GYROSCOPIC EFFECTS ON VIBRATORY RESPONSES OF NONLINEAR MISALIGNED ROTOR SYSTEMS

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Abstract - In engineering practices, misalignment of the rotors of rotor systems is inevitable and may affect the dynamic behavior and therefore the operation and operation life of the system. The other effects of the systems such as gyroscopic effects of the rotors and nonlinearities involved in the systems may also play a considerable role when it comes to high speed rotors with misalignment. This research is to analyze a nonlinear multi-rotor system which is affected by gyroscopic effects of the system and misalignments of the rotors. The significances of the gyroscopic effect on the vibratory responses of the system are focused in the research. The results of the research contribute to understanding of the dynamic behavior of nonlinear multi-rotor systems and provide guidance for designing and manufacturing such systems.

Key words - Gyroscopic effects, nonlinear vibrations, nonlinear rotor supports, rotor systems, misalignment.

I. INTRODUCTION

A typical rotor system used in industry is a body suspended through a set of cylindrical hinges or bearings that allow it to rotate freely about an axis fixed in space. The non-rotating supporting structure of a rotor system is defined as a stator. Rotor systems are widely seen in various engineering areas such as those found in the engines of aircraft jets, automobile, the pumps used in household appliances, the drums of the washing machine, spindles of machine tools etc. (Maurya, 2013). The computer hard disc drives are also rotor systems. Rotating machinery is used in many applications such as turbo-machines, power stations, machine tools and aerospace applications. (Amirtharajah, 1999).The rotors and rotor systems are there important components or systems implemented in industries.

Numerous types of rotor systems are applied in industries, in terms of size, geometric shapes and applications. The main responses of the systems are vibratory and the responses can be complex, especially when the systems involve multi-rotors or high speed rotors.Rotors of the rotor systems are usually mounted on the bearings of the systems. Certain level of misalignment of the rotors on their bearings is almost impossible to avoid in engineering practice.The misalignment of the rotors affects the rotation and responses of the rotor systems. Nonlinearities involved in the rotor systems, such as the nonlinear supports of the rotors, may also affect the response of the rotor systems.
In engineering designing for rotor systems and in manufacturing especially in operating the rotor systems, comprehension and analysis of the rotor dynamics are crucial. Numerous research works are found in literature for investigating the vibratory responses of rotor systems (Maurya, 2013; Kicinski, 1996; Ma, 2011; Yao, 2015). Many factors affecting the vibratory responses of the rotor systems are considered by the researchers, such as rotor speed, number of rotors involved and misalignments of the rotors. However, there is still lack of a systematic and thorough study on the responses of the rotor systems with considerations some of the factors which may play an important role in controlling the vibrations of the rotor systems. Nonlinearity for example, is not widely considered in rotor dynamics studies, though nonlinearities of the rotor systems may lead to nonlinear vibration of the rotor systems and cause difficulties in operation of systems. Gyroscopic effects are also recognized as a factor affecting the rotational motion of rotor systems. However, very few archived documents can be found in the literature in studying the gyroscopic effects on the rotational vibrations of the rotor systems.

This research is to quantitatively investigate the nonlinear responses of a multi-rotor system. The gyroscopic effects of the rotors on the rotational responses of the system are to be studies with considerations of possible misalignment of the rotors and nonlinear supports provided by the bearings on which the rotors are rotating. The findings of the research are expected to provide guidance for accurately and efficiently studying and analysing the nonlinear dynamic behaviour of the rotor systems, which is significantly important for the design and manufacturing of the rotor systems.

II. ROTOR SYSTEM AND ITS MODELING

Thesketch of a typical multi-rotor system considered in this research is shown in Fig. 1,in which the two rotors of mass m_1 and $m_2$are as shown. The two rotors are supported by 4 cylindrical roller bearings and rotating on the bearings.

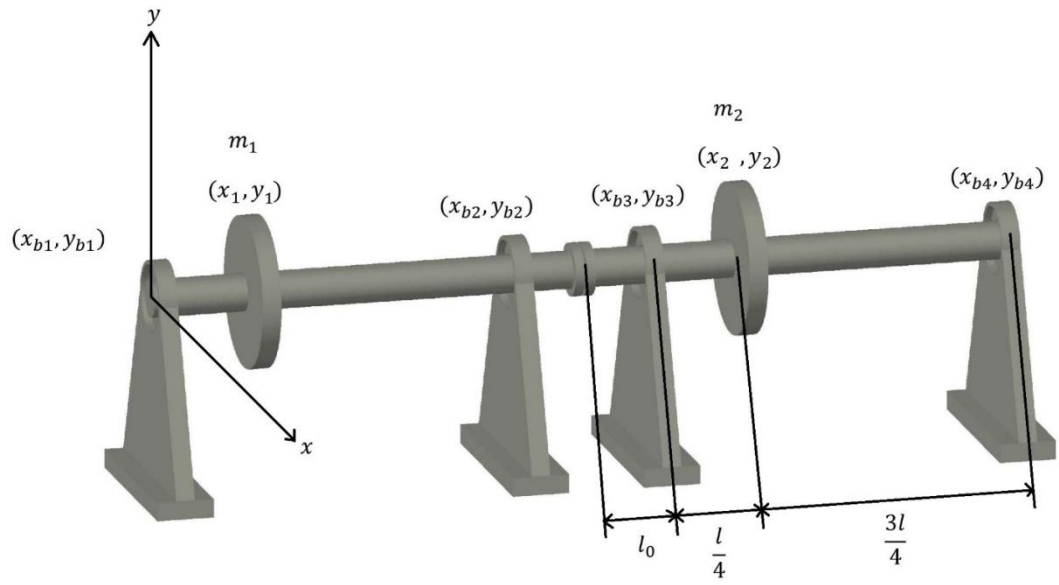


Figure 1 Sketch of a two rotor system

The two rotors are coupled with a flexible coupling. An angular misalignment of the two rotors are assumed and it is assumed that the rotor rotation is considered constant and the angle between the two parts of the coupling does not change during operation. (Rotor is rotating in clockwise direction in XY plane, and the displacement of the system along the z direction is negligible).

In the figure, x_1, y_1 are the coordinates of rotor 1; x_2, y_2 are coordinates of rotor 2, along the x and y directions; x_{bi}, y_{bj} arethe coordinates of the four supporting bearing in the x and y directions respectively $(i, j = 1,2,3,4)$; l_0 is the distance between the third supporting bearing and the coupling; and l is the total length between the third and fourth bearings

Governing Equations:

The equation of motion, in generalized matrix form, for an axially symmetric rotor rotating at a constant spin speed ω is (Yoon, 2009)

$$M\ddot{X} + \omega G\dot{X} + KX = F(t) \quad (1)$$

whereMis the mass matrix, X is generalized displacement vector, ω is the angular speed, G is the gyroscopic matrix, K is the stiffness matrix, and is the rotor unbalance force $(me\omega^2)$

Individual matrix from the above equation can be given as below:

$$M = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_1 & 0 \\ 0 & 0 & 0 & m_2 \end{bmatrix} \quad (2)$$

$$G = \begin{bmatrix} 0 & -J_p & 0 & 0 \\ J_p & 0 & 0 & 0 \\ 0 & 0 & 0 & -J_p \\ 0 & 0 & J_p & 0 \end{bmatrix} \quad (3)$$

$$K = \begin{bmatrix} k_1 + k_2 & 0 & 0 & 0 \\ 0 & k_1 + k_2 & 0 & 0 \\ 0 & 0 & k_3 + k_4 & 0 \\ 0 & 0 & 0 & k_3 + k_4 \end{bmatrix} \quad (4)$$

$$X = \begin{bmatrix} x_1 \\ y_1 \\ x_2 \\ y_2 \end{bmatrix} \quad (5)$$

where J_p is the polar moment of inertia of the rotor andk_i is the bearing stiffness (i=1,2,3,4); x_j, y_j represents displacement of rotor in x and y direction respectively (j=1,2).

Rotor misalignment is one of the most common difficulties in the operation of rotating machinery, yet it remains incompletely understood (Lees, 2007). Coupling misalignment is common, and to a point, desirable in many types of couplings. However, the amount of coupling backlash required for efficient coupling backlash is minimal. Often, excessive coupling backlash is caused by a worn coupling insert (Lawrence, 2010).

Gyroscopic effect has to be considered when a rotating body is present in the system. Under certain conditions like when rotor is mounted at the center of shaft, gyroscopic effect do not play dominant role and can be neglected. This is due to the fact that the precession of the disc takes place along with the

spinning, which leads to the gyroscopic couple on the disc.

For thealigned two-rotor system with considerations of gyroscopic effects, the governing equation can be given by,

$$m\ddot{x}_1 - \omega J_p \dot{y}_1 + 2kx_1 = me\omega^2 \cos(\omega t) \quad (6)$$

$$m\ddot{y}_1 + \omega J_p \dot{x}_1 + 2ky_1 = me\omega^2 \sin(\omega t) - mg \quad (7)$$

$$m\ddot{x}_2 - \omega J_p \dot{y}_2 + 2kx_2 = me\omega^2 \cos(\omega t + \varphi) \quad (8)$$

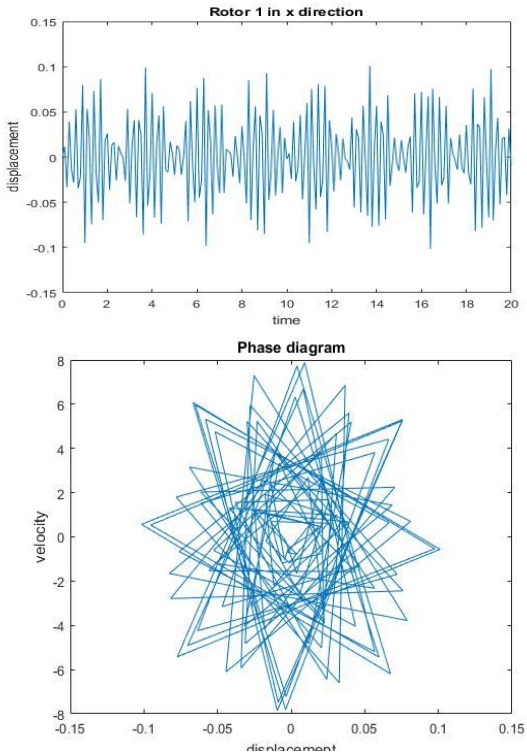
$$m\ddot{y}_2 + \omega J_p \dot{x}_2 + 2ky_2 = me\omega^2 \sin(\omega t + \varphi) - mg \quad (9)$$

In the equations, m is the of rotor (identical for both rotors), φ is the phase angle betweenthe vectors of unbalance forces, and Unbalance force = $me\omega^2$where (m*e) is the mass unbalance, and e is specific unbalance

Based on the model expressed in the above governing equations, numerical simulation are carried out with implementation of MATLAB using ode45 function (based on explicit Runge-Kuttaof 4^{th} order).Thesystem parameters used are as shown below: m = 5.5 kg, k = $2*10^5$ N/m, N = 7500 rpm, diameter of disc = 500 mm, $\varphi = \frac{\pi}{6}$, specific unbalance (eccentricity) e = 0.01m, g = 9.81m/s^2, and $J_p = \frac{m*R^2}{2}$. All results are in mm vs sec.

The displacement of rotor shown in numerical analysis represents the Center of Gravity of the respective rotor.

Typical results of the simulations are shown in the following figures, as wave forms, phase diagrams and Poincare maps.



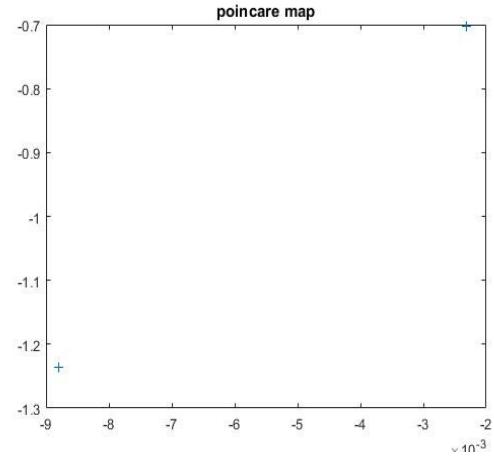


Figure 2 Wave curve, phase diagram and Poincare map for a rotor with gyroscopic effects

As a comparison, the phase diagram for the same system without considering the gyroscopic effects is shown in the following figure.

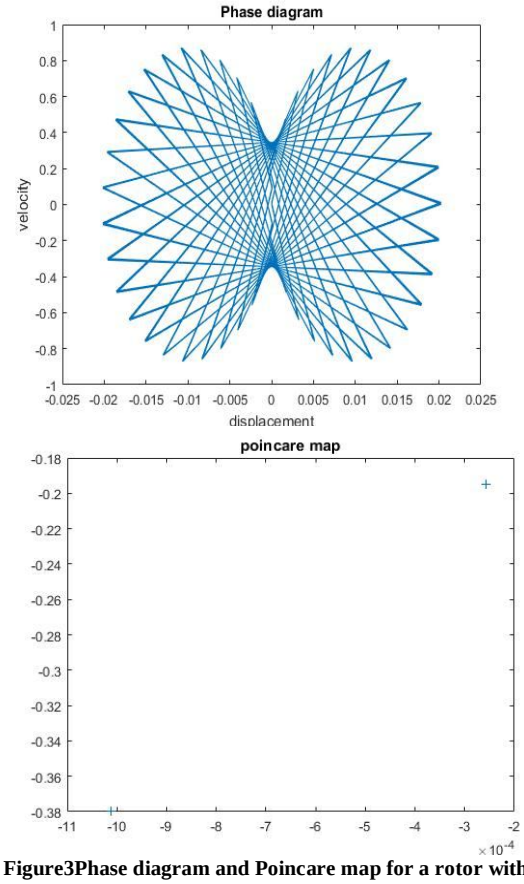


Figure3Phase diagram and Poincare map for a rotor without gyroscopic effects

CONCLUSION

Based on the research, it can be concluded that there is a significant difference in displacement in the direction of precession when gyroscopic effects are taken into consideration. Vibration analysis of such system without considering the gyroscopic effect can be misleading and the system can exhibit different behavior in practice. This can lead to increase in

vibration, noise and can damage the system over time.

Perfectly aligned multi rotor system is generally not possible in practice as it can get misaligned even due to frequent starting and stopping of the system. Misalignment in small range (2° or less) is not much damaging but excessive misalignment can have negative impacts on coupling as well as the entire system.

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REFERENCES

[1] J.S. Amirtharajah, "Critical speed and unbalance response of cantilever-sleeve rotors using finite elements with efficient higher order basis functions", Thesis in department of Mechanical Engineering, Concordia University, May 1999.

[2] J. Kicinski, R. Drozdowski, P. Materny (1996), "Mon-linear model of vibrations in a rotor-bearing system", Institute of Fluid Flow Machinery of the polish Academy of sciences, Vol. 14, 80-952 Gdansk, 1996.

[3] A.W. Lees (2007), "Misalignment in rigidly coupled rotors", Journal of sound and Vibration Vol. 305, pp 261-271, 2007.

[4] P. Lawrence, Coupling Backlash – How it Affects Alignment, and How to Minimize It, "https://vibralign.com/shaft-alignment/coupling-backlash-how-it-affects-alignment-and-how-to-minimize-it", March 24, 2010.

[5] H. Ma, X. Zhao, Y. Teng and B. Wen (2011), "Analysis of dynamic characteristics for a rotor system with pedestal looseness", Shock and Vibration, Vol. 18, pp 13-27, 2011.

[6] G. Maurya (2013), "Analysis of gyroscopic effects in rotor disc system", Department of Mechanical Engineering, National Institute of Technology, Rourkela 2013.

[7] J. Yao, J. Gao, Y. Zhang, and W. Wang (2015), "The Dynamic Analysis of Two-Rotor Three-Bearing System, International Journal of Rotating Machinery", Article ID 342636, 2015.

[8] S. Yoon, Z. Lin, P. Allaire, "Introduction to Rotor Dynamics, Control of Surge in Centrifugal Compressors by Active Magnetic Bearings -Theory and Implementation", ISBN: 978-1-4471-4239-3,2013.

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