3P4-7

Acoustic streaming analysis around electronic chip parts levitated in airborne ultrasound

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1. Introduction

Ultrasonic levitation[1-4] is attracting attention for non-contact transportation of electronic components[5], precision machinery, pharmaceuticals because they can avoid damage, contamination, dust, static electricity, and yield where small parts enter unintended places. Compared with aerodynamic, magnetic, and electrostatic levitation, ultrasonic levitation has the advantage that there are no restrictions on the target material and there is less dust problem, but the disadvantage is that the holding force is slightly lower than other methods and the levitation target must be lightweight.

The authors[6] have focused on the levitation of chip components and have studied the vibration system necessary for levitation. The experimental results show that a 50–100 kHz vibration system is more suitable for small chip component levitation than a 20–40 kHz vibration system, which is often used for ultrasonic levitation. Low-frequency transducers could not levitate small chip components even with large vibration velocity inputs. This cannot be explained by the conventional theory[7] of acoustic radiation force alone.

The authors consider that the Schlichting streaming[8] generated around a chip component prevents the chip component from being levitated, and perform an acoustic field analysis considering a viscous boundary layer and an acoustic streaming analysis[9-11] driven by Reynolds stresses. By comparing the calculated hydrodynamic forces of the acoustic streaming with the acoustic radiation forces, the authors will investigate why small chip components are difficult to levitate in lower frequency.

2. Levitation force evaluation

Acoustic radiation force $\mathbf{F}_A$ act on the target object with surface S is

$$\mathbf{F}_A = -\int \left[\langle p \rangle \mathbf{n} + \rho_0 \langle \mathbf{u} u_n \rangle \right] dS, \tag{1}$$

$$\langle p \rangle = \frac{\langle p^2 \rangle}{2\rho_0 c^2} - \rho_0 \frac{\langle u^2 \rangle}{2}, \tag{2}$$

where p, u, ρ_0, c, $\mathbf{n}$, and <...> are sound pressure, particle velocity, density of air, sound speed, surface normal vector, and process of time average, respectively.

Acoustic streaming is derived through static incompressible fluid dynamics equation using Reynolds stress τ calculated from acoustic field.

$$\begin{aligned} &\rho_0 (\nabla \cdot \mathbf{U}) \mathbf{U} = -\nabla \{ P + \langle p \rangle \} + \nabla \cdot \{ T + \tau \}, \\ &T = \eta \left(\nabla \mathbf{U} + \nabla \mathbf{U}^T \right),\ \tau = -\rho_0 \langle \mathbf{u}\mathbf{u}^T \rangle. \end{aligned} \tag{3}$$

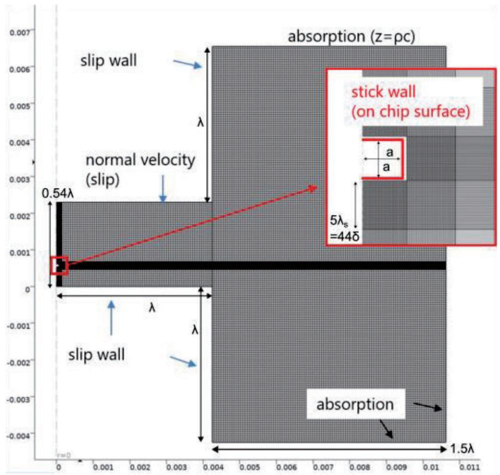

Fig. 1 Axisymmetrical calculation model for ultrasonic levitation in half wavelength mode.

Since the specific weight of the chip component is not constant (1.8–3.0), the evaluation of radiation force L_A and fluid force by the acoustic streaming L_U in this study is normalized by the gravity acting on the same volume of water.

$$L_A = \frac{\mathbf{e}_z \cdot \mathbf{F}_A}{\rho_w g V},\ L_U = \frac{\mathbf{e}_z \cdot \int (-P\mathbf{I} + T) \mathbf{n} dS}{\rho_w g V}, \tag{4}$$

where ρ_w, g, V, and $\mathbf{e}_z$ are density of water, gravitational acceleration, volume of the target object, and direction of gravity, respectively.

3. Analysis model

Fig. 2 shows axisymmetrical calculation model in this study. We assume conditions in which a chip component is levitated and trapped in a half-wavelength standing wave formed by a piston vibrator and a reflector with radius of a wavelength $\lambda = c/f$. Contrary to the actual chip component, it is modeled as a cylinder with radius a and height a in a cylindrical coordinate system. The vibration velocity input is set to 0.17 m/s so that the maximum sound pressure amplitude is160 dB in rms. In this paper, we mainly focus on the case of 80 kHz, but when analyzing at other frequencies, the analytical model is set to scale similarly with respect to the wavelength.

Thermo-viscous acoustic analysis and laminar steady-state fluid analysis were used in the acoustic analysis module of COMSOL 6.1 for the analysis. Stick boundary conditions is set on the chip surface, and the outer boundary is an absorption boundary for acoustic analysis and an outflow boundary for fluid analysis.

4. Results and discussions

Fig. 3 shows (a) sound pressure, (b) particle velocity distribution and indicates that the analysis is half-wavelength mode and stick boundary conditions are properly set. Fig. 3(c) and (d) shows acoustic streaming distribution when the chip component with a=0.0016λ is placed on z=λ/2 and λ/4, respectively. In Fig. 3(c), a vertically symmetric circulation is generated. However, in Fig. 3 (d), downward streaming over the chip component is generated, which inhibit the levitation of the chip component.

Fig. 4 shows the dependence of the levitation force on the chip size a. Since Schlichting streaming is a phenomenon related to boundary layer thickness δ, chip size is normalized by $\delta = (\nu/\omega)^{1/2}$, where ν and ω are kinematic viscosity and angular frequency, respectively. At 80 kHz, the radiation force L_A is almost independent of the chip size, but the streaming inhibiting force L_F become relatively larger as the chip size decreases, and the total value becomes zero when the chip size a/δ=4. A similar trend occurs at 20 kHz. Since the boundary layer becomes thicker at lower frequencies, small chip components approach this threshold value of 4δ, making levitation difficult.

5. Conclusion

The reason for the difficulty in levitating small chip components was investigated by analyzing acoustic streaming. It was found that there is a lower limit of radius (4δ) at which a chip component cannot be levitated, no matter how large its input velocity, because the circulating acoustic streaming around the chip component inhibit its levitation.

Acknowledgment

This work was supported by JSPS KAKENHI, Grant Number 23H01365.

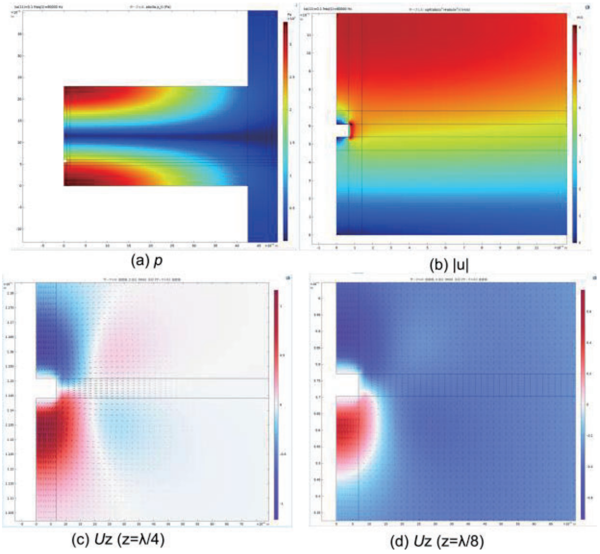

Fig. 3 (a) sound pressure, (b) particle velocity, and (c)(d) acoustic streaming distribution when chip is placed at z=λ/4 and λ/8, respectively.

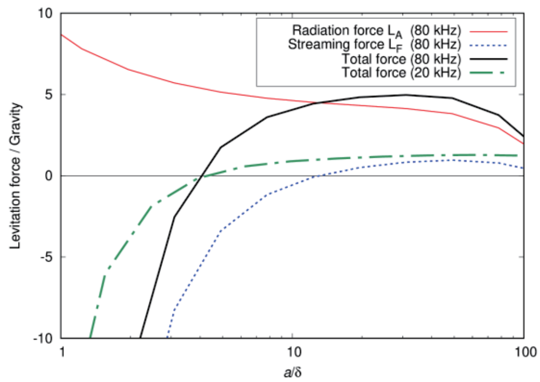

Fig. 4 Levitation force vs. chip size a/δ.

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