STUDY EFFECT OF USING A DIFFERENT BEARINGS COMBINATION ON THE DYNAMIC RESPONSE OF ROTOR BEARING SYSTEMS

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Abstract

In this paper, the effect of dynamic coefficients of different bearings types on the dynamic response and the frequency of maximum response of rotor bearing system have been studied. The ANSYS Mechanical APDL 18.0 was used to model rotor with different bearings types. MATLAB software has been used to achieve the analytical solution. The results showed that the using of ball bearing, roller bearing or self aligning bearing with fluid film journal bearing strongly increasing the dynamic response amplitude and slightly increasing frequency of maximum response compared with the using of journal bearing to support rotor while using ball bearing with roller bearing have insignificant effect on the dynamic response and frequency of maximum response also using of self aligning bearing with ball bearing or roller bearing strongly decreasing the dynamic response and slightly decreasing the frequency of maximum response and using the self aligning bearing with others bearings types give the misalignment self-overcoming feature.

Keywords: Rotor, Dynamic Response, Journal Bearing, Roller Bearing, Ball Bearing

I. Introduction

The dynamic response amplitude of a rotor depends mainly on the dynamic coefficients of bearings which support the rotor. The ball bearings and roller bearings
have high value of stiffness coefficients but very low value of damping coefficients so that the response amplitude of rotor supported on roller element bearings usually very high. The damping coefficients play a major role to improve the operation of rotor bearing system by decreases the amplitude of dynamic response. The journal bearings have high damping coefficients therefore using these types of bearings with roller element bearings will be an improving factor and leads to decreases the magnitude of the rotor dynamic response.

II. Stiffness and Damping Coefficients of Bearings

The stiffness and damping coefficients of different bearing types have been analytically determined by many researchers and documented in the many references and these dynamic coefficients calculated depending on the relation between the applied force on the journal of journal bearings or on the rolling element of ball, roller and self aligning bearings and displacement which occurs due to this force.

Rolling Element Bearings

The dynamic coefficients of roller element bearings can be calculated from the relationship between force and deflection of rolling elements. The mathematical relationship for stiffness and deflection of roller element bearings based on hertzian theory for solid body contacts can be written as following, [III, VI]

For ball bearing

\[ x = 4.251 \times 10^{-4} \ d^{-1/3} \ (F/\pi)^{2/3} \ m \]

\[ k = 13 \times 10^6 z^{2/3} \ d^{1/3} \ F^{1/3} \ N/m \]  

(1)

For roller bearings

\[ x = 2.6846 \times 10^{-4} \ l^{-0.8} \ (F/\pi)^{0.9} \ m \]

\[ k = 1 \times 10^9 z^{0.9} \ l^{0.8} \ F^{0.1} \ N/m \]  

(2)

For self Aligning ball bearing, [VII]

\[ x = 68 \times 10^{-5} \ d^{-1/3}z^{-2/3} \ F^{2/3} \ m \]

\[ k = 7.3537 \times 10^6 \ d^{1/3}z^{2/3} \ F^{1/3} \ N/m \]  

(3)

Where

\( x = \text{deflection displacement of rolling element} \ (m) \), \( k = \text{radial stiffness} \ (N/m) \)

\( z = \text{number of rolling elements} \), \( d = \text{ball diameter} \ (m) \)

\( l = \text{roller effective length} \ (m) \), \( F = \text{external radial force} \ (N) \)
The above stiffness expressions of the ball and roller element bearings are represent the lateral stiffness \( k_{yy} \) and the stiffness in the horizontal direction \( k_{xx} \) can be determine as follows, [IV]

Ball bearing:
\[
\frac{k_{xx}}{k_{yy}} = (0.46, 0.64, 0.73,) \text{ for } (8, 12, 16) \text{ balls respectively}
\]

Roller bearing:
\[
\frac{k_{xx}}{k_{yy}} = (0.49, 0.66, 0.74,) \text{ for } (8, 12, 16) \text{ balls respectively}
\]

The ratio between vertical and horizontal stiffness \( k_{xx}/k_{yy} \) is independent of the external static load. Damping of rolling element bearings is very low and the coefficient of damping is usually in the range of \((0.25\sim2.5) \times 10^5 \text{ s} \times k\), where \( k \) is bearing stiffness.

In the study of rotor mounted on the ball or roller bearings, the ball and roller bearings can be represented by a radial stiffness \( k \) and damping coefficients can be neglected because their values are very small, [VII].

**Fluid Film Journal Bearings**

The stiffness and damping coefficients of journal bearing have a major effect on the dynamic response of rotor bearing systems because this type of bearing characterized by high damping. The dynamic coefficients of journal bearings can be found in most of the rotordynamics books, [V]

### III. Dynamic Response of Rotor Bearing System

The dynamic response of rotor mounted on two bearings is the value of rotor bend due to unbalance mass and also it called harmonic unbalance response. The maximum value of dynamic response take places at disk location where rotor bend due to unbalance mass and also it called harmonic unbalance response. The dynamic response of rotor mounted on journal bearings can be calculated as following, [V]

\[
r = r_t \exp(i\omega t) + r_b \exp(-i\omega t) \tag{4}
\]

Where,
\[
r_t = \frac{\Omega^2\[(\Omega^2+\Omega^2-2\Omega^2)\text{-(}\mu_1\Omega^2+\mu_2\Omega^2)\]}{2\[(\Omega^2-\Omega^2)\text{-(}\mu_1\Omega^2+\mu_2\Omega^2)\]}, \quad r_b = \frac{\Omega^2\[(\Omega^2+\Omega^2+\mu_1\Omega^2+\mu_2\Omega^2)\]}{2\[(\Omega^2-\Omega^2)\text{-(}\mu_1\Omega^2+\mu_2\Omega^2)\]}
\]

\[
\Omega_1^2 = \frac{K_1}{M}, \quad \Omega_2^2 = \frac{K_2}{M}, \quad \mu_1 = \frac{K_{12}}{K_1}, \quad \mu_2 = \frac{K_{21}}{K_2}
\]

Where \( r_t \) and \( r_b \) are the components of unbalance dynamic response called forward and backward respectively.

\[
K_1 = \frac{K_{sh}\{(K_{xx}+i\Omega_{xx})(K_{yy}+K_{sh}+i\Omega_{yy})-(K_{yy}+i\Omega_{yy})(K_{xx}+i\Omega_{xx})\}}{(K_{xx}+K_{sh}+i\Omega_{xx})(K_{yy}+K_{sh}+i\Omega_{yy})-(K_{yy}+i\Omega_{yy})(K_{xx}+i\Omega_{xx})}
\]

\[
K_2 = \frac{K_{sh}\{(K_{yy}+i\Omega_{yy})(K_{xx}+K_{sh}+i\Omega_{xx})-(K_{xx}+i\Omega_{xx})(K_{yy}+i\Omega_{yy})\}}{(K_{xx}+K_{sh}+i\Omega_{xx})(K_{yy}+K_{sh}+i\Omega_{yy})-(K_{yy}+i\Omega_{yy})(K_{xx}+i\Omega_{xx})}
\]

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The stiffness and damping coefficients in the previous equations are as following, 
For journal bearing with Journal Bearing,

\[ K_{xx} = (K_{xx1} + K_{xx2}), \quad K_{xy} = (K_{xy1} + K_{xy2}), \quad K_{yx} = (K_{yx1} + K_{yx2}), \quad K_{yy} = (K_{yy1} + K_{yy2}), \quad C_{xx} = (C_{xx1} + C_{xx2}), \quad C_{xy} = (C_{xy1} + C_{xy2}), \quad C_{yx} = (C_{yx1} + C_{yx2}), \quad C_{yy} = (C_{yy1} + C_{yy2}) \]

Where subscript numbers 1 and 2 represent bearing one and bearing two respectively, in this work, roller, ball and self aligning bearings using as bearing number two in the rotor bearing system while bearing number one remains journal bearing, the following changes must be taken into consideration.

For journal bearing with ball bearing

\[ K_{xx} = (K_{xx1} + K_{b}), \quad K_{yy} = (K_{yy1} + K_{b}), \quad K_{xy} = K_{xy1}, \quad K_{yx} = K_{yx1}, \quad C_{xx} = (C_{xx1} + C_{b}), \quad C_{yy} = (C_{yy1} + C_{b}), \quad C_{xy} = C_{xy1}, \quad C_{yx} = C_{yx1} \]

For journal bearing with roller bearing or with self aligning ball bearing the above expressions of stiffness and damping can be used by replace \( K_{b} \) and \( C_{b} \) with \( K_{r} \), \( C_{r} \) and \( K_{s} \),\( C_{s} \), for roller bearing and self aligning ball bearing respectively.

Where \( K_{ij} \) = dynamic coefficients, \( i, j = x, y \), \( K_{b} \) = ball bearing stiffness,(N/m) \( K_{r} \) = Roller bearing stiffness, (N/m), \( K_{s} \) = self aligning bearing stiffness , (N/m) \( K_{sh} \) = Rotor shaft stiffness, (N/m), \( C_{s} \) = self aligning bearing damping , (Ns/m) \( C_{r} \) =Roller bearing damping, (Ns/m), \( \Omega \) = rotor speed (rpm)

The maximum dynamic response is the major radius of elliptic orbit of rotor at disc location, The major and minor radius of elliptic orbit of rotor at disc location are, [II]

\[ |r|_{maj} = |r_{r}| + |r_{b}| \quad |r|_{min} = |r_{r}| - |r_{b}| \]

the maximum dynamic response at disc location is equal to, \( |r|_{maj} \). And this value will be used to compare response amplitude of different bearing combinations.

IV. Objective of this Research

The resources of vibration in the rotor bearing systems can't be avoid completely so that the aim of this research is decreasing vibration level as much as
The using of fluid film journal bearing with another bearing type in the two bearing rotor system leads to decrease amplitude of dynamic response and make system more stable. The two bearing system combinations that will be investigated in this research are listed in Table 1.

### Table- 1: Two bearing combinations systems.

| Bearing No.1     | Bearing No.2     |
|------------------|------------------|
| Journal Bearing  | Journal Bearing  |
| Journal Bearing  | Ball Bearing     |
| Journal Bearing  | Roller Bearing   |
| Ball Bearing     | Ball Bearing     |
| Ball Bearing     | Roller Bearing   |
| Roller Bearing   | Roller Bearing   |

V. Two Bearings Rotor System Analysis by ANSYS

3-D Solid model or 1-D beam model can be used to model the two bearing rotor system, [I]. In the case of using 3-D solid model, solid186 element has been used to model shaft and disk while beam188 element can be used in the case of 1-D as shown in the Figure 1, also comi214 element has been used to model bearings. The dynamic coefficients of roller and ball bearings are independent of rotational rotor speed while dynamic coefficients of fluid film journal bearings are depending on the rotor rotational speed so that this should be taken into account in the ANSYS program. The rotor bearing system dimensions which were used in this research are shown in Figure 2, and listed in Table 2.

Fig 1. ANSYS Rotor Model, a: 3-D, Rotor Model Using Solid186, b: 1-D, Rotor Model Using Beam188.

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Fig 2. Mechanical Drawing of Two Bearings Rotor System.

**Table- 2:** Rotor Material and Lubricant Oil Specifications.

| Shaft length (mm) | Shaft diam. (mm) | Disc diam. (mm) | Disc thickness (mm) | Modulus of Elasticity (pa) | Shaft and Disk Density (Kg/m³) | Unbalance force (Kg - m) |
|-------------------|------------------|-----------------|--------------------|---------------------------|-------------------------------|--------------------------|
| 600               | 20               | 200             | 50                 | 2.1x10¹¹                  | 7850                          | 1x10⁻⁵                   |

VI. Results and Discussion

The stiffness and displacement of rolling element bearings (ball, roller and self aligning bearings) are depend heavily on the applied load as shown in Figure 3.

Fig 3. Stiffness and Displacement of Self-aligning Ball Bearings, Ball Bearings and Roller Bearings as a Function of Load F.
The stiffness of roller bearing is five times the stiffness of ball bearing while the stiffness of ball bearing is about two times the stiffness of self aligning ball bearing therefore the displacement which take place due to applied load in the roller bearing is smaller than ball bearing and self aligning bearing as shown in Figure 3.

The rolling bearings types (Roller, Ball and Self Aligning) have very small Damping Coefficients as mentioned previous but it have noticeable effect on the dynamic response of rotor as shown in the Figure 4, therefore to get more accurate results the damping coefficients of rolling bearings types have been taken $(1.25 \times 10^{-5} \times k)$, whereas the value of damping coefficient of roller bearing and ball bearing is about $(0.25\sim 2.5) \times 10^{-5} \times k$, where $k$ is a bearing stiffness [III]

![Fig 4. Effect of Rolling Bearing Damping on the Dynamic Response of Rotor Mounted on Rolling Bearings Types.](image)

The dynamic response of rotor bearing systems is mainly depends on the bearings dynamic coefficients (stiffness and damping) and has been calculated by using equation 5. Figure 5, shows the response displacement of rotor mounted on combination of ball bearing with different bearings types (ball - ball bearings, ball - roller bearings, ball - self aligning bearings) . The use of roller bearing with ball bearing led to increases response displacement and the speed of maximum response while use of self aligning leads to decreases of response displacement and speed of maximum response.

Figure 6, shows the response displacement of rotor mounted on combination of roller bearing with different bearings types (roller - roller bearings, roller - ball bearings, roller - self aligning bearings). This combination of bearings cause decreasing in the response displacement and speed of maximum response because the ball and self aligning have stiffness less than roller bearing and the difference in response and speed between ball bearing and self aligning bearing is small because there is small difference in stiffness between the two bearings types (stiffness of ball bearing is about twice stiffness of self aligning bearing).

The load carrying capacity of self aligning bearing in the radial and axial direction is lower than ball bearing and roller bearing but has a good point of accommodating the large rotor shaft misalignment. The stiffness of self aligning bearing is less than

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stiffness of others bearing types so that the using of ball bearing and roller bearings together with self aligning bearing enhance response displacement and increase speed of the maximum response displacement as shown in Figure 7, therefore the using of self aligning bearing with different bearings types in the same system has advantage and disadvantage in the same time and in this case the type of application will be the reference of select any type of bearing combination more useful

Fig 5. Response displacement of rotor mounted on combination of ball Bearing with different bearings types.

Fig 6. Response displacement of rotor mounted on combination of Roller Bearing with different bearings types.

Fig 7. Response Displacement of Rotor Mounted on Combination of Self Aligning Bearing with Different Bearings Types.
The fluid film journal bearing, often called the hydrodynamic bearing is widely used in big rotating machines due to its high carrying capacity of load. This type of bearings have high damping coefficients and usually reactive cross couple stiffness therefore the systems with this type of bearing more stable but journal bearing need to continuous oil flow system with constant temperature. The temperature of lubricant oil increases during operation due to the friction of oil with the internal surface of bearing and outer surface of journal so that a suitable cooling system must be used to cool lubricant oil continuously. The using of rolling element bearings with journal bearing in the same system lead to strongly increasing the response displacement and slightly increasing speed of maximum response while ball bearing and self aligning bearing slightly increasing response displacement and slightly decreasing speed of maximum response as shown in Figure 8. In general the response of rotor mounted on journal bearings is very low because the journal bearings have high damping coefficients also cross couple stiffness ($K_{xy}$, $K_{yx}$) all or one of them usually has negative value which are in turn decrease the response displacement of rotor bearing systems.

The previous mentioned figures have been plotted by using MATLAB software and to get more accurate results, the increment of rotor speed must be select carefully depending on experience of researcher and the expected response displacement therefore the results of MATLAB must be compare with ANSYS results to increasing the contentment in the analytical results.

The ANSYS software has been used to get the dynamic response of rotor bearing systems with select rotor speed increment equal to 0.1 or less, also select small range of rotor speed about five rpm which content the speed of rotor when the maximum

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Fig 8. Response displacement of rotor mounted on combination of journal bearing with different bearings types, a: journal bearing alone b: journal with different bearing types.
response take place. The speed of rotor when the maximum response of rotor occurs can be determine by take full speed range of rotor with high increment (for example 10) and the ANSYS software will determine the value of speed when maximum response occur.

The using of ball - roller bearings system considerably increasing the response displacement and slightly increasing speed of the maximum response compared with rotor mounted on ball - ball bearings as shown in Figure 10.a , 10.b and Table 3, because the stiffness of roller bearing is higher than stiffness of ball bearing while using self aligning bearing - roller bearing system considerably decreasing the response displacement and slightly decreasing speed of the maximum response compared with rotor mounted on roller - roller bearings as shown in Figure 10.c, 10.d and Table 4.

Fig 10. Response of rotor mounted on, a:ball - ball Bearings, b:ball - roller bearings, c:roller - roller bearings, d:roller - self aligning bearings, e:self - self aligning bearings, f:self aligning - ball bearings.

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Generally, the response displacement and speed when maximum response take place of rotor mounted on self aligning bearings are clearly less than the response displacement and speed of maximum response of rotor mounted on self aligning bearing - ball bearing as shown in Figure 10.e, 10.f and Table 5. The combination of roller bearing with different bearing types when using to support rotor leads to reduce the rotor dynamic response and maximum response speed compared with the rotor mounted on roller bearings alone as it clear in Table 4.

**Table- 3**: Effect of Using Combination of Ball Bearing with Different Bearings Types on the Response Displacement and Maximum Response Speed.

| Combination of bearings | Response (m) | Speed of maximum response (Rpm) | Response Ratio (2,3/1) | Increase or decrease | Speed Ratio (2,3/1) | Increase or decrease |
|-------------------------|--------------|---------------------------------|-----------------------|---------------------|--------------------|---------------------|
| 1 Ball - ball           | 0.07819      | 1594                            |                       |                     |                    |                     |
| 2 Ball - roller         | 0.1337       | 1595                            | 41%                   | increase            | 0.062%             | increase            |
| 3 Ball - self           | 0.06195      | 1592                            | 26%                   | decrease            | 0.125%             | decrease            |

**Table-4**: Effect of Using Combination of Roller Bearing with Different Bearings Types on the Response Displacement and Maximum Response Speed.

| Combination of bearings | Response (m) | Speed of maximum response (Rpm) | Response Ratio (2,3/1) | Increase or decrease | Speed Ratio (2,3/1) | Increase or decrease |
|-------------------------|--------------|---------------------------------|-----------------------|---------------------|--------------------|---------------------|
| 1 Roller - roller       | 0.1912       | 1596                            |                       |                     |                    |                     |
| 2 Roller - ball         | 0.1337       | 1595                            | 30%                   | decrease            | 0.062%             | decrease            |
| 3 Roller - self         | 0.09073      | 1594                            | 52%                   | decrease            | 0.125%             | decrease            |

**Table-5**: Effect of Using Combination of Self Aligning Bearing with Different Bearings Types on the Response Displacement and Maximum Response Speed.

| Combination of bearings | Response (m) | Speed of maximum response (Rpm) | Response Ratio (2,3/1) | Increase or decrease | Speed Ratio (2,3/1) | Increase or decrease |
|-------------------------|--------------|---------------------------------|-----------------------|---------------------|--------------------|---------------------|
| 1 Self - self           | 0.04912      | 1591                            |                       |                     |                    |                     |
| 2 Self - ball           | 0.06195      | 1592                            | 20%                   | increase            | 0.062%             | increase            |
| 3 Self - roller         | 0.09073      | 1594                            | 45%                   | increase            | 0.125%             | increase            |
The rotor-fluid film journal bearing systems have high damping due to using oil to lubricate journal bearings so that the response displacement of rotor is very low as well as using journal bearing make system more stable and has high load carrying capacity but these type of systems need to continuous oil flow to lubricate bearings and also need to cooling system to keep oil at desirable temperature because the variations in the oil temperature lead to variations in the oil viscosity and consequently variations in the stiffness and damping coefficients of journal bearings. The stiffness and damping (also called dynamic coefficients of bearing) have high effect on the dynamic response and speed of maximum response of rotor supported on fluid film journal bearings.

Generally, the fluid film journal bearing using in the heavy duty and high speed system, whereas the journal bearings have low stiffness and high damping coefficients which make systems operate more stable with very small response displacement but that not mean there are no disadvantage with using fluid film journal bearings like oil whip and oil whirl, these two oil phenomena must be avoidable in the operation of rotor-fluid film bearings.

The using of journal bearing-ball bearing, journal-self Aligning Bearing and journal-roller bearing system to support rotor have strongly effect on the response displacement (50% increasing) compared with journal bearing-journal bearing system but there is very small difference between the response displacements of other combinations of bearings types (journal-self aligning, journal-ball and journal-roller), also the speed of rotor at maximum response slightly increasing when using self aligning, ball and roller bearings with journal bearing as can be seen in Table 6.

The decreasing in the response displacement when using journal-journal bearing to support rotor compared with using another bearings types with journal bearing as shown in Figure 11, is due to the effect of high damping coefficients of journal bearings as well as the effect of negative values of cross couple stiffness of journal bearing which led to decrease response displacement.

**Table 6:** Effect of Using Combination of Journal Bearing with Different Bearing Types on the Response Displacement and Maximum Response Speed.

| Combination of bearings | Response (m) | Speed of maximum response (Rpm) | Response Ratio (2,3,4/1) | Increase or decrease | Speed Ratio (2,3,4/1) | Increase or decrease |
|-------------------------|-------------|---------------------------------|--------------------------|----------------------|----------------------|----------------------|
| 1 Journal - journal     | 0.7388      | 1585                            |                          |                      |                      |                      |
| 2 Journal - self        | 1.475       | 1588                            | 50% increase            | 0.2% increase        |                      |                      |
| 3 Journal - ball        | 1.473       | 1589                            | 50% increase            | 0.25% increase       |                      |                      |
| 4 Journal - roller      | 1.468       | 1591                            | 50% increase            | 0.37% increase       |                      |                      |
VII. Conclusions

1. The dynamic response of rotor mounted on ball - ball bearings is small than the response of rotor mounted on roller - roller bearings while the speed of maximum response for different bearings combinations is slightly differ.
2. Using of roller bearing with ball bearing or with self aligning bearing to support rotor strongly increasing the response displacement and slightly increasing the speed of maximum response.
3. Using of self aligning bearing with ball bearing or with roller bearing to support rotor strongly decreasing the response displacement and slightly decreasing the speed of maximum response.
4. Using of ball bearing with Roller bearing to support rotor significantly decreasing the response displacement and slightly decreasing the speed of maximum response.
5. Using of ball bearing, roller bearing or self aligning bearing with journal bearing to support rotor strongly increasing the response displacement and slightly increasing the speed of maximum response.
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