Available online at www.sciencedirect.com

SCIENCE DIRECT®

Sensors and Actuators A 119 (2005) 177–186

SENSORS AND ACTUATORS A PHYSICAL

www.elsevier.com/locate/sna

Nonlinear compensation of active electrostatic bearings supporting a spherical rotor

Fengtian Han*, Zhongyu Gao, Dongmei Li, Yongliang Wang

Department of Precision Instruments and Mechanology, Tsinghua University, Beijing 100084, China

Received 20 December 2003; received in revised form 12 July 2004; accepted 18 August 2004
Available online 12 October 2004

Abstract

This paper proposes a nonlinear compensation scheme to deal with the nonlinear, uncertain dynamics of electrostatic bearing systems. A feedback linearization technique that utilizes the approximate nonlinear model of the electric field distribution is employed to compensate for the unstable position stiffness inherent in electrostatic suspension for global stability and enhanced dynamic performance. Robustness of the nonlinear compensation to the model uncertainty is analytically verified in an effort to obtain a more consistent and predictable performance. Theoretical relationship is also developed to relate the characteristics of the proportional-integral-derivative (PID) controller to the dynamic stiffness properties of the linearized electrostatic bearing system. The performance of the proposed nonlinear compensation algorithm is experimentally investigated on a three-degree-of-freedom (3-DOF) electrostatic bearing supporting a spherical rotor. The experimental results demonstrate the superiority of the nonlinear controller over a classical linear control system in transient response, stability, dynamic stiffness, and force-disturbance rejection performance.

Keywords: Dynamic stiffness; Feedback linearization; Electrostatic bearing; Electrostatic suspension; Digital control

1. Introduction

Noncontact, actively controlled electrostatic bearings (AEBs) for inertial instruments such as gyroscopes have the potential to satisfy the demand for high-precision inertial navigation systems or satellite-based scientific experiment [1–4]. By maintaining the rotating inertial member free of physical contact with its support, mechanical friction torque normally associated with conventional bearings is virtually eliminated. Thus, the accuracy and the life of the inertial instruments can thus be greatly increased.

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 [2–4]. The highly nonlinear behavior of the electrostatic bearings in addition to the inherent instability of such a system makes the controller design complex. Electrostatic suspension has already been utilized to implement contactless support of a 4-in. silicon wafer [5], a 3.5-in. aluminum disk [6], a polished glass plate [7], and a stepping motor [8]. These devices employ linear control strategies that are based on an approximate linearized force model of the actual nonlinear force distribution at the nominal operating point. However, the dynamic performance of the linear control systems continuously degrades with increasing deviations from the nominal operating point. Several researchers have proposed various nonlinear control designs to compensate for the nonlinear dynamics. One approach is that of gain scheduling, where the nonlinear force model of the electrostatic suspension is successively linearized at various operating points with a suitable controller designed for each of these operating points [9]. However, gain scheduling controllers require the operating range to be broken up into very fine intervals and stored in large lookup tables of controller gains. Nonlinear systems with uncertainties have been explored to

* Corresponding author. Tel.: +86 10 6279 2116; fax: +86 10 6279 2118.
E-mail address: hanft@zzu.edu.cn (F. Han).

0924-4247/$ – see front matter © 2004 Published by Elsevier B.V.
doi:10.1016/j.sna.2004.08.030

improve robustness using sliding mode control approaches [10,11]. Although sliding mode control offers asymptotic stability in the presence of modeling uncertainties and disturbances, it results in large control efforts and chattering of the control response due to the discontinuous control law. Other nonlinear controllers are considered for electrostatically suspended gyroscopes [4,12] to achieve a minimum gyro drift introduced by bias voltages, but the inherent instability of such a system is neglected in these designs. Recently, much attention has focused on feedback linearization approach, which utilizes the complete nonlinear description of the plant model and hence yields consistent performance largely independent of operating points. However, most of these applications are for active magnetic bearings [13–15].

This paper examines feedback linearization techniques for an electrostatic bearing system supporting a spherical rotor. A nonlinear compensation algorithm utilizing three-axis coupled and nonlinear model of the electrostatic force is proposed and implemented through the concept of discrete-time delay control [16] and a high-speed digital signal processor (DSP). The objective is to determine the uncertain content at each sampling instant and then fed it back to achieve exact compensation. Robustness of the nonlinear compensation to model uncertainties is verified by considering a major source of parameter variations in rotor-electrode gap. The theoretical relationship to relate the characteristics of the proportional-integral-derivative (PID) controller to the dynamic stiffness of a linearized suspension system is then developed and verified by extensive tests. The experimental results demonstrate the superiority of the nonlinear control algorithm over classical linear controllers in terms of transient response, stability, dynamic stiffness, and force-disturbance rejection performance.

This paper is organized as follows: Section 2 presents the principle of the bearing suspension system, while Section 3 details the system dynamics. The nonlinear compensation scheme and the dynamic stiffness properties are discussed in Section 4 and its robustness to parameter variations is analyzed in Section 5. Experimental results are presented in Section 6 and conclusions are drawn in Section 7.

2. Principle of active electrostatic bearings

The electrostatic bearing, in which the paper is utilized is one wherein a spherical rotor is suspended by electrical fields between six pairs of electrodes as shown in Fig. 1. The bearing system contains twelve 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. A control system 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 degree-of-freedom (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 [3].

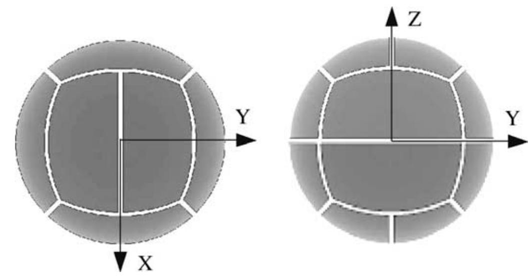

Fig. 1. Cross-sectional view of electrode shape.

The schematic diagram of an electrostatic bearing suspension system is shown in Fig. 2. It actively controls the movement of the suspended rotor in the vertical direction. The position error information from a capacitive position sensor is fed into a controller as feedback signal. Then the position error signal is processed by a controller to generate a control voltage. After being added to the bias voltage, the electrode control voltages are amplified by a pair of high-voltage amplifiers. These amplified voltages are supplied to the two pairs of electrodes, shown in Fig. 2, to stabilize the motion of the rotor with respect to that axis. The effect of this is to modify the force-gap characteristics such that the voltage, and thus the attractive forces increase as the gap increases, and vice versa. In the equilibrium position, the attractive force is balanced against that of gravity, the rotor is stably suspended in the center of vacuum electrodes cavity. Meanwhile, the freely suspended rotor is commonly rotated from 400 to 600 Hz for a hollow rotor by a driving force generated by a rotating magnetic field. Therefore, the orientation of the spin axis of the rotor relative to the bearing housing for arbitrary attitude can be sensed, for example, by an optical sensor or a mass-unbalance modulation approach for gyroscope applications [2].

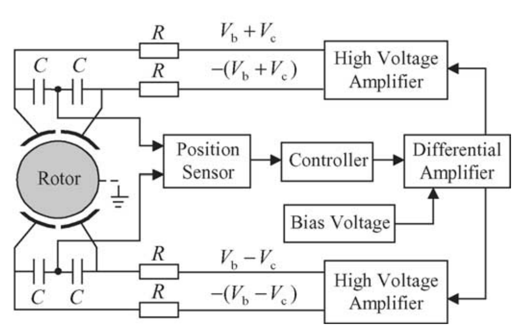

Fig. 2. Schematic diagram of an electrostaic bearing suspension system, one channel of three.