Study on near-field acoustic levitation by multi-mode ultrasonic transducer

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Abstract:

Near-field acoustic levitation (NFAL) is one of the high-power ultrasonic applications that are based on the nonlinear phenomena. The NFAL enables non-contact transportation by levitating kg-order objects. In this study, we propose to utilize various wave shapes to improve NFAL performances. For this purpose, new designed ultrasonic transducer was fabricated, whose resonance frequencies ratio can be controlled precisely. From the experimental results, we confirmed the nonlinear bulk modulus of air contributes to NFAL significantly and establish an appropriate model using Poisson's law. According to these studies, it was clarified that the shape controlled wave is effective especially in the case of highly-loaded conditions.

Key words: high power ultrasonic, near-field acoustic levitation, acoustic pressure, non-contact transportation

Introduction

In recent years, high-power ultrasonic technologies are put to practical use in various fields. Near-field acoustic levitation (NFAL) is one of the high-power ultrasonic technologies, which can levitate kg-order bodies with flat surfaces. Traditionally, the shape of ultrasonic wave had been a simple sinusoidal wave with this technology, however, NFAL are based on nonlinear phenomena owing to large amplitude of ultrasonic wave. Therefore there is a capability that a shape-controlled ultrasonic wave could improve their performances. In fact, there are some reports that the performances of their high-power ultrasonic experiments with f Hz and 2f Hz combined wave (f + 2f ultrasonic wave) was better than those with only f Hz wave. For example, Prof. Umemura succeeded in making cavitation effectively with f + 2f ultrasonic wave which had lower ultrasonic intensity than the previous studies, and our researching group improved the performance of ultrasonic pump with f + 2f ultrasonic wave[1)2)].

In this study, we propose new NFAL method using f Hz and 2f Hz combined wave. First, an optimized multi-mode transducer was designed to excite f + 2f ultrasonic wave. Next, the NFAL experiments were carried out with the optimized transducer, and we found that the levitation gap depends on the ultrasonic wave shape. Finally, the experimental result was explained with the Poisson's law model which was usually utilized for an air bearing experiments[3)]. With this Poisson's law model, we clarified the dependency of the levitation gap on the wave shape of the f + 2f ultrasonic wave. At the same time, the calculation indicated that the f + 2f ultrasonic wave could levitate heavy objects efficiently by introducing our proposal.

New designed multi-mode transducer

In this study, various wave shapes were examined to clarify the dependency of the levitation gap on the wave shape; therefore we used combined ultrasonic waves where driving frequencies were f and 2f. By controlling the amplitude and the phase difference between f Hz wave and 2f Hz wave, the combined wave shape could be modified. For this purpose, Suzuki designed a bolted Langevin transducer whose the primary and 3rd mode resonance frequencies ratio was 1:2. It was named a multi-mode transducer[2)]. As shown in Fig. 1, the diameter of the multi-mode transducer was changed at the middle of the total length to adjust the resonance frequencies ratio. Previous final adjustment for controlling the ratio was carried out by changing the diameter with machining; however, the ratio control was not precise enough to excite fully high-power f + 2f wave for this study. Therefore, a new multi-mode transducer was designed with a new mechanism for the preciser final adjustment of the ratio. The new mechanism of new multi-mode transducer was to controll the resonance frequencies ratio by attaching additional rings at the step position. Figure 2 shows the fabricated transducer, whose length was 144.8 mm, the diameters were 9 mm and 15 mm and the step position was 25.9 mm with no rings from the center. The resonance frequencies ratio was adjusted by attaching rings as shown in Fig. 3. With 7.3 mm thickness additional rings, the resonance frequencies ratio f_3/f_1 became 2.001 which was precise enough for this study.

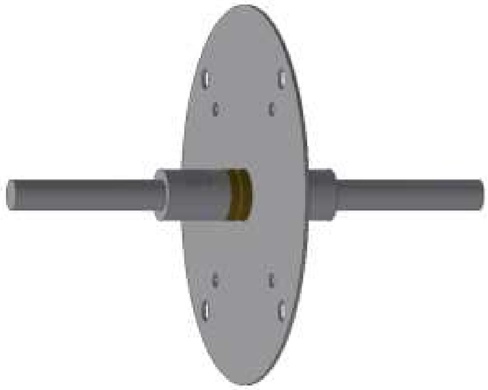

Fig. 1 Traditional multi-mode transducer

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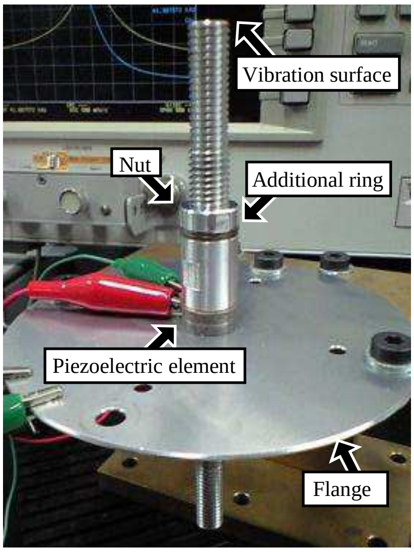

Fig. 2 Fabricated multimode transducer

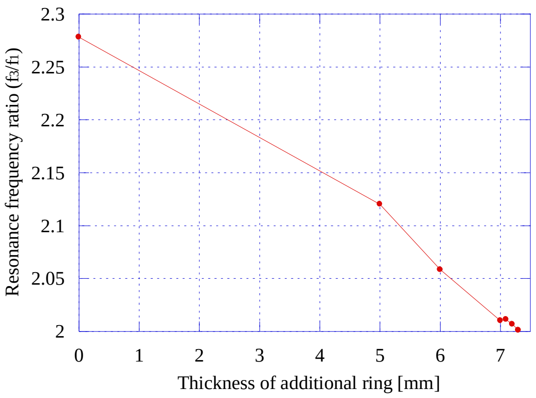

Fig. 3 Resonance frequencies ratio change by additional rings

NFAL experiment

Using the fabricated transducer, NFAL experiments were carried out with f + 2f ultrasonic wave by modifying the phase difference between the primary and third mode. The levitation gap depended on the phase difference as shown in Fig. 4, which means that the levitation gap depended on the wave shape.

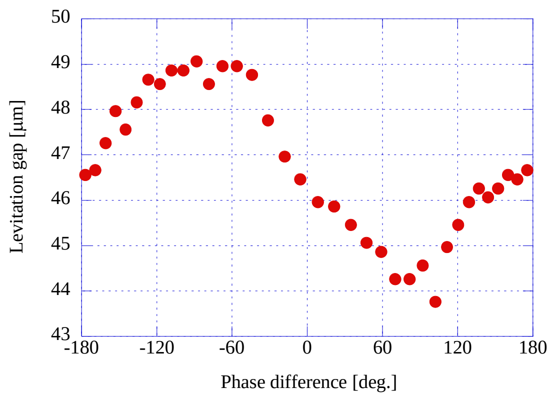

Fig. 4 Levitation gap change by the phase difference

Traditional acoustic model

We tried to explain the experimental results with a traditional acoustic model[4]. In this model, there were some hypotheses; the levitated object's position was fixed; the ultrasonic wave was reflected perfectly at the levitated object's surface; the transducer excited plane wave; there was no air leakage from the sidewall of the gap because of the air's viscosity. Figure 5 shows the conceptual diagram of the model for NFAL. An upper one is levitated object and a lower one is vibration surface of the transducer. The velocity of the transducer's surface $v_0(t)$ is expressed as

$$v_0(t) = v_1 \cos(\omega t) + v_2 \cos(2\omega t + \phi). \qquad (4.1)$$

And the acoustic pressure p is represent as

$$p = \frac{\rho}{2}\left(\left(\frac{v_1}{\sin k_1 h}\right)^2 \left(\frac{1}{2} - \frac{\sin 2k_1 h}{4k_1 h}\right) + \frac{1}{2}\left(\frac{v_2}{\sin k_2 h}\right)^2 \left(\frac{1}{2} - \frac{\sin 2k_2 h}{4k_2 h}\right)\right) \qquad (4.2)$$

Eqn. (4.2) shows that the pressure p is independent of the phase difference ϕ, that disagree with the experimental results; therefore other model was introduced as follow.

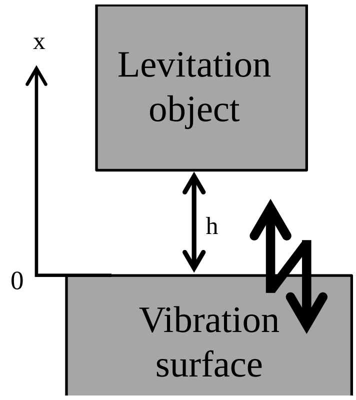

Fig. 5 Conceptual diagram of NFAL

NFAL model by Poisson's law

In the case of NFAL, the levitation gap is much shorter than the wave length. It means the sound pressure can be considered as a constant value P(t) as a function of position. To calculate the sound pressure $P(t) = P_0 + \Delta P$, Poisson's law is utilized, which is usually used in the field of air bearing. The parameter P_0 shows the atmospheric pressure and ΔP does the pressure change.

The Poisson's law is expressed as

$$PV^{\gamma} = const., \qquad (5.1)$$

where γ is the heat capacity ratio and V is he air gap volume, which is equal to $V_0+\Delta V$. The V_0 is the average gap volume and the ΔV is the gap volume change due to the vibration of the transducer.

The pressure is the essential parameter to indicate the performance of NFAL. From above mentioned calculation, ΔP can be obtained as

$$\Delta P = \frac{P_0}{\left(1+\frac{\Delta V}{V_0}\right)^{\gamma}} - P_0. \qquad (5.2)$$

This equation shows the nonlinearity of pressure change caused by the ultrasonic vibration. By assigning the vibration equation (4.1) to equation (5.2), the pressure

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change can be calculated. The levitated object can't follow the high frequency pressure change; therefore, the essential pressure for levitating force is the time average pressure calculated by $\int \Delta P \mathrm{d}t / T$, where the T is the cycle.

As a result, we calculated the time average sound pressure as a function of the phase difference as shown in Fig. 6. This relationship agreed with the experimental results in a quantitative way.

With the experimental results and the proposed model, it was verified that the combined f + 2f ultrasonic wave was effective for NFAL. As a next step, the time average pressure was calculated by fixing the phase difference as -90 deg. The vibration amplitudes for primary and third mode were both 10 μm and the frequency f is 20.84 kHz.

Figure 7 shows the relationship between time average pressure and the levitation gap with various conditions. With the single sinusoidal wave excitation, with only f mode or 2f mode, the result was same. On the other hand, by combining these waves, the time average pressure was increased dramatically. This tendency depends on the nonlinear relationship between the pressure and the volume change. From this result, it was clarified that this nonlinear effect was remarkable where the gap was small. Therefore, the proposed f + 2f ultrasonic wave excitation is quite useful when the levitated object is heavy.

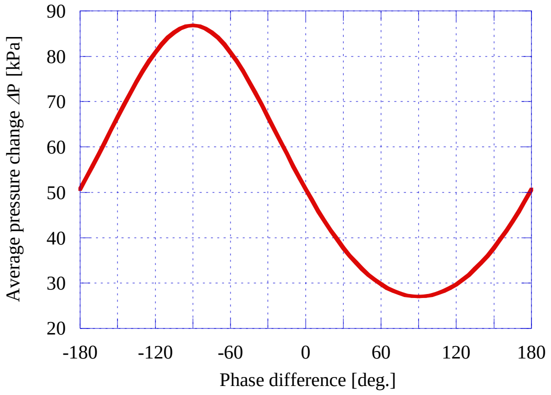

Fig. 6 Average pressure change by the phase difference

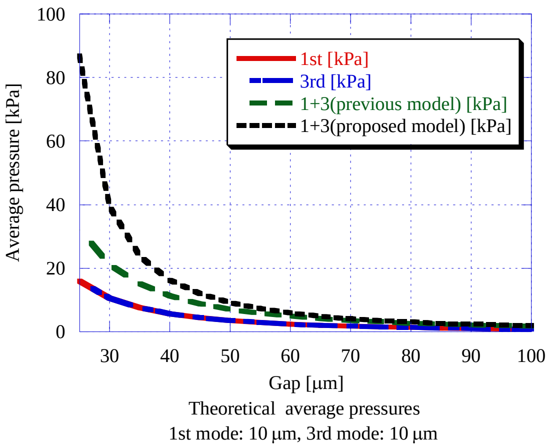

Fig. 7 Calculated average pressures

Conclusion

A multi-mode transducer was designed and fabricated which was optimized for this study. It was clarified that the levitation gap depended on the wave shape and it could be explained quantitatively with the Poisson's law. According to the calculation result based on the Poisson's law, the more levitated objects are heavy, the more shape-controlled ultrasonic wave effect becomes useful.

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