Mechanical Systems and Signal Processing 85 (2017) 367–381

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Modeling and closed loop control of near-field acoustically levitated objects

Dotan Ilssar [a], Izhak Bucher [a,*], Henryk Flashner [b]

[a] Dynamics Laboratory, Faculty of Mechanical Engineering, Technion – Israel Institute of Technology, Haifa 3200003, Israel
[b] The Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA 90089, USA

ARTICLE INFO

Article history:
Received 20 January 2016
Received in revised form
6 August 2016
Accepted 11 August 2016

Keywords:
Near-field acoustic levitation
Semi-analytical model
Gain-scheduled control
Squeeze film

ABSTRACT

The present paper introduces a novel approach for modeling the governing, slow dynamics of near-field acoustically levitated objects. This model is sufficiently simple and concise to enable designing a closed-loop controller, capable of accurate vertical positioning of a carried object. The near-field acoustic levitation phenomenon exploits the compressibility, the nonlinearity and the viscosity of the gas trapped between a rapidly oscillating surface and a freely suspended planar object, to elevate its time averaged pressure above the ambient pressure. By these means, the vertical position of loads weighing up to several kilograms can be varied between dozens and hundreds of micrometers. The simplified model developed in this paper is a second order ordinary differential equation where the height-dependent stiffness and damping terms of the gas layer are derived explicitly. This simplified model replaces a traditional model consisting of the equation of motion of the levitated object, coupled to a nonlinear partial differential equation, accounting for the behavior of the entrapped gas. Due to the relatively simple form of the model developed here, it constitutes a convenient foundation for model based control algorithms, governing the slow dynamics of near-field acoustically levitated objects. Indeed, based on the former, a height dependent, gain scheduled PID controller is developed and verified numerically and experimentally, both providing satisfying results.
© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

During handling and transportation of silicon wafers throughout inspection and manufacturing processes, the micro-electronics industry uses conveyers, chucks and robotic arms, making mechanical contact with the substrates. Such contact generates particles, contaminating the highly controlled work environment, and thus affecting the yield significantly. To overcome this problem it was proposed to utilize the near-field acoustic levitation phenomenon, allowing a controlled levitation and transportation of the wafers without any physical contact [1]. The near-field acoustic levitation phenomenon uses high frequency, ultrasonic oscillations of a driving surface to build a high-pressured layer of gas, commonly known as squeeze film, between the driving surface and the handled object (e.g. a silicon wafer). The abovementioned pressure elevation originates from the compressibility of the entrapped gas, allowing to increase the average pressure inside the squeeze film, above the ambient, atmospheric pressure. The pressure elevation also depends on the viscosity of the gas, preventing the latter from leaking out of the film. As a result, a load carrying force is produced, levitating the carried object

* Corresponding author.
E-mail addresses: dilssar@technion.ac.il (D. Ilssar), bucher@technion.ac.il (I. Bucher), hflashne@usc.edu (H. Flashner).

http://dx.doi.org/10.1016/j.ymssp.2016.08.011
0888-3270/© 2016 Elsevier Ltd. All rights reserved.

above the driving surface, assuming the former is freely suspended. The ultrasonic oscillations also produce rapid pressure fluctuations, but the resulting oscillations experienced by the levitated object are considerably attenuated by the inertia, and are often in the nanometer scale.

The dynamic behavior of a near-field acoustically levitated object is commonly modeled by its equations of motion, coupled with the equation governing the flow regime inside the squeeze film (e.g. [2,3]). However, for practical applications such as controlling the dynamics of the levitated object, such model is too complex. Ilssar and Bucher [4] developed a manageable, second order ordinary differential equation, describing the more significant, slow component of the levitated object's vertical motion. This model incorporates the conservative levitation force originating from the compressibility of the gas, and the damping force acting due to its viscosity, explicitly. Yet, since the model in [4] is restricted to the case where the driving surface oscillates uniformly as a piston, the simplified model, previously suggested by Ilssar and Bucher [4] cannot describe most realistic systems. Namely, it cannot describe the dynamics of high performance systems where the driving surface exhibits spatial deformations, resulting in a non-uniform squeeze film (e.g. [5]).

In the present paper, the aforementioned simplified model is generalized and extended for the case where the driving surface oscillates as a non-uniform standing wave. This is done following a calibration process used to adjust the height dependent levitation force to a specific form of excitation. This calibration process can be performed following either a numerical or experiment-based approach. The numerical approach is based on a finite differences scheme of Reynolds equation, accounting for the flow regime inside the film (e.g. [6,7]). Whereas the experiment-based approach relies on measurements, and a signal processing stage relating the levitation height at steady state to the magnitude of the excitation.

The model developed in this paper is then utilized to describe an experimental setup, enabling the formulation of a model based control loop, governing the slow dynamics of a levitated object. Indeed, after a satisfactory experimental validation of the model, the latter is exploited in order to devise a height dependent, gain-scheduled PID controller, providing rapid and accurate positioning.

2. Statement of the problem

Fig. 1 presents a schematic layout of the system studied in this paper. Here, a freely suspended planar object is levitated due to the elevated average pressure produced by a driving surface, oscillating at a constant frequency ω and according to a designated spatial profile a. From efficiency considerations, the driving surface is assumed to oscillate only at resonance, namely, its spatial displacements are determined by a single, real eigen function [8]. Therefore, and assuming axisymmetry, the spatial profile a depends merely on the radial coordinate r. The levitated object and the driving surface are axisymmetric, parallel, and have the same outer radius r_0, implying that the only DOF (degree of freedom) of the levitated object considered here, is its vertical position. Obviously, the instantaneous position of the levitated object is determined by equilibrium of its inertia, the gravity and the forces induced by the pressure exerted on it by the surrounding fluid.

As shown in Fig. 5, displaying in solid black lines the overall dynamics of the system under different excitation and loading conditions, and by former experiments and analyses (e.g. [2,4]), the dynamics of the system illustrated in Fig. 1 can be represented as a superposition of two time scales. The first time scale relates to the excitation and the resulting low amplitude rapid oscillations experienced by the levitated object, whereas the second time scale is associated with the evolution of the levitated object, which is 2–3 orders of magnitude slower than the excitation. Consequently, the air-gap between the driving surface and the levitated object can be decomposed as follows

$$h(r,t) = z(t) - a(r)\sin(\omega t) = \bar{h}(t) + \chi(t) - a(r)\sin(\omega t). \tag{1}$$

Here, t denotes the time, and z is the overall dynamics of the levitated object, consisting of χ and $\bar{h}$, representing the rapid oscillations and slow evolution of the levitated object, respectively. It is important to note that $\bar{h}$ equivalently represents the slow evolution of the air-gap, since the driving surface does not experience motions relating to the slower time scale.

2.1. The governing equations

In order to formulate the dynamics of the system illustrated in Fig. 1 non-dimensionally, the following measures are defined:

$$P = \frac{p}{p_a}, \quad H = \frac{h}{h_0}, \quad \bar{H} = \frac{\bar{h}}{h_0}, \quad R = \frac{r}{r_0}, \quad T = \omega t, \quad \sigma = \frac{12\mu\omega r_0^2}{p_a \bar{h}^2} = \frac{12\mu\omega r_0^2}{p_a h_0^2 \bar{H}^2}, \quad \varepsilon = \frac{a}{\bar{h}} = \frac{a}{h_0 \bar{H}}, \tag{2}$$

where p, p_a are the pressure distribution inside the squeeze film, and the ambient pressure respectively, h_0 denotes a reference, typical clearance between the driving surface and the levitated object, and μ stands for the dynamic viscosity of the fluid. As demonstrated in the following section, the non-dimensional excitation function ε, whose magnitude is much smaller than unity, and the squeeze number σ, govern the system's instantaneous behavior (e.g. [4,7]).

The dynamics of the investigated system is represented by two equations, coupling the behavior of the fluid residing inside the squeeze film, with the dynamics of the levitated object. Under the assumptions of isothermal conditions [6,7] and

Download English Version:

https://daneshyari.com/en/article/6954845

Download Persian Version:

https://daneshyari.com/article/6954845

Daneshyari.com