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Noncontact grasping using acoustic streaming air pressure and negative acoustic radiation force

Yuta Fujioka[1], Yimeng Wang[1], Hideki Tamura[2], Kohei Aono[3], and Manabu Aoyagi[1†]
([1]Muroran Inst. of Tech.; [2]Tohoku Inst. of Tech.; [3]Seidensha Electronics)

1. Introduction

When a cylinder with a small hole at its center is placed near a vibration source and the source is excited, an air jet is generated[1)]. Furthermore, when the cylinder is inserted between the vibration source and a flat object, it is slightly levitated[2)]. It has been found that this levitation is caused by a small gap between the cylinder and the flat surface. In addition, introducing a shallow recess (spotface) at the bottom of the cylinder changes the levitation force acting on the bottom, and under certain conditions, its direction can be reversed[3)]. This suggests the existence of a force that attracts the flat surface via the cylinder.

This paper presents the results of finite element analysis and experiments on forces acting on an object placed below the cylinder.

2. Finite element analysis

2.1 Analysis model

Finite element analysis (FEA) software (COMSOL Multiphysics 6.3) was used to perform acoustic pressure field and acoustic streaming analyses, as well as to investigate the forces acting on an object placed under the cylinder. The 2D axisymmetric analysis model is shown in **Fig. 1**. From top to bottom in the figure, the model consists of a vibration source (diameter of radiating surface: 10 mm), a cylinder (diameter: 10 mm, height: 5 mm, through-hole diameter: 1mm), and an acrylic plate (diameter: 12 mm, thickness: 1.3 mm). A spotface 50 µm deep and 7.6 mm in diameter is formed at the bottom of the cylinder. The gap between the vibration source and the cylinder is set to 500 µm, and the gap between the cylinder and the acrylic plate is denoted as h. The red line outside the air region in Fig. 1 is an absorbing boundary, and the dark green region represents a viscous air layer. The analysis was performed with a vibration amplitude of A = 10 µm and a vibration frequency of f = 28 kHz.

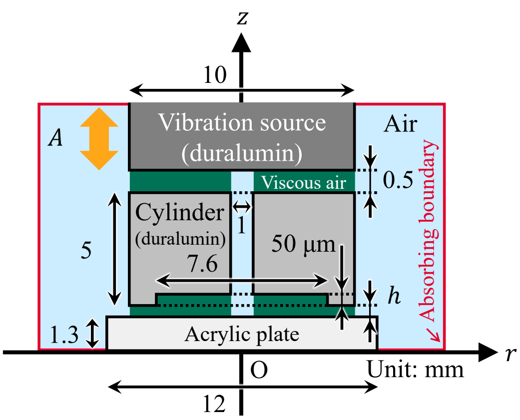


Fig. 1 2D axisymmetric model for FEA.

2.2 Analysis results

Figure 2 shows the analytical results summarizing the forces acting on the acrylic plate as the gap h is varied. The force F_{jet} due to acoustic streaming is shown in blue, while the acoustic radiation force F_{rad} acting on the acrylic plate is shown in rad. The total attractive force F_T is calculated as

$$F_T = F_{jet} + F_{rad}, \quad (1)$$

and is shown in black. The directions of all forces are defined as positive in the negative z-axis direction.

Since F_{jet} is always positive, it acts to push the acrylic plate away from the cylinder. In contrast, F_{rad} is always negative, indicating that it acts to attract the acrylic plate toward the cylinder. As h increases, both forces approach zero, meaning that the interaction becomes weaker as the gap widens.

Focusing on F_T, it is positive when h is small, indicating that a net force separates the acrylic plate from the cylinder. However, as h increases, F_T becomes negative, indicating that the direction of the force changes and attracts the plate toward the cylinder. The most negative value of F_T occurs at h = 40 µm.

These results suggest that it is possible to attract an object in a non-contact manner by combining a repulsive force from acoustic streaming with an attractive force from acoustic radiation.

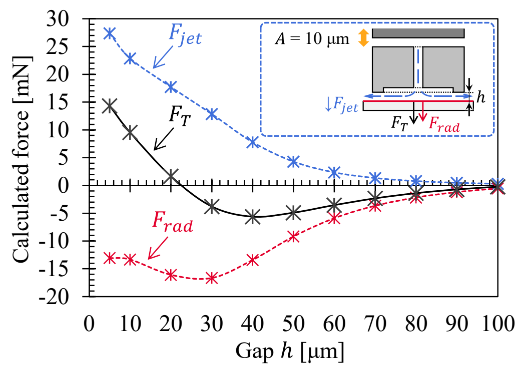
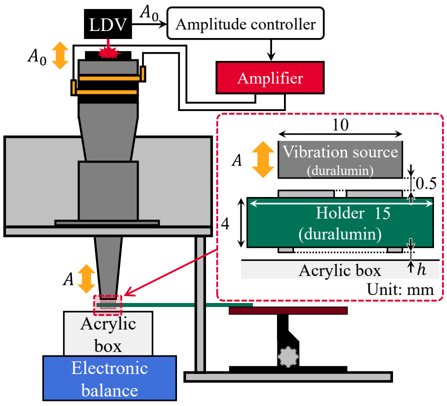
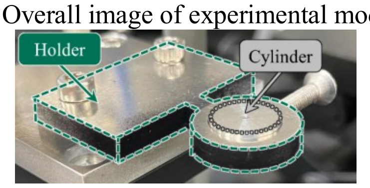


Fig. 2 Calculated force vs. gap h.

E-mail: †maoyagi@muroran-it.ac.jp



(a) Overall image of experimental model.



(b) Holder for fixing cylinder.

Fig. 3 Experimental apparatus.

3. Experiment

3.1 Experimental method

The experimental setup is shown in **Fig. 3**. The force F_M generated by the cylinder was measured using an electronic balance. The electronic balance was placed under the cylinder through an acrylic box. The vibration source and the cylinder were arranged with the same dimensions as in the analysis model shown in Fig. 1. As shown in Fig. 3(b), the cylinder was fixed using a holder (diameter: 15 mm, thickness: 4 mm). A bolt-clamped Langevin transducer (BLT) was used as a vibration source. The vibration amplitude A of the radiating surface was determined by measuring the amplitude A_0 at the bottom of the BLT using a laser Doppler vibrometer (LDV). The value of A_0 was controlled to a target value using MATLAB.

3.2 Experimental results

The experimental results are shown in **Fig. 4**. The experiments were conducted with two vibration amplitudes: A = 10 µm (black) and A = 20 µm (red). For each amplitude, two measurements were taken, the first indicated by a diamond-shaped marker and the second by a square marker. The analysis results in Fig. 2 are also shown as solid lines for comparison.

Figure 4 shows that the force changes with h regardless of the amplitude A, indicating that it is possible to generate an attractive force. On the other hand, A =10 µm, which corresponds to the simulation conditions, was found to be insufficient for generating the required force. Additionally, the maximum negative force was observed at h = 20 µm, which differs from the analytical results. This discrepancy may be due to deviations in the experiment definition of h = 0 µm or to the influence of the holder, which was not considered in the analysis.

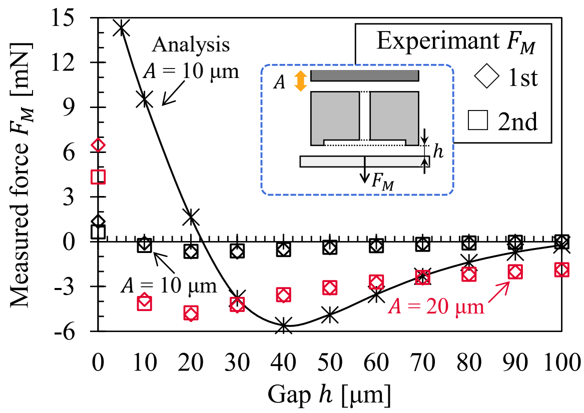


Fig. 4 Measured force F_M vs. gap h.

3.3 Attraction experiment using the cylinder

The acrylic box shown in Fig. 3(a) was replaced with an acrylic disk (diameter: 12 mm, thickness: 1.3 mm, mass: 153 mg), and experiments were conducted to see whether an attractive force could be generated. A photograph of the experiment is shown in **Fig. 5**. The holder is visible at the top, the cylinder in the center, and the acrylic disk at the bottom.

Figure 5 shows that the acrylic disk is attracted toward the cylinder. Additionally, light leaked through the gap between the cylinder and the acrylic disk, confirming that the two are not in contact.

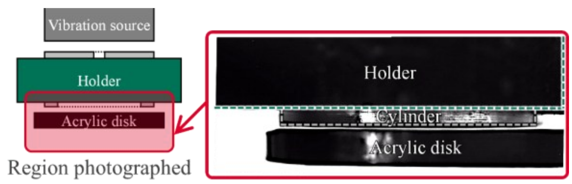


Fig. 5 Captured image of contactless suspension.

4. Conclusion

Analyses and experiments were conducted to investigate the force acting on an object placed under a cylinder with a spotface. Both the analytical and experimental results confirmed the existence of an attractive force. Furthermore, by observing the light leakage between the cylinder and the acrylic disk, it was confirmed that the disk was successfully attracted without any physical contact.

Acknowledgment

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References

1) K. Aono *et al.*, USE2022, 3Pb4-5, 2022.
2) K. Aono *et al.*, C0221, pp.469-467, 2021.
3) Y. Fujioka *et al.*, JJAP, 05SP06 (2025).