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Optimum Design of Journal Bearings Dimensions for Rotating Machines

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K E Y W O R D S

ANSYS, Critical speed, Dynamic Response, Journal Bearing, Rotor

A B S T R A C T

The values of Many parameters which involve in the design of fluid film journal bearings mainly depend on the bearing applied load when using the conventional design method to design the journal bearings, in this study, as well as applied bearing load, the dynamic response and critical speed have been used to calculate the dimensions of journal bearings. In the field of rotating machine, especially a heavy-duty rotating machines, the critical speed and response are the main parameters that specify bearing dimensions. The bearing aspect ratio (bearing length to bore diameter) and bearing clearance have been determined based on rotor maximum critical speed and minimum response displacement. The analytical solution of rotor Eq. of motion was verified by numerical solution via using ANSYS Mechanical APDL 18.0 and by comparing the numerical solution with the preceding study. The final study results clearly showed that the bearing aspect ratio has little effect on the critical speed, but it has a high effect on the dynamic response also the bearing clearance has little effect on the critical speed and considerable effect on the dynamic response. The study showed that the more accurate values of bearing aspect ratio to make the response of rotor as low as possible are about 0.65 - 1 and bearing percent clearance is about 0.15 - 0.2 for different rotor dimensions.

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1. Introduction

The journal bearings are widely used to support the rotor in the rotating machines. The bearing bore diameter is constantly designed slightly greater than the journal diameter where the gap between the bearing and journal called clearance. The clearance between the bearing and journal equal to zero when the rotor at rest state, that means the journal (shaft of the rotor) directly contacts with bearing internal surface. The bearing clearance is increased when the lubrication oil with specified pressure and a certain temperature is constantly supplied to the journal bearing. Due to the lubrication oil adhesiveness, once the rotor starts to rotate and the lube oil layer becomes close-fitting on the journal as well as rotates with him. When the lubricant oil pressure is becoming high enough to equilibrium the acting rotor force on the bearing so that the rotor is lifted from the lubricant oil film. The reaction forces which arise due to dynamic coefficients of the bearing are depending on the lubricant oil as well as the clearance and aspect ratio (bearing length to bore diameter) of supporting bearings [1] so that this study will concern on the clearance and aspect ratio of supporting bearings. Since the material of the rotor cannot be uniform definitely, and deviations are unavoidable during the installation, there is a specified deviation between the rotor rotation center and its gravity center. Thus, unavoidable vibrations during the rotation are appearing. Rotor like any object has its vibration natural frequency. In the process of the rotor rising speed, when the rotational speed rises to amount merely synchronous with a vibration natural frequency of the rotor, at this state, the rotor will experience strong vibrations. When the rotor speed is coinciding with its vibration natural frequency, the rotor will generate the spin speed with intense vibrations which called the rotor critical speed. The rotor critical speed is the rotating speed of the rotor at the maximum response and it is of course occurring at the natural frequency. [2] If the rotor rotates at the critical speed for the long term, the vibration may be increasing gradually therefore the journal bearings which support the rotor will bear suffer dynamic loads, and this state leading to bearing damage. The rotor dynamic deflection becomes considerable with approaching the rotating critical speed. [3]

The rotating system dynamic behavior is strongly affected by several parameters such as rotor shaft stiffness and mass distribution, inertial properties of the rigid disk, support bearing locations, and dynamic coefficients. So that many researchers concerned on the study the rotor dynamic to determine best dynamic parameters of the rotor to get rotor system with high stability, high critical speed, low response displacement, and lightweight, Reinhard and Nils [4], investigated the rotors optimal design with respect to the bearing stiffness, discs diameters, positions of bearings and discs, Hamit et al. [5] used the genetic algorithm method in developing optimum design procedures for tilting pad bearing. Leonid et al. [6] studied the optimal design of hydrodynamic journal bearing for intermediate induction motors based on the rotor dynamics analyses. Several plain cylindrical journal bearings with a different configuration have been considered to select the most suitable design for the induction motor application. Satoshi et al. [7] carried out a unique test for various types of large hydrodynamic journal bearings by utilizing an equivalent big rotor to determine the oil film profile, temperature, and pressure along the surface of each pad and the values of pad vibrations under rotating state. Stocki et al. [8] determined the optimal balance between admissible rotor bending flexibility and reducing the weight of rotor shaft to get a robust design for a rotor-bearing system based on high critical speed and low response displacement. Zi et al. [9] proposed an optimization method for the rotor vibration absorbers to estimate the best parameters of a rotor vibration absorber with better vibration damping performance. The main objectives of this study are to estimate the optimal dimensions of journal bearing which used in rotating machines based on the suitable response and critical speed. The response displacement and thus critical speed are influenced by the dynamic coefficients of journal bearing and these coefficients depending on the geometrical bearing dimension such as clearance and aspect ratio (the ratio of bearing length to the bearing diameter) as well as the rotating speed of the rotor and lubricant oil viscosity and since this study is concerned with estimating the optimal dimensions of journal bearings, the effect of viscosity of lubricating fluid was not taken into consideration in this study.

2. Critical speed and response displacement

The critical speed of the rotor always should be higher or lower than the speed of the equipment to be rotated by more than 15% of its working speed to guarantee the safe unit operation [10], the values of the bearing clearance and aspect ratio are depending on the appropriate values of critical speed and response displacement of the rotor, so that firstly the critical speed and response of the rotor must be calculated. The critical speed and response of the rotor can be calculated via the solution of Eq. of motion of rotor support on the journal bearings and the journal bearings represent by eight dynamic coefficients, the solution of Eq. of motion as follows:

$$M\ddot{x} + K(x - x_j) = mu\Omega^2 \cos \Omega t \qquad (1)$$
$$M\ddot{y} + K(y - y_j) = mu\Omega^2 \sin \Omega t$$

Where (x) and (y) are the rotor disk position, (x_j) and (y_j) are the journal center position in the journal bearing, $(mu\Omega^2 \cos \Omega t\ , mu\Omega^2 \sin \Omega t)$ are the, $(x)$and (y) unbalance forces due to unbalance mass (m), (u) unbalance mass eccentricity and (M) is the total mass of disk plus percent of shaft mass [11], $(M = disk\ mass + \frac{17}{35}\ rotor\ s\square aft\ mass)$, the relation between rotor shaft stiffness and bearing reaction forces (F_{jx}, F_{jy}) as follows

$$K(x - x_j) = 2F_{jx} \qquad (2)$$
$$K(y - y_j) = 2F_{jy}$$

Where, $$\begin{bmatrix} F_{jx} \\ F_{jy} \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix} \begin{Bmatrix} x_j \\ y_j \end{Bmatrix} + \begin{bmatrix} C_{xx} & C_{xy} \\ C_{yx} & C_{yy} \end{bmatrix} \begin{Bmatrix} \dot{x}_j \\ \dot{y}_j \end{Bmatrix} \qquad (3)$$

The eight dynamic coefficients of journal bearing are four stiffness coefficients and four damping coefficients as shown in Eq. (3).
The solution of Eq. (1) with takes into account Eq. (2) and Eq. (3), for harmonic motion can be written as follows;

$$M\ddot{x} + K_{11}x + K_{12}y = mu\Omega^2 \cos \Omega t \qquad M\ddot{y} + K_{21}x + K_{22}y = mu\Omega^2 \sin \Omega t \qquad (4)$$

Where,

$$K_{11} = \frac{K(K_2K_3 - K_1K_4 + KK_4)}{K_2K_3 - K_1K_4} \quad K_{12} = -\frac{K^2K_2}{K_2K_3 - K_1K_4} \quad K_{21} = -\frac{K^2K_3}{K_2K_3 - K_1K_4} \quad K_{22} = \frac{K(K_2K_3 - K_1K_4 + KK_1)}{K_2K_3 - K_1K_4}$$
$$K_1 = K + 2(K_{xx} + \mathrm{i}\Omega C_{xx}) \quad K_2 = 2(K_{xy} + \mathrm{i}\Omega C_{xy})$$
$$K_3 = 2(K_{yx} + \mathrm{i}\Omega C_{yx}) \quad K_4 = K + 2(K_{yy} + \mathrm{i}\Omega C_{yy})$$

The solution of Eq. (4) is as following;

$$x = Ae^{i\Omega t} + Be^{-i\Omega t} \qquad y = Ce^{i\Omega t} + De^{-i\Omega t}$$

Substitute values of (x) and (y) into Eq. (4) and using the Euler formula for sine and cosine $(\cos(\Omega t) = 1/2(e^{i\Omega t} + e^{-i\Omega t}), \sin(\Omega t) = 1/2i(e^{i\Omega t} - e^{-i\Omega t})$, yields

$$A = \frac{mu\Omega^2[i(K_{21} - m\Omega^2) - K_{12}]}{2i[(K_{11} - m\Omega^2)(K_{21} - m\Omega^2) - K_{12}K_{22}]}\ , \qquad B = \frac{mu\Omega^2[i(K_{21} - m\Omega^2) + K_{12}]}{2i[(K_{11} - m\Omega^2)(K_{21} - m\Omega^2) - K_{12}K_{22}]}$$
$$C = \frac{mu\Omega^2[K_{11} - m\Omega^2 - iK_{22}]}{2i[(K_{11} - m\Omega^2)(K_{21} - m\Omega^2) - K_{12}K_{22}]}\ , \qquad D = \frac{-mu\Omega^2[K_{11} - m\Omega^2 + iK_{22}]}{2i[(K_{11} - m\Omega^2)(K_{21} - m\Omega^2) - K_{12}K_{22}]}$$

The rotor response due to unbalance mass can be written in the following form,

$$r = x + iy = (A + iC)e^{i\Omega t} + (B + iD)e^{-i\Omega t} = r_f e^{i\Omega t} + r_b e^{-i\Omega t} \qquad (5)$$

Where $r_f = (A + iC) \qquad r_b = (B + iD)$

Where r_f is the forward whirl radius component in the same direction of rotor rotation and r_b is the backward whirl radius component in the reverse direction of rotation.
The maximum radius of the whirl is the maximum response of the rotor and is the large radii of the rotor elliptical orbit at disk center

$$|r|_{maj} = |r_f| + |r_b| |r|_{min} = |r_f| - |r_b|$$

Therefore, the critical speed is the rotating speed at maximum whirl radius$|r|_{maj}$.

3. Results and discussion

The influence of bearing aspect ratio on the response displacement for various rotor shaft diameters has been studied. The dimensions of rotor shaft such as diameter and length and disk dimensions have been selected for one model depending on the dimensions of a simple rotor that has been used in [12] and the remaining models' dimensions have been selected with the same ratio of (Ls/Ds = 30, Hd/Ds = 1, Dd/Ds = 17.5), where Ls, Ds, Hd, and Dd are shaft length, shaft diameter, disk thickness, and disk diameter respectively. The dimensions of rotor models that have been used in this study are listed in Table 1

Table1: Rotor models dimensions

Ds, mm	Ls, mm	Dd, mm	Hd, mm
10	300	175	10
20	600	350	20
30	900	525	30
40	1200	700	40
50	1500	875	50
60	1800	1050	60

The finite element rotor model has been represented by using the BEAM188 element which is a two dimensions beam element. The finite element rotor model verified by comparing the unbalance response obtained from ANSYS with the unbalance response of the rotor model represented in [12], as shown in Figure 1; it is observed that the response values are very comparable. The analytical solution for unbalance response (Eq. 5), has been verified by comparing the results with the results of the finite element model which accomplished by ANSYS as in Figure 2.

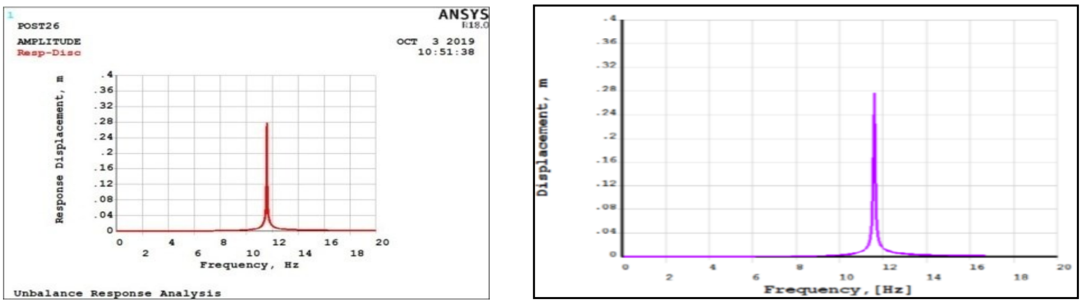

Figure 1: Unbalance response a: ANSYS software, b: [9]

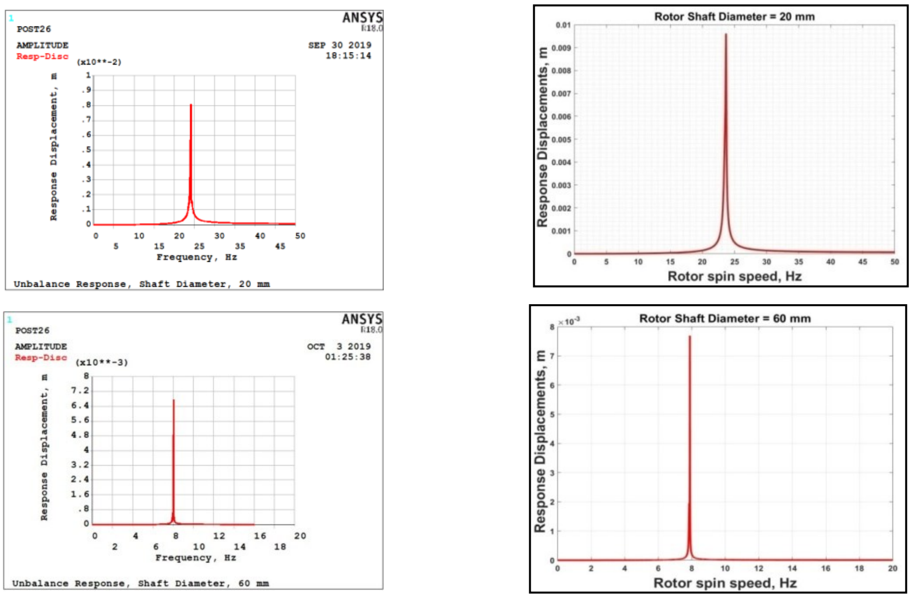

Figure 2: Comparison between ANSYS and MATLAB results

The best value of aspect ratio for various rotor shaft diameters depending on the response displacement is between 0.65 - 0.8, for rotor shaft diameter up to 30 mm and it is between 0.7 - 1 for rotor shaft diameter more than 30 mm, for different bearing percent clearances because the response approximately becomes constant and has the low value as shown in Figure 3.

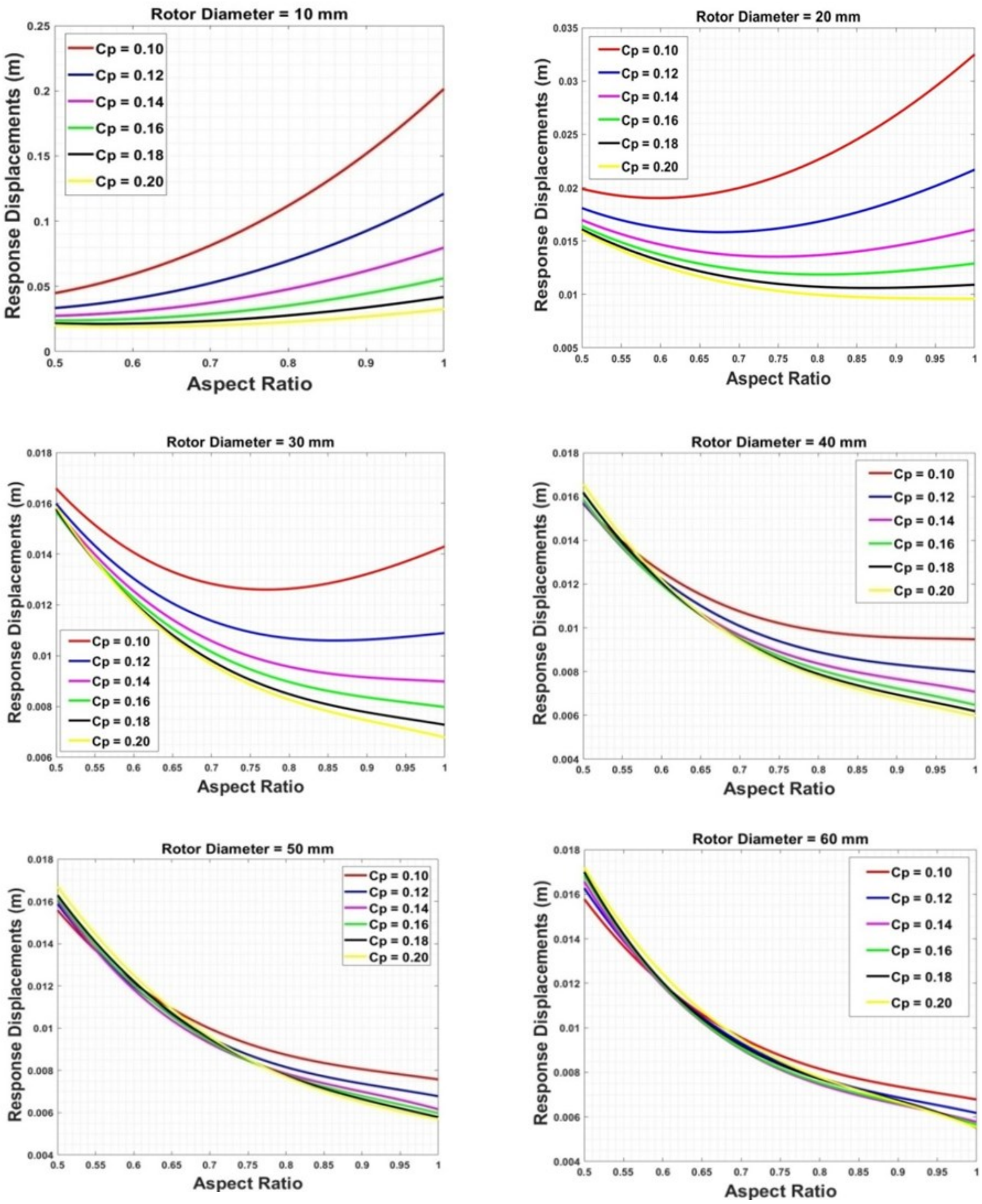

Figure 3: Effect of bearing aspect ratio on the rotor Response displacement

The effect of change of bearing aspect ratio on the critical speed is very small for different rotor shaft diameters as shown in Figure 4. Where the speed difference is about 7 rpm when the rotor shaft diameter is 10 mm and the difference becomes very small with the increasing of rotor diameter especially for rotor diameter 30 mm and more.

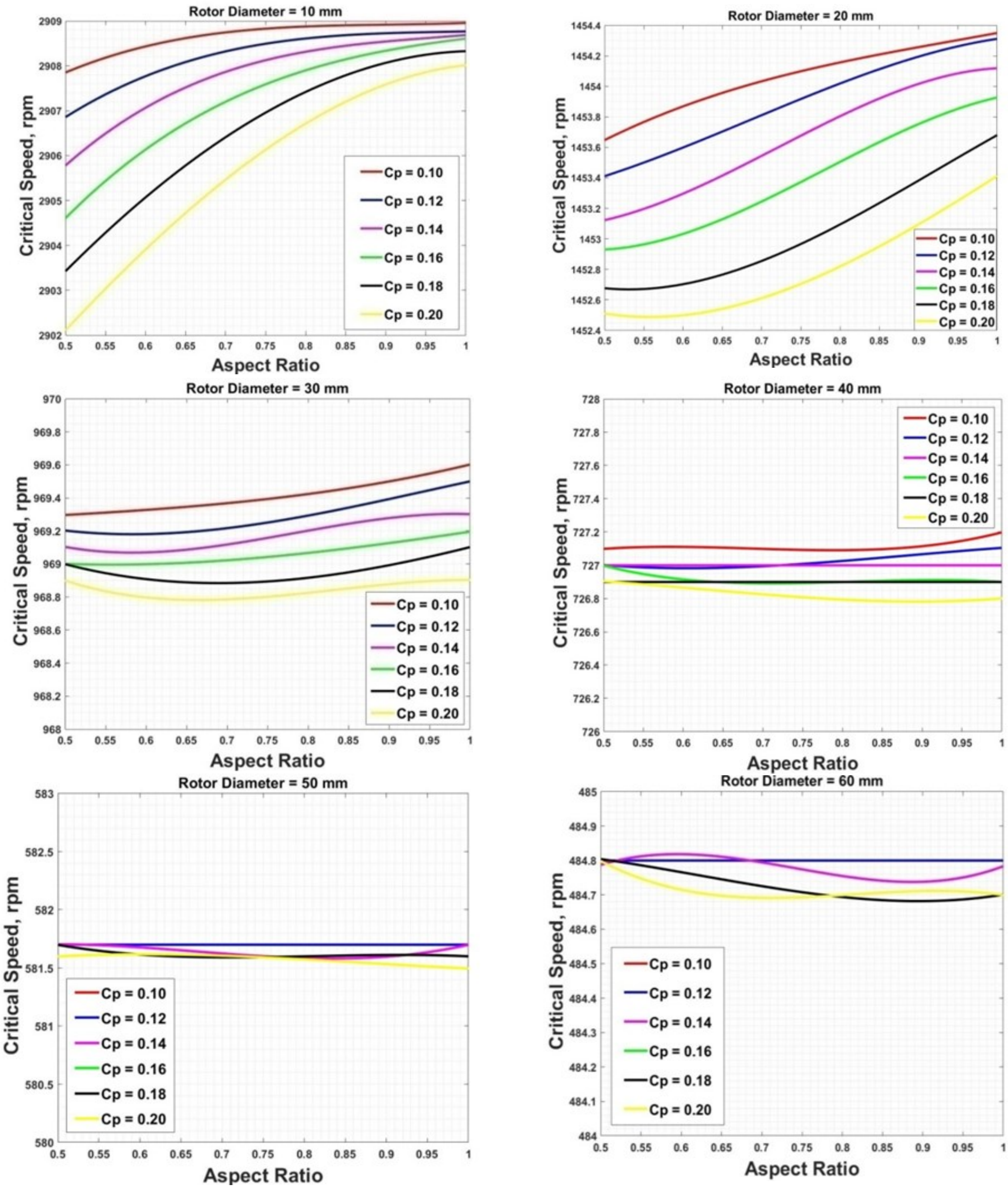

Figure 4: Effect of bearing aspect ratio on the rotor critical speed

The best clearance percent of journal bearings for rotor-bearing systems is about 0.15 to 0.2 where the response displacement becomes low and the critical speed is approximately constant for different bearing clearance percent as shown in Figure 5, and Table 2 and Table 3. The decrease in the response of the rotor with the increase in the bearing clearance is to increases of a lubricant oil amount which of course will increase the damping effect in the rotor system. The increasing of damping coefficients due to the increase of lubricant oil amount has no effect on the critical speed because it depends on the location of the maximum response that not affect due to increase of damping coefficients.

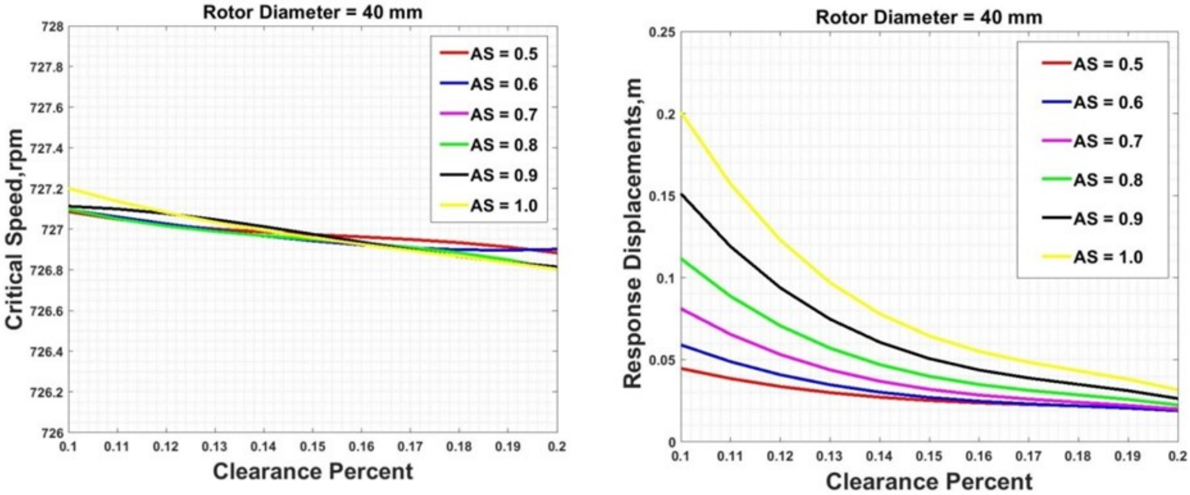

Figure 5: Effect of bearing clearance on the response and critical speed

Table 2: Effect of bearing clearance on the critical speed for different bearing aspect ratio

AS \ CP	0.10	0.12	0.14	0.16	0.18	0.20
0.5	727.1	727	727	727	726.9	726.9
0.6	727.1	727	727	726.9	726.9	726.9
0.7	727.1	727	727	726.9	726.9	726.8
0.8	727.1	727	727	726.9	726.9	726.8
0.9	727.1	727.1	727	726.9	726.9	726.8
1.0	727.2	727.1	727	726.9	726.9	726.8

Table 3: Effect of bearing clearance on the response for different bearing aspect ratio

AS \ CP	0.10	0.12	0.14	0.16	0.18	0.20
0.5	0.0448	0.0334	0.0274	0.0239	0.0216	0.0201
0.6	0.0592	0.0404	0.0306	0.025	0.0214	0.0191
0.7	0.0814	0.0525	0.0375	0.0288	0.0235	0.0201
0.8	0.1119	0.0697	0.0478	0.0353	0.0277	0.0227
0.9	0.1516	0.0924	0.0618	0.0444	0.0338	0.0268
1.0	0.2015	0.1211	0.0797	0.0562	0.0418	0.0325

5. Conclusions

1. The bearing aspect ratio has a considerable effect on the response displacement of the rotor.
2. The effect of change of bearing aspect ratio of the critical speed is very small for the different rotor shaft diameter.
3. The value of aspect ratio for various rotor shaft diameters depending on the response displacement is between 0.65 - 0.8, for rotor shaft diameter up to 30 mm and it is between 0.7 - 1 for rotor shaft diameter more than 30 mm, for different bearing percent clearances.
4. The best clearance percent of journal bearings for rotor-bearing systems is about 0.15 to 0.2.
5. Increasing the rotor shaft diameter leads to increase critical speed and decrease response displacement, but this option does not have the preferability because it leads to an increase in the weight of rotor systems.

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