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On the slow dynamics of near-field acoustically levitated objects under High excitation frequencies

Dotan Ilssar, Izhak Bucher *

Dynamics Laboratory, Faculty of Mechanical Engineering, Technion – Israel Institute of Technology, Haifa 3200003, Israel

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ABSTRACT

This paper introduces a simplified analytical model describing the governing dynamics of near-field acoustically levitated objects. The simplification converts the equation of motion coupled with the partial differential equation of a compressible fluid, into a compact, second order ordinary differential equation, where the local stiffness and damping are transparent. The simplified model allows one to more easily analyse and design near-field acoustic levitation based systems, and it also helps to devise closed-loop controller algorithms for such systems. Near-field acoustic levitation employs fast ultrasonic vibrations of a driving surface and exploits the viscosity and the compressibility of a gaseous medium to achieve average, load carrying pressure. It is demonstrated that the slow dynamics dominates the transient behaviour, while the time-scale associated with the fast, ultrasonic excitation has a small presence in the oscillations of the levitated object. Indeed, the present paper formulates the slow dynamics under an ultrasonic excitation without the need to explicitly consider the latter. The simplified model is compared with a numerical scheme based on Reynolds equation and with experiments, both showing reasonably good results.

1. Introduction

Near-field acoustic levitation, which is also known as squeeze film levitation, occurs when a planar object is placed in proximity to a vibrating surface. Consequently, a thin layer of the ambient gas, commonly referred to as squeeze film, is trapped in the clearance between the vibrating surface and the adjacent planar object. The abovementioned phenomenon depends on the viscosity of the gas, which plays an important role such that the flow regime can be referred to as viscous (e.g. [1,2]). Thanks to its viscous behaviour, the gas which resides inside the squeeze film cannot be immediately squeezed out. Additionally, due to the compressibility of the entrapped gas, the average pressure inside the film is usually higher than the surroundings, what results in a load carrying force. This force can levitate the planar object above the vibrating surface, assuming the former is freely suspended. One possible application of the near-field acoustic levitation phenomenon is a non-contacting bearing [3] where the stiffness and damping properties are important.

The abovementioned levitation mechanism can be represented by a combination of two distinct forces. The first force considered here is the displacement related levitation force emanating from the compressibility of the gas. Langlois [2] who proposed to use Reynolds equation for the modelling of the squeeze film, employed first order perturbation on this

* Corresponding author. Tel.: 972 77 8873153.
E-mail addresses: dilssar@technion.ac.il (D. Ilssar), bucher@technion.ac.il (I. Bucher).

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equation. Nevertheless, this approach cannot predict the nominal value of the levitation force, which is a nonlinear effect. Salbu [4] evaluated the levitation force using a simplified model of the squeeze film based on Boyle's law, under the assumption of mass conservation. This assumption suggests that there is no flow at the peripheries of the film, what violates the boundary conditions since it leads to a discontinuity in the pressure distribution. However, the solution presented by Salbu [4] is suitable at extremely high squeeze numbers (this measure will be introduced below). Minikes *et al.* [5] developed an empirical expression which manages to predict the time averaged levitation force for wide intervals of excitation amplitudes (of the vibrating surface) and squeeze numbers. Minikes also showed that a second order perturbation solution of Reynolds equation can approximate this value, but for a limited range of excitation amplitudes. Nevertheless, according to numerical simulations, this range is sufficiently wide for most purposes of near-field acoustic levitation. Therefore the spirit of this approach is adopted in the current study.

The second force needed to be described within the levitation mechanism is the damping force resulting from the viscosity of the gas. This force was studied extensively in the past (e.g. [6–10]), usually in the context of MEMS devices. In all of these studies the clearance between the bounding surfaces was assumed to be oscillating at small amplitudes, and so the squeeze film was modelled by the linearized Reynolds equation [6]. Moreover, Griffin *et al.* [9] made an additional assumption which claims that the clearance varies slowly compared with the cut-off frequency and is thus confined to slow frequencies. Griffin noted that under this assumption, the estimated damping force can be generalized to the case of large displacements. In the current paper it is shown that a similar approach can be utilized for the calculation of the damping force throughout near-field acoustic levitation. The latter is despite the presence of fast oscillations which originate in the high excitation frequency.

It is important to note that the papers mentioned above deal with each of the forces exerted by the film separately, assessing their steady-state values. The latter is carried out for the case where the mean clearance between the bounding surfaces is pre-determined. However, a simplified analytical model which combines these forces in order to describe the time varying dynamics of an acoustically levitated object was not presented in previous publications. Obviously, in this case, the nominal clearance is determined due to equilibrium of forces.

For the purpose of controlling the dynamics of an acoustically levitated object, be it open or closed loop, a manageable mathematical model is essential. Clearly, a full CFD or even a Reynolds equation based model coupled to the structural dynamics, are by far too complex and impractical for devising a control strategy or for assessing the stiffness and damping during design cycles. Indeed, the present paper seeks a simplified analytical model that describes merely the slow evolution of the levitated object, given the enforced rapid oscillations.

The current paper begins with presentation of the governing equations describing the levitation mechanism. Next, based on former numerical schemes (e.g. [11]), it is shown that the dynamics of the levitated object can be represented as a superposition of slow and fast processes. This implies that it is possible to formulate a simplified analytical model which describes merely the slow evolution of the levitated object, given the enforced and nonlinearly coupled fast oscillations. Therefore, such simplified model is developed following two main steps. The first step relates only to the levitation force and results in an equation which represents the slow evolution of the levitated object in absence of damping. Obviously, the second step relates to the damping force and results in modification of the conservative equation so it includes the effect of dissipation. The entire development is carried out under the assumption that the vibrating surface oscillates uniformly – as a rigid piston.

Finally, after a satisfactory numerical verification, an experimental validation of the simplified model is carried out. The results of this validation shows reasonable agreement of both the momentary frequency of the slow oscillations, and the steady state levitation height. However, it is shown in the experiments that there is a significant deviation in the prediction of the damping. Therefore, based on numerous experiments, a linear correction coefficient is determined for the dissipative term in the abovementioned simplified model. That so this model will suit the system on which the experiments were carried out.

2. Problem description

A simplified model of an acoustically levitated object is illustrated in Fig. 1. This model consists of an oscillating surface producing the required excitation, and a freely suspended planar object, which are both cylindrical (disks) and with equal diameters. As can be seen from Fig. 1, in this model, the excitation surface does not deform and it oscillates at a constant

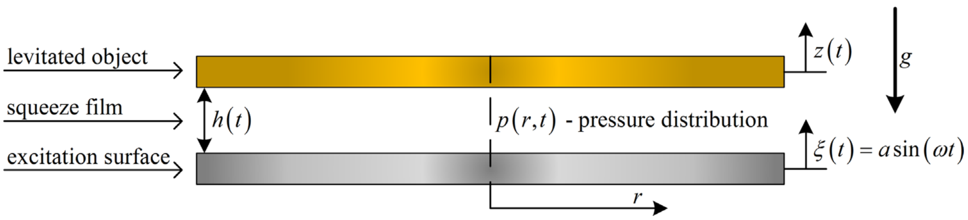

Fig. 1. Schematic layout of the system.