Study of Pressure Distributions in A Flexural Gas Squeeze Film

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***Abstract*-Near field acoustic levitation (NFAL) has been used in non-contact handling and transportation. The levitation force is generated by the squeeze film. In order to descript the levitation force precisely, we built a mathematic model of the squeeze film, considering the gas inertia and relevant nonlinear effect with high frequency oscillation. Finite element method (FEM) simulation and measurement test are used to obtain the distribution of squeeze film pressure. Results show that the gas inertia has a significant influence on pressure distribution. The predicted levitation force also agrees with our experimental measurements. This study presents the gas pressure distribution with different mode shapes and explains the mechanism of the NFAL.**

Keywords-NFAL; pressure distribution; flexural mode; squeeze film

I. INTRODUCTION

Near field acoustic levitation (NFAL) has been used in non-contact handling and transportation of small objects to avoid contamination. In semiconductor manufacturing andmicro-assembly, it is difficult to handle and transfer the wafer or component of MicroElectromechanical System (MEMS) due to their fragility and surface sensitive characteristics.Classical processes usually contain mechanical contacts, which may result in the destructionof fragile parts or cause some degree of surface damage. Also, particles are generated andthus contaminate the working space. The major advantage of NFAL lies in the fact that anymaterial, insulator or conductor, magnetic or non-magnetic, can be manipulated by acousticlevitation and transportation without physical contacts [1].

NFAL is successfully applied to non-contact transportation where planer and surface sensitive objects can be levitated and transported.Experimental results indicate the existence of NFAL levitation force and positive characteristics [2], theoretical studies are performed as well.Some of the theoretical studies focused on the mechanism of the gas squeeze film. According to their assumptions, the radiator is supposed to be rigid and performs a piston-like movement with uniform amplitude along the radius [3]. However in the real situation, vibrator can't be traded as a rigid body, the vibrator deforms itself and the mode shape is quite different at each resonant frequency. Thus different vibration shape totally changes the boundary condition of the model.

For simplicity, the radiator was assumed to be rigid and performing a piston-like movement with uniform displacement across the vibrating surface. Although such simplification can leads to beautiful analytical solutions, it does not describe the real situation, especially when the vibrating plate is much larger than the transducer. Depending on the mode of operation and the resonance frequency of the vibrator, the displacement on the radiating surface is generally position dependent. Different vibration shape on the surface totally changes the boundary condition of the squeeze film model and makes the analytical solution impossible. Nomura [4] pointed out that further investigation is needed to clarify such boundary nonlinearities. Moreover, the effect of gas inertia becomes significant as the Reynolds number increases [5]. The gas inertia plays an important role in the 'acoustic' region. Unfortunately in piston-like model, the governing equation assumes that the fluid inertia is negligible compared with viscous forces [6]. To enhance the precision of the model, gas inertia should be included. It was demonstrated that by considering the nonuniform displacement on the radiator surface, the gas squeeze film model could produce much better fit to the experimental measured levitation force[7].

In this paper, we studied the gas squeeze film between the levitated object and the acoustic radiator. A mathematic model of the gas film has been built, concerning the gas inertia and relevant nonlinear effect with high frequency oscillations. Finally we have investigated the pressure distribution on the levitation surface with different mode shapes.

II.THEORETICAL ANALYSIS

A. *Brief Description of Physical Model*

Pressure arises in a fluid film between two mutually approaching surfaces. This iscalled the squeeze effect and the fluid film is called the squeeze film. O. Reynoldsreferred to the squeeze effect in his famous paper on lubrication (1886) and stated thatit was an important mechanism, together with the edge effect, for the generationof pressure in a lubricating film. Two mutually approaching surfaces were considered,however, two mutually receding surfaces are also worth considering. In this case,since negative pressure arises in the fluid film, this phenomenon is called negativesqueeze. The case of two approaching surfaces is called positive squeeze.

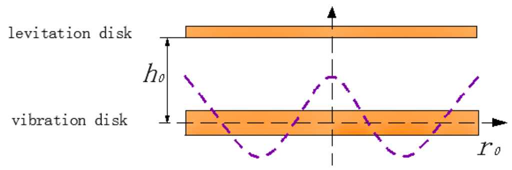


FIGURE I. THEORETICAL MODEL FOR NEAR FIELD ACOUSTIC LEVITATION.

As shown in Fig. 1, the vibration disk used for ultrasonic radiation is connected with the piezoelectric vibrator through the horn. Above the vibration disk is the levitation disk, which has the same diameter r_0 with the vibration disk. It can reflect the acoustic wave, so it is also called reflector. Between the two disks is the squeeze film we studied, and its thickness is h_0 ($h_0 << r_0$). The ultrasonic wave travelled in the gas is reflected by the above disk. Using inverse piezoelectric effect of piezoelectric ceramics, the piezoelectric vibrator under the stimulus of sinusoidal voltage converts electrical energy into mechanical energy, making the piezoelectric vibrator harmonic vibrate along the z axis. The vibration amplitude is amplified through the horn. However, the vibration disk can’t be treated as a rigid body vibrating along the z axis approximatelybecause of its large diameter. Actually, the vibration disk generates flexural deformation and forms corresponding vibration mode. Due to the effect of the flexural mode of the vibration disk, the thickness of the squeeze film is different along the direction of radius even in the same time. Meanwhile, it varies harmonically in a period.

B. *Theoretical Model of Squeeze Film And Modification With Gas Inertia*

The equation of squeeze film including gas inertia is also derived by N-S equation. As the model shown in Fig.1, for axisymmetric distribution of the acoustic field, we derived the equation in cylindrical coordinate with several assumptions. We assume that the gas in the film is isothermal classical Newtonian fluid, ignoring the coupling stress of the non-Newtonian fluid. The pressure and the levitation force generated by the squeeze film are very small, the effect of which on the vibration disk’s flexural mode is also ignored. Because the squeeze coefficient in the squeeze film is high, we assume the pressure along the thickness of the film is the same. We treat the gas movement in the squeeze film as laminar flow and it is compressible. Besides, the gas has small heat capacity and thin thickness, thus it is also can be treated as having the same heat inner the squeeze film.

Considering gas viscous force and gas inertia, the constitutive equation is derived based on the N-S equation:

$$\rho\left(\frac{\partial v_r}{\partial z}+v_r\frac{\partial v_r}{\partial r}+v_z\frac{\partial v_r}{\partial z}\right)=-\frac{\partial p}{\partial r}+\frac{\partial \tau_{rz}}{\partial z} \qquad (1)$$

Where $\tau_{rz}=\mu\frac{\partial v_r}{\partial z}$ is shear stress, p, ρ and μ are pressure, density and viscous coefficient of the gas film, respectively. v_r and v_z are the movement velocities of the gas along the radial direction and the thickness direction, respectively.

Here we introduce an approximated mean volume average across the film thickness [8], and we obtained the pressure distribution in an axisymmetric radial squeeze film:

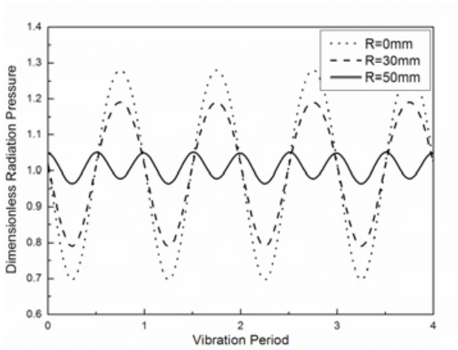
$$\frac{\partial p}{\partial r}=\frac{6\mu r}{h^3}\frac{dh}{dt}-\frac{9}{10}\frac{r\rho}{h^2}\left(\frac{dh}{dt}\right)^2+\frac{r\rho}{2h}\frac{d^2h}{dt^2} \qquad (2)$$

Integrating the convective inertia Eq. (2) with respect to r and t, the time-averaged pressure distribution along the radius of the vibrating surface can be obtained.

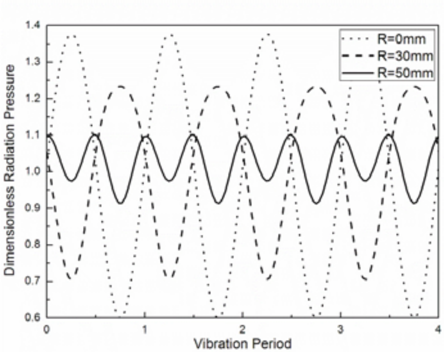
III. NUMERICAL STUDY

A. *Numerical Calculations of Pressure Distribution*

Fig. 2 shows the calculated consequences of the pressure distribution changing with time under different flexural modes, considering gas inertia. Fig. 2 also shows that the pressure in the squeeze film is periodically changing with harmonic vibration of the vibration disk. We can also see that in a period the value of the upper half part (more than one standard pressure) is larger than the value of the lower half part, thus the average pressure is larger than one standard pressure, so the upper levitation force is generated. On the other hand, Fig. 2 (a) and (b) also separately show the pressure in the same drive mode at the different radius which are r=0mm, r=30mm and r=50mm, from which we can see the pressure at the three radius is not the same. The pressure is relevant with the bending shape of the specific boundary. We also found that the gas film pressure distribution response amplitude is larger, nonlinear effect is more obvious, period average levitation force is large for the effect of gas inertia.



(a)



(b)

FIGURE II. PRESSURE DISTRIBUTION AT DIFFERENT RADIUS WITH INERTIA EFFECT. (A) 1ST ORDER MODE. (B) 2ND ORDER MODE.

B. Experimental Validation

According to the FEM (finite element method) calculation and the oscillator radiation surface mode measured by laser scanner, we obtained the dynamic boundary condition of the squeeze film. We put the boundary condition into the model considering gas inertia and boundary effect, and then we obtained the solution of the film pressure distribution.

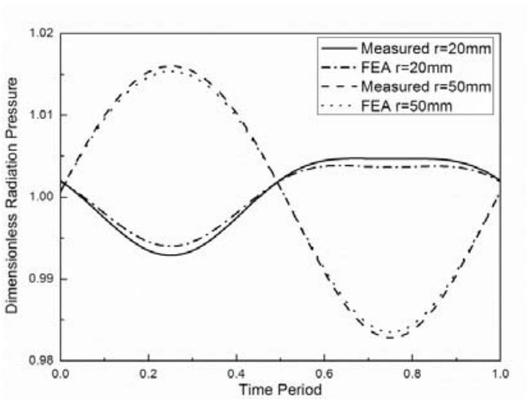


FIGURE III. COMPARISON OF PRESSURE DISTRIBUTION WITH DIFFERENT VIBRATION AMPLITUDE

Fig. 3shows the pressure distribution with different vibration amplitude. The effect on pressure made by FEM calculated mode and measured mode is also presented in Fig. 3. Pressure vibration amplitude at different radius calculated by the FEM agrees with the measured results. According to all the data, the pressure vibration phrase calculated by the FEM and measured are in good agreement, and is related to the phase of the vibrator surface mode. For the pressure vibration amplitude at different position, the results measured are larger than the results calculated by FEM, which is caused by the deviation of the vibration mode. The vibration mode as dynamic boundary is put into the mathematic model, and then deviation is generated.

IV. SUMMARY AND OUTLOOK

With the development of the MEMS precision manufactory, higher requirement to wafer is put forward. The wafer has sensitive surface and is easy to fragile. Besides, it is more and more small and thin. Tradition transportation can't meet the requirements. The technology of near field acoustic levitation (NFAL) has been played an important role in Micro Electromechanical system (MEMS) for handling and transportation of the wafer to avoid contamination.

The levitation force is generated by the squeeze film between the levitated body and the acoustic vibrator. We have been built a mathematic model of the squeeze film, considering the gas inertia and relevant nonlinear effect with high frequency oscillation. We obtain the gas film pressure distribution using the method of FEM calculation and the test measurement for different vibration mode. We found that the pressure distribution is relevant with the vibration mode for different vibration modes representing different dynamic boundaries of the mathematic model. This research has a significant guide for the application of the acoustic levitation. Along with the levitation force, acoustic wave travelling in the squeeze film forms a driving force. These two forces can be used for transporting planar objects such as MEMS devices, glass substrates and IC chips, without any physical contact.

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