ANALYTICAL AND EXPERIMENTAL STUDIES OF FLEXIBLE ROTOR-BEARING-DAMPER SYSTEM TO IDENTIFY INSTABILITY MECHANISM

by

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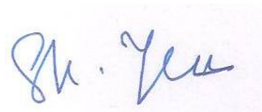

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DECLARATION

I, hereby declare that the investigation presented in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree / diploma at this or any other Institution / University.

(Karimulla Shaik)

List of Publications arising from the thesis

Journals

1. Shaik Karimulla, B. K. Dutta & G. Gouthaman, Experimental and Analytical Investigation of Short Squeeze-Film Damper (SFD) Under Circular-Centered Orbit (CCO) Motion, *Journal of Vibration Engineering & Technology*, Vol. 8, p. 215–224, (2020), https://doi.org/10.1007/s42417-019-00100-9.
2. Shaik Karimulla & B. K. Dutta, Tuning Criteria of Nonlinear Flexible Rotor Mounted on Squeeze Film Damper Using Analytical Approach, *Journal of Vibration Engineering & Technology*, Vol. 9, p. 325–339, (2021), https://doi.org/10.1007/s42417-020-00229-y.
3. Shaik Karimulla & B. K. Dutta, Stability Analysis of Symmetric Flexible Rotor Mounted on Hydrodynamic Bearing and Squeeze Film Damper Using Analytical Approach, *Tribology International*, Vol. 158, (2021), https://doi.org/10.1016/j.triboint.2021.106924.
4. Shaik Karimulla & B. K. Dutta, Non-linear Tuning Criteria of Vertical Flexible Rotor Mounted on Squeeze Film Damper (SFD): Rotor dynamics and Experimental validation, *Journal of Sound and Vibration,* (2021), Communicated.
5. Shaik Karimulla & B. K. Dutta, Stability Analysis of Flexible Vertical Rotor Mounted on Hydrodynamic Bearing and Squeeze Film Damper Using Analytical Approach, *Tribology International,* (2021), Communicated.

<u>Conference / Symposium:</u>

1. "Vibration monitoring of ball bearing using Wavelet transform and neural network", *NSRD- National Symposium on Rotor Dynamics*, Bangalore, 2014.
2. "Fluid Structure Interaction (FSI) of Incompressible Navier Fluid Structure Interaction (FSI) of Incompressible Navier Stokes Equation using Characteristic Based Split (CBS) Method" , *NPDE-TCA advanced workshop on Finite element methods for Navier-Stokes equations,* September, 8 – 12, 2014, SERC, IISc, Bangalore
3. "Parametric studies on floating pad journal bearing for high speed cryogenic turbo expanders", *IOP Conf. Series: Materials Science and Engineering, 278, (012026)*, 2017
4. "Studies on steady state response of floating pad journal bearing for high speed cryogenic turbo expanders", *IOP Conf. Series: Materials Science and Engineering, 171, (012027)*, 2017
5. "Non-linear Response of Asymmetric Flexible Vertical Rotor Mounted on Hydrodynamic Bearing (HDB) with Squeeze Film Damper (SFD) Using Analytical and Rotordynamics Approach", *VETOMAC-21*, 2021, Bangalore, communicated

(Karimulla Shaik)

DEDICATIONS

Dedicated to my Parents, Guide, Teachers, Wife, Children and Friends ……

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ABSTRACT

There is huge demand to operate rotating bearing systems at higher operational speeds to achieve higher specific power output. Horizontal flexible rotors mounted on hydrodynamic journal bearings undergo unstable operations at nearly two times of their bending critical speeds. Further, vertical rotors mounted on hydrodynamic journal bearing, theoretically exhibit unstable operation at all the speeds. Accurate calculation of non-linear forces of bearing, damper and its validation is most important to predict the stability threshold of both the systems accurately.

In the present thesis, development of an experimental setup with eccentric shaft extension to find the damper forces of submerged type Squeeze Film Damper with synchronous Circular Centered Orbit motion is presented. Submerged oil sump was mounted with load cells, two eddy current probes and with Resistance Temperature Detector probe to measure the damper forces and eccentric shaft orbit at known oil temperatures. All instruments were connected to high speed data acquisition system and data was recorded at high sampling rate. Fourier Transformation of experimental data was used to compute the damper forces. Above experimental setup was extended to validate tuning criteria of flexible vertical rotor mounted on Squeeze Film Damper. A vertical flexible shaft with central disc mounted with ball bearing at top end and ball bearing with Squeeze Film Damper at bottom end was used to predict the rotor and damper responses. Parameters of tuned mass system and various unbalances were used to predict rotor responses during crossing of bending critical speeds. This test setup was used to demonstrate smooth crossing of critical speeds with widening of response at critical speed and lowering of shaft

amplitudes. This experimental test setup was further extended to demonstrate the instability of rotor bearing damper system. Bottom support of the system was modified to accommodate the Hydrodynamic journal bearing as well as Squeeze Film Damper and run the system to two times of its bending critical speeds smoothly.

Analytical approach using modified Reynolds equation with short bearing/damper approximation was used to find the nonlinear fluid forces of Hydrodynamic journal bearing and Squeeze Film Damper by considering viscous, inertial, temporal contributions under both laminar and turbulent conditions with cavitated (π-film) and uncavitated (2π-film) fluid film. Both isoviscous and thermohydrodynamic modeling of hydrodynamic bearing were considered to account for viscosity change with temperature. Theoretical models of squeeze film damper were validated with experiments and a good agreement between theoretical and experimental results was observed.

Smooth crossing of flexural critical speeds is very important to avoid damage to bearing support system due to heavy loads and to ensure long life. Initially, analytical solution to find the optimum tuning criteria was derived using linear model of rotor mounted with Squeeze Film Damper with symmetric and asymmetric supports. Later, it was extended to nonlinear system using Circular Centered Orbit condition. The solution of the system of equations helped to predict optimum tuning parameters like cross over frequency, peak amplitudes and optimum damping required. To validate the tuning criteria of the flexible rotor-damper system, a vertical experimental setup was developed and the results were compared with theoretical predictions.

Analytical method was developed to find the static equilibrium position and stability threshold of rotor-bearing system about its static equilibrium position by introducing SFD to it. A simple iterative method was used to predict the stability threshold of rotor bearing damper system. Role of support flexibility, damper support mass, shaft flexibility, turbulence and fluid inertia of damper fluids on stability was discussed. Theoretical model was extended to find the stability threshold of vertical rotor-bearing-damper system with symmetric and asymmetric supports under both isoviscous and thermo hydrodynamic conditions. An experimental rotor setup with vertical configuration was designed and operated beyond its bending critical speeds to demonstrate the theoretical results.

Results show that stiffness of the half shaft at damper end in asymmetric supported system plays an important role in tuning criteria as compared with symmetrically supported system. Stability threshold of rigid rotor-bearing-damper system can be increased significantly by increasing support stiffness of damper and decreasing mass ratio of damper, where as the limit was reduced to less than two times of its original limit in case of tuned flexible rotor bearing damper system. Stability threshold of rigid vertical system reduces to half the limit of rigid horizontal system, whereas, not much change is observed in stability of flexible vertical system in comparison with flexible horizontal system. Lower the shaft stiffness reduces the stability limit and turbulence reduces the stability limit further.

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STABILITY ANALYSIS OF ROTOR MOUNTED ON HDB AND SFD USING ANALYTICAL APPROACH

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NOMENCLATURE

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Thesis Highlight

Name of the Student: Karimulla Shaik

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Thesis Title: Analytical and Experimental Studies of Flexible Rotor-Bearing-Damper System to Identify Instability Mechanism

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The requirement to operate rotor-bearing systems at higher speeds to achieve higher specific power output leads to three major areas of research viz., finding out nonlinear fluid forces on hydrodynamic bearings (HDB) and squeeze film dampers (SFD), crossing over of bending critical speeds with minimum rotor amplitudes and overcoming high speed instabilities. Analytical solutions of nonlinear fluid forces of HDB and SFD including inertia and turbulence effects have benn developed for synchronous circular center orbit (CCO) & validated experimentally. Subsequently, analytical solutions of linear and non-linear tuning criteria of vertical rotor with symmetric supports (squeeze film damper (SFD) at both ends) and asymmetric supports (ball bearing at one end & SFD at other end) have been developed and validated experimentally. It has been that tuned supports of

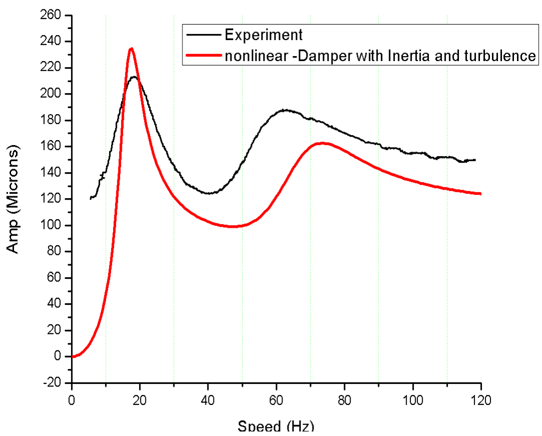

Fig. 1. Demonstration of tuning criteria

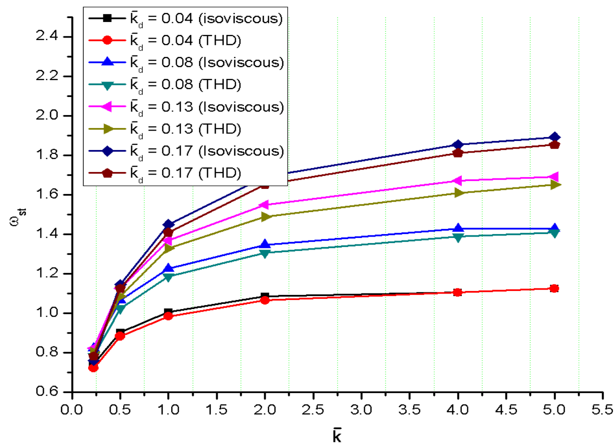

Fig. 2 Stability threshold of flexible vertical rotor on tuned supports

asymmetric system not only depends on mass ratios but also on stiffness of bottom half of the shaft. Fig.1 shows a comparison of theoretical and experimental results to demonstrate reduction of peak amplitudes and widening of base of peaks of rotor. An analytical method has been developed to find out stability threshold at equilibrium positions of rigid & flexible rotors mounted on HDB and SFD. Fig.2 shows the stability threshold of a vertical flexible asymmetric rotor mounted on HDB and tuned SFD by using iso-viscous and Thermo-hydrodynamic (THD) models. Experimental test setup of three disk rotor with asymmetric supports has been developed to operate at higher speeds without encountering instabilities. The stability of rigid rotor system can be further increased by increasing the support stiffness and by reducing the damper mass. Whereas the stability of untuned flexible rotor system primarily depends on the support to rotor mass ratio. Lower the support stiffness, lower the cross over amplitudes while crossing bending critical speeds. This results in lower stability threshold.