MODELING NEAR FIELD ACOUSTIC LEVITATION BY FLEXURAL MODE INCLUDING GAS INERTIA

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We report a combined theoretical and experimental investigation on the near field acoustic levitation (NFAL). In NFAL a disk is levitated at a height much smaller than the acoustic wavelength. The levitation force is induced by the gas squeeze film between the sound radiation surface and the levitated disk. By taking into account the flexural vibration of the sound radiation surface as well as the gas inertia effect, a modified Reynolds equation has been developed. A high-order finite difference scheme was used to numerically solve the nonlinear convection-diffusion equations. The numerical results and the experimental observations show excellent agreement.

1. Introduction

In micro-assembly, the handling of fragile and surface-sensitive components in microsystem and semiconductor technologies presents a special challenge. Many concepts are not easy to scale down to micro dimensions. Full-wafer bonding, for instance, is a possible application, where defined forces are used to join two wafers across their full surface. Another application is the integration of sound transducers non-contact tool heads for flip-chip or bare-die bonding.

Most handling systems use contact between the support and the object. Even though these contact systems provide high load capacity, high speed and precise positioning, they have several problems:

(1) Wear phenomenon due to abrasion along the contact region causes the precision to deteriorate.

(2) Dust is produced due to wear. In semiconductor manufacturing clean rooms, machines the produce dust are unacceptable.

(3) Nonlinear phenomena including backlash and hysteresis are common.

(4) Even high-performance systems make noise.

However, non-contact systems can resolve most problems associated with contact systems.

There are two types of acoustic levitation to apply forces on manipulated parts: standing wave levitation and near field levitation. In standing wave levitation, small particles can be levitated in the pressure nodes of an acoustic standing wave between a vibrating plate and a reflector. While in near field levitation, the reflector is replaced by the levitated object itself. Standing wave levitation is a conventional acoustic levitation which levitates only small objects of a few grams at the nodal points.

NFAL is a phenomenon that objects levitated at a distance of several tens to hundreds of micrometers above the acoustic wave radiation surface. NFAL is successfully applied to non-contact
transportation where planer objects are levitated and transported. Compared with standing wave levitation, considerable forces can be generated by near field levitation. Sadayuki Ueha\(^4\) presented ultrasonic actuators based on NFAL and determined conditions for attractive force in NFAL in air. Y. Hashimoto et. al.\(^5\) experimentally proved a planar mass of 10 kg levitated without any reflector. Experimental results indicate the existence of NFAL levitation force and positive characteristics, theoretical studies are performed as well. Hasegawa\(^6\) calculates the acoustic radiation pressure on a small rigid sphere situated on the axis of a circular piston vibrator including the points in the near zone where the diffraction effects can no longer be neglected. B. Chu and R. E. Apfel\(^7\) derived formulation to express the radiation pressure. Chu summarizes the confusion generated by acoustic radiation pressure. He calculates the Rayleigh radiation pressure successively on a plane target perfectly absorbing, partially reflecting and perfectly reflecting. Wiesendanger\(^8\) first explains the basic working principle of squeeze film with very simple models, for example infinite plate. Minikes\(^9\) solves the coupled dynamic problem of a vibrating piezoelectric disk generating an air squeeze film.

All these works focused on the relationship between vibration amplitude of the radiator, and levitation force. According to their assumptions, the radiator is supposed to be rigid and performs a piston like movement where vibration amplitude along radius is uniform. However in real situation, vibrator can not supposed to be a rigid body, the vibrator deforms itself and totally changes the boundary condition of gas squeeze film. Since the boundary condition is pivotal to nonlinear differential equations, each previous model with that assumption lacks of precision to express and design a real NFAL apparatus. In present paper, the disunity of vibration amplitude along the radius

In this study, a model to analyze the acoustic levitation force is developed. In the model, the deformation of acoustic radiator surface is properly taken into account in the theoretical calculation of levitation force. A novel finite-difference scheme is employed to perform the numerical study. Levitating apparatuses has been fabricated and the characteristics measured. Good agreement between theoretical and experimental results is achieved at resonant frequency. The relationship between levitation distance, vibration amplitude and force has been studied for the flexural vibration mode.

2. **Principles of Squeeze film**

As illustrated in Fig.1, consider a vibrating sound surface of radius R to vibrate along the vertical axis z at a frequency \(\omega\). The reflector surface is placed initially at a distance \(h_0\) from the vibrating surface, and is assumed to be steady rigid (can not move and deform). However in practical situation, any levitated disk vibrates more or less in response to the sound source motion. However as the diameter of the disk is much larger than the end of horn, the vibrating disk can not oscillate a piston motion at a resonant frequency around 20kHz. It has the vibrating mode itself. As a consequence, the vibrating surface in this paper oscillates at different amplitude along radius. Com-
pare with the work presented by Minikes, the displacement of each point on the surface changes with time and radius.

To model this complex system, we first divide it into two parts with appropriate constraints. We assume that the levitation force in the gas film cannot affect the vibration of the sound source surface. Hence the coupling between fluid and solid plate is negligible. Then we solved the vibrating disk independently, calculating its surface displacements with time and radius, which serve as boundary conditions in the later squeeze film solution.

The fluctuating vibrating surface squeezes the compressible gas film, thus generating a time-averaged pressure higher than the ambient. According to a low non-dimensional Reynolds number in the present case, assume that the fluid inertia is negligible compared to viscous forces. Moreover, we assume the thin gas film is isothermal because of its low heat capacity. Taking the squeeze number into consideration, the high squeeze number reveals that the pressure gradient in the normal direction can be neglected. Consequently, the model is reduced to one dimension.

Reynolds equation is employed as the governing equation for pressure distribution in a compressible thin fluid, which is suitable for laminar, isothermal, and compressible thin fluid. Reynolds equation is derived from classical Navier-Stokes equation with continuity restriction:

$$\frac{\partial}{\partial X} \left( H^3 \frac{\partial P}{\partial X} \right) = \sigma \frac{\partial}{\partial T} (PT)$$  \hspace{1cm} (1)

Where $P_a$ is the atmospheric pressure, $P$, $H$, $X$, and $T$ are the dimensionless pressure, mean clearance, horizontal coordinate, and time, respectively. $\sigma$ represents the squeeze number.

The equation in polar coordinates is

$$\frac{1}{R} \frac{\partial}{\partial R} \left( RH^3 \frac{\partial P}{\partial R} \right) = \sigma \frac{\partial (PH)}{\partial T}$$  \hspace{1cm} (2)

The traditional Reynolds equation ignored gas inertia, which is suitable if $Re \ll 1$, where $Re = \frac{\rho h^2 \omega}{\eta}$ is a modified Reynolds number. However, in the acoustic region, $Re \gg 1$, the gas inertia can be significant. Based on the compact model with gas inertia [10], a modified squeeze number with a relative flow rate coefficient $Q_{pr}$ is set up as:

$$\sigma = \frac{12 \omega \eta \cdot r_0^2}{P_a h_0^3 Q_{pr}} = \frac{\sigma_0}{Q_{pr}}$$  \hspace{1cm} (3)

Boundary and initial conditions are as follows:

The pressure at the disk edge is equal to atmospheric pressure, while the pressure gradient in the center of the disk is zero.

$$P(R = 1, T) = 1, \quad \frac{\partial P}{\partial R} (R = 0, T) = 0$$  \hspace{1cm} (4)

The displacement of points on the vibration surface is

$$Y(R, T) = y(R) \cdot \sin(T) \cdot h_0$$  \hspace{1cm} (5)

So the thickness of the gas film is

$$H(R, T) = 1 + y(R) \cdot \sin(T)$$  \hspace{1cm} (6)

When $T = 0$, the pressure in the film is equal to atmospheric pressure,
The time averaged pressure at each point can be integrated as

\[ P_{\text{average}}(R) = \frac{1}{T} \int_{0}^{T} P(R) \cdot dT \]  

The total levitation force on the surface is

\[ F = 2\pi \int_{0}^{1} R(P_{\text{average}} - 1)dR \]

3. Numerical study

In present assumption, the gas thickness \( H \) is much more complicated than in the piston like motion. \( \frac{\partial}{\partial R} (H^3 P \frac{\partial P}{\partial R}) \) can not be solved separately, which increase the difference of analytical solution and call for a higher accuracy finite-difference scheme in numerical calculations. The new high-resolution central schemes presented by Alexander Kurganov et al. are used for convection-diffusion equations.

Based on classical thick plate theory, the disk has several vibrating modes at different resonance frequencies. The one we can employ to generate an axisymmetrical levitation force should be an axisymmetrical vibration mode, where points at the same radius have a uniform displacement at any time. Finite element analysis is employed in modal solution. By constraining the resonance frequency to match the horn, the thickness of the disk is determined. Fig.2 shows the mode shape of vibrating plate and the corresponding resonant frequency. The thickness and frequency are later used in experimental design.

![Finite element analysis on mode shape of vibrating plate](image)

The FEA model indicates that the largest deflection magnitude occurs in the center of the plate. Once the central amplitude was given, the displacement of each point along radius can be calculated. Therefore, the displacement of the radiation surface is a function of time and radius. As long as the applied voltage is in the linear range of the piezoelectric material, the deformation is proportional to the applied voltage. According to the experimental apparatus presented in this case, the output voltage is supposed to be constant, which results in an unchangeable maximum vibrating amplitude. Fig.3 shows the amplitude of vibration along radius and the resonant frequency is 21.024 kHz. Here the maximum amplitude at central point is 0.05mm.
Fig. 3. Vibration amplitude of radiation plate along radius

The numerical calculation of the pressure distribution of the air gap as a function of time is shown in Fig 4. The pressure distribution along radius reveals that near the edge of the disk, the mean pressure is equal to the atmosphere, while the largest time averaged pressure is at the center of the vibrator. Furthermore, the gas near the edge barely experiences any compression or decompression, so no cushion effect takes place in this region. The squeeze film phenomenon takes place close to the centre of the disk, where the pressure cycle is changing from compression to decompression while the mean pressure is above the atmospheric pressure. However, the forces achievable in this way decrease shortly with increasing levitation distance from the radiator.

Fig. 4. Dimensionless radiation pressure distribution along radius

The numerical results of levitation force and stiffness at different levitation distance are illustrated in Fig. 5 and Fig. 6. Clearly visible on this plot is the steeply rising levitation forces in the near field. The stiffness with different vibration amplitude shown in Fig 6 reveals that the stiffness decreases as the clearance increase.
4. **Experimental study**

Fig. 7 illustrates the configuration of the experimental setup. A rigid aluminium plate is placed on the radiation surface as the reflector. This disk has the same radius with the vibration surface, and is connected to the load cell on a position stage. The 3 DOF position stage is used to position the reflector precisely over the radiator, and move the reflector in Z direction so as to change levitation distance. The levitation distance was measured with laser displacement sensor, meanwhile, the load cell measured the levitation force correspondingly. The real radiator is excited at a frequency of 21.75kHz with a conical horn which is driven by a pre-stressed sandwich transducer also referred to as Langevin-Bolt transducer (LBT). The measurements were carried out keeping the vibration amplitude of the radiation surface constant (0.05mm).
Fig. 8 Comparison of experimental and theoretical results

The levitation force is plotted in Fig. 8 as a function of levitation distance. The figure indicates that the measured values at the distance more than 0.35 mm agree well with the theoretical values which are calculated in accordance with Eq. (2). However, the discrepancy becomes larger as levitation distance decreases. Since the gas clearance is close to the vibration amplitude, the pressure gradient in the normal direction can be neglected. The pressure gradient can cause higher order squeeze film effect with an increase in the levitation force. The discrepancy between two values may be due to the finite dimension of the surfaces and the amplitude non-uniformity of the surface.

5. Summary and outlook

The employment of high-intensity acoustics offers a promising approach for non-contact handling of both micro parts and fragile and surface-sensitive wafers and substrates. Furthermore, acoustic transfer systems for planar parts are not subject to any restrictions in terms of the size or shape of the feed paths. Near field acoustic levitation is successfully applied to non-contact transportation of objects. In this paper, levitating apparatuses have been fabricated and the characteristics measured.

A disc is levitated at a height much smaller than the acoustic wavelength where NFAL effect is dominant. A high-order analytical and numerical study on the levitation force induced by gas squeeze film is studied. By taking into account the modal solution on the vibrator whose disunity of the surface displacement cannot be ignored, detailed boundary condition of gas squeeze film can achieve a high accuracy in final calculations of time-averaged pressure distribution and load capacity of the system.

In future works, a unified model will then be implemented to perform calculations of the levitation forces and stable positions as a function of the amplitude and frequency of the vibrations, the sound wave features, the shape and density of the object and other parameters.

Furthermore, the final goal is the implementation of a simulation tool devoted to the design of non-contact handling system based on acoustical levitation. It should be as general as possible to allow a potential use in industrial design in the near future.

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REFERENCES


