Phenomena, theory and applications of near-field acoustic levitation

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Abstract

A phenomenon called near-field acoustic levitation (NFAL) has been reported by the author's research group where planar objects of several kilograms in weight are levitated in the air a few hundred micrometers away from a radiation surface. Unexpected characteristics, in which acoustic radiation pressure changes from repulsive to attractive under certain conditions, have been found by the group. In this paper, these experimental phenomena are described together with a theoretical approach. In addition to the phenomena, NFAL-based non-contact transportation systems both in air and underwater are also mentioned. Finally, ultrasonic motor based on NFAL is mentioned briefly

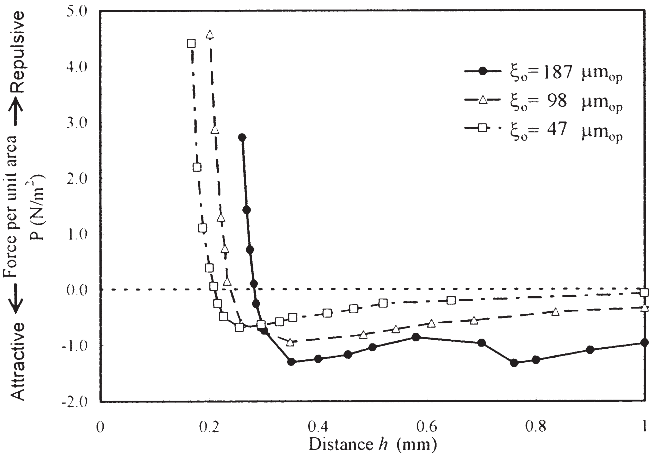
Resumen

Un fenómeno llamado levitación acústica en campo próximo (LACP) ha sido publicado por el grupo de investigación del autor según el cual objetos planos de varios kilogramos de peso levitan en el aire a unos cientos de micras de la superficie de radiación. El grupo ha encontrado características inesperadas en las que la presión de radiación acústica cambia de repulsiva a atractiva bajo ciertas condiciones. En este trabajo, se describen los fenómenos experimentales junto con una aproximación teórica. Además de los fenómenos, se presentan los sistemas de transporte sin contacto basado en LACP tanto en aire como en agua. Finalmente se menciona brevemente un motor ultrasónico basado en LACP.

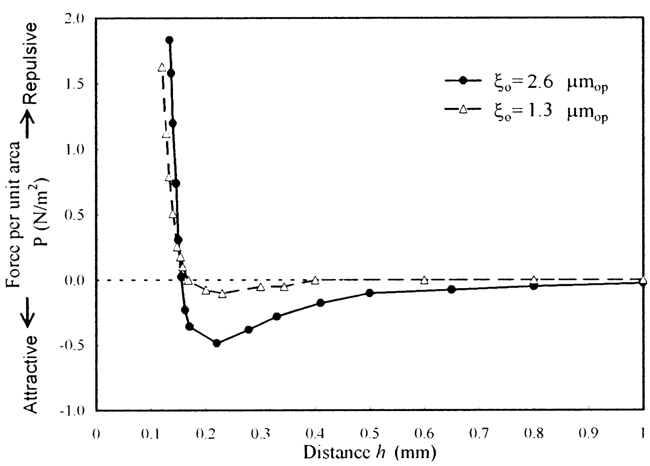
1. Introduction

The author's research group has reported a near-field acoustic levitation (NFAL) phenomenon where a heavy planar object of several kilograms in weight can be levitated very close to a radiation surface. Based on in-air NFAL, levitation and suspension systems for planar objects have been successfully fabricated[1)-4)]. The group also found that attrac-

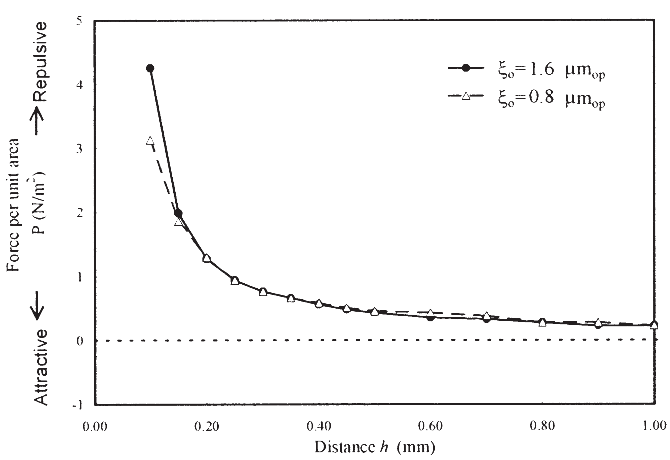
Fig. 1. Experimental setup for measuring the near-field acoustic radiation force.



(a) Frequency = 200Hz



(b) Frequency = 1.6kHz



(c) Frequency = 4kHz

Fig.2. The variation of the force P acting on the planar object against the distance h. The frequencies of the shaker are (a)200Hz, (b) 1.6kHz and (c) 4kHz.

tive acoustic force acts on a planar object at certain conditions instead of a repulsive force [5)].

In this paper, the characteristics of the acoustic force acting on plates placed near a radiation surface in air is described at first to show the behavior of the acoustic force. As both the repulsive and attractive acoustic forces can be used for ultrasonic actuators, underwater non-contact transporting systems for planar objects have been fabricated. These systems are described together with NFAL-based non-contact transportation systems in-air and ultrasonic motors.

2. Brief description of near-field acoutic levitation

Phenomena and theory

An experimental setup for measuring near-field acoustic radiation forces is shown in **Fig.1**. A shaker with an aluminum vibration plate 10mm in thickness is used as a sound source. In the experiments, vibration plates with diameters of 75mm, 95mm and 125mm were used. These plates vibrate uniformly below 6kHz. In order to measure the radiation pressure acting on an aluminum reflection disk 7mm in thickness, whose diameter is 6mm smaller than the vibration plate, faces the vibration plate and is connected to an electric balance through a suspension rod. The resolution of the electric balance is 0.01g.

Figure 2 shows typical results for the 70 mm plate, where the radiation force is measured as a function of distance *h* and the driving frequency is a parameter. Figures 2(a), (b) and (c) show the measurement results at the frequencies of 200Hz, 1.6kHz and 4kHz, respectively. It is obvious that for a driving frequency of 4 kHz the force steadily decreases in the repulsive region as the distance h increases. For frequencies of both 200 Hz and 1.6 kHz, however, the force decreases down to the attractive region showing a minimum value and approaches zero as h increases. The situation is almost the same for other reflection plates [6)].

This phenomena is explained by the theory of radiation pressure by B. Chu and R. E. Apfel [7)]:

$$\Pi = \frac{1+\gamma}{4}\rho_a {c_a}^2 \frac{a_0^2}{h^2} \quad (1)$$

where Π, radiation pressure; specific heat ratio; ρ_a, density of medium; c_a , sound velocity of medium; a_o, vibration amplitude (= v_0/ω), and h , levitation distance.

The negative radiation force, that is, the attractive force, can not be explained by the theory. The changeover frequency, at which the force changes from repulsive to attractive, is plotted in **Fig.3** as a function of the diameter of the reflection plate *D*.

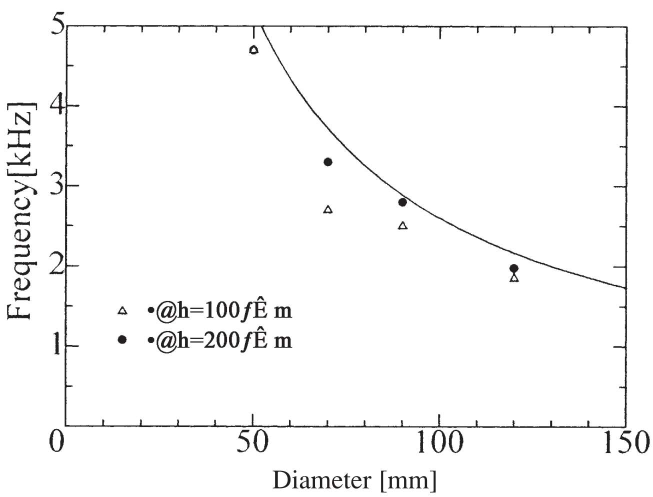


Fig.3. The frequency versus the diameter of the planar object at which attractive force varies to repulsive force. The solid line shows the fundamental resonance frequency of the thin air disk.

The solid line shows the fundamental resonance frequency *f* of the radial expansion mode of the gap in between the vibration and reflection plate. The fundamental resonance frequency *f* of the radial expansion is calculated by the equation

$$J_o(\frac{2\pi f}{c} \cdot D) = 0 \quad (2)$$

where c is sound velocity, D is the diameter of the reflection disk, and J_o denotes the zeroth-order Bessel function of the first kind.

It is clear in the figure that the changeover frequency decreases with the fundamental resonance frequency *f* as calculated by eq. (2). This suggests that the attractive force can be effectively generated if the driving frequency is much less than the fundamental resonance frequency *f* of the radial expansion mode of the gap.

3. Nfal-based non-contact ultrasonic actuators

Non-contact transportation of planar specimen using flexural waves in-air [8)]

Consider the case where planar object is levitated and transported by a flexural traveling wave as shown in **Fig.4**(a). The operation mechanism can be explained as follows [9-12)]. The traveling sound field in the gap produces two unidirectional forces on the object. One is in the normal direction and levitates the object, and the other induces near-boundary streaming along the surface of the object. The velocity gradient of the near-boundary streaming on the surface of the object produces a viscous force which causes the object to move in the horizontal direction. As the result, the levitated object is rapidly levitated vertically and gradually accelerated in the horizontal direction by the viscous force. The exact formulation for the thrust force is now under study.

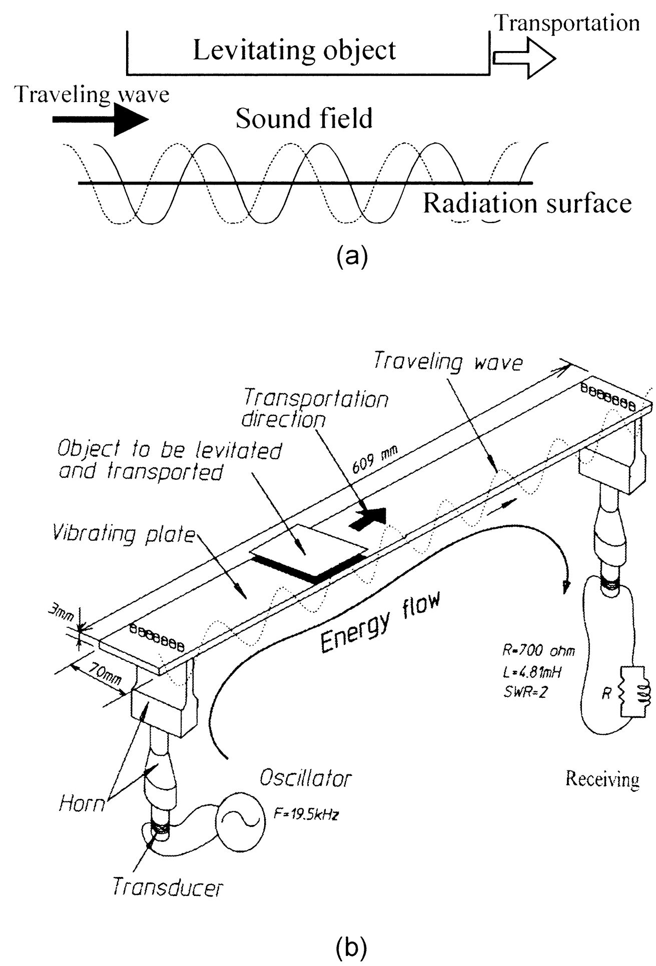


Fig.4. Principle and configuration of transportation system by NFAL. (a) Schematic, (b) Setup configuration.

Figure 4(b) shows a configuration of the trial-made transportation system. A 609x70x3mm^3 duralumin plate is connected to two longitudinal vibration systems and is vibrated in a flexural mode by one of them. The two longitudinal vibration systems consist of the transducers and the horns with the same specifications. In order to obtain a traveling wave, one transducer is connected with the oscillator and the other transducer with a resistance and an inductance [13]. To make the traveling wave component large, the distance from the screw to the end of the vibration plate is set to one-fourth of the flexural wavelength of the vibration plate. As the plate is vibrated at a resonant frequency of 19.5 kHz, the wavelength is 38.06 mm. The vibrating plate is precisely leveled horizontally with a digital level meter so that almost the same transportation speed is obtained even if the driving and the receiving sides are exchanged.

NFAL based ultrasonic motor [14,15]

A prototype motor is shown in **Fig.5**. Two Langevin transducers are attached with screws to a cylindrical stator made of aluminum. A thin cylindrical rotor is inserted into the stator so that there is a narrow gap between them. To generate a traveling wave of flexural vibration along the stator, the two transducers are driven by two alternating voltage with a phase difference of 90°, and the distance between the excitation points is three quarters of a flexural wavelength. Thus, a traveling wave in the circumferential direction is excited by superposition of two degenerated standing waves with a 90° phase difference. This technique is commonly used in conventional ultrasonic motors. The resonance fre-

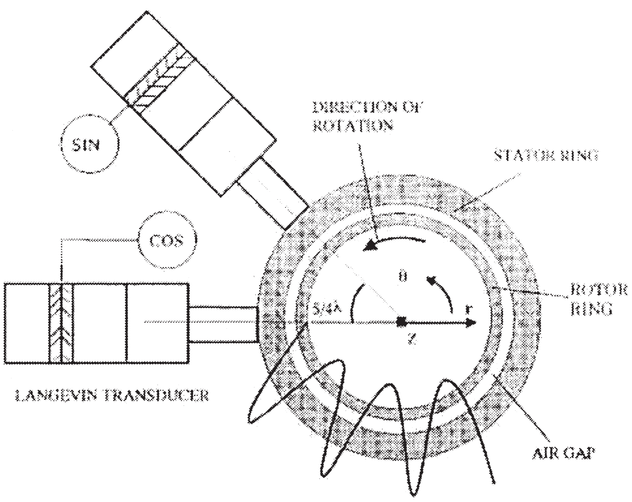


Fig.5. Configuration of ultrasonic motor using NFAL.

quency of the stator ring is tuned to that of transducers. In the trial made motor, the 6th flexural mode can be excited along the stator ring.

Non-contact underwater transportation system of planar specimen using flexural wave [16]

Figure 6 shows a diagram of an underwater non-contact transportation system of planar specimens based on NFAL. The system is almost the same as that in air. The vibration

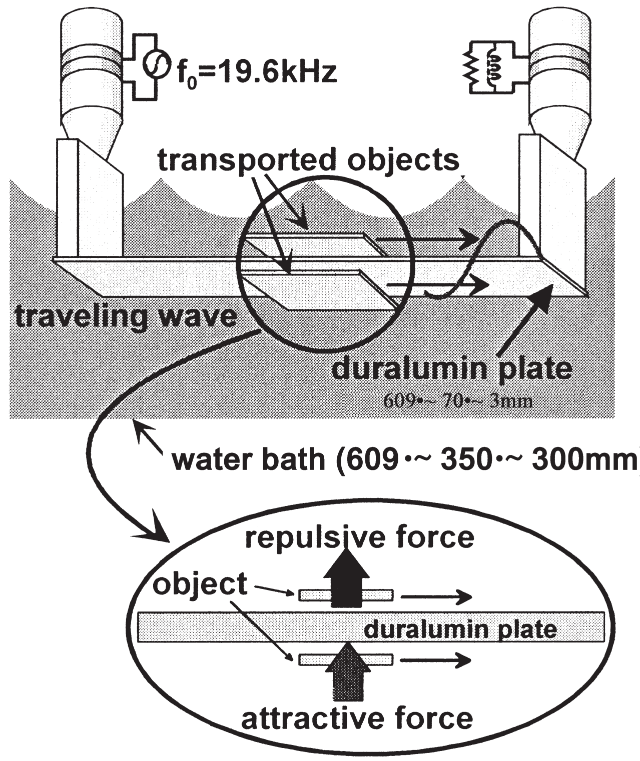


Fig.6. Underwater transportation system using a traveling wave

plate is, however, immersed underwater in this case and three operation modes are possible. One is a levitation mode whose operation principle is the same as that of in-air. The second one is an attraction mode, where objects are attracted near the flexural vibration plate and the thrust is generated by the viscous force due to acoustic streaming. This operation mode is possible only underwater, because the underwater attractive fore is much lager than that of in-air. The third one is a twin mode where levitation and attraction modes occur simultaneously.

Underwater NFAL based ultrasonic lifter [17]

Figure 7 shows a proposed ultrasonic lifter where an ultrasonic transducer with a straight horn is immersed in a water tank. The radiation surface is placed parallel to face of an object. If the transducer is energized, and both vibration amplitude and the distance *h* are appropriate, the object is attracted to the radiation surface, that is, the object is lifted. It should be noted that the object does not touch the radiation surface as is expected from Fig.2. If any conditions of attraction is broken, the object is released from the vibration system and falls under gravitation. One can move the object without contact.

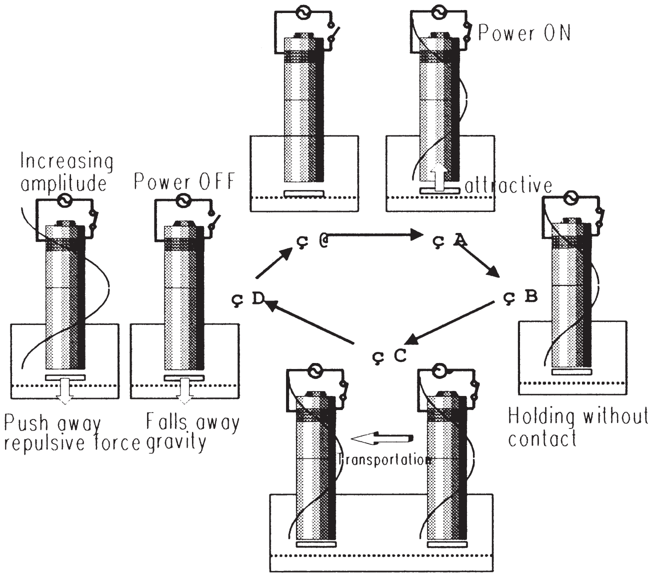


Fig.7. Sequence of non-contact transportation by using an ultrasonic lifter.

4. Conclusion

The characteristics of Near Field Acoustic Levitation (NFAL) were briefly described. The criteria where the force is attractive was suggested to be explained in terms of the vibration amplitude, the distance h between the vibration plate and the planar object, and the frequency.

Four ultrasonic actuators based on NFAL which work in air were described together with their operating principles. These non-contact transportation techniques will be widely used in the near future, because the demands for making fine LSI and larger computer displays are increasing.

The mechanism of acoustic radiation force, especially the attractive force has to be clarified theoretically in the near future.

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