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Removal of Liquid in a Long Pore Opened at Both Ends Using High-Intensity Aerial Ultrasonic Waves

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ABSTRACT

We experimentally verified a method by which a liquid that has entered a long pore with open ends can be removed from the pore by using the acoustic radiation force produced by high-intensity aerial ultrasonic waves at a frequency of 20 kHz. The intensity of the ultrasonic waves was about 6 to 10 kPa. By using this method, it was confirmed that a liquid in pores of 1.5 to 5.0 mm diameter and 3 to 20 mm length could be instantaneously removed from the pores. This method, which did not use any air flow at a high pressure, has the significant advantage that it does not produce any strong air flow around the pore. We consider the intensity of the ultrasonic waves required to remove the liquid, the time required to remove the liquid, and the quantity of liquid removed, all of which were determined by varying the diameter and length of the pore.

1. INTRODUCTION

It has previously been shown that solid particles or liquid droplets adhering to the surface of an object instantaneously fall off and scatter aerially when high-intensity aerial ultrasonic waves (frequency: approximately 20kHz) is applied to them. Several technologies that employ this phenomenon have been developed. The same effects can also be expected when acoustic waves are applied to adhesions in narrow grooves or linear holes. Regarding this, we previously studied the incidence of acoustic waves into holes with a diameter smaller than the wavelength of the acoustic waves, and clarified that under such circumstance it was possible to achieve both good acoustic waves penetration and the formation of a high-intensity sound field inside the holes.

In this paper, we verify a method by which a liquid that has entered a long pore can be removed by using high-intensity aerial ultrasonic waves. Once a liquid enters a long pore, it is generally kept there by the retaining force produced by the capillary phenomenon. The conventional methods of applying acceleration to the pore itself, blowing a high-pressure gas into the pore, or absorbing the liquid out of the pore are currently used to remove the liquid from a pore. If the first method is used, complicated equipment is required. If the second or third method is used, a strong air flow is produced; thus, the method cannot be used if a delicate object is present in the air flow. To solve these problems, we considered a method using the acoustic radiation force of aerial ultrasonic waves. By using this method, a liquid that has entered a long pore with open ends can be forced out of the pore by irradiating high-intensity ultrasonic waves. Because a strong air flow is not produced, this method has a very small effect on the area around the pore. We performed an experiment in which a point-convergence-type source of aerial ultrasonic waves at the frequency of 20 kHz was used to emit ultrasonic waves onto the liquid in a long pore with open ends to remove it from the pore. Thus, we revealed that the liquid in the pore could be instantaneously removed from the pore by irradiating the opening of the pore with high-intensity ultrasonic waves. Here, we consider the intensity of the ultrasonic waves required to remove the liquid, the time required to remove the liquid, and the quantity of liquid removed, all of which were determined by varying the diameter and length of the pore.

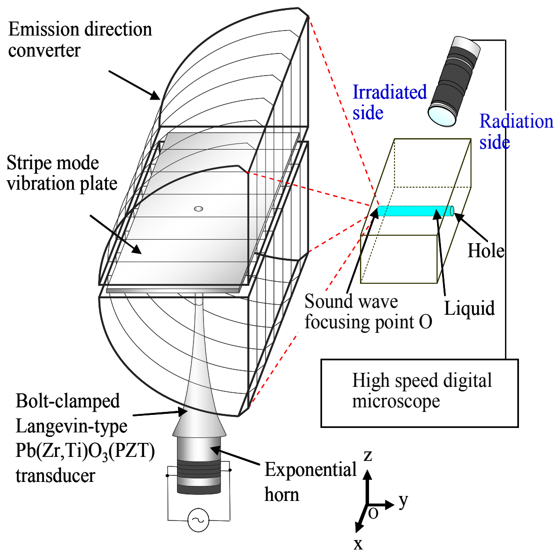

Figure 1. Schematic of experimental equipment

2. GENERATION OF INTENSIVE CONVERGENT ULTRASONIC WAVES

The equipment used for generating high-intensity convergent ultrasonic waves in air shown in Fig. 1. The sound source consists of a longitudinal vibration system, a vibration plate, and an emission direction converter. The longitudinal vibration system consists of a bolt-clamped Langevin-type

Pb(Zr,Ti)O_3 (PZT) transducer (55 mm in diameter, Nippon Tokushu Togyo D25540), an exponential horn (made of aluminum alloy: JISA2017-T4) with a vibration velocity transform ratio of 6, and a vibration transmission rod. Ultrasonic waves are aerially created by the transverse vibration plate (width: 168 mm, length: 326 mm, thickness: 5.0 mm, material: aluminum alloy plate). The vibration plate vibrates in the stripe mode, which results in vibratory nodes being parallel and at equal intervals.

The generation of high-intensity aerial ultrasonic waves is achieved by focusing the acoustic waves radiated from the vibration plate on a single point. As shown in Fig. 1, the acoustic waves radiated from the vibration plate were incident to the convergence point at an angle of approximately 43° to the y-axis. Their convergence point O is on the y-axis, which runs through the center of the vibration plate, 135 mm from its edge. Figure 2(a)-2(c) show the sound pressure distribution near the convergent area of the acoustic waves in a free field. The sound pressure was measured with a 1/8-inch-diameter condenser microphone (frequency range: 6.5 Hz-140 kHz). The solid lines indicate the results, normalized according to the maximum sound pressure values, when the power supplied to the sound source was 50 W, while the dotted lines represent the normalized results when the power supplied was 0.5 W. As shown, the focusing area of the ultrasonic waves from this sound source is approximately l cm in diameter. Moreover, it was found that even when the power supplied to the sound source (that is, the strength of the emitted acoustic waves) varied greatly, there was almost no variation in the convergence properties of the acoustic waves.

3. Experimental Methods

Figure 1 shows a schematic view of the equipment used in our experiments. The equipment comprised an ultrasonic source to produce high-intensity aerial ultrasonic waves as well as a sample consisting of a long pore filled with a liquid. As shown in the figure, the behavior of the liquid irradiated with the ultrasonic waves was observed in detail by using a digital microscope with a high-speed camera (Keyence VW-5000). The sample used for each experiment was a long cylindrical pore with open ends made of acrylic. Table I gives the size of the pore. As the liquid in the pore, we used pure water, in which a trace of a white water paint was mixed to observe the liquid more easily.

4. Production of Acoustic Radiation Force

To remove a liquid that has entered a long pore with open ends from the pore, this type of experiment generally uses the acoustic radiation force produced by irradiating the surface of the liquid at one end of the pore with ultrasonic waves, which acts on the surface of the liquid, as shown in Fig. 3. In our experiment, we used, instead of a liquid, the top face of an acrylic rod of 5 mm diameter vertically mounted on the pan of an electronic balance, as shown in Fig. 3, to measure the acoustic radiation force produced by the irradiation of ultrasonic waves.

Figure 4 shows the relationship between the sound pressure in the focused sound field and the electric power supplied to the sound source. The measurement results indicate the sound pressure on the irradiated side of the liquid in the pore. According to both sets of results, the sound pressure increased proportionally to the 0.5th power of the supplied electric input power.

Figure 5 shows the results of measurements, which indicate that the acoustic radiation force was proportional to the electric power supplied to the ultrasonic source. The solid line in the figure shows the calculated values of the acoustic radiation force produced on the end face of the acrylic rod. These values were calculated from the sound pressure values of the ultrasonic waves emitted by the ultrasonic source. Thus, the calculated values of acoustic radiation force had high consistency with the measured values.

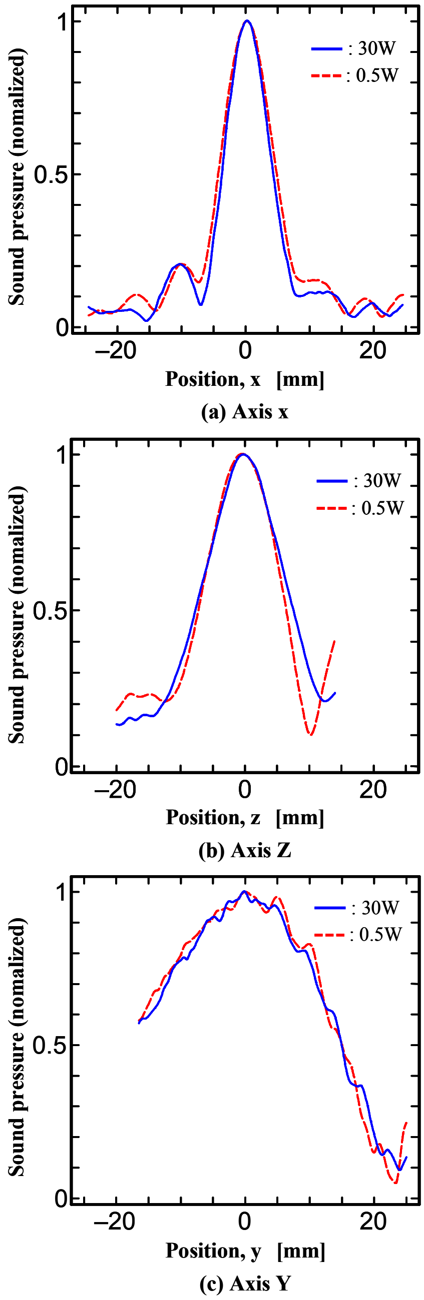

Figure 2. Distribution of sound pressure in the vicinity of the converging point of acoustic waves in the experimental system.

Table I. Details of samples used in experiments.

Diameter (mm)	Length (mm)
1.5~3.0	3
1.5~5.0	5
2	3~20
5	5~20

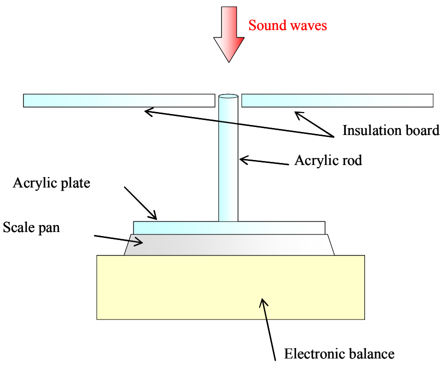

Figure 3. Schematic of device used for measurement of acoustic radiation force.

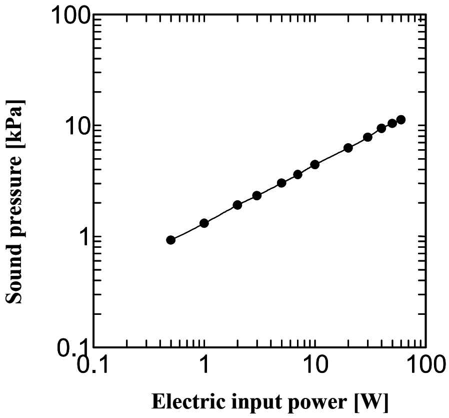

Figure 4. Relationship between sound pressure in the focused sound field and electric input power supplied to the sound source.

5. Behavior of Liquid in a Pore Irradiated with Ultrasonic Waves

As shown in Fig. 1, the behavior of a liquid in the pore when the liquid was irradiated with the ultrasonic waves by making an opening (on the irradiated side of the sample) coincident with the convergent point of the ultrasonic waves was observed by using a digital microscope with a high-speed camera. Figures 6 and 7 show the behavior of the liquid in a pore of 5 mm diameter and 5 mm length and in a pore of 5 mm diameter and 20 mm length, respectively. Figure 6 indicates that the water in the pore was forced out of the pore at the other opening (radiation side) about 10 ms after the sample started to be irradiated with the ultrasonic waves. It also indicates that almost all the liquid was forced out of the pore 30 ms after the irradiation of the ultrasonic waves and that the residual liquid in the pore was completely removed 40 ms after the irradiation of the sample started.

Figure 7 shows that the liquid in the pore started to jut out from the radiation end of the pore 5 ms after the sample started to be irradiated with the ultrasonic waves. It also indicates that the liquid in the pore was continuously forced out of the pore thereafter, and that almost all the liquid was removed from the pore about 65 ms after the irradiation of the sample started. At this point, it was found that a small amount of liquid remained on the inside wall of the pore. Figure 7(g) indicates that the residual liquid on the inside wall of the pore accumulated to form a striped pattern about 83 ms after the irradiation of the sample started. The space between the stripes was equivalent to half the wavelength of the ultrasonic waves. After almost all the liquid in the pore had been removed, a sound field of the standing ultrasonic waves was formed in the pore. The liquid accumulated at the positions corresponding to the sound pressure nodes. The liquid was soon moved by the acoustic radiation force to the radiation end of the pore and ejected from the pore, as shown in Fig. 7(h). When the same experiment was performed using a pore of 2 mm diameter, the liquid exhibited similar behavior.

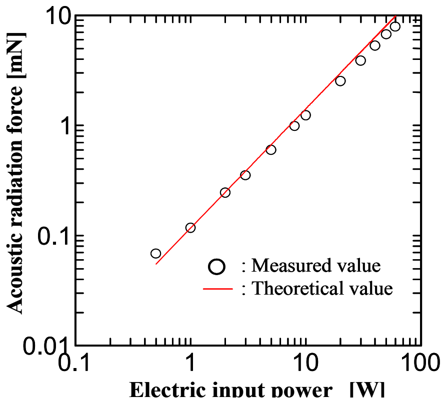

Figure 5. Relationship between acoustic radiation force and electric input power supplied to the sound source.

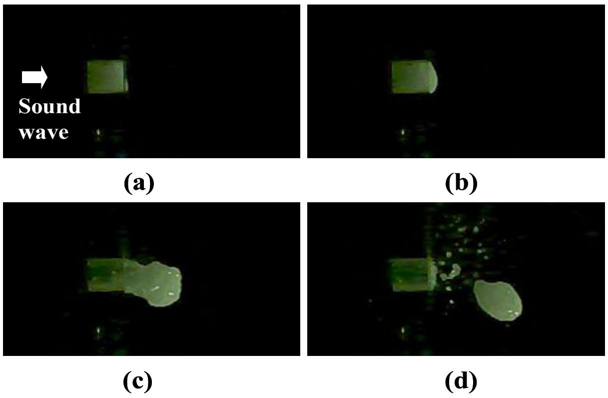

Figure 6. Behavior of liquid irradiated with high-intensity aerial ultrasonic waves in a pore of 5 mm diameter and 5 mm length: (a) 0, (b) 10, (c) 30, and (d) 40 ms.

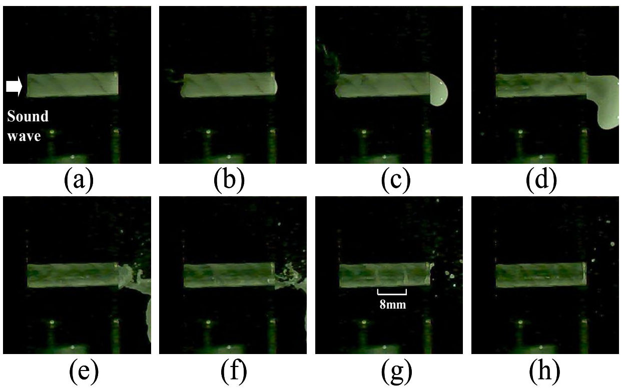

Figure 7. Behavior of liquid irradiated with ultrasonic waves in a pore of 5 mm diameter and 20 mm length: (a) 0, (b) 5, (c) 30, (d) 55, (e) 63, (f) 65, (g) 83, and (h) 150 ms.

6. Intensity of Acoustic Radiation Force Required to Remove Liquid

It is well known that once a liquid enters a pore it remains there under the capillary pressure produced by the capillary phenomenon. To remove the liquid from the pore, it is necessary to ensure that the acoustic radiation force acting on the liquid exceeds the liquid-retaining force produced by the capillary pressure acting on the liquid. In this experiment, the equipment shown in Fig. 1 and the samples given in Table I were used to measure the acoustic radiation force necessary to remove the liquid from the pore.

We irradiated pores of 1.5 to 5.0 mm diameter and 3 and 5 mm length with the ultrasonic waves and determined the acoustic radiation force required to remove the liquid from the pores. Figure 8 shows the results of the measurements. In this figure, the acoustic radiation force acting on the liquid was expressed as the acoustic radiation pressure. This conversion was made to clarify that higher-intensity ultrasonic waves (or higher acoustic radiation pressure) was required to remove the liquid from a pore having a smaller diameter. In the figure, the gradient of the curve indicates that the acoustic radiation pressure required to remove the liquid is proportional to the reciprocal of the diameter of the pore. The solid line shows the capillary pressure acting on the liquid in the pore. Here, the surface tension was 64 mN/m. Thus, the calculated acoustic radiation pressure had high consistency with the measured value. If the measured acoustic radiation pressures are expressed as the corresponding acoustic radiation forces, the profile curve has a gradient indicating that the capillary pressure acting on both ends of the pore is equivalent to the reciprocal of the diameter of the pore.

Figure 9 shows the measured acoustic radiation force required to remove the liquid from pores of 2 and 5 mm diameter and 3, 5, 8, 10, 13, 15, 18, and 20 mm length respectively. In the figure, the horizontal axis indicates the length of the pore. The figure reveals that the acoustic radiation force required to remove the liquid from in the pore remained almost constant when the length of the pore was varied.

7. Effect of Ultrasonic Waves on Removal of Liquid from a Pore

(a) Determination of the time required to remove the liquid

As shown in Fig. 1, the time required to remove the liquid from the pore was determined by using a microscope with a high-speed camera, with the ultrasonic waves applied to the opening (on the irradiated side) of the pore of 5 mm diameter and 5 to 20 mm length kept coincident with the convergent point of the ultrasonic waves.

Figure 10 shows the time required to remove the liquid from the pore when an acoustic radiation force of 2.5 to 6.7 mN

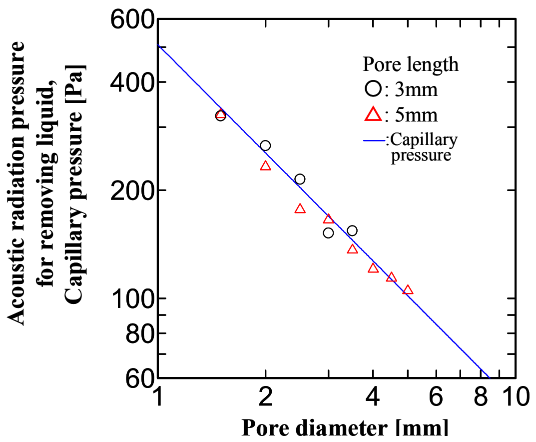

Figure 8. Relationship between acoustic radiation pressure required to remove liquid and diameter of pore.

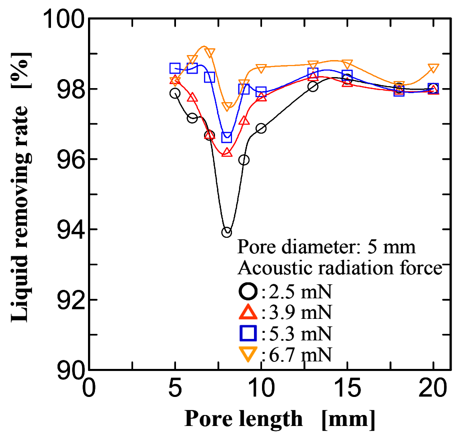

Figure 10. Relationship between time required to remove liquid and length of pore.

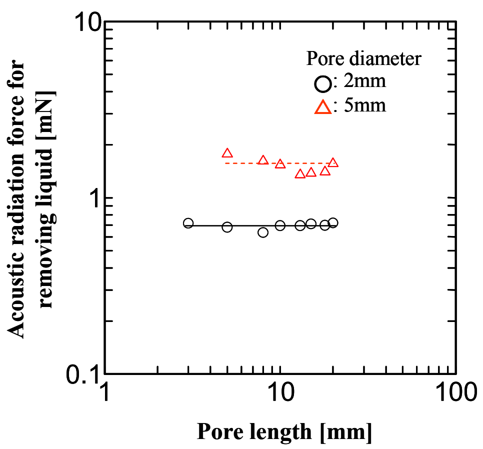

Figure. 9. Relationship between acoustic radiation force required to remove liquid and length of pore.

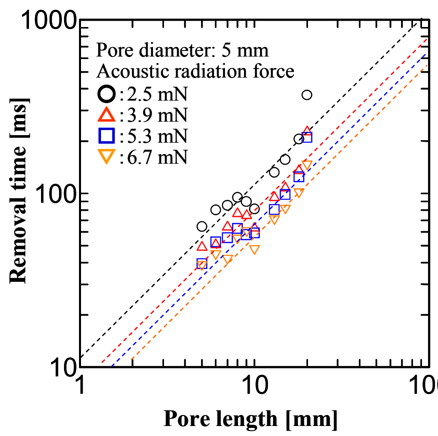

Figure 11. Relationship between liquid removal rate and length of pore.

acted on the irradiated side of the liquid face (corresponding to a sound pressure of 6.3 to 10.4 kPa). In the figure, the horizontal axis indicates the length of the pore, and the vertical axis indicates the time required to remove the liquid. The figure reveals that the time required to remove the liquid increased with the length of the pore, regardless of the intensity of the ultrasonic waves. The dotted lines shown in the figure are straight lines having a gradient of 1. Almost all the characteristic curves have a gradient of nearly 1.

(b) Liquid removal rate

We determined the liquid-removing effect of the ultrasonic waves for different lengths of the pore. The intensity of the acoustic radiation force acting on the face of the liquid in the pore was varied in the range of 2.5 to 6.7 mN (corresponding to a sound pressure of 6.3 to 10.4 kPa). The liquid removal rate was determined from the weight ratio between the liquid in the pore before and after the irradiation of the liquid with the ultrasonic waves. Figure 11 shows the relationship between the liquid removal rate and the length of the pore having a diameter of 5 mm. The figure indicates that the liquid removal rate was 98 to 99%, regardless of the length of the pore, when an acoustic radiation force of 6.7 mN (a sound pressure of 10.4 kPa) acted on the face of the liquid. It was also found that the liquid removal rate depended on the length of the pore when the intensity of the ultrasonic waves emitted onto the liquid was constant. The liquid removal rate was lowest when the length of the pore was 8 mm. The reason for this can be considered to be that the liquid removal rate was significantly influenced by a sound field of standing waves which was formed within the pore after a certain quantity of liquid has been removed from the pore. We also attempted to remove the liquid from a pore of 2 mm diameter. In this case, the liquid removal rate was about 92 to 96% at an acoustic radiation force of 6.7 mN (a sound pressure of 10.4 kPa).

8. Conclusions

We experimentally verified a method by which a liquid that has entered a long pore with open ends can be removed from the pore by using the acoustic radiation force produced when the liquid is irradiated with aerial ultrasonic waves at a frequency of 20 kHz. By using this method, it was revealed that the liquid in a long pore could be instantaneously removed from the pore by irradiating it with high-intensity ultrasonic waves (about 6 to 10 kPa). In the experiment, the behavior of the liquid irradiated with the ultrasonic waves was observed in detail by using a digital microscope with a high-speed camera to determine its characteristics. As a result, it was confirmed that the acoustic radiation pressure required to remove the liquid was higher when the diameter of the pore was smaller. The relationship between the diameter of the pore and the required acoustic radiation pressure was indicated by characteristic curves having a gradient of -1. It was also confirmed that there was no relationship between the length of the pore and the intensity of the ultrasonic waves required to remove the liquid. The time required to remove the liquid by irradiating it with the ultrasonic waves was almost proportional to the length of the pore, although different results were obtained for some pore lengths. We also determined the relationships between the removal rate of the liquid in the pore and the diameter and length of the pore.

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