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Critical Speed Analysis and Root Locus Plot Analysis of Hybrid Bearing

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***Abstract*: Bump foil bearing is a self-acting hydrodynamic bearing which uses bump foils as a spring to fulfill the functions of a bearing. They can be fixed into the rotor radially to support the rotor and permit the relative motion. Permanent Magnetic Bearings(PMBs) are simple lubricant free options for high speed rotors. They can be used to support the shaft in either axial or radial direction but they offers negative stiffness in perpendicular direction. With only permanent magnet bearing it's not possible to support the rotor. So to support the rotor in both the directions a foil bearing is used in conjunction with permanent magnet bearing where foil bearing supports the negative stiffness of magnet along with dead weight and rotor dynamic loads. The objective of this research work is to conduct a critical speed analysis and root locus plots for determining stability under dynamic operating conditions up to the speeds of 120000 RPM using SAMSEF Rotor dynamic tool.**

***Keywords*: Rotor dynamics, Stability, Air bearing, magnetic bearing, Critical speeds, Root locus plot, Stiffness, Whirling, Clearance, Lift off.**

1. Introduction

Air Foil Bearings (AFBs) or gas foil bearings uses hydrodynamic principle that operates on gas or air for the purpose of rotation of shaft as operational fluid. It is called foil bearing, as it uses foils (sheets of metal) as spring for fulfilling the functions of the bearing. Hydrodynamic theory of lubrication is the basic working principle of foil bearings. An air film formed by hydrodynamic principle during operation separates the rotating shaft from encircling foil or top foil of bearing, at starting and shut-down as the shaft speeds is inadequate to generate gas film pressure causes friction between top foil of the bearing and shaft surfaces. Once the shaft or journal attains enough whirling speed the working fluid (air) drives the foil away from the shaft making it levitate without contact. Passive Magnetic Bearings (PMB's) uses permanent magnets and do not require any input power and it uses permanent magnets as a means to support the rotating object. In this paper critical speeds of hybrid support system (Combination of foil and magnetic bearing) is analyzed up to the speed of 120000 rpm which is done in Samsef field software and root locus plots are plotted to predict the stability of the system.

2. Literature survey

Instability of the rotor in dynamic condition at critical speeds is mainly due to the increase in internal clearances in between the shaft and top foil, influence of internal friction, development of high speeds, mechanical preloads and imbalance of shaft.

Concept of foil bearing was introduced by Blok and Rossom [1] in the year 1953. Blok and Rossom have pointed out that a foil bearing film thickness, thicker than the rigid gas bearing, could improve the operational reliability and it can provide a solution for problems related to thermal expansion of both journal and its bearing.

Kevin Radil, Samuel Howard and Brian Dykes [2] worked on radial clearances and stated "radial clearance plays an important role in the performance of compliant foil air bearing". With an insufficient amount of radial clearance, the bearing imparts a high preload on the shaft and excessive radial clearance can reduce the load carrying capacity of the bearing. Systems using foil bearings with excessive clearance may experience rotor dynamic instabilities.

Amar Hatti worked experimentally on stability of hybrid support system and provided the experimental values of clearances, stiffness values and liftoff speeds in his paper "Rotor Dynamic Stability Analysis of Hybrid Support System" [3]. Data required for critical speed analysis are taken from this paper.

S.Y. Yoon et al [4] investigated the rotor dynamic system's stability in the presence of common destabilizing forces. In his rotor dynamic stability analysis author normally evaluated the stability by the amount of damping on the first forward mode. Author stated two stability analysis levels where in the level I stability analysis, the stability of the rotor-dynamic system is tested for a varying amount of the total cross-coupling stiffness. During the Level II analysis, initially identify the frequency and logarithmic decrement of the first forward damped mode for the bare rotor/support system. Then the analysis is done after adding the dynamics of each component previously identified to affect the rotor dynamic system's stability. Finally, frequency and logarithmic decrement of the first damped forward mode is computed for the total assembled system.

Peng [5] has developed a mathematical model and a numerical scheme for simulation of the hydrodynamic pressure variation and temperature rise of a compliant foil. To illustrate the utility of the developed algorithm for characterization of performance of the foil bearing using isothermal and thermo hydrodynamic theories he has presented a series of parametric

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studies. Peng and Khonsari [6] have presented a thermo hydrodynamic analysis which predicts the thermal performance of compliant foil bearing.

The effect of foil local deflection has been investigated by Feng and Kaneko [7]. A finite difference computer program has developed to solve the Reynold's equation along with the elastic deflection equations. To determine the dynamic co-efficient, perturbation techniques have been used. Lee et al. [8] have developed a static structural model of the foil journal bearing considering the hysteresis behaviour of the friction between bumps and the rubbing surfaces. Nalepa et al. [9] have overviewed the technology with bearing deformable elements which utilizes sleeves of bearing. They have distinguished three types of foil bearing generations which have difference in their structures and their properties with regard to load carrying capacity, bearing stiffness and undesirable damping variations. They have incorporated the technical solutions of the foil bearing and the thrust bearing.

3. Objectives

CSIR-NAL developed a concept of Hybrid bearing with foil bearing for radial support and for axial support permanent magnetic bearing. Developed hybrid bearing may go unstable at critical speeds and leads to failure.

Objectives of this paper work is to analyse the hybrid bearing's critical speeds at the speed ranges of 120000 RPM using SAMSEF Rotor dynamic tool and stability is analysed using root locus plots.

4. Critical speed analysis

The motto of this chapter is to determine the stability of the hybrid support system under various stiffness conditions in the operating speed range up to 120000 RPM. For this axisymmetric model is used to create a model of rotating system with required boundary conditions and analyzed for critical speeds using SAMCEF FIELD - a rotor dynamic analysis tool.

The steps followed in the analysis are,

- Creating an axisymmetric model of the rotor.
- Assigning the physical and structural properties.
- Applying boundary conditions.
- Solution to get the critical speed map and Eigen values of the system

Bearing dimensions and other required data considered here for critical speed analysis and root locus analysis is taken from the paper "Rotor Dynamic Stability Analysis of Hybrid Support System" authored by Amar Hatti [3].

A. *The Modeler Module*

The Modeler module is concerned with the geometric model on which the analysis is based.

Here in this section creating the model representing the rotating system has done. This system will be modelled using a 2D representation of the axisymmetric section of the rotor. The first stage is to create the points that define the shape of the 2d surface / section.

Click on the Vertex tool and create a series of vertices with the following coordinates.

Table 1
Co-ordinate Vertices

Point number	X – Coordinate (mm)	Y – Coordinate (mm)
1	0	0
2	65	0
3	135	0
4	200	0
5	200	5
6	160	5
7	160	7.5
8	135	7.5
9	110	7.5
10	110	8.25
11	90	8.25
12	90	7.5
13	65	7.5
14	40	7.5
15	40	5
16	0	5

Create the wire by connecting all vertices.

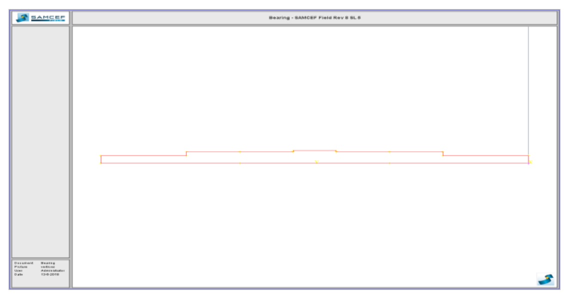

Fig. 1. Vertices

Click on Wire1 in the data tree and click [Apply] to create the face.

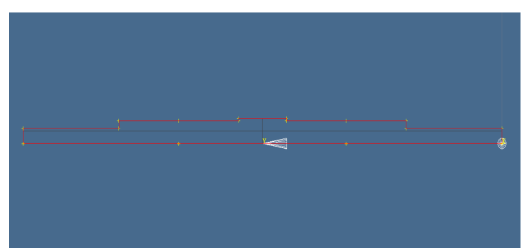

Fig. 2. Facing

B. *The Analysis Data Module*

The Analysis data module is the step where engineering design data to be used in the analysis is assigned to the model and required boundary conditions are applied.

The whole structure is made of steel.

Enter the values for Steel,

Young's Modulus = 210000 MPa

Mass Density = 7800 kg/m^3

Poisson's Ratio= 0.3

Use two ground bearings and two magnetic bearings stiffness to support the shaft and it is shown in Fig. 3.

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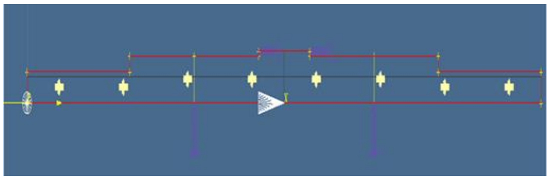
Fig. 3. Hybrid bearing setup

C. The Mesh Module

In this module, we create the mesh that will be used for the finite element analysis.

Meshing is done by selecting length of the mesh elements to be 5mm.

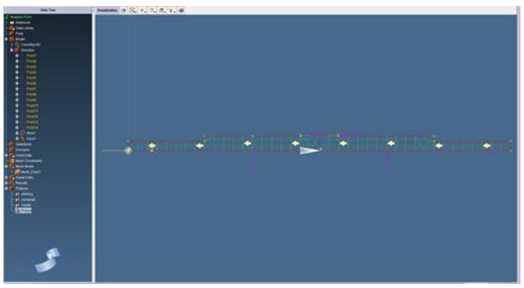
Fig. 4. Meshed model

D. The Solver Module

In this module the analysis is computed based on the data defined.

Here provide such data that the system should compute 8 Eigen frequencies at 10 rotational speeds between 0 and 2000 Hz (i.e. 0 and 120,000 rpm).

E. Critical Speed Analysis Results

1) Bearing offering maximum axial stiffness

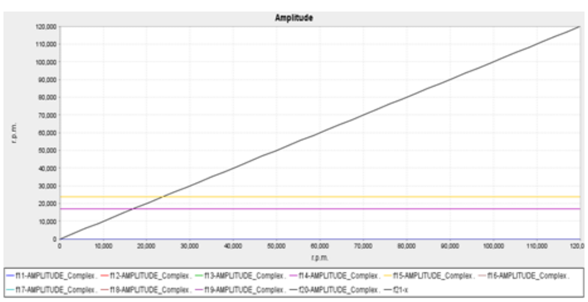

Fig. 5. Campbell Diagram-Bearing, K=0.0223 MN/m

2) Bearing offering zero axial stiffness

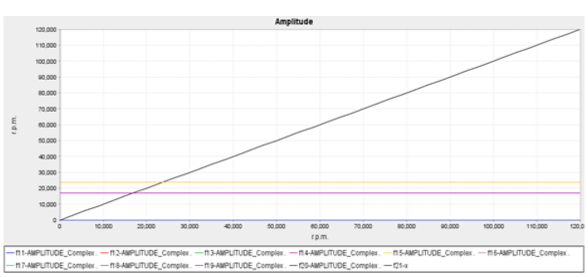

Fig. 6. Campbell Diagram-Bearing, K=0 MN/m

3) Bearing offering minimum axial stiffness

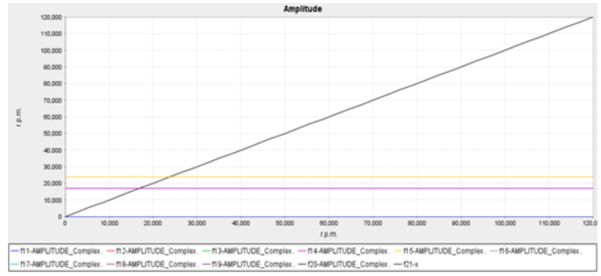

Fig. 7. Campbell Diagram-Bearing, K= -0.012 MN/m

5. Root locus analysis

Root locus criterion is a graphical method for examining how the roots of a system changes with variation of a certain system parameters, commonly gain within a feedback system.

In addition to determining the stability of the system, the root locus can be used to design the damping ratio (ζ) and natural frequency (ω_n) of a feedback system. The required data i.e. damping ratio (ζ), natural frequency (ω_n), circular frequency/angular velocity can be obtained from the results obtained from the samsef field software with different speeds of the shaft rotation. The roots of the equation, Alpha(α) can be found from the below equation,

$$\alpha = -\frac{c}{2m} \pm \sqrt{(\frac{c}{2m})^2 - \omega^2}$$

Where,

c = Damping co-efficient which is found out from the equation,

$$\text{Damping ratio, } \zeta = \frac{c}{cc} = \frac{c}{2m\omega n}$$

Roots of the equations are to be determined for different speeds of the rotation and different magnetic bearing stiffness from the maximum stiffness it is offering to the minimum negative stiffness it offers.

Roots obtained for the bearing,

$\zeta = 0.05$

m = 0.8 kg

for 12000 rpm,

$$\omega_n = 1256.63 \frac{\text{rad}}{\text{s}}$$

$\omega = 1788.76$ rad/s, obtained from samsef field results for K=0.0223 MN/m

$$\zeta = \frac{c}{cc} = \frac{c}{2m\omega n} = 0.05 = \frac{c}{2*0.8*1256.63}$$

c=2*0.8*0.05*1256.63 = 100.5304

Roots of the equation,

$$\alpha = -\frac{c}{2m} \pm \sqrt{(\frac{c}{2m})^2 - \omega^2}$$

$$\alpha = -\frac{100.5304}{2*0.8} \pm \sqrt{(\frac{100.53}{2*0.8})^2 - 1788.76^2}$$

α = -62.83±1788 for stiffness K=0.0223 MN/m

α = -62.83±1795 for stiffness K=0 MN/m

α = -62.83±1798 for stiffness K=-0.012 MN/m for speed 12000 rpm.

A. *Root Locus Plot Results*

Table 2
Roots for Bearing

Speed of the shaft (rpm)	Roots of the equations for different magnetic stiffness (MN/m)		
	K=0.0223	K=0	K=-0.012
12000	-62.83±1788	-62.83±1795	-62.83±1798
24000	-125.66±1784	-125.66±1791	-125.66±1795
36000	-188.4±1779	-188.49±1786	-188.49±1789
48000	-251.32±1771	-251.32±1778	-251.32±1781
60000	-314.15±1761	-314.15±1768	-314.15±1771
72000	-376.99±1749	-376.99±1756	-376.99±1759
84000	-439.82±1734	-439.82±1741	-439.82±1744
96000	-502.65±1717	-502.65±1724	-502.65±1727
108000	-565.48±1697	-565.48±1704	-565.48±1708
120000	-628.31±1675	-628.31±1682	-628.31±1686

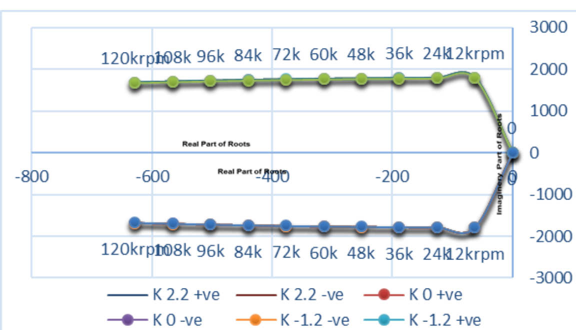

Fig. 8. Root Locus plot

6. Results and discussion

A. *Critical speed analysis*

Results obtained from critical speed analysis done in Samsef field software for bearing gives the promising results. Bearing with the maximum axial stiffness offered by the magnets had come up with two critical speeds, one at or near 17500 rpm and another at 24000 rpm and indicated in Fig. 5.

Experimentally from the paper "Rotor Dynamic Stability Analysis of Hybrid Support System" results show some instability at speeds from 16000 rpm to 25000 rpm with some whirling of shaft. Once system passes these speeds i.e. 25000 rpm no appreciable critical speeds are observed up to 50000 rpm. So, bearing used is stable for the speed's ranges above 24000 rpm. Lesser number of the critical speeds indicates more stable system.

Bearing with zero and minimum axial stiffness gives results near to that of the results obtained for maximum axial stiffness but with very little variations. Bearing operating with zero axial stiffness have two critical speeds one at 17000 rpm and one more at 24000 rpm which is shown in Fig. 6. Bearing operating with minimum axial stiffness have two critical speeds one at 17000 rpm and one more at 24000 rpm and it is shown in Fig. 7. Almost zero whirl is experienced during tests up 50000 rpm. Results obtained from critical speed analysis gives almost same results when the system is experimentally tested and analysed.

B. *Root locus analysis*

Results obtained from the root locus analysis gives the roots which lay in stable region of the root locus plot which indicates the system is stable. Roots are obtained from the equation for different speeds from 0 to 120000 rpm with varying stiffness. Real part of the equation gives roots from -62.83 to -628.31 and imaginary roots are from ±1788 to ±1675 for speeds 12000 rpm to 120000 rpm tabulated in Table 2. Roots of the equations are calculated for maximum axial stiffness (K=0.0223 MN/m), zero and minimum axial stiffness (K=-0.012 MN/m) and plotted in the root locus plot shown in Fig. 8. All the roots lay in the stable region of the plot indicating the stable system.

7. Conclusion

In the present work critical speed and root locus analysis of hybrid bearing is successfully analyzed and tested up to a speed of 120000 rpm.

The analysis results presented here indicated that the system has a stable working condition for the desired dimensions and speed ranges. Critical speed analysis for this bearing has lesser number of critical speeds which indicates a stable system and root locus plots gives the roots obtained for the bearing are laying in the stable region of the analysis plot.

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