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Bifurcation onset delay in magnetic bearing systems by time varying stiffness

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ABSTRACT

We study the nonlinear dynamics behaviours of a rigid rotor supported by magnetic bearings. In particular, we consider the effect of rotor unbalanced mass and geometric coupling. Existing works in literature have mostly focused on a single value of parameter or a smaller range of the nonlinearities introduced by rotor imbalance and geometric coupling. This is partly due to the use of a linear PD controller which limits the system performance. In this paper, we use a nonlinear PD controller by adopting a time varying stiffness term. The control gains are chosen according to the stability chart for a Mathieu's equation. Consequently, we observe a delay in the onset of bifurcation indicating an improved rotor performance.

1. Introduction

Increasing the speed of modern machinery enhances its performance but at the same time increases lubrication requirement and cost in traditional bearings. The use of magnetic bearings provides solutions by eliminating the need for a lubrication system and lubricants due to its contact less rotor and stator. This results in a long machinery life span and low maintenance cost. However, as with any actively controlled systems, stability becomes a unique problem, crucial to the performance of magnetic bearing systems. This requires a complete understanding of the rotor dynamics and its stability.

The rotor dynamics in a magnetic bearing system typically behave in periodic, quasi-periodic, and chaotic forms. Chaotic vibration is commonly seen in high speed, or with a large unbalance mass and large rotor displacement where nonlinearities are significant. Geometric coupling between the two orthogonal axes of motion is also among the causes of such nonlinearities significant when large rotor displacement is involved. When including the geometric coupling terms in bearing equations, Chinta et al. [1] reported bifurcation jumps and hysteresis in the rotor response of a two degrees of freedom magnetic bearing system. The bearing system was controlled using a linear PD controller for a small amount of unbalance mass and with a particular value of the geometric coupling parameter. Steinschaden et al. [2] also investigated the rotor response in the presence of an unbalance mass. They associated the stability to symmetric rotor force displacement and instability to asymmetric of rotor force displacement response. They pointed out that rotor dynamics cannot be accurately predicted by linear equations of motion. Nonlinearities arising from the effect of geometric coupling is also investigated by

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Inayat-Hussain [3–6]. In addition, the author also studied the effect of bearing misalignment and the use of an auxiliary bearing. However, most of the author's works considered one fixed value of geometric coupling coefficient.

Recently, control of chaotic behaviour in magnetic bearings has gained increasing attention. Ji et al. considered a nonlinear strategy for bifurcation control [7]. A stability condition corresponding to the bifurcation point is provided. Zhang et al. [8]and Amer et al. [9] proposed the use of time varying stiffness to study the transient and steady-state nonlinear responses. They showed the potential of using time varying stiffness in the controller to enlarge the stability region. Again, their work is largely limited to a particular choice of system parameters such as unbalanced mass. A broader investigation of a rotor chaotic response for a wide range of system parameters is desirable to improve our understanding of the effect of nonlinearity and more importantly, to improve the range of system stability. Soren et al. studied nonlinear dynamic behaviour of a vertical rigid rotor interacting with a flexible foundation by means of two passive magnetic bearings [12]. Sun et al. have developed a method to identify an AMB system with a flexible rotor [13]. Chouchane et al. have used a dynamic model of a short journal bearing to analyze the bifurcation of the steady state equilibrium point of the journal center. They have applied numerical continuation to determine stable or unstable limit cycles bifurcating from the equilibrium point at the critical speed [14]. Ji et al. have examined the bifurcation behaviour of a rotor AMB system with critical feedback gains near the double-zero degenerate point [15].

Ji has investigated the effect of time delays on the linear stability of a simple magnetic bearing system by analyzing the associated characteristic transcendental equation [16].

In the present work, we investigate the nonlinear rotor dynamics for a range of system parameters. Specifically, we consider a range of unbalanced mass and different values of geometric coupling coefficient. This allows us to understand how different model parameters affect rotor dynamic. We also investigate the use of time varying stiffness first proposed by Zhang et al. [8] to delay the onset of bifurcation and improve system performance.

2. Governing equations

Magnetic bearings utilize magnetic forces to suspend a rotor in order to avoid metal to metal contact. The rotor motion in a magnetic bearing system can be captured by the displacement of the shaft geometric center. As shown in Fig. 1, the solid circle represents the actual location of rotor while the dashed circle is the desired rotor position. A fixed coordinate frame XOY with its origin O located at the bearing center is used to measure the shaft motion. Axis Y is parallel to the earth gravity. Shaft geometric center is denoted as point C. Therefore, coordinates x and y measures the location of C in XOY. When unbalanced, the rotor center of mass is not collocated with the rotor geometric center C. Two sets of electro-magnets are used to provide bearing forces needed to position the shaft. Although practically the magnets may be oriented in 45 deg with earth gravity, here we show an equivalent set up for simplicity.

To derive the equations of motion, we use the pair of magnets in x-direction as illustration. The y-direction equations can be arrived by replacing subscript x with y. The only difference is that a constant force due to gravity appears in y-direction motion equation, which will be done later. Refer to Fig. 1, magnetic flux in each magnet is given by

$$\Phi_{1x}(i_{1x}, x) = K\left(\frac{i_{1x}}{g_0 + x}\right) \tag{1a}$$

$$\Phi_{2x}(i_{2x}, x) = K\left(\frac{i_{2x}}{g_0 - x}\right) \tag{1b}$$

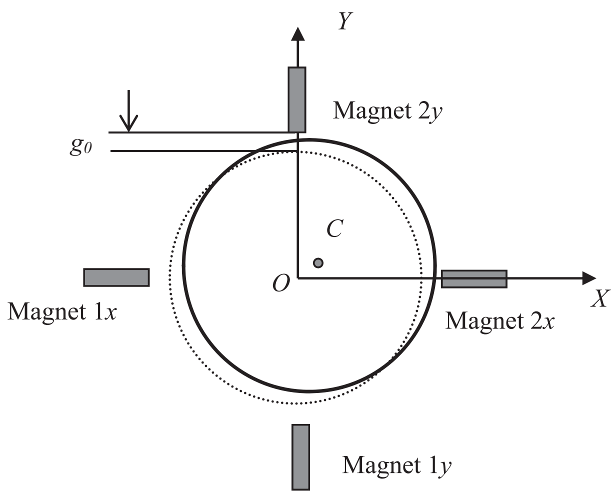

Fig. 1. A two DOF magnetic bearing system.