



A review on Dynamic Behavior of Rotor Roller System with Bearing Defects

A. V. Prajapati

Student of M.E. (CAD/CAM) L. D. College of Engineering Mechanical Department, Navrangpura, Ahmedabad-15

Prof. U. A. Patel

Asst. prof. Mechanical Engg. L. D. College of Engineering Mechanical Department, Navrangpura, Ahmedabad-15

Nemisha Gauswami

Student of M.E. (CAD/CAM) L. D. College of Engineering Mechanical Department, Navrangpura, Ahmedabad-15

ABSTRACT

Rotating machinery is becoming faster and lightweight due to the advanced technologies made in engineering and materials sciences. It is required them to run for longer periods of time. The high speed rotor bearing system often shows unpredictable dynamic response due to manufacturing defects. As it is not possible to produce perfect surface or contour even with the best available machine tools so imperfection such as surface waviness in the rolling element and races developed during manufacturing process cannot be avoided. The radial and axial clearance provided in the design of bearings to compensate for thermal expansion, can also be a source of vibrations and introduce nonlinearity in the dynamic system. Using vibration analysis, the condition of a machine can be periodically monitored. The main objective of this paper is to study the nonlinear dynamic behavior of rotor-roller bearing system with localized and distributed bearing defects. Like, internal clearance, waviness, off sized rolling element, case run-out etc. The localized defects include cracks, pits and spalls caused by fatigue on rolling races. Distributed defects include surface roughness, waviness and misaligned races and off size rolling elements.

KEYWORDS: Nonlinear Dynamics, Varying compliance frequency, ball passage frequency, chaotic vibration, Poincare maps.

1. INTRODUCTION

Rotating machinery is very commonly used in mechanical systems, including machining tools, industrial turbo

Machinery and aircraft gas turbine engines analysis and design rotating machinery is extremely critical in terms of the cost of both production and maintenance. The design rotating machinery is increasingly getting complex due to rapid progress in the technology. Thus the machinery condition-monitoring strategies are getting more advanced in order to cope with the physical burden took place of the individual components of a machine. Adequate monitoring predicts the possibility of a breakdown before it actually occurs.

Modern condition monitoring techniques consist of different technologies like, vibration measurement, acoustic measurement, wear analysis and temperature measurement. Vibration based condition monitoring are most widely used techniques. Both time domain and frequency domain methods are used for monitoring the health of bearings.^[10]

The stiffness, rotational accuracy and vibration characteristics of a high speed shafts are partly controlled by bearing that support it. An analysis of bearing dynamic behavior is important to predict the system vibration response.^[10]

The behavior of nonlinear systems often demonstrates unexpected behavior pattern that are extremely sensitive to initial condition. When rolling element bearings are operated at high speed they generate vibrations and noise. The principal forces, which drive these vibrations, are time varying nonlinear contact forces, which exist between the various components of the bearings: rolling elements, races and shafts. In the rotor bearing assembly supported by perfect ball bearings, the vibration spectrum is dominated by the vibration at the natural frequency and the ball passage frequency (BPF). The vibrations at this later frequency are called ball passage vibration. M. Tiwari^[11] studied the nonlinear behavior of a balanced rotor by taking in to account the defects of internal clearance of a roller bearing, and analyzed the dynamic characteristics of an unbalanced rotor. Tandon and Choudhury [8] predicted frequency having peaks at characteristic defect frequencies.

2. PAST RESEARCH IN ROTOR-ROLLER BEARING WITH BEARING DEFECTS.

This section will provide an overview of researches on the dynamic behavior of the rotor roller system with deferent bearing defects.

JingJianPi et al (2002)^[1] developed a continuum rotor-bearing system is modeled by finite element technique and the vibrational responses are calculated by employing Newmark and Mode Superposition schemes.

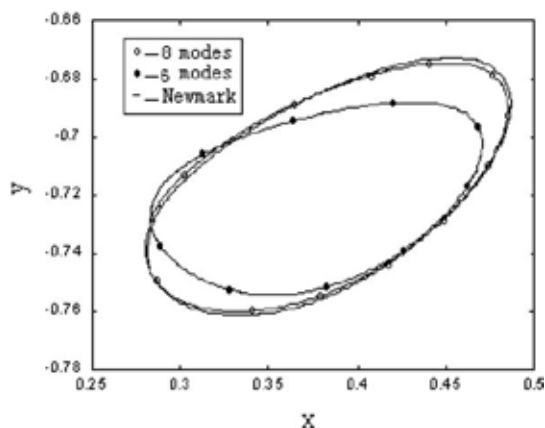


Figure: 2.1 Comparison of the results of Newmark and Mode Superposition scheme $\delta\omega \frac{1}{4} 600 \text{ rad} = \text{sP}$:

The comparison of the results from the Newmark and Mode Superposition method shows that the mode reduction will bring about error in the solution of rotor's non-linear vibration responses. The more the modes are reduced, the more the error occurs. The results show that the Direct Integration method is more accurate and practical than the Superstition method in the calculation of the non-linear dynamic response. He suggested that Oil Whip may take place in the speed descending process, and from the view of non-linear dynamics, it is a Hopf bifurcation, and they should be avoided in the design of this kind of rotor.

S.P. Harsha et al (2003)^[2] studied the effect of speed of balanced rotor on nonlinear vibrations associated with ball bearings. The mathematical model takes into account the sources of nonlinearity such as Hertzian contact force, surface waviness, varying compliance and internal radial clearance resulting transition from no contact to contact state between rolling elements and races.

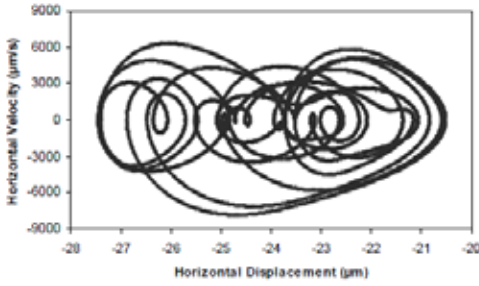


Figure: 2.2 Poincare map for horizontal displacement response at 2650 rpm

As rotating speed increase quasi-periodic nature changes to chaotic. The quasi-periodic nature converts to chaotic nature, which is one of the characteristics of chaos. Poincar map is also shown its fractal structure, which is a strong indication of chaotic nature of the system and frequency spectra at this speed also show broadband spectrum. In the range 4500–5150 rpm system show quasi-periodic and chaotic nature. The system becomes unstable at 5300 rpm after that it shows instability.

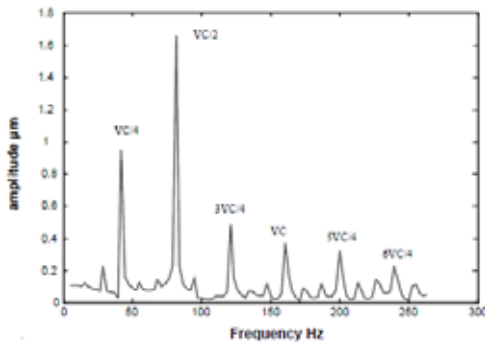


Figure: 2.3 FFT for horizontal displacement response at 2650 rpm

The system responses are periodic and are not sensitive to initial conditions. The periodic impact force increase s smoothly.

The system responses are chaotic but near quasi periodic or sub-harmonic nature and are not sensitive to initial conditions but extremely sensitive to small variations of the system parameters and operating conditions. The contact force significantly fluctuates as the operating speed changes.

The response are unpredictable, either periodic or chaotic and is extremely sensitive to both initial condition and small variations in system parameters as speed increases.

S.P. Harsha (2005) [3] studied the nonlinear dynamic response of a balanced rotor Supported by rolling element bearings due to radial internal clearance effect. He developed a model for investigating structural vibrations in rolling element bearings due to radial internal clearance.

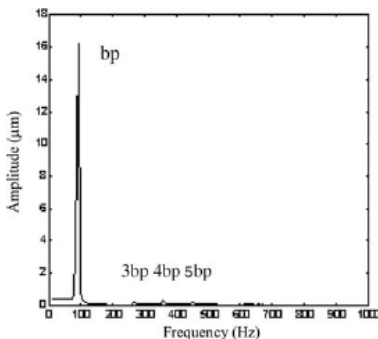


Figure: 2.4 FFT Responses at 1500 rpm with radial clearance = 6 µm.

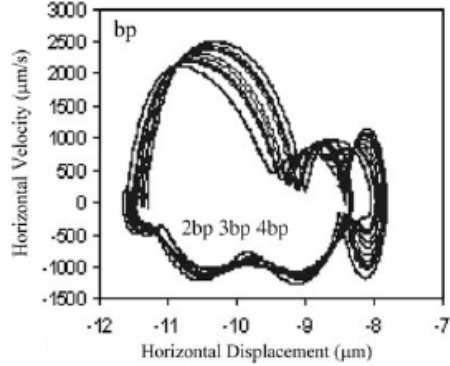


Figure: 2.5 poincare map for horizontal displacement response at 1500 rpm with radial clearance = 6 µm.

The nonlinear response of a balanced rotor has been demonstrated to be chaotic for some specific combination rotational speed combined with varying internal radial clearance to provide sufficient nonlinearity. Varying the internal radial clearance bound the region of quasi-periodic, sub-harmonic and chaotic for ball bearing excited by various defects.

Decrease in radial clearance increase the linear characteristics of the system. There is no chaos appears as clearance decreases. It is observed that the peak amplitude of vibration always appear in the spectrum only at the ball passage frequency (BPF).

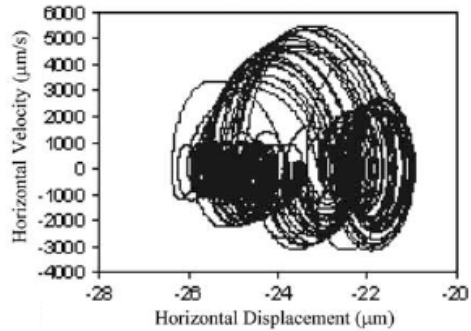


Figure: 2.6 poincare map for horizontal displacement response at 1500 rpm with radial clearance = 20 µm.

As the clearance is changes from 6 µm to 12 µm, the corresponding response changes as sub-harmonic to onset of chaos.

Zeki Kiral, et al (2005) [4] studied Vibration analysis of rolling element bearings with various defects under the action of an unbalanced force. They presented the finite element vibration analysis method for defect detection in rolling element bearings with single or multiple defects on different components of the bearing structure using the time and frequency domain parameters. They used Time and frequency domain parameters such as rms, crest factor, kurtosis and band energy ratio to analyze the effect of the defect location and the number of defects on the time and frequency domain parameters. Depending on the working conditions, a localized defect may appear on different components in a rolling element bearing. Each fault case has its own repetition frequency and defined for stationary outer ring as follows.

$$\text{Defect on the outer ring : } f_{or} = \frac{Zf_r}{2d_o} \left(1 - \frac{d_o}{d_c} \cos \alpha \right).$$

$$\text{Defect on the inner ring : } f_{ir} = \frac{Zf_r}{2} \left(1 + \frac{d_o}{d_n} \cos \alpha \right).$$

$$\text{Defect on the rolling element : } f_{re} = f_s \frac{d_o}{d_c} \left(1 - \frac{d_o^2}{d_c^2} \cos^2 \alpha \right).$$

They conclude that the statistical parameters show that the defect position on the outer ring, number of defects and defect locations, on the inner ring or on the rolling element, and the shaft speed affect the statistical indices. The envelope method can be used efficiently in order to detect the outer and inner ring defects, but rolling element defects are not easy to detect via envelope and band energy ratio procedures.

C. Nataraj, et al (2006) [5] they developed an analytical model to investigate the nonlinear dynamic behavior of an unbalanced rotor-bearing system due to cage run-out. They consider mathematical model takes into account the sources of nonlinearity such as Hertzian contact forces and cage run-out, and the resulting transition from a state of no contact to contact between the rolling elements and the races.

Due to the cage run-out, the rolling elements no longer stay equally spaced which leads to the modulation of the ball passage frequency with the cage frequency. The variation of the circumferential angle for a small run-out (C) is assumed to be 0.001 lm and the unbalance force magnitude (Fu) is taken to be 15% of the radial load. The results of the computations are presented in the form of FFT and Poincaré maps. When the number of balls is 5, the dense frequency spectrum observed with peak amplitude of vibration appears at the ball passage frequency, $\omega_{bp} = 166.67$ Hz, and at $\omega = 83.33$ Hz as shown in Fig. 2.7

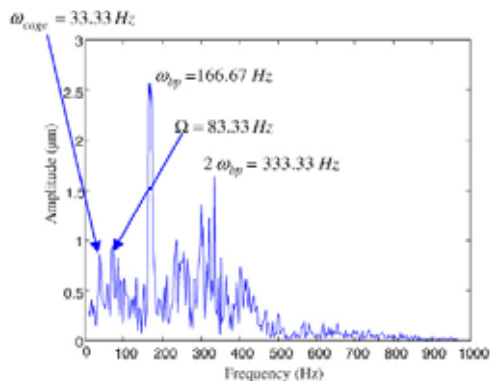


Figure: 2.7 FFT response with Nb = 5.

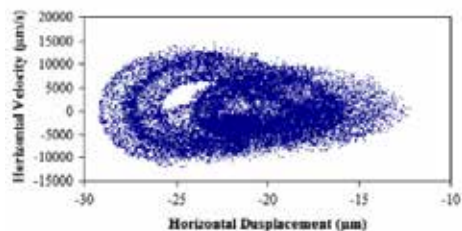


Figure: 2.8 Poincaré maps with Nb = 5.

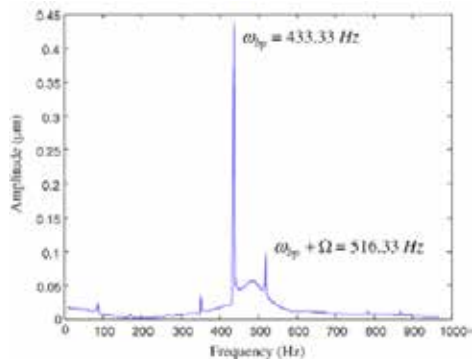


Figure: 2.9 FFT response with Nb = 13.

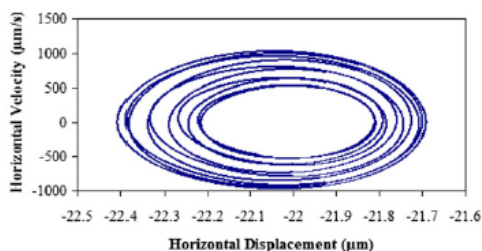


Figure: 2.10 Poincaré maps with Nb = 13.

Increasing the number of balls increases the system stiffness and results in a reduction of the vibration amplitude. This effect is exhibited in the results, which shows the Poincaré maps of the displacements for different number of balls. When the number of balls is increased, the vibration reduces drastically implying a stiffer system. It can be predicted that increasing the number of balls will reduce the effect of the modulating frequency and because of the cage run-out, ball passage frequency becomes dominant in the vibration spectrum. The number of balls with cage run-out in the bearings can hence be of importance in the rotor-bearing dynamics and should be considered at the design stage. Analysis predicts that the highest vibrations due to cage run-out for a generic number of balls are at $(\omega = q\omega_{bp} \pm k\omega_c)$.

Ahmad Rafsanjani, et al (2008) [6] developed an analytical model to study the nonlinear dynamic behavior of rolling element bearing systems including surface defects. Various surface defects due to local imperfections on raceways and rolling elements are introduced to the proposed model. Mathematical expressions were derived for inner race, outer race and rolling element local defects.

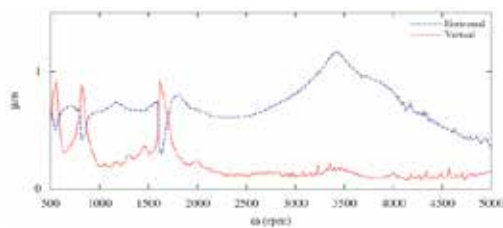


Figure: 2.11 peak-to-peak displacement response of single point defect on outer raceway with 5µm internal clearance.

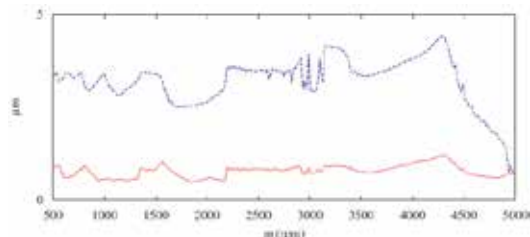


Figure: 2.12 peak-to-peak displacement response of single point defect on outer raceway with 13µm internal clearance.

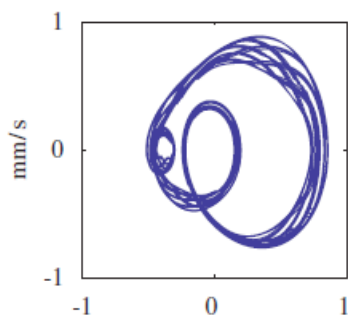


Figure: 2.13 poincaré map of single point defect on outer raceway with 5µm internal clearance and $\omega=1265$ rev/m.

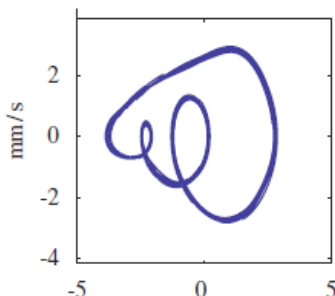


Figure: 2.14 poincare map of single point defect on outer raceway with 13µm internal clearance and $\omega=1000\text{rev/m}$.

In most range of shaft speeds, the system is not depended on initial conditions but strongly affected by the parameters of the system particularly radial internal clearance and surface defects. For normal and large clearances the motion is quite unstable and in most speed ranges the system undergoing the quasi-periodic and chaotic motion. In this case the regions of unstable periodic motion would be extended. The chaotic nature of motion rises up in the presence of rolling element defects while the outer race defect has minimal effect on unstable routes to chaos.

S. H. Upadhyay, et al (2008)^[7] studied Nonlinear Vibration Signature Analysis of High Speed Rotor Due to Defects of Rolling Element. They developed a mathematical model to investigate the nonlinear dynamic behavior of a high speed rotor-bearing system due to defects of rolling elements. They considered two defects, one defect as off-sized rolling elements and other defect as rolling element waviness. They used Lagrange's equation for formulation of equations of motion. For off-sized Rolling Elements defects as under.

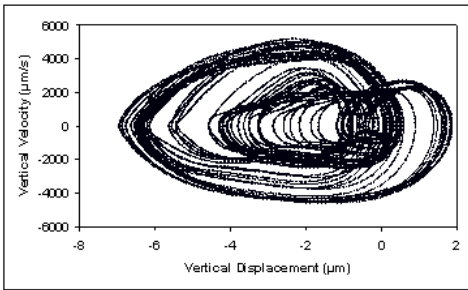


Figure: 2.15 poincare map for Nb= 6

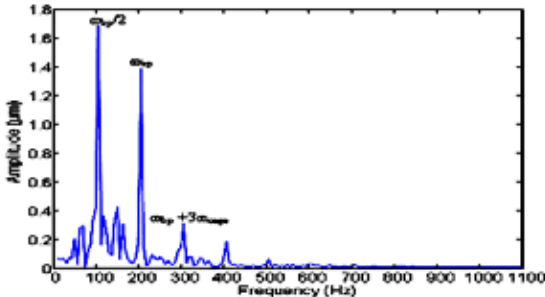


Figure: 2.16 FFT for Nb= 6

Nonlinear dynamic responses are found to be associated with ball passage Frequency. When the number of balls is increased, reduce the effect of the BPF.

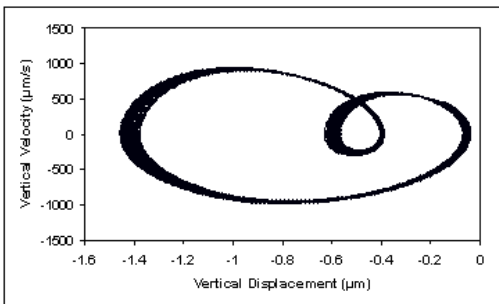


Figure: 2.17 poincare map for Nb= 9

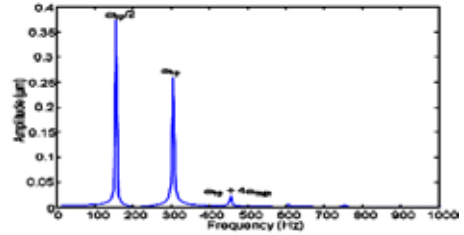


Figure: 2.18 FFT for Nb= 9 Rolling elements Waviness defect as under.

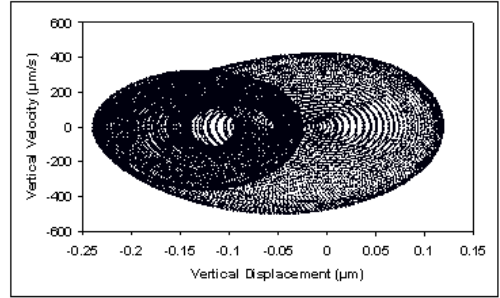


Figure: 2.19 poincare map for Nb= 6 & Nw=6

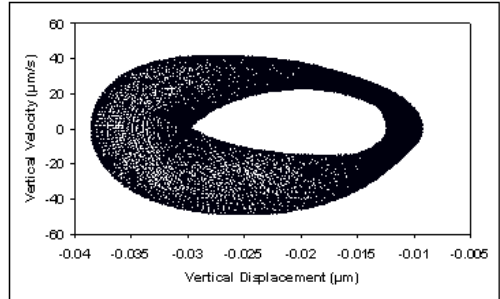


Figure: 2.20 poincare map for Nb= 13 Nw=13

The peak amplitude of vibrations due to ball waviness with varying number of balls appears at the wave passage frequency and ball passage frequency. Increasing the number of waves means making the ball smoother with a larger diameter. Increasing the order of waviness will diminish the vibrations and only vibrations at the wave passage frequency will mainly remain in the spectrum.

3. CURRENT RESEARCH TRENDS IN CONDITION MONITORING OF BEARING.

Condition Monitoring is most frequently used as a Predictive or Condition-Based Maintenance technique. Now a day following techniques are used for condition monitoring of bearing.

- 1) Infrared Thermography
- 2) Oil Analysis and Tribology
- 3) Ultrasonic
- 4) Motor Current Analysis
- 5) On-line sensing technology

4. FUTURE DIRECTION OF RESEARCH

Roller skidding is the function of lubrication. Lubrication traction has dominant effect on the roller skidding. Slip arise when the moment due to the drag force on the roller, which is created by viscous shearing resistance of the grease exceed the traction moment at the race way contact.

Predict the dynamic behavior of the rotor roller bearing system having 4-DOF system with consideration of skewing, declining, thickness of lubrication film, waviness, internal clearance and the localized defect of bearing.

REFERENCES

- [1] JingJianPing, MengGuang, Sun Yi, Xia SongBo, "On the non-linear dynamic behavior of a rotor-bearing system", *Journal of Sound and Vibration* (2004); 274: pp.1031–1044. | [2] S.P. Harsha, K. Sandeep, R. Prakash, 'The effect of speed of balanced rotor on nonlinear vibrations associated with ball bearings', *International Journal of Mechanical Sciences* (2003) ; 45: pp.724–740 | [3] S.P. Harsha, "Non-linear dynamic response of a balanced rotor supported on rolling element bearings", *Mechanical Systems and Signal Processing* (2005)19; pp: 551–578 | [4] Zeki Kiral, Hira Karagu" lle, "Vibration analysis of rolling element bearings with various defects under the action of an unbalanced force", *Mechanical Systems and Signal Processing* (2006) 20; pp: 1967–1991 | [5] C. Nataraj, S.P. Harsha, "The effect of bearing cage run-out on the nonlinear dynamics of a rotating shaft", *Communications in Nonlinear Science and Numerical Simulation* (2008) 13; pp:822–838 | [6] Ahmad Rafsanjani, SaeedAbbasion, Hamid Moeenfard, "Nonlinear dynamic modeling of surface defects in rolling element bearing systems", *Journal of Sound and Vibration* (2009) 319; pp: 1150–1174 | [7] S. H. Upadhyay, S. P. Harsha and S. C. Jain, "Nonlinear Vibration Signature Analysis of High Speed Rotor Due to Defects of Rolling Element", *Adv. Theor. Appl. Mech.*, Vol. 1, 2008, no. 7, pp: 301 – 314 | [8] Chaudhary, A. and N. Tandon, 1998. A Theoretical Model to Predict Vibration | Response of Rolling outer race, inner race and roller malfunction Bearings to Distributed Defects under Radial Load. *Journal of Vibration and Acoustics, Transactions of ASME*, vol 120, no. 1, pp: 214-220. | [9] T.A.Harris, *Rolling Bearing Analysis*. 4th ed. New York: John Willy and Sons. 2001 | [10] Shigley J.E. and Mischke C.R., *Mechanical Engineering Design*, 5th edition, | McGraw-Hill, 1989. | [11] M. Tiwari, K. Gupta, O. Prakash, Dynamic response of an unbalanced rotor supported on ball bearings, *J. Sound Vib.* 238 (2000) 757–779. | [12] *Hand Book Rolling Element*, Charles A. Moyer, Xiaolan Ai, |