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# INFLUENCE OF ACOUSTIC PRESSURE AND FLEXURAL VIBRATION ON FRICTION REDUCTION EFFECT BY ULTRASONIC

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## ABSTRACT

The influence of acoustic pressure and flexural vibration on friction reduction effect by ultrasonic has been investigated in this study. Then the relationship between friction reduction of particles by each effect and the particle density has been shown by using of ultrasonic. Additionally, the maximum of particle density which could receive the friction reduction effect by the acoustic pressure has been expressed.

In short, when the particle density was large, the influence of friction reduction effect by the acoustic pressure decreased and the influence of friction reduction effect by the flexural vibration grew. In this study, two plates were set parallel to each other. The dried particles were scattered on the lower plate, and the ultrasonic was applied. Then, the entire equipment setup was tilted slowly until the scattered particles began to move, and the friction coefficient was measured. Then, influence of acoustic pressure and flexural vibration were evaluated. In order to evaluate the reduction effect by acoustic pressure and flexural vibration, firstly, the distribution of acoustic pressure between reflection plate and the vibration plate have been measured. As a result, it was clarified that acoustic pressure distribution became the almost same whether ultrasonic was applied for the upper or lower plate, and the reflection plate vibrated little. Therefore it was possible to divide the influence of acoustic pressure and flexural vibration on the friction reduction.

## INTRODUCTION

In general, the frequency that can be listened by human ear is from 20 Hz to 20 kHz. The acoustic oscillation of 20 kHz or more is called ultrasonic waves. Recently, ultrasonic waves have been applied in various fields such as industry, electronics, chemical, and so on. For instance, in industry, the ultrasonic has been used for washing machine, metal-semiconductor junction, processing machine, and flaw detection machine. It can be said that the ultrasonic has been widely researched. The following have been mentioned in recent research: searches for sunken undersea objects [1], decontamination of hazardous chemicals [2], effects in cancer cells [3-5], piping inspection in food factories [6], etc.

The authors have researched the handling of particles in various industries by ultrasonic. One of them, ultrasonic was applied to plug transportation to reduce the transportation power and formulate a theoretical method that can predict this effect accurately. To begin with, it has been shown that the ultrasonic can reduce the frictional resistance between static particles and flat plate regardless of the kind of particles [7]. The particle properties that have an effect on friction reduction by ultrasonic, influence of the acoustic transmission coefficient and bulk density were shown. In contrast, the particle shape and particle diameter have little influence in the effect of the friction reduction. In past research, we applied ultrasonic to horizontal plug transportation lines, and experiments were performed by using four kinds of granular particles [8]. The results showed that ultrasonic can reduce the pressure drop regardless of the kind of particles and transportation condition. In this research, it was shown that the particle pressure that acted on the pipe wall influenced the effect of the friction reduction. From the above-mentioned result, the friction reduction effect between particles and wall surface by ultrasonic was confirmed for static and dynamic particles.

It can be assumed that one of the effects of the friction reduction is generation of acoustic pressure distribution in the air. By acoustic pressure difference, particles are forced and

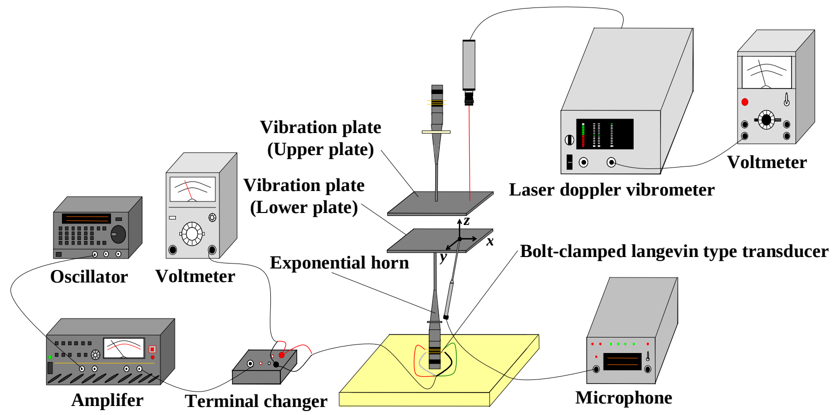


**FIGURE 1.** ULTRASONIC GENERATION APPARATUS

moved to the vertical direction. Another effect of friction reduction is generation of flexural vibration. In other words, particles spring up from the wall by vibration and the number of contact between particles and wall decrease. However, the degree of these factors on friction reduction has not been clarified until now. By clarifying this, the high-precision prediction of the power reduction in the plug transportation can be realized by ultrasonic. The purpose of this research is analyzing the influence of acoustic pressure and flexural vibration.

## EXPERIMENT APPARATUS

An oscillator, amplifier and bolt-clamped langevine type transducer are connected as shown in figure 1. A voltage of frequency $f$=20.5 kHz is generated by an oscillator because the resonance frequency of the piezoelectric device in a bolt-clamped langevine type transducer is 20.5 kHz. This voltage is amplified to 55 dB by the amplifier, and then input into the piezoelectric device, and ultrasonic vibration is generated. This vibration is amplified by the exponential horn. To connect the horn and vibration plate, and to transmit maximum vibration to the plate, a resonance rod is used.

The materials of vibration plate and resonance rod are duralumin. The vibration plate and resonance rod was designed to resonate at 20.5 kHz similar to piezoelectric ceramics. The plate width is 162 mm, the length is 226.8 mm, and the thickness is 9.0 mm. The vibration mode of the plate is shown in figure 2, when a 20.5 kHz frequency voltage was input. Copper powders were scattered on the vibration plate and a resonance frequency was input. In this figure, the point that particles were gathered shows the node, and the interval of node is 32.4mm. The center of two nodes shows the anti-node. Here, the vibration velocity $v_A$ at the anti-node of the vibration plate was measured by a laser doppler vibrometer, and the amplitude $A_m$ [$\mu$m] was obtained from equation (1).

$$A_m = \frac{v_A}{2\pi f} \tag{1}$$

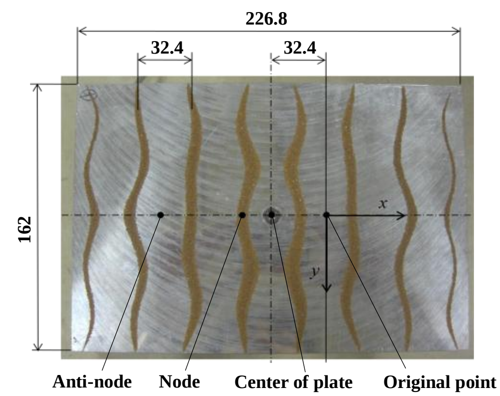


**FIGURE 2.** VIBRATION PLATE

In this study, two vibrating plates were set parallel to each other as shown in figure 1 to generate large acoustic pressure distribution between two plates. The interval of the vibration plate was decided in consideration of being able to observe the particle behavior, the attenuation of the acoustic pressure is small and the other plate does not vibrate by the acoustic pressure. Under this condition, the interval $l$ between the plates was set at 27mm and 29 mm because the behavior of particles on the vibration plate was strong at $l$=27 mm, and they crept at $l$ =29 mm. Then, I also examined the difference of the result by the difference of interval $l$.

## EXPERIMENTAL METHOD

### Preliminary Experiments

The experimental method should be able to evaluate the influence of acoustic pressure and flexural vibration on friction reduction separately. Therefore, in this study, we used two parallel plates, and each plate was vibrated, as described later. Two different preliminary experiments were carried out to confirm the validity of this experimental method.

**Acoustic Pressure Distribution.** In the experimental apparatus shown in figure 1, ultrasonic is applied to only one of plates. Then the acoustic pressure distribution is measured

**TABLE 1**. PARTICLE PROPERTIES

| Particle | Mean diameter $d_p$ [$\mu$m] | Density $\rho_s$ [g/cm$^3$] |
|---|---|---|
| Polystyrene | 80 | 1.11 |
| Aluminum | | 2.76 |
| Ceramic | | 3.85 |
| Titanium | | 4.48 |
| Stainless steel | | 7.65 |
| Iron | | 7.83 |

when only upper plate or lower plate is vibrated. If the acoustic pressure distribution is the same in the vibrating plate, it can be said that the effect by acoustic pressure can be evaluated.

First, voltage $V$=95.4 mVrms was generated by the oscillator, and the ultrasonic vibration that amplitude $A_m$=0.05 $\mu$m was given only to one plate. At this time, a 1/4 inch microphone with a probe tube having an inner diameter of 1 mm and length of 200 mm was set between the plates. Then it was moved from -20 to 20 mm in the $x$ direction, from -10 to 10 mm in the $y$ direction, and from 0 to 10 mm in the $z$ direction which is perpendicular to the surface of the plate. The ultrasonic was given to upper plate and lower plate individually, and $l$ was changed to either 27mm or 29 mm, and the acoustic pressure was measured. However, acoustic pressure loss in the probe tube occurred since this tube was so long. Then, to investigate the attenuation, the acoustic pressure under the same voltage $V$ was measured both with and without the probe tube. The next equation represents the relationship between the acoustic pressure with the probe tube and without the tube. $P_m$ is the acoustic pressure measured by probe tube.

$$P = 1.0974 P_m \qquad (2)$$

**Plate Vibration Amplitude.** The influence of acoustic pressure on friction reduction cannot be evaluated if the plate without the ultrasonic vibrates by the acoustic pressure change between two plates. Then, the existence of plate vibration was examined.

First, the voltage from 0 to 800 mVrms was generated only to the upper plate shown in figure 1. Then, the amplitude of both plates was measured by a laser doppler vibrometer when the plate interval was changed into 27mm and 29mm. The measurement point was the origin which is defined at 32.4mm in $x$ direction from the plate center and

### Effect of Acoustic Pressure and Flexural Vibration

The friction reduction effect by acoustic pressure and flexural vibration was examined. The particle properties are shown in table 1. To exclude the influence of the particle diameter, the particle diameter was equated. The particles stick with the plate because moisture is contained in the particle. Therefore, before the experiment, the moisture was removed to less than 1% by an aqua meter and drying oven to alleviate the adhesion effect.

To begin with, the dried particles were transferred by paper and scattered as a monolayer near the origin of the lower vibration plate. Then, under the following conditions from (1) to (3), the entire equipment setup was slowly tilted in the $y$ direction so that the vibration plate also had this angle. All experimental apparatus was tilted until the scattered particles began to move in the $y$ direction, which means the direction parallel to the vibration mode, and then the angle was measured by the digital angle meter. The angle was measured 5 times and the average of each condition was set as $\alpha$. Tangent $\alpha$ is equal to the friction coefficient $\mu$.

$$\mu = \tan\alpha \qquad (3)$$

As in the preliminary experiments, $l$ was set at 27 and 29 mm.

(1) Without acoustic pressure and flexural vibration

Without the ultrasonic applied to both boards, the device was tilted, and the friction coefficient $\mu$ was measured. This $\mu$ was set as $\mu_1$. In other words, $\mu_1$ shows the friction coefficient between the vibration plate and particles under the condition of no acoustic pressure and no flexural vibration.

(2) With acoustic pressure and flexural vibration

The ultrasonic was applied only to the lower plate, and the vibration that the amplitude $A_m$= 0.025, 0.05, 0.1, 0.2 $\mu$m were generated. The device was tilted until the particles began to move, and the angle was measured. This $\mu$ was set as $\mu_2$. In other words, $\mu_2$ shows the friction coefficient under the condition of generating acoustic pressure and flexural vibration.

(3) Only acoustic pressure

The same amplitude used in case (2) was generated, in which ultrasonic was given only to the upper plate, and the vibration was generated. The device was tilted until the particles began to move, and angle was measured. This $\mu$ was set as $\mu_3$. This $\mu_3$ is the friction coefficient under the condition of only generating acoustic pressure.

## EXPERIMENTAL RESULT

### Preliminary Experiments

**Acoustic Pressure Distribution.** The result of the acoustic pressure distribution of $l$=27mm and $l$=29mm at the position of $z$=0mm is shown in Figure 3. The top line shows the result when ultrasonic is applied only to the lower plate, the middle line shows the result of only the upper plate vibration, and the bottom line is the ratio of these values at the same location. In short, the pressure distribution is equal when the ratio is about 1.0, regardless of which plate received the ultrasonic. Figure 3 shows that the acoustic pressure mode is almost equal to the vibration mode regardless of the vibrating plate and the interval between the plates. Additionally, this figure shows that the pressure difference in the $x$ and $y$ direction near the origin is very small. Therefore, the force by the acoustic pressure difference near the origin in the $x$ and $y$ direction is very small, and it is assumed that only the pressure distribution in the $z$ direction affects the particle behavior near the origin. In addition, the ratio ranges from 0.91 to 1.03 in the anti-node near the origin, although there is a difference near the

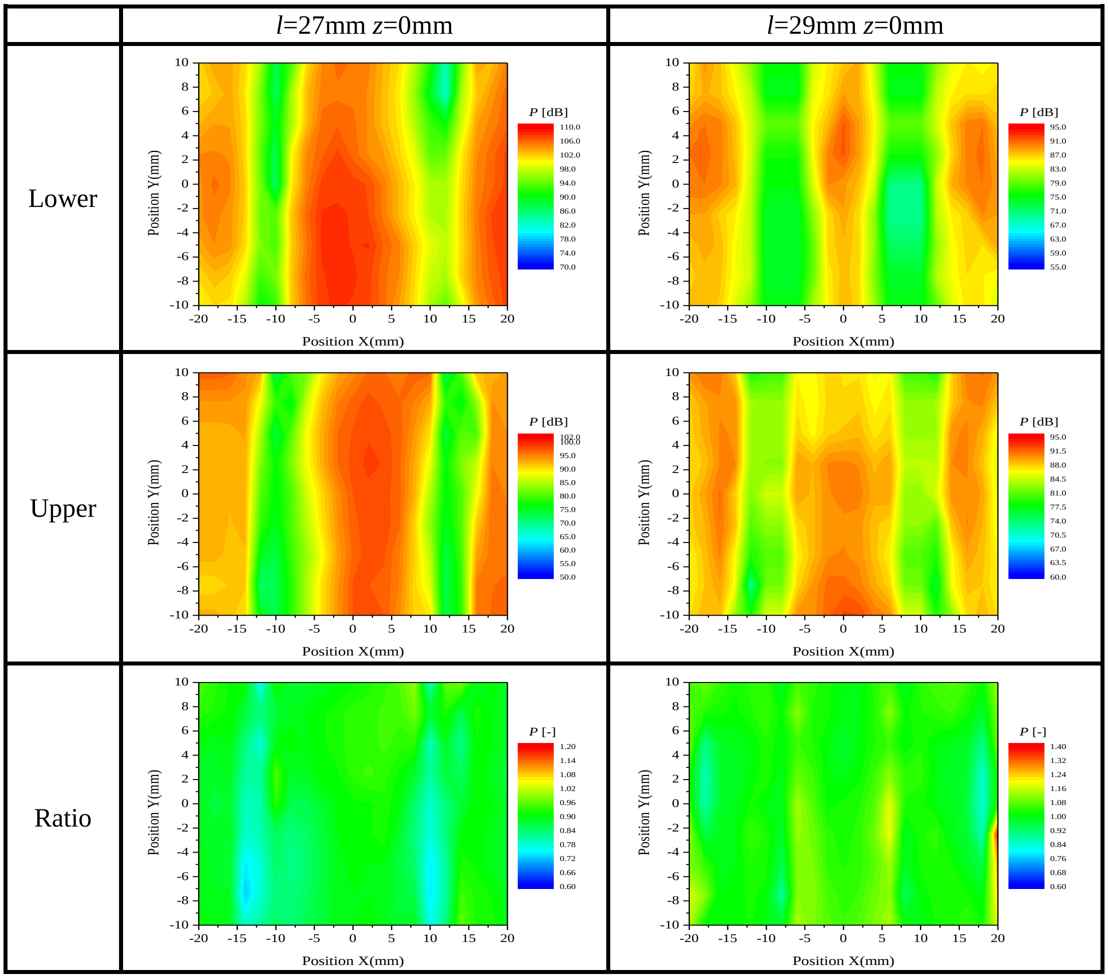


**FIGURE 3.** ACOUSTIC PRESSURE DISTRIBUTION ON VIBRATION PLATE

node of the vibration plate. This means the pressure distribution becomes almost the same. Thus, it is proven that there is only a little difference of acoustic pressure even when the ultrasonic is given to which plate.

Next, the acoustic pressure distribution in the $z$ direction at the origin is shown in figure 4. This figure shows that the difference of the acoustic pressure distribution is small, even when the ultrasonic is given to which plate. The acoustic pressure in the vertical direction at $l$=27, 29 mm can be treated as the same. From the above result, it can be said that there is only a little difference on the acoustic pressure distributions even when the ultrasonic is given to which plate This result shows that the acoustic pressure difference between $z$=0 and $z$ =1 mm of $l$=27 mm are larger than that of $l$ =29 mm. It is able to regard the difference of copper powders behavior as this pressure difference. Thus, it can be said that particles struggle hardly because the pressure difference at $l$=27 mm is larger than that at $l$=29 mm and the force which works on particles in the $z$ direction increases.

**Plate Vibration Amplitude.** The amplitude of the upper plate and lower plate are shown in figure 5, when $V$ is

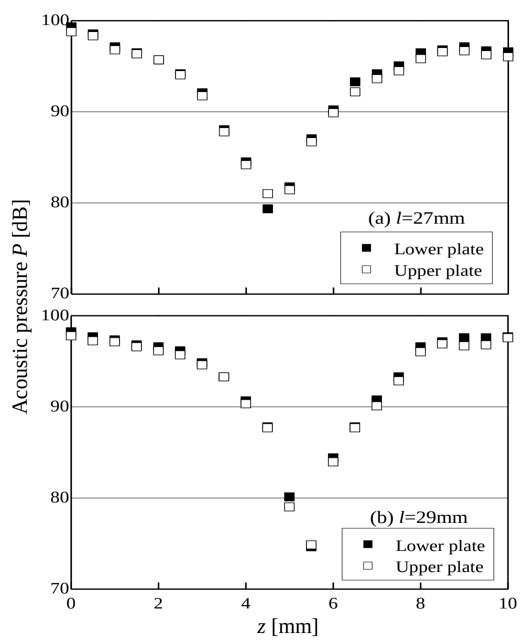


**FIGURE 4.** ACOUSTIC PRESSURE DISTRIBUTION AT A $Z$ DIMENTION

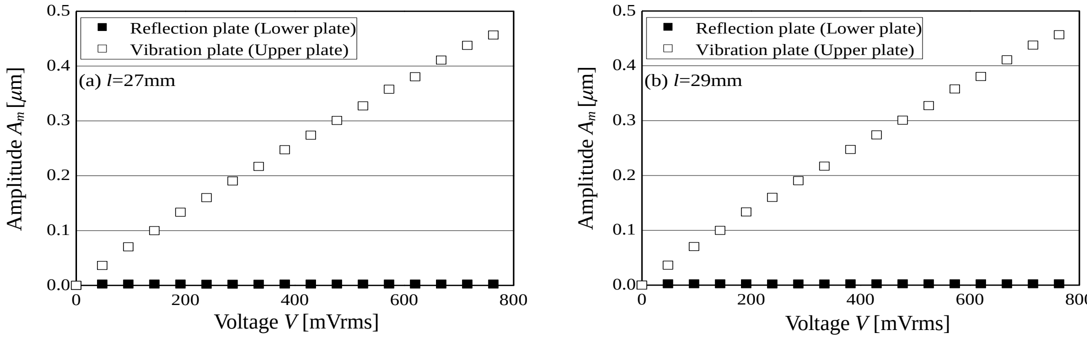


**FIGURE 5.** VIBRATION OF REFLECTION PLATE BY ACOUSTIC PRESSURE

changed by the oscillator and ultrasonic is applied only to the upper plate. Figure 5 shows that $A_m$ of the upper plate increases in proportion to the increase of $V$. However, the amplitude of the lower plate which has not given the ultrasonic is very small compared with the amplitude of upper plates. Therefore, acoustic pressure vibration only slight affects the vibration of the plate to which ultrasonic is not applied.

According to the above results, the influence of acoustic pressure and flexural vibration on friction reduction can be evaluated separately because the acoustic pressure between the plates becomes the same whether ultrasonic is applied to either plate and the plate vibration is only slightly affected by the acoustic pressure variation.

## Effect of Acoustic Pressure and Flexural Vibration

Figure 6 shows the result of iron and ceramic powders at $l$=27mm and 29 mm. The amplitude of vibration plate is the horizontal axis, and friction coefficient ratio $\mu_2/\mu_1$ or $\mu_3/\mu_1$ is the vertical axis. The friction coefficient ratio at $A_m$=0 is $\mu_1$. Figure 6 shows that the friction coefficient ratio decreases as $A_m$ is increased. Moreover, similar friction reduction effect was observed in other kinds of particles. This is due to the increase of acoustic pressure and flexural vibration with increasing $A_m$, and the force of floating particles became large. As shown figure 6, it turned out that friction coefficient ratio decreases greatly when the effect of flexural vibration is also taken into consideration. It is thought that particles were moved to the vertical direction and the numbers of contact with plate become fewer.

Next, the relationship between friction coefficient ratios $\mu_2/\mu_1$ and $\mu_3/\mu_1$, and particle density $\rho_s$ at $A_m$=0.025, 0.05, 0.1, 0.2 $\mu$m for $l$=27 mm, 29 mm is shown in figures 7 and 8. It turned out that a friction coefficient ratio becomes large as the particles density becomes large. So, if these ratios are equal to 1.0, friction is not reduced by each factor.

From figures 7 and 8, the decreasing rate of friction by acoustic pressure and flexural vibration can be seen. The gap between $\mu_3/\mu_1$ and 1.0 shows the decreasing rate of friction by the acoustic pressure, and the difference between $\mu_3/\mu_1$ and $\mu_2/\mu_1$ primarily shows the friction reduction by flexural vibration. In addition, these figures show the friction coefficient

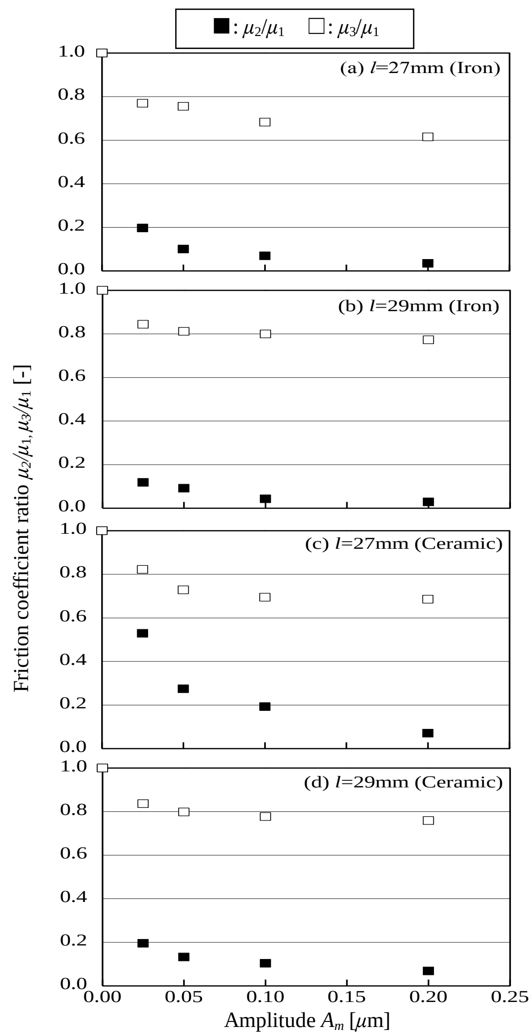


**FIGURE 6.** RELATION OF INPUT AMPLITUDE AND FRICTION COEFFICIENT RATIO

ratio approaches gradually to 1.0 as $\rho_s$ increases. This means the influence of each factor on friction reduction decreases with the increase of the particle density. The following are some possible. By the acoustic pressure distribution in the $z$ direction,

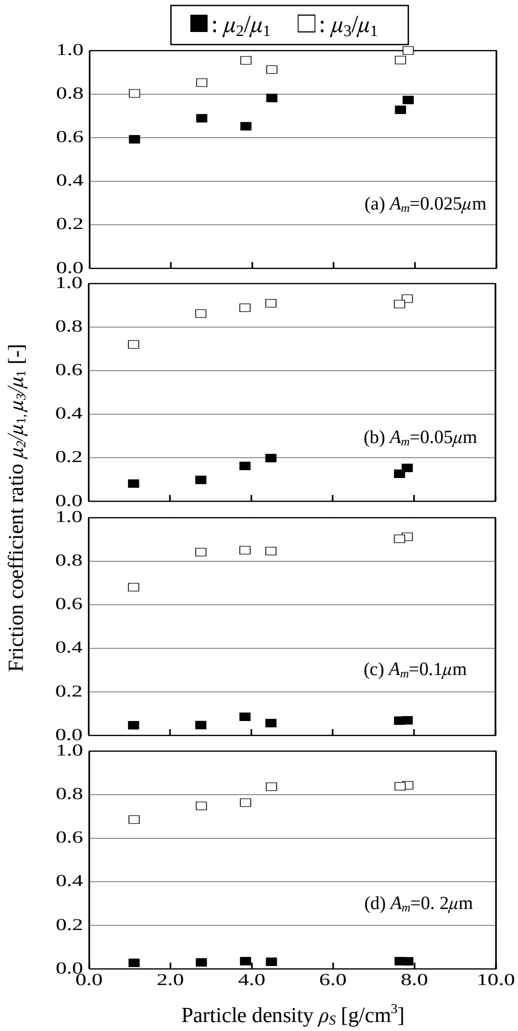


**FIGURE 7.** RELATION OF PARTICLE DENSITY AND FRICTION COEFFICIENT RATIO ($l$=27mm)

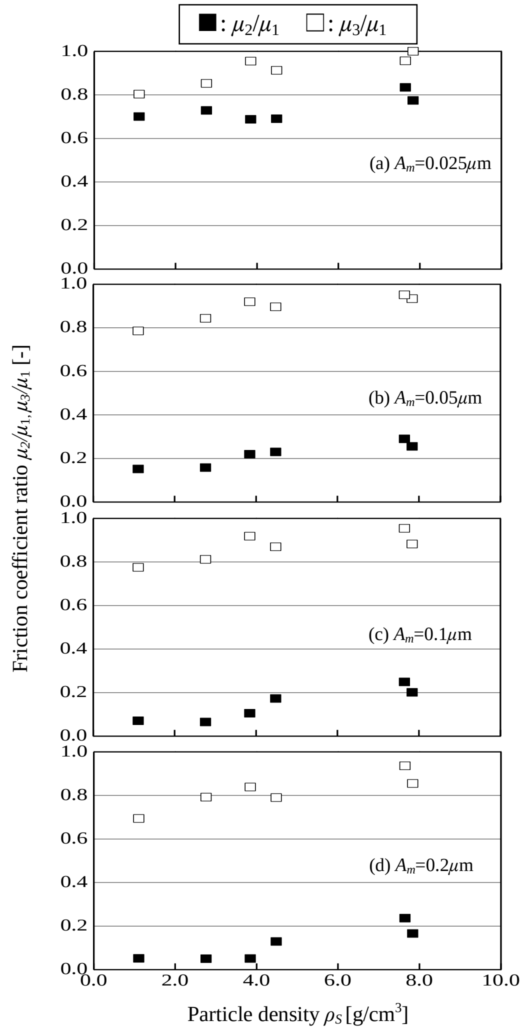


**FIGURE 8.** RELATION OF PARTICLE DENSITY AND FRICTION COEFFICIENT RATIO ($l$=29mm)

as shown in figure 4, the force in the vertical direction works on the particles. The hydrostatics indicates that the force by which a particle floats is affected by the particle density, and the force and density are in a proportional relationship [9]. That is, a large force is required as the density is large, and the necessary force decreases as the density is small. Therefore, particles float more easily as $\rho_s$ becomes smaller, and the friction coefficient ratio seems to also decrease.

The effect of acoustic pressures and flexural vibration is showed in Figure 7 and 8. As a reason why friction reduction effect by acoustic pressures is small, particle size is small and it is supposed that the influence by acoustic pressure difference was small. Moreover, it is mentioned that the area of particles which receives acoustic pressures is also small. On the other hand, since particle diameter and mass are much small, it is thought that a friction coefficient ratio decreases sharply by flexural vibration.

It can be said that the friction reduction effect by acoustic pressure cannot be expected if the particle density is more than a certain value. The limit value of the particle density that obtains the friction reduction effect by the acoustic pressure is shown $\rho_{s0}$. In our study, $\rho_{s0}$ becomes 7.14 g/cm$^3$ at $A_m$=0.025 $\mu$m, 9.68 g/cm$^3$ at $A_m$=0.05 $\mu$m, 13.54 g/cm$^3$ at $A_m$=0.1 $\mu$m and 9.51 g/cm$^3$ at $A_m$=0.2 $\mu$m in the case of $l$=27 mm. This shows $\rho_{s0}$ increases with the increase of $A_m$. Additionally, $\rho_{s0}$ at $l$=27 mm is much larger than it is at $l$=29 mm. The reason for this may be as follows: the acoustic pressure difference between $z$=0 and $z$=1 mm at $l$=27 mm is larger than it is at $l$=29 mm, and the forces that work on the particle in the $z$ direction become large.

Then, the validity of this consideration is confirmed. The relationship between the gap of the acoustic pressure at $z$=0 and $z$=1 mm in each condition and $\rho_{s0}$ is shown in figure 9. Figure 9 clearly shows that $\rho_{s0}$ increases with the increase of $\Delta P$.

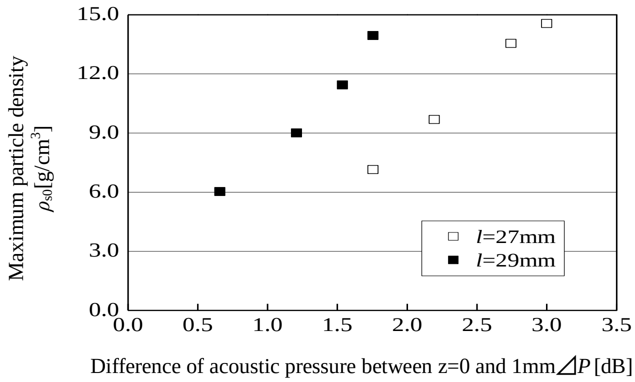


**FIGURE 9.** RELATION OF ACOUSTIC PRESSURE DIFFERENCE AND MAXIMUM PARTICLE DENSITY

Therefore, it can be said that the force of the particles also increases as $A_m$ increases, and the maximum particle density that can realize the friction reduction effect by acoustic pressure becomes larger.

## CONCLUSION

In this experiment, the primary purpose was to analyze the influence of acoustic pressure on friction reduction. As the result, the following conclusions were obtained.

(1) The friction reduction effect by acoustic pressure and flexural vibration can be expressed quantitatively. The particle of 80 $\mu$m in diameter is greatly influenced by flexural vibration compared with acoustic pressure.

(2) The limit value of the particle density that obtains the friction reduction effect by the acoustic pressure is shown, and this maximum density becomes larger as the pressure difference near the wall becomes larger.

(3) The experimental method using two plates can be applied to investigate the influences of acoustic pressure and flexural vibration separately, because the acoustic pressure distribution is almost the same regardless of which plate receives the ultrasonic, and the vibration of the plate is small, as determined by the pressure fluctuation.

(4) The acoustic pressure mode in the space between the two plates is similar to the vibration mode of the plate.

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