Modeling of Near-Field Ultrasonic Levitation: Resolving Viscous and Acoustic Effects

I. F. Melikhov[1], A. S. Amosov[1], S. A. Chivilikhin[2]

[1]Corning Scientific Center, Saint Petersburg, Russia
[2]ITMO University, Saint Petersburg, Russia

Abstract

Ultrasonic levitation is a developing technology for contactless handling of various objects in certain manufacturing processes where keeping untouched surface is critical. Typical example is transportation of large silicon wafers in semiconductor industry. This technology allows object floating over a transportation system at the heights of 10-300 microns. While designing such systems it is important to know an expected lifting force and corresponding levitation distance.
We focus on the levitation of an axisymmetric rigid disk of 20-30 mm radius, shown on the (Figure 1). Modeling of the air flow in a narrow gap is a complex task. In addition to the large aspect ratio of the geometry, the problem includes many physical effects such as gas compressibility, inertial and viscous effects, and viscosity-temperature dependence. A straightforward transient numerical calculation is possible [1], but requires large amount of computation resources.
Theoretical studies of the problem can be divided into two types: acoustic and viscous. First study of acoustic radiation pressure in inviscid fluids was made by Lord Rayleigh [2]. Later the results on this topic were summarized and generalized by Lee and Wang [3]. Their approach is currently used for prediction of the lifting force for some levitation systems, see for example [4]. However, this method is limited to the cases when the gas viscosity is negligible. On the other hand, there is an approach based on the lubrication model, or Reynolds equation, to describe the case of purely viscous air flow in a gap of a few tens of microns. This method is also used in practice [5], but it is limited to very small gap thicknesses.
We introduce a simplified model which resolves both viscous and acoustic effects. We start with the general Navier-Stokes equations, the energy equation, the ideal gas law, and Sutherland's law for viscosity-temperature dependence. Due to a number of reasonable assumptions we managed to simplify these equations to a set of five linear PDE in frequency domain. Moreover, we show that the pressure distribution does not vary through the gap thickness. Thus equations on pressure can be solved only on the surface of the vibration source.
Though the equations are simplified, they are not solvable analytically. COMSOL Multiphysics® with its equation-based modeling tool allows us to formulate and solve the problem. Weak form equations are used extensively. Moreover, the Component Coupling facility allows coupling between equations of different dimensions. In addition, we show how to implement non-reflective boundary condition in order to allow acoustic wave propagation out of the gap.

The model allows computations of the air flow in the gap [time-averaged velocity is shown in Figure 2] and calculation of the lifting force as well as pressure distribution in the gap (Figure 3). The resulting force is compared to experimental data with very good agreement.
The developed model covers viscous and acoustic effects of ultrasonic levitation. COMSOL Multiphysics allows elegant and simple solution of the derived equations.

Reference

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[5] S. Yoshimoto et al., Float characteristics of a squeeze-film air bearing for a linear motion guide using ultrasonic vibration, Tribology International, 40(3), 503-511 (2007)

Figures used in the abstract

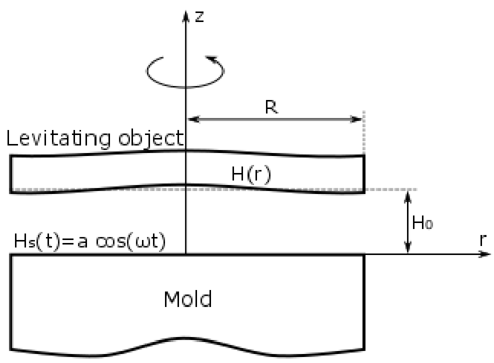

Figure 1: Levitation of a disk.

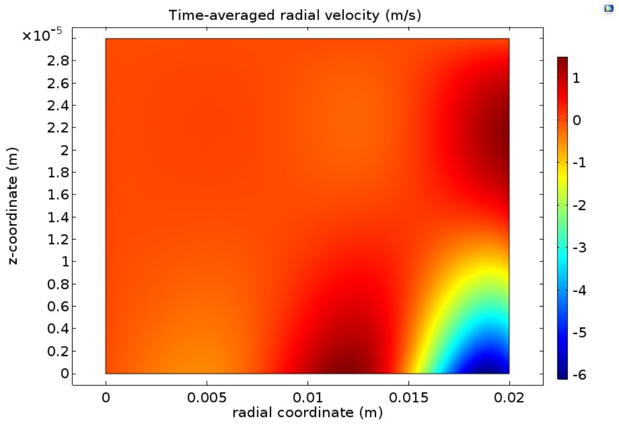

Figure 2: Time-averaged radial velocity.

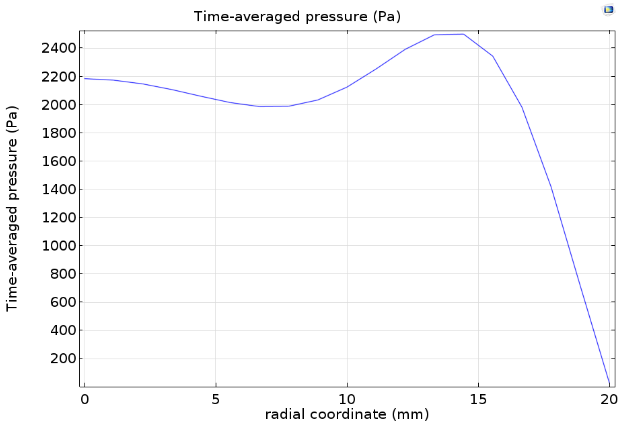

Figure 3: Time-averaged pressure distribution.