Mechanical Systems and Signal Processing 36 (2013) 168–181

Contents lists available at SciVerse ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

An ultrasonic levitation journal bearing able to control spindle center position

Su Zhao [a,*], Sebastian Mojrzisch [b], Joerg Wallaschek [b]

[a] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore
[b] Institute for Dynamics and Vibration Research, Leibniz University Hannover, Germany

ARTICLE INFO

Article history:
Received 1 December 2011
Received in revised form
30 April 2012
Accepted 18 May 2012
Available online 12 June 2012

Keywords:
Non-contact bearing
Ultrasonic transducer
Squeeze film levitation
Near-field acoustic levitation
State feedback control
Auto-resonant

ABSTRACT

A novel active non-contact journal bearing based on squeeze film levitation is presented. Two qualities distinguish the proposed design from the previous ones: significantly improved load capacity and the ability of precision spindle position control. Theoretical models to calculate load carrying forces induced by squeeze film ultrasonic levitation are studied and validated by experimental results. Dynamic behavior of the ultrasonic transducer is investigated using electro-mechanical equivalent circuit model. Levitation forces generated by each transducer are individually controlled by a state feedback controller with auto-resonant (self-excited) frequency control. Active control of the spindle center position is achieved with positioning accuracy of the spindle center in the range of 100 nm. The load capacity achieved by the proposed bearing is dramatically improved compared to previously reported approaches.

1. Introduction

In application areas such as computer hard disc drive, machine tools for micro and nano-scale machining, high precision and high speed motions are required. Traditional ball bearings cannot meet the requirements any more due to problems such as wear, heat generation and so on. Non-contact bearings such as electromagnetic bearings, hydrodynamic/hydrostatic bearings, aerodynamic/aerostatic bearings, have been intensively investigated and developed. The non-contact feature allows these bearings to achieve high precision, low friction, low wear and/or lubricant-free operations. However, a continuous supply of a large volume of clean lubricant is required for air bearings and hydrostatic bearings, which leads to high running cost. And, the requirement of an external compressor excludes this type of bearing from many applications. Magnetic bearings cannot be used for magnetically sensitive configurations due to the strong magnetic flux. Therefore, it is of great interest to find other concepts for realizing non-contact bearings which can overcome some of these problems.

Squeeze film type ultrasonic levitation has been found to be a promising alternative solution to construct non-contact bearings and has been investigated since several decades [1]. The so called squeeze film effect is observed when a flat surface oscillates closely to a conformal surface in high frequency. A non-symmetrical force per cycle is generated with a greater force value occurring on the compressing part of the cycle. Due to the nature of squeeze film levitation, it can be directly applied to support non-contact linear motions between two flat surfaces. Hence, majority of the previous investigations focused on applications

* Corresponding author. Tel.: +65 67904377; fax: +65 67935921.
E-mail address: zhaosu@ntu.edu.sg (S. Zhao).

0888-3270/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ymssp.2012.05.006

requiring non-contact linear motions such as non-contact linear guides [2–6], non-contact transportation systems [7–10], non-contact thrust bearings [11] and ultrasonic clutch [12].

However, a journal bearing is aimed to provide support to the spindle and carry loads in radial directions around the rotation axis. Squeeze film effect must be generated along the circumference of the spindle, which increases the complicity of the design and construction of the system. Several configurations for squeeze film journal bearings have been reported. In 1964, Salbu [1] introduced the concept of constructing a non-contact bearing using squeeze film effect. Salbu used magnetic actuators to generate oscillations and the operating frequency was within the audible range. Several designs of squeeze film bearings using bulk piezoelectric ceramics can be found in early US patents filed in 1960s, invented by Warnock [13], Farron and John [14], and Emmerich [15]. These designs used bulk piezoelectric materials to create uniform vibration amplitude over the entire bearing surfaces. The transducers were rather massive and required high power to generate sufficient vibration amplitude. Scranton and Robert [16] suggested using piezo-tubes with a flexural vibration mode as the bearing sleeve. However, only basic concepts were sketched in Scranton's patent. Following Scranton's idea, Wiesendanger [3] presented a rotational bearing using a tubular piezoelectric bending element mounted in a steel sleeve. The size and load capacity of such bearings are limited by the size of the available piezo-tubes. Only low vibration amplitude and load capacity was achieved. Ha et al. [17] presented an aerodynamic journal bearing which used squeeze film levitation to lift the spindle at the starting phase. Piezoelectric stack actuators and flexure hinges were used to deform the bearing sleeve. The bearing had a bore diameter of 30.12 mm and a length of 25 mm, and could support a static load of 2.18 N with a minimum film thickness of 1.5 μm. Recently, the same research group reported a new configuration for squeeze film journal bearing for spindles of 30 mm diameter. Flexural piezoelectric elements were attached to tubular bearing sleeves made of aluminum alloy to excite flexural vibration modes. The maximum load capacity of 5.6 N was obtained for the bearing with bore diameter of 30 mm and length of 50 mm. The reported bearings could not carry the self-weight of the spindles. Similar concept was used earlier by Hu et al. [18] to develop a non-contact ultrasonic motor with an ultrasonically levitated rotor. Two Langevin transducers driven by two AC voltages with a phase difference of 90 degree were bolted on the stator with an interval of a quarter wavelength to generate traveling waves. Although the maximum load capacity could be higher, it was reported to successfully levitate the rotors weighted up to 2.7 N (diameter of 56 mm) and to drive them at rotation speed up to 3000 rpm.

Despite different ways to excite vibrations, it can be concluded that a common approach was shared by all the previous reported squeeze film journal bearings, which is to use tubular vibrators as the sleeves of the journal bearings. The sleeves were often excited to vibrate in flexural resonant modes. The advantage of using tubular vibrator is that the system is compact and easy to fabricate. However, the output power of bending piezoelectric elements is limited by their size and lack of prestress. Hence the achievable load capacity is also limited. According to the model and experimental results presented previously, squeeze film ultrasonic levitation can provide load capacity of up to 7 N/cm^2 [19,20]. It is comparable to common air bearings which commonly have load capacity in the range of 10–20 N/cm^2. In principle, squeeze film bearings have most of the advantages offered by aerostatic bearings. However, all the previously reported tubular vibrator based squeeze film bearings had limited load capacities much lower than the load capacity measured on a piston vibrator. The inadequacy of load capacity excludes squeeze film journal bearings from most of the practical applications.

This paper presents a novel design which directly utilizes the radiation surfaces of three high power ultrasonic transducers to levitate the spindle. Each transducer is an individual piston-like vibrator whose vibration amplitude can be controlled. Section 2 starts with a review on the theoretical models for calculating the load capacity of squeeze film levitation, followed by an experimental setup to validate the models. Based on the theoretical studies, the design and control of a novel non-contact journal bearing using squeeze film ultrasonic levitation will be presented in Section 3. Initial experimental results obtained from the prototype bearing will be presented in Section 5.

2. The load-carrying force induced by squeeze film ultrasonic levitation

A schematic diagram of a typical squeeze film levitation system is shown in Fig. 1. It consists of two flat plates with the lower plate being the radiator which oscillates normally against the upper plate (levitated object). The distance between

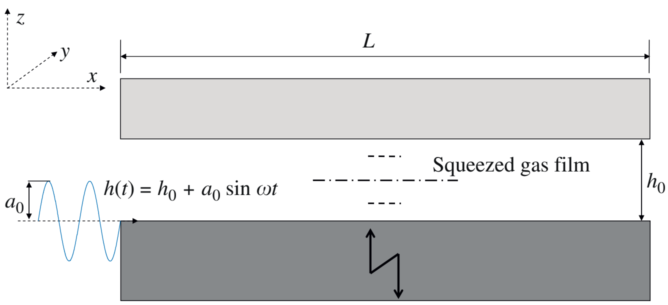

Fig. 1. Schematic diagram of squeeze film levitation.