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Analysis of the levitation force acting on a cylinder with a hole placed between vibrating surface and a plane

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1. Introduction

Placing a cylinder with a through hole, the diameter was the same as that of the vibrating surface; between the vibrating surface and a flat surface, it has been observed to cause slight levitation [1]. The fact that levitation does not occur in a cylinder without a through hole suggests that the acoustic effects of the through hole affect levitation. This paper analyzed the acoustic radiation force and the hydrodynamic action force derived from acoustic streaming on a cylinder with a hole as forces related to levitation. In addition, based on the analytical results, cylinders with holes were fabricated with a spot facing, and the levitation was experimentally evaluated.

2. Analysis model

The analytical model is shown in **Fig. 1**. The diameter of the transducer and the cylinder with a hole is 10 mm, the height of the cylinder is 5 mm, and the diameter of the through hole is 1 mm. In addition, a spot facing with a depth of 50 μm and a diameter D_z is provided at the bottom of the cylinder. The vibration amplitude is 10 μm, and the vibration frequency is 28 kHz. In addition, the gap h_1 between the vibration surface and the cylinder and the gap h_2 between the cylinder and the base are set to 500 μm in total. An absorbing boundary is set outside the air layer. In addition, the light blue area in Fig. 1 considers the viscous air [2]. The finite element analysis software COMSOL Multiphysics 6.2 was used, and a 2D axisymmetric model was created.

3. Effect of spot-facing diameter D_z

3.1 When $h_2 = 0$ μm

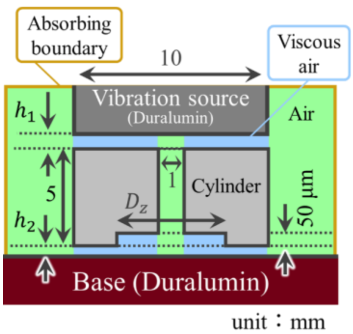


Fig. 1 Analysis model.

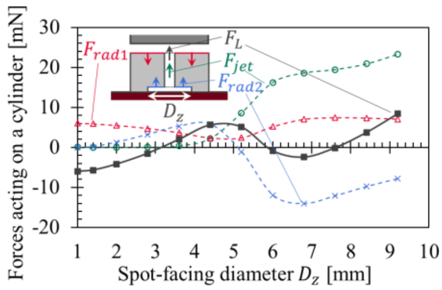


Fig. 2 Forces vs. spot-facing diameter D_z at h_2= 0 μm.

Fig. 2 shows the analytical results of the forces acting on the cylinder when and D_z is changed at $h_2 = 0$ μm. Note that D_z = 1 mm is a cylinder without a spot facing. The acoustic radiation force F_{rad1} acting on the top of the cylinder is shown by a red triangle, the acoustic radiation force F_{rad2} acting on the bottom of the cylinder is shown by a blue cross, and the levitation force F_{jet} due to acoustic streaming is shown by a green circle. In addition, the levitation force F_L is calculated from eq. (1) and shown by a black square.

$$F_L = F_{jet} + F_{rad2} - F_{rad1} \quad (1)$$

Fig. 2 shows that there are levitating and non-levitating places because F_L can take positive and negative values. F_L has a positive peak at D_z = 4.4 mm and a negative peak at D_z = 6.8 mm. The maximum value is D_z = 9.2 mm, and the minimum value is D_z = 1 mm. Looking at each component, F_{rad1} is always positive and therefore not involved in levitation. F_{rad2} is positive when $D_z \leq$ 4.4 mm, and negative when $D_z \geq$ 5.2 mm. F_{jet} increases rapidly when $D_z \geq$ 4.4 mm. From this, it is considered that levitation occurs due to acoustic radiation force at the maximum value D_z = 4.4 mm and due to acoustic streaming at the maximum value D_z = 9.2 mm. In other words, it is believed that levitation can occur more efficiently by providing an appropriate gap at the bottom of the cylinder. However, it is shown that levitation does not occur when F_L is negative, which differs from the experimental results described below.

3.2 When h_2 = 0.5 μm

Fig. 3 shows the analytical results of the force action on the cylinder when D_z is changed at h_2 = 0.5 μm. The meaning of each plot point is the same as in Fig.2. Unlike the case of h_2 = 0 μm, all values of F_L are positive, so levitation occurs

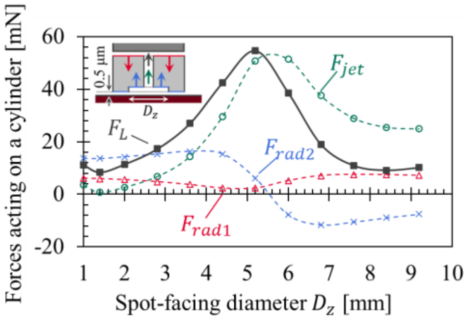


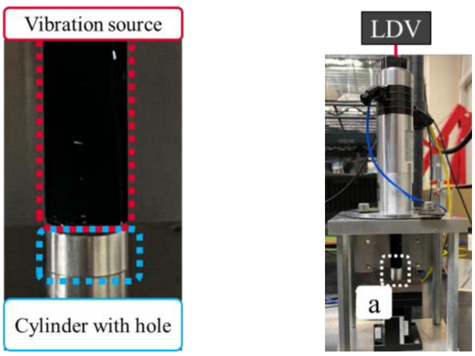
Fig. 3 Forces vs. spot-facing diameter D_z at h_2= 0.5 μm.

regardless of D_z. In addition, the F_L has a maximum value at D_z = 5.2 mm. F_{rad1} and F_{rad2} show a similar distribution as when h_2= 0 μm, but that F_{rad2} does not become smaller even at $D_z \leq$ 2.8 mm. F_{jet} increases from D_z = 1.4 mm and reaches a maximum around D_z = 5.2 mm. It is thought that the presence of a smaller gap between the cylinder and the base causes significant changes in the acoustic streaming and acoustic radiation force, resulting in the cylinder levitating.

4. Experiment

4.1 Experimental Equipment

Based on the analysis results, the same number of cylinders with spot facing (12 pieces) as in the analysis were made, and experiments were conducted to confirm whether F_L changes with D_z. **Fig. 4(a)** shows the vibration source and the cylinder with a hole arranged in the same manner as the analytical model in Fig. 1. **Fig. 4(b)** shows an overall view of the experimental setup. The vibration source used in the experiments was a bolt-clamped Langevin transducer (BLT) with a resonant frequency of 28 kHz. Since measuring the levitation force acting on the cylinder directly is difficult, the change in levitation force was estimated from the change in the vibration amplitude at which the cylinder begins to be levitated. The vibration amplitude of the bottom of the BLT was measured by



(a) Arrangement of cylinder with hole and vibration source. (b) Equipment overview.

Fig. 4 Experimental apparatus.

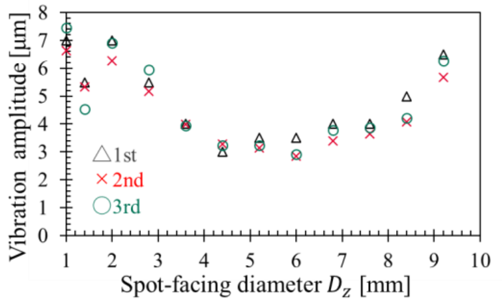


Fig. 5 Minimum vibration amplitude required for levitation vs. spot-facing diameter D_z.

a laser Doppler vibrometer (LDV), and the amplitude of the vibrating surface was estimated.

4.2 Experimental Results

Fig. 5 shows the measurement results of the vibration amplitude at which levitation begins when the spot-facing diameter D_z was changed. The experiment was carried out three times, with the first time indicated by a triangle, the second by a cross, and the third by a circle. Since the vibration amplitude at the start of levitation changed with the spot-facing diameter D_z, it was considered that the levitation force was also changed. The vibration amplitude at which levitation began was the smallest around $4 \leq D_z \leq 6$ mm, suggesting that the levitation force was generated most effectively. On the other hand, when $D_z \geq$ 8 mm, a large vibration amplitude was required, meaning that the levitation force was small. These results were generally consistent with the analysis results shown in Fig. 3. The experiments confirmed that changes in the spot-facing diameter affect the levitation force.

5. Conclusion

The forces involved in levitation concerning the spot-facing diameter D_z at the cylinder bottom were analyzed and experimented. As a result, it was found that D_z affects the levitation force F_z. No levitation force was observed in the analysis for h_2=0 μm, whereas levitation occurred in all experiments, which was in close agreement with the analysis for h_2 = 0.5 μm. Therefore, levitation may occur if a gap of approximately the size of the surface roughness exists under the cylinder.

Acknowledgment

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References

1) K. Aono et al., C0221,pp. 469-467, 2021.
2) J W. M. Beltman, University of Twente, Enschede, 1998.