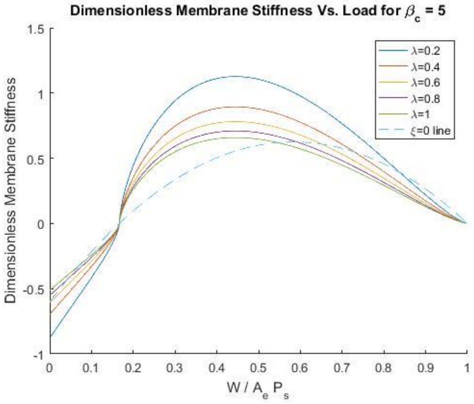

Fig.3.b: Dimensionless membrane stiffness variation for β_c = 5

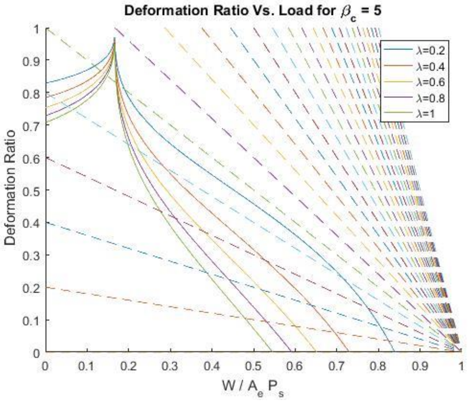

Fig.4.b: Deformation Ratio variation for β_c = 5

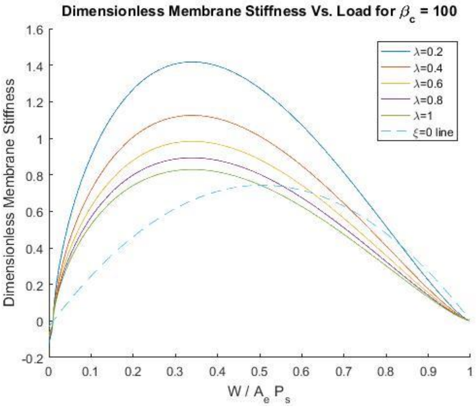

Fig.3.c: Dimensionless membrane stiffness variation for β_c = 100

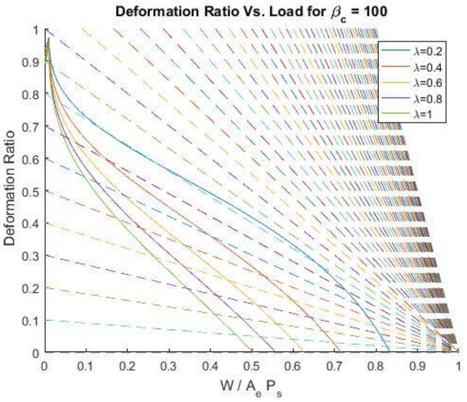

Fig.4.c: Deformation Ratio variation for β_c = 100

The following points can be concluded from Fig.3.a, Fig.3.b and Fig.3.c

- The dimensionless stiffness of the membrane varies with the loading.
- The variation of the dimensionless stiffness is similar when Design Restriction Ratio (DRR) and Dimensionless Capillary Ratio (DCR) is varied.
- For a constant DCR, the dimensionless membrane stiffness increases with a decrease in DRR.
- With a larger DCR, the pick of the stiffness vs. load curve increases and also the possible loading range increases significantly.

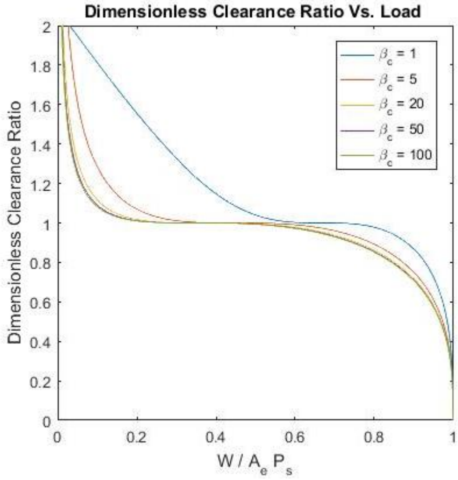

Fig.5: Dimensionless clearance ratio variation

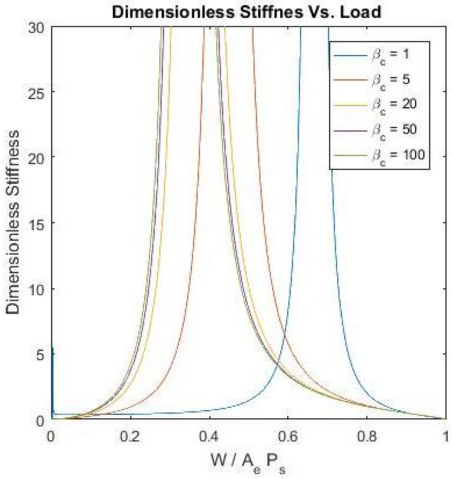

Fig.6: Dimensionless membrane stiffness variation

The following points can be concluded from Fig.5 and Fig.6

- With a smaller dimensionless capillary ratio, the clearance ratio is constant for a short range of load capacity. Hence the bearing stiffness will be very high in that range. But the high static stiffness is attained at relatively high load capacity.
- With increase in capillary resistance, the constant clearance ratio range and high bearing stiffness range is getting wider.

Conclusions

The effect of capillary restrictor has significant effect on the hydrostatic bearing setup. The introduction of such extra resistance decreases the load capacity, range of constant clearance ratio zone and range of high static stiffness zone. With introduction of capillary restrictor to the membrane restrictor set-up the bearing will attain high static stiffness at a relatively higher load capacity if other parameters are selected properly. It was derived that a design restriction ratio of $\frac{1}{4}\left(\frac{\beta_c}{1+\beta_c}\right)$ and a dimensionless membrane stiffness of $\frac{4}{3}\left(\frac{\beta_c}{1+\beta_c}\right)$ is the solution for such high static stiffness. The bearing setup will attain its maximum stiffness when the dimensionless load capacity is $\frac{1}{3}\left(\frac{3+\beta_c}{1+\beta_c}\right)$. The dimensionless load capacity will vary from $\frac{1}{1+\beta_c}$ to 1. It is desirable to operate the bearing in this range. Below $\frac{1}{1+\beta_c}$, the dimensionless membrane stiffness becomes negative which will induce instability in the system. The capillary restrictor will act as a bypass to delay the flow minimizing clogging effect at starting.

References

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