Transactions of the KSNVE, Vol. 14, No. 5, pp. 432~438, 2004.

Acoustic Levitation and Rotation Produced by Ultrasonic Flexural Vibration

초음파 굽힘 진동에 의한 음향 부상 및 회전

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(Received February 6, 2004 ; Accepted April 9, 2004)

Key Words : Acoustic Levitation(음향부상), Ultrasonic Vibration(초음파진동), Acoustic Resonance(음향공진), Acoustic Streaming(음향유동)

ABSTRACT

Acoustic levitation induced by ultrasonic flexural vibration at 28.4 kHz with a vibration amplitude of 10 micrometers is presented. Levitation of multiple objects along the length of the beam in a gap of 8.3 mm which is the half of acoustic wavelength is experimentally demonstrated. Analytical analysis predicts that levitated objects for the gap of half-the wavelength converges to the center of the gap, which is experimentally verified. It is observed that levitated objects with well-balanced mass distribution are set into rotation due to acoustic streaming. For cylinder-shaped Styrofoam with a diameter of 1.8 mm and a length of 3 mm, measured rotational velocity is 2400 revolution per minute. Applications of standing wave field levitation (SWFL) include manipulation of biological cells and blood constituents in biotechnology, and fine powder in material engineering.

요 약

10 마이크로미터의 진폭을 갖는 28.4 kHz의 초음파 굽힘진동을 이용하여 초음파 진동판과 정지판 사이에서 다수의 소형 실린더 형태의 스티로폼를 진동판의 길이 방향으로 안정적으로 부양시켰다. 진동자와 정지판의 간격이 음향파장 (16.6 mm)의 1/2일 경우, 부양된 물체가 음향파장의 1/4 지점에서 안정적으로 부양되는 이유를 이론적으로 증명하였으며, 또한 실험적으로 검증하였다. 질량이 균형적으로 분포된 물체의 경우 부양시 고속으로 회전하게 되는데 이는 초음파 진동에 의해서 생성된 음향유동에 의한 것이다. 지름 1.8 mm, 길이 3 mm의 실린더 형태의 스티로폼의 경우 2400 rpm 으로 회전하는 것이 실험적으로 관찰되었다. 음향부양은 작은 세포나 혈액내의 구성체 혹은 미세 분진의 조작에 응용될 수 있다.

1. Introduction

Objects in the high-intensity sound field can be levitated by air pressure developed under the objects. This phenomenon is known as acoustic levitation.(1~7) There exist two kinds of acoustic levitation: near-field acoustic levitation (NFAL)(1~4) and standing-wave-field levitation (SWFL)(5~7). When the propagation of ultrasonic traveling wave in a medium is obstructed by a planar object, lifting pressure is developed under the object.

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Then, it is levitated in the direction of the wave propagation. This kind of acoustic levitation is called NFAL, and the planarity of the surface of the object to be lifted is the most important factor in inducing levitation. Hashimoto(2) reported the levitation of a planar object of 10 kg. The levitation distance is found to be proportional to the oscillatory velocity of the transducer, and inversely proportional to the ratio of mass to the surface area. But the practical limitations of the transducer confine the levitation distance within the order of hundreds of micrometers.(4) In SWFL, a standing-wave field is created by the transducer and reflector pair and objects are levitated and collected at the pressure nodes of the standing wave field that occur at every half of the acoustic wavelength. Also, restrictions on the shape of levitating objects are not imposed. In other words, non-planar objects can also be levitated, but the weight of the objects to be levitated significantly reduces compared to that of NFAL. Applications of SWFL include manipulation of biological cells and blood constituents in biotechnology, and fine powder in material engineering(5~7) and NFAL is primarily used for transporting planar objects such as optical disks, silicon wafers, and LCD panels.(1~4) In most of previous study on SWFL, levitation is induced inside an enclosed cylindrical container and the source of ultrasonic vibration stems from the longitudinal vibration. In this study, SWFL in an open space employing the flexural ultrasonic vibration is experimentally investigated. An advantage of employing the flexural vibration is that multiple objects can be stably levitated along the length of a ultrasonically-excited beam.

2. Experiment

2.1 Experimental Setup

The experimental setup shown in Figure 1 consists of vibrating and stationary beams and modules that contain a piezoelectric actuator and a horn. The beam and horn are made of 6061-T6 aluminum. The piezoelectric actuator is a bolted Langevin type transducer (BLT)(8) designed to resonate at 28 kHz. The conical horn is utilized to increase the amplitude of vibration supplied by the actuator. A mounting flange is included in the design of the horn and is located at the nodal lines where the velocity of vibration of the horn goes to zero. This allows the mounting of the horn and BLT assembly onto a supporting base plate that is in turn bolted to the surface of an air-driven vibration absorption table. The small end of the horn is threaded to connect the beam with the horn using a machine screw. The dimension of the beam is determined such that one of the natural frequency of the beam is located in the vicinity of the resonant frequency of the actuator, thereby maximizing the displacement of the beam for a given power supply. Following the classical Euler beam theory,(9) the determined dimension is 10 mm wide, 1 mm thick and 128 mm long. From frequency spectrum analysis of the system, it is found that the maximum vibration amplitude of the beam is obtained at an excitation frequency of 28.4 kHz. This frequency is selected as the

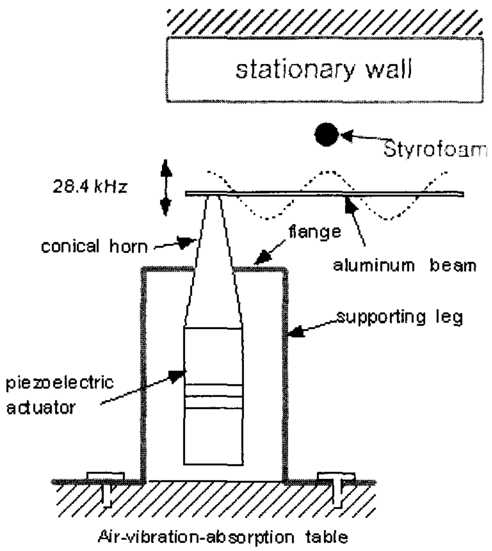

Fig. 1 Schematic drawing of experimental setup

excitation frequency of the system throughout the experiment. The stationary wall is made of aluminum which is 30 mm thick, 12 mm wide, and 110 mm long. The location of the stationary wall is selected such that the gap between the stationary wall and vibrating beam corresponds to the half of an acoustic wavelength to maximize acoustic levitation pressure in the gap due to resonance. Following the procedure of calculating acoustic resonant gap detailed in the Chapter 3, the obtained half of the acoustic wavelength is 8.3 mm and wavelength of the vibrating beam is 18.2 mm. To investigate acoustic levitation in the gap, cylinder-shaped Styrofoam with a diameter of 2.8 mm and a length of 3 mm is injected in the gap as in Figs. 1, 2.

2.2 Experimental Results and Discussion

Figure 2 shows stably levitated and rotating two pieces of cylinder-shaped Styrofoam in a gap of 8.3 mm with a vibration amplitude of 10 micrometers at 28.4 kHz. When a high intensity sound wave propagates, it propagates like a laser beam with strong directionality and insignificant scattering for a short distance of travel. Upon encountering a boundary, the wave is reflected, resulting in a pressure standing wave due to the interaction with the incident wave. At certain sizes of gaps, the interaction becomes significantly strong and these gaps are called acoustic resonant gaps. A gap of 8.3 mm is the half of the theoretically predicted acoustic wavelength and the fundamental acoustic resonant gap.

Two pieces of Styrofoam are levitated above the velocity anti-nodes of the vibrating beam. The distance between the two levitated Styrofoam is the half of the wavelength of the vibrating beam. Calculated wavelength of the beam is 18.2 mm according to the classical Euler beam theory. But the beam has a stepped shape that serves to securely connect the beam to the conical horn, which renders the actual wavelength to slightly differ from the analytical prediction of the wavelength. Placing fine ceramic powder on the surface of the vibrating beam allows the nodal lines to be experimentally identified. The wavelength corresponds to the half of the distance between nodal lines. The experimentally obtained wavelength is 20 mm.

At a gap of half the acoustic wavelength, the center of the gap is not only the pressure nodes of the sound wave but the stable levitation location in the gap. Therefore, objects in the gap converge to the center. Because the high intensity sound wave propagates with directionality like a laser beam, it is observed that a region of the beam involving an anti-node and two nodes functions as an independent source of vibration, resulting in insignificant interaction with neighboring regions as in Fig. 3. Pressure

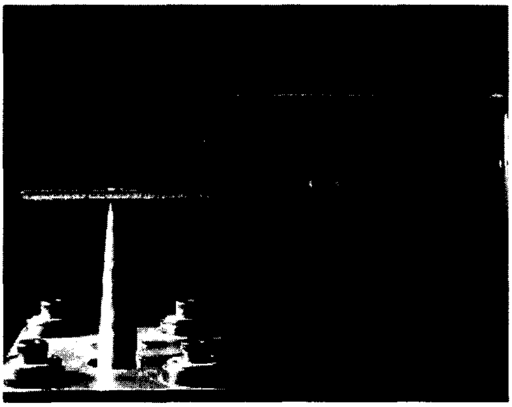

Fig. 2 Acoustically levitated styrofoam

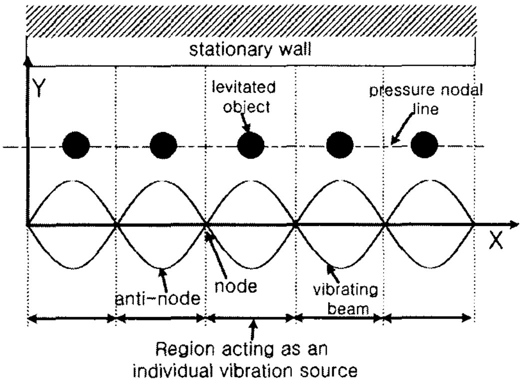

Fig. 3 Position of stable levitation

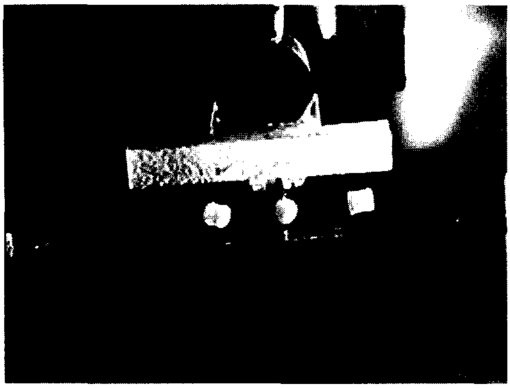

Fig. 4 Acoustic Levitation of Multiple Objects

distribution in the gap is analytically studied in the Chapter 3. Another characteristic of the high intensity sound field is steady circular air-flow called acoustic streaming(10~13) that causes levitated objects with well-balanced mass distribution to rotate. The measured rotational velocity of the Styrofoam using a strobe light is approximately 2400 revolution per minute with a vibration amplitude of 10 micrometers, which correlates to a linear velocity of 0.35 meter/second.

To investigate the effect of the property of the stationary wall, the aluminum stationary wall is replaced with a rectangular Plexiglas block which is 5 mm thick and 40 mm long as in Fig. 4. Three pieces of Styrofoam are stably levitated at the center of gap and rotate. But it is observed that the axes of rotation of the levitated objects are not identical.

3. Analytical Analysis & Discussion

The pressure distribution in the gap is obtained by using linear acoustics theory(14) and imposing boundary conditions, $\xi(x,y,t)=\xi_0\sin(k_b x)e^{-i\omega t}$ at $y=0$ and $\xi(x,y,t)=0$ at $y=h$ where ξ_0: vibration amplitude, k_b: bending wave number of the beam defined as $k_b=2\pi/\lambda$, λ: wavelength of beam, ω: excitation frequency (radian/second), $i=\sqrt{-1}$, h: gap, t: time. The governing equation for the pressure distribution is given by the wave equation as

$$\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}-\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}=0 \qquad (1)$$

where c: speed of sound

The pressure is assumed to be superposition of the incident and reflected traveling waves as

$$\begin{aligned}p(x,y,t)&=A\sin(k_b x)e^{-i(\omega t-k_y y)}\\&+B\sin(k_b x)e^{-i(\omega t+k_y y)}\end{aligned} \qquad (2)$$

where $k_y=\sqrt{k^2-k_b^2}$, k: acoustic wave number defined as $k=\omega/c$, A,B: complex constants

Imposing boundary conditions gives the pressure distribution in the gap as

$$p(x,y,t)=\frac{\omega^2\rho\xi_0}{k_y}\sin(k_b x)\frac{\cos(k_y(h-y))}{\sin k_y h}e^{-i\omega t} \qquad (3)$$

where ρ : density of air

It is noted that when $\sin k_y h=0$, the derived pressure in Eq. 3 goes to infinity. This is because the viscous effect of the air is not considered in Eq. 3, causing the pressure to grow without a bound at resonance. Therefore, the acoustic resonant gap h is calculated as $n\pi/k_y$ where q = 1, 2, 3, ··· To obtain exact pressure distribution in the gap, Eq. 1 should be modified to take into account the viscous effect of air, but the inclusion of the viscous term in Eq. 1 would greatly increase the complexity of the problem. In addition, the purpose of derivation in this Section is not to gain the quantitative measure of pressure but to obtain pressure distribution in the gap that enables to identify the resonant gaps and the pressure nodal lines in the gap. Therefore, the Eq. 3 is used for analysis with minor modification that at a resonant gap, h is replaced by $h+\alpha$ where α is an arbitrary small number preventing pressure at resonance from becoming infinite.

Figure 5 shows normalized equi-pressure contour lines when the gap calculated by Eq. 3 is the half of the acoustic wave length, assuming that a is 0.0001 and the length of the vibrating beam is one wavelength. The pressure is sinusoidally varying and Fig. 5 is a snap shot of the periodically-varying pressure when the displacement of the beam is defined as $y(x,t) = \sin kx$, $0 \le x \le \lambda$. The numbers on the contour lines represent the normalized pressure. The contour lines clearly show the center of the gap is the pressure nodes where levitated objects converge. Equi-pressure contour lines for a gap of one full acoustic wavelength are shown in Fig. 6. Two pressure nodal lines exist, one at y = 4.1 mm and the other at y = 12.4 mm that would be stable levitation positions in the gap where levitated objects converge. An increase in the size of the gap would cause the intensity of the sound pressure to drop. As a result, the levitation force for the full acoustic wavelength would decrease compared to that of the half-acoustic wavelength.

Moreover, the gap should be greater than the quarter of the acoustic wavelength to induce acoustic levitation because the pressure nodal line does not exist for the gaps smaller than the quarter of the acoustic wavelength. The locations of the pressure nodal lines at resonant gaps are odd multiples of a quarter of the acoustic wave length, i.e. $(2n-1)\lambda/4$, where n = 1, 2, 3, With a vibration amplitude of 10 micrometers which is the maximum amplitude that the current experimental apparatus can produce, the acoustic levitation of Styrofoam is observed only for a gap of the half of the acoustic wave length because a decrease in the intensity of the sound pressure field resulting from the increase of the gap significantly reduces the levitation force. But, as analysis predicts, if the vibration amplitude is increased, acoustic levitation at all the pressure nodal lines present along the gap would be possible. A characteristic of acoustic levitation induced by the ultrasonic flexural vibration is that multiple objects can be levitated without

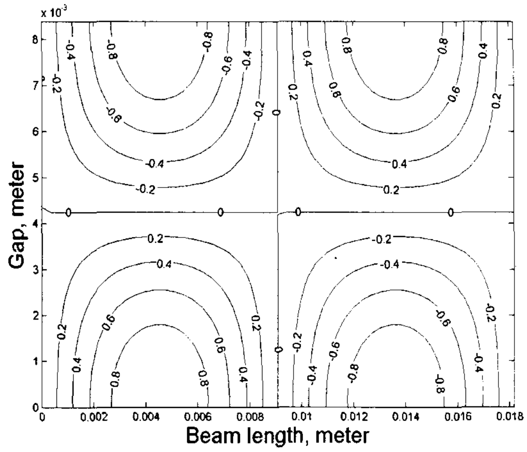

Fig. 5 Equi-pressure contour for a gap of half of acoustic wavelength

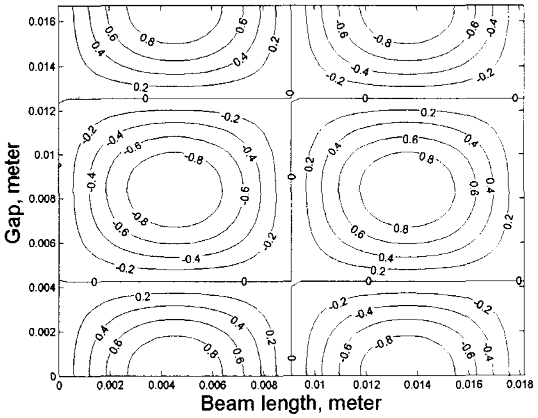

Fig. 6 Equi-pressure contour for a gap of full acoustic wavelength

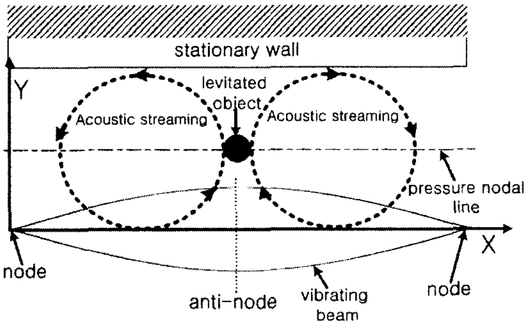

Fig. 7 Schematic drawing of acoustic streaming

interfering the levitation of the neighboring objects along the pressure nodal lines present in the beam length's direction while the longitudinal rod vibration induces only single object levitation. Repeating pressure patterns occurring at every half of the beam wave length contribute to the levitation of multiple objects.

Rotation of levitated objects is caused by acoustic streaming that is circular air-flow created by the frictional loss associated with the interaction between the high-intensity sound waves and the physical boundaries. Lo et. al(8) derived the limiting velocity that creates acoustic streaming in the gap as

$$U_{limit} = -\frac{3}{16}\frac{\omega\lambda}{\pi}\left(\frac{\xi_o}{h}\right)^2 \sin 2k_b x \tag{4}$$

U_{limit} is used as a slip velocity at the solid surface by assuming Stokes boundary layer thickness negligible.(11)

Theoretically, there exist two acoustic streaming patterns symmetrical with respect to the anti-nodes in every half-wavelength interval along the length of the beam as illustrated in Fig. 7.

Because acoustic streaming patterns are symmetrical, levitated objects should stand still above the anti-nodes. But induced acoustic streaming patterns are not perfectly symmetrical, owing to the non-uniform thickness of the beam and the gap. As a result the levitated objects spin.

4. Conclusions

Acoustic levitation of multiple objects using ultrasonic flexural vibration is experimentally and analytically investigated. From analytical analysis, it is found that when the gap coincides with the odd multiples of a quarter of the acoustic wavelength, the sound pressure in the gap is drastically increased due to resonance and the objects can be levitated at the pressure nodal lines in the gap. Experiments involving cylinder-shaped Styrofoam reveal that multiple objects can be stably levitated without disturbing the levitation of adjacent objects. Due to the straightly-propagating characteristic of the sound pressure wave induced by ultrasonic vibration, the sections of the beam spanning a node to adjacent node, which is quarter-wavelength long, act as individual vibration sources and create acoustic levitation above the velocity anti-nodes in each sections. Levitated objects are also set into rotation that is attributed to acoustic streaming. It is envisaged that acoustic levitation of multiple objects created by ultrasonic flexural vibration can be applied to non-contact manipulation of small-scale nonmetal objects and the formation of micro-spheres that can be produced by rotation induced by acoustic streaming without the interference from the contacting wall and gravity.

Acknowledgements

This research was financially supported by Hansung University in the year of 2004.

References

(1) Ueha, S., Hashimoto, Y. and Koike, K., 1998, "Ultrasonic actuators using near field acoustic levitation," IEEE Ultrasonics Symposium, pp. 661~666.

(2) Ueha, S., Hashimoto Y. and Koike K., 1995, "Near-field acoustic levitation using flexural vibration mode," Ultrasonic World Congress Proceddings, pp. 835~838.

(3) Ueha, S., Hashimoto Y. and Koike K., 1995, "Acoustic levitation of planar objects using a longitudinal vibration mode", J. Acoust. Soc. Jpn(E), Vol. 16, No. 3, pp. 139~192.

(4) Hashimoto, Y., Koike, Y. and Ueha, S., 1996, "Near-field acoustic levitation of planar specimens using flexural vibration," J. Acoust. Soc. Am. Vol. 100, No. 4, pp. 2057~2061.

(5) Matsui T., Ohdaira E. and Masuzawa N.,Ide M., 1995, "Translation of an Object Using Phase-Controlled Sound Sources in Acoustic Levitation," Jpn. J. Appl. Phys. Vol. 34, No. 5B part 1, pp. 2771~2773.

(6) Kozuka, T., Tuziuti, T., Mitome H. and Fukuda, T., 1994, "Acoustic Manipulation of Micro Objects Using an Ultrasonic Staanding Wave," 5th Int. Sympo. Micro Machine & Human Science Proc., pp. 83~87.

(7) Kozuka, T., Tuziuti, T., Mitome H. and Fukuda, T., 1995, "One dimensional Transportation of Particles Using an Ultrasonic Standing wave," 6th Int. Sympo. Micro Machine & Human Science Proc., pp. 179~185.

(8) Loh, B.G., Hyun, S., Ro, P. and Kleinstreuer, C., 2002, "Acoustic streaming induced by ultrasonic flexural vibrations and associated enhancement of convective heat transfer", J. Acoust. Soc. Am. , Vol. 111, No. 2, pp. 875-883.

(9) Graff, K. F., 1991, Wave Motion in Elastic Solids, Dover Publications Inc., New York.

(10) Lee, C. P. and Wang, T. G., 1999, "Outer acoustic streaming", J. of Acoust. Soc. Am., Vol. 88, No. 5, pp. 2367~2375.

(11) Lighthill, J., 1978, "acoustic streaming", J. of Sound and Vib. Vol. 61, No. 3, pp. 391~418.

(12) Nyborg, W. L., 1958, "acoustic streaming near a Boundary", J. of Acoust. Soc. Am., Vol. 30, No. 4, pp. 329~339.

(13) Andres, J. M. and Ingard, U., 1953, "acoustic streaming at High Reynolds Numbers", J. of Acoust. Soc. Am., Vol. 25, No. 5, pp. 928~937.

(14) Kinsler, L.E., Frey, A.R. , Coppens, A.B. and Sanders, J.V., 1982, Fundamentals of Acoustics, John Wiley &Sons, Inc., New York.