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Initial levitation of an electrostatic bearing system without bias

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Abstract

The force analysis of a three-axis electrostatic bearing supporting a spherical rotor shows that classical linear control using linearization by a fixed bias necessitates the supporting lands due to highly nonlinear and coupled nature of electrostatic bearings. This paper proposes a suspension control without voltage bias to achieve a steady levitation of the rotor over the entire housing orientations for a class of electrostatic bearings without supports. A nonlinear controller which minimizes the cross-axis coupling is designed using a nonlinear model and feedback linearization techniques. A linear controller is then utilized for this linearized plant to stabilize the closed-loop system. The performance of the proposed nonlinear suspension control system is experimentally investigated on a three-degree freedom electrostatic bearing in the absence of supporting lands. The experimental results demonstrate that the rotor lift in an arbitrary orientation is realized with desired dynamic performance and global stability.

Keywords: Electrostatic bearing; Feedback linearization; Electrostatic suspension; Nonlinear control; Digital control

1. Introduction

The active electrostatic bearing (AEB) is a critical component of those inertial instruments such as gyroscopes in high-precision navigation applications or satellite-based experiments [1–3]. The rotor of the electrostatic bearing is a free-spinning sphere suspended and centered in an evacuated spherical cavity with forces produced by an electrostatic suspension system [3–7]. Initial levitation of the bearing, where the rotor is lifted from its initial position to near the center of the electrode cavity, is perhaps the most difficult task for the bearing suspension systems [3], because the rotor is initially rested on the supporting electrodes and far away from the center position. An approximate linear force model around the nominal operating point is commonly used for normal suspension. However, these linear control systems, which inevitably result in poor dynamic performance for large motion of the rotor, are not suitable for initial levitation of the AEB system because of highly nonlinear and cross-coupled nature neglected in the rotor dynamics [6]. A nonlinear compensation of the AEB system operated at a fixed voltage bias in each electrode is presented in Ref. [6] in order to achieve enhanced dynamic stiffness and stability. Some electrostatic suspension systems with single-electrode suspension are also considered in Refs. [3–5] to achieve a minimum gyro drift introduced by bias forces, but the suspension design they consider are all for normal suspension in which the rotor motion is limited near the center of the electrode cavity and not in the context of initial levitation.

Two approaches to the problem of eliminating electric breakdown and ensuring a smooth rotor trajectory during initial levitation have been reported in literature. One approach is that of single-axis support [7] where only a pair of electrodes is energized by the suspension system during initial levitation. The system switches to its normal three-axis suspension once the rotor is near the cavity center. However, such single-axis support approach requires the gravitational field to be approximately collinear with the support axis, which somewhat restricts their application in practical inertial navigation systems.

An alternative to the single-axis support is the supporting land approach [3]. A set of raised supporting lands which are rested on the inner surface of electrode cavity is utilized to prevent the rotor from touching the electrodes and limit the total allowable range of motion of the rotor. As a result, it is easier for suspension controller synthesis to achieve stable levitation of the rotor with any initial orientation due to significant reduction in coupled system nonlinearities. However, the housing construc-

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tion becomes much more complicated in the presence of the supporting lands for the sake of critical accuracy and material constraint. Additionally, high-voltage requirement and resultant electric field intensity increases the probability of rotor charging and arcing because of only part of the available electrode areas to generate the required suspension force.

In this paper, force analysis and nonlinear control of a three-degree-of-freedom (3-DOF) electrostatic bearing system without voltage bias are presented to achieve stable levitation of the spherical rotor with any bearing orientation. The first part of the paper discusses the cross-axis coupling effect with an aim to clarify the necessity of single-electrode suspension during initial levitation for such AEB systems without supports. The second part presents the control system design and some experimental results in initial levitation. The experimental results presented here are aimed at showing the effectiveness of the nonlinear controller in stable levitation of the rotor for various initial orientations with desired global stability and dynamic performance.

2. Overview of electrostatic bearing system

The electrostatic bearing system in which the paper is utilized is one wherein a hallow spherical rotor is supported freely by electrical fields between six pairs of electrodes [6]. The bearing system used in the experiment work contains 12 electrically isolated electrodes partitioned in a regular hexahedron scheme, outlining a spherical cavity with a radius somewhat larger than the radius of a spherical rotor [6]. A control system is utilized for electrostatically supporting the rotor with respect to three mutually perpendicular axes in which six pairs of electrodes are arranged symmetrically around the rotor with two pairs of electrodes arranged along each of the axes and on opposite sides of the rotor to suspend the rotor with respect to that axis. Each DOF of the rotor motion is associated with a suspension servo loop which generates electrical signals necessary to control the position of the spherical rotor along one of three orthogonal axes. The schematic diagram of a typical bearing suspension system with fixed voltage bias on each electrode is shown in Fig. 1.

To stabilize the movement of the spherical rotor, we need to control its motion in 3-DOF. If all the cross-coupling effects among the different axes are ignored, the coupled 3-DOF dynamics of the rigid rotor can be represented by three, uncoupled 1-DOF systems. The uncoupled equation for the AEB rotor dynamics in X direction is simply

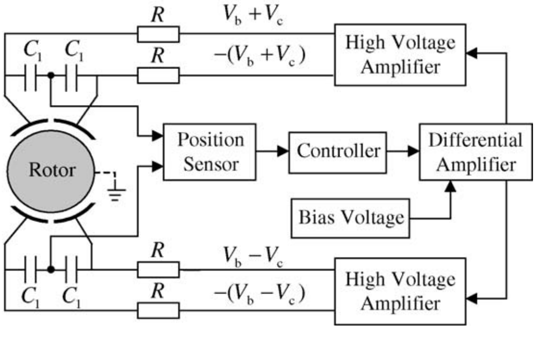

Fig. 1. Schematic diagram of the electrostatic suspension system, one channel of three.

$$m\ddot{x} = F_x + F_\mathrm{d} \tag{1}$$

where m is the mass of the rotor, x and F_x are, respectively, rotor displacement and the electrostatic force acting on the rotor in the X direction and F_d is the external disturbance, mainly gravity.

The force/voltage/gap relationship of electrostatic suspension is inherently nonlinear and coupled between the different axes. However, the suspension system is usually designed to operate with some bias voltage on the electrodes, which is typically equal to half of the maximum voltage. This accomplishes small signal linearization and helps to maintain constant servo loop gain. Given that V_c is the control voltage and V_b is the bias voltage, the force F_x represents the difference between the two electrode forces [6]

$$F_x(x, V_\mathrm{c}) = \frac{\varepsilon_0 \alpha A_0}{2}\left[\frac{(V_\mathrm{b}+V_\mathrm{c})^2}{(d_0-\alpha x)^2} - \frac{(V_\mathrm{b}-V_\mathrm{c})^2}{(d_0+\alpha x)^2}\right] \tag{2}$$

where ε_0 is the vacuum permittivity, A_0 the nominal area of each electrode pair, α the ratio of projected area to spherical area of the electrode and d_0 the nominal gap between a centered rotor and associated electrodes, respectively.

The governing equation for the AEB system of this type, which only small displacements of the rotor around its nominal point, $x^* = 0$ and $V_\mathrm{c}^* = 0$, are considered, can be linearized as

$$F_x = K_\mathrm{v} V_\mathrm{c} + K_x x \tag{3}$$

where $K_x = 2\varepsilon_0 \alpha^2 A_0 V_\mathrm{b}^2 / d_0^3$ and $K_\mathrm{v} = 2\varepsilon_0 \alpha A_0 V_\mathrm{b} / d_0^2$.

Substituting (3) into (1) yields the motion equation of the rotor as

$$m\ddot{x} = K_\mathrm{v} V_\mathrm{c} + K_x x + F_\mathrm{d} \tag{4}$$

Thus, a linear controller is sufficient to maintain stability and performance near the equilibrium point for normal suspension operation.

3. Analysis of electrostatic force in initial levitation

In this section, the suspension forces as a function of electrode shape, size, voltage and gap are developed by a voltage gradient across the gap between the spherical rotor and metallic electrodes which form part of the inner surface of the housing. Several assumptions made as part of the derivation are: (1) the electrodes and rotor are perfectly spherical; (2) the electric field is uniform over the electrode surface because the rotor-electrode gap is, by over an order of magnitude, the smallest spacing which exists in the structure and (3) the rotor is at virtual ground potential since a 12-electrode bearing accomplishes electrode voltage balance in each half channel, as shown in Fig. 1.

3.1. Electrostatic force

Shown in Fig. 2 is a general configuration of the electrostatic bearing. S_1 represents the rotor of radius r_0 with its center at O′ floating freely inside the spherical cavity. The cavity center is