Remote Friction Reduction on Resonant Film Surface by Airborne Ultrasound

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***Abstract*—We propose a film device that can be attached to flat surfaces, including touch panels, to remotely reduce surface friction by irradiating airborne ultrasound. In this article, we present a film-air resonance structure that produces large-amplitude surface vibrations excited by airborne ultrasound. We confirmed via simulation that the surface amplitude increases to a level sufficient to reduce friction at the designed frequency. It was also observed in an experiment using a prototype that the friction between a finger and film surface is sharply reduced, and the surface vibrates with sufficient amplitude when touched with a finger.**

***Index Terms*—Surface haptics, friction, airborne ultrasound, midair haptics.**

I. Introduction

In the last decade, surface haptics [1], [2] has greatly advanced and various tactile feelings are provided on rigid plates, including touch panels. Conventional surface haptics have focused on the mechanism of friction change using ultrasonic vibration sources [1], [3], [4] or electrostatic forces [5], [6] implemented on the surface.

Conversely, Ohmori *et al.* demonstrated a friction-reducing tactile display not incorporating a mechanism for tactile presentation on the display side [7]. This study changed the surface friction of a display made of polystyrene foam by remotely oscillating the surface with converged ultrasound from airborne ultrasound phased arrays [8]–[10] (AUPAs, see Fig. 1.) deployed in the environment. This technique enables a disposable surface of a tactile display, opening up new application possibilities for surface haptics. However, this phenomenon was only found in a special material, namely polystyrene foam [7].

In this study, we propose a passive film device whose surface friction is controlled by irradiating airborne ultrasound. To expand the application target of remote friction change shown by [7], we designed a simple thin device with a film-air resonance structure that produces a large-amplitude vibration excited by airborne ultrasound. This device can be transparent and thus installed on rigid surfaces, including touch panels and various kinds of designed plates. As the structure is simple and manufactured at a low cost, it is disposable. Herein, we present the device structure and show that it can reduce surface friction when touched with a finger.

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II. Proposed Method

The squeeze film effect is considered to be the main mechanism that causes tactile sensation to change when a surface is ultrasonically vibrated. It is a phenomenon in which a compressible air film is formed between the vibrating surface and the finger, reducing the friction between the finger and the surface. Many factors, such as the frequency and amplitude of ultrasonic vibration, skin elasticity, and fingertip speed are involved in friction reduction; however, it has been confirmed via simulations and *in-vivo* experiments that the amplitude of surface vibration is the dominant parameter [11]–[13]. As the amplitude increases, the coefficient of friction between the finger and the surface decreases monotonically. For example, for 40 kHz ultrasonic waves, an amplitude of at least 1.5 μm is required [14] to perceive the reduction in friction.

Generally, because the acoustic impedance of a solid surface is much larger than that of air, the displacement of the ultrasound-irradiated surface is smaller than 1.5 μm. In a previous study [7], ultrasonic vibration with sufficient amplitude was observed exceptionally in polystyrene foam, whereas other materials, including a sheet of paper and cardboard, could not cause a significant friction-change.

We propose a film-air resonance structure shown in Fig. 2 as a structure that reduces the surface acoustic impedance at the resonance frequency. This structure comprises a rigid plate, an air layer, and a thin film in order from the bottom. Both film and air are separated by partitions, and the air trapped in each cylindrical chamber acts as a spring determined by its volume modulus when the film is deformed by an external force. Thus, when a force is applied from the outside by ultrasonic waves, it is expected to form a spring mass system as a whole.

In general, the displacement of the film is spatially distributed, while lateral propagation occurs. In this section, however, the displacement is simply modeled by a single parameter of the displacement normal to the film. Therefore,

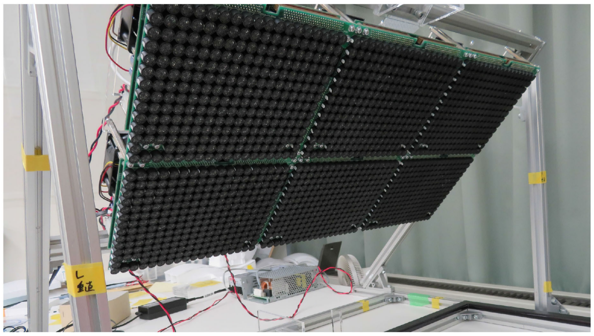

Fig. 1. Airborne ultrasound phased arrays (six units).

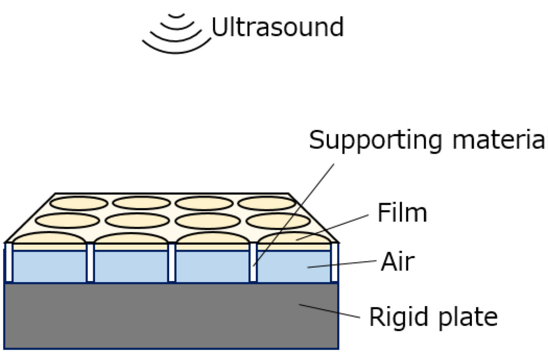

Fig. 2. Film-air resonance structure.

the one-dimensional vibration equation is expressed as follows:

$$\rho S l \ddot{x} = -K \frac{x}{h} S \tag{1}$$

$$\ddot{x} = -\frac{K}{\rho h l} x \tag{2}$$

where ρ, l, h, and K represent the density of the film, thickness of the film, thickness of air, and volume modulus of air, respectively. S represents the minute area of the film and x represents the displacement of the film normal to its surface.

Using $K = \rho_0 c^2$, where ρ_0 is the density of air and c is the sound speed of air, the resonance frequency is obtained as follows.

$$f = \frac{c}{2\pi} \sqrt{\frac{\rho_0}{\rho h l}} \tag{3}$$

Here, when using a polyimide film with a thickness of 5 μm and an air layer with a thickness of 300 μm (see Table I for physical property values), according to (3), the resonance frequency is estimated to be 41.4 kHz, which is close to the AUPA's driving frequency (40 kHz). As shown in Fig. 3, using the AUPAs deployed on the environment side and forming an ultrasonic focus at the fingertip position, which can be detected by a depth sensor, the film under the finger is excited to reduce the surface friction. It should be noted that the finger may obscure the ultrasonic focus to some extent, which will be discussed later.

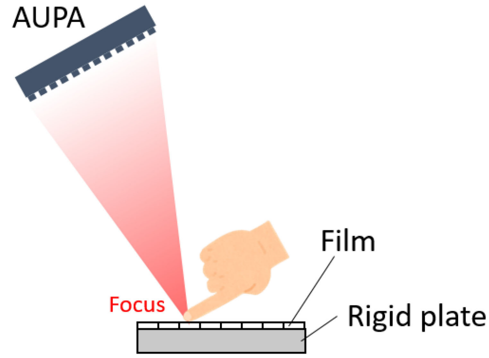

Fig. 3. Proposed system.

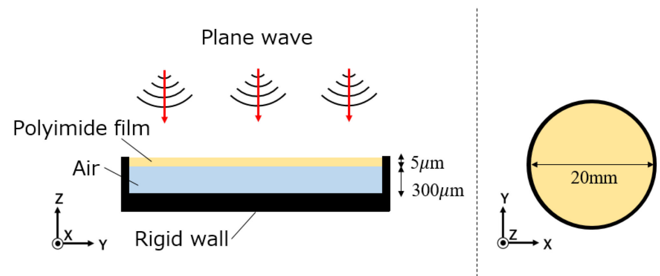

Fig. 4. Analysis model of simulation. The front view (left) and the top view (right) are shown.

III. Simulation

To confirm the characteristics and effectiveness of our proposed system described in Section II, a simulation was performed using the finite element method. In this section, the elastic force of the film depending on its deformation and the horizontal vibration of the air layer were ignored and modeled as one-dimensional vibrations. However, in the simulation, these factors were considered and analyzed as three-dimensional vibrations.

The ultrasonic friction reduction was not directly considered in this simulation. Because it is known that the friction when the surface is touched with a finger monotonically decreases as the amplitude of the surface vibration increases [11]–[14], we focused on the amplitude of the film surface without a finger. Note that the calculated amplitude will be affected by the existence of a finger on the structure, but these conditions were not modeled in the following simulation.

A. Simulation Condition

The finite element method analysis software ANSYS 2019 R1 was used. The analysis model is shown in Fig. 4. The bottom of the structure was regarded as a rigid wall, and an air layer with a thickness of 300 μm was placed on it. Subsequently, a polyimide film with a thickness of 5 μm was placed on it without applying initial tension. A circular structure with a diameter of 20 mm was analyzed, and a position-fixing constraint was imposed on the circumference of the film.

For use in a realistic environment, it is assumed that AUPAs are used to create an ultrasonic focal point at the fingertip

TABLE I
PHYSICAL PROPERTIES USED IN THE SIMULATION

properties	polyimide	air
density [kg/m^3]	1450	1.225
sound speed [m/s]	2500	346
Young's modulus [GPa]	5.0	—
Poisson's ratio	0.30	—
viscosity [kg/(m·s)]	—	1.8×10^{-5}

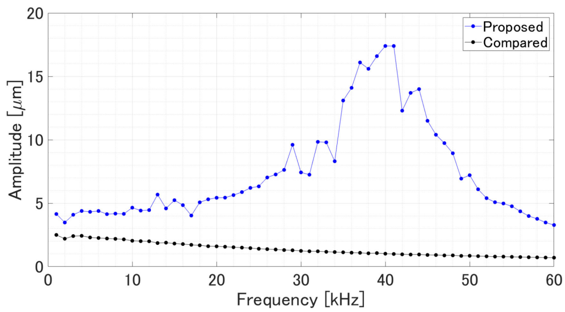

Fig. 5. Averaged surface amplitude of the film in the proposed model and the compared model without air layer.

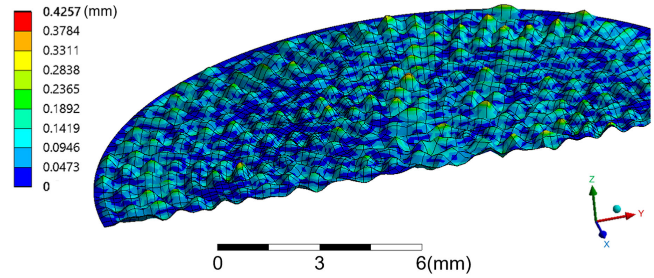

Fig. 6. Amplitude distribution of film in the proposed condition (40 kHz).

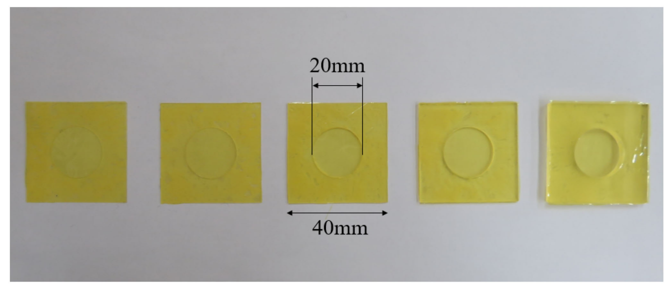

Fig. 7. Manufactured prototypes (0.2 mm, 0.3 mm, 0.5 mm, 1 mm, and 3 mm thickness are shown from left to right).

position. In this simulation, however, we applied a plane wave perpendicular to the film to analyze the behavior of the film near the focal point for simplification. The incident angle was not taken into account since we aimed to investigate the general response of the proposed structure to ultrasound. It has been reported that the sound pressure amplitude when forming a focal point 60–80 cm apart from four AUPAs with each oscillator's output adjusted to be lower than its maximum is approximately 2 kPa [8], [15]; the sound pressure amplitude of a plane wave was set to 2 kPa. It should be noted that the sound pressure amplitude is assumed smaller than that in the experiment described later. The ultrasonic driving frequency was varied in the range of 1–60 kHz in 1 kHz increments, and the frequency characteristics of the amplitude of the film surface were obtained.

The physical property values used in the simulation are listed in Table I. For polyimide, the data sheet of Kapton® 20EN manufactured by DU PONT-TORAY Co., Ltd. was used. For the sound speed not described in the data sheet, 2500 $\mathrm{m/s}$, which is the general value of plastic, was used. The mesh was automatically generated by the ANSYS software by combining tetrahedrons and hexahedrons with side lengths of 0.3 mm or less. The acoustic space was assumed to be open. The steady state results were calculated.

To confirm the effectiveness of this structure, we compared the results with those of a model in which the film vibrates in the open air with its circumference fixed. In the compared condition, the frequency characteristics of the surface amplitude were analyzed in the same manner as the proposed condition.

B. Result

Fig. 5 shows the calculated amplitude of the film surface normal displacement excited by ultrasound. Each value indicates the averaged amplitude over the entire film surface. In the proposed condition, an evident peak of vibration amplitude near 40 kHz was observed, although there were some irregularities. Conversely, in the compared condition without air layer, the value was small in all frequency bands compared to the proposed condition, confirming the effectiveness of our proposed method that used the air layer as a spring.

In addition, Fig. 6 shows the distribution of the surface displacement amplitude in the proposed condition when excited at 40 kHz. It can be observed that the film surface is waved and vibrates greatly as a whole. It is confirmed that there are propagation modes along the film surface, which generate a standing wave with an anti-node interval of approximately 1 mm. The lateral distribution, along with the elasticity and viscosity, which was not modeled in the theoretical design, absorbs the acoustic power and causes the low-Q frequency characteristics shown in Fig. 5.

IV. EXPERIMENT

Since we confirmed that the film surface without a finger vibrates with an amplitude of more than 15 μm at 40 kHz through the simulation, we made a prototype of the device and measured the surface amplitude and actual friction characteristics.

The manufactured prototypes are shown in Fig. 7. We used a polyimide film with a thickness of 5 μm (DU PONT-TORAY Co., Ltd., Kapton® 20EN), which has high durability and heat resistance. An acrylic plate with a thickness equal to that of the air layer was used as the supporting material. A circle with a diameter of 20 mm was hollowed out in the center of the acrylic plate, and a polyimide film was adhered on it with an epoxy adhesive. As a result, a circle with a diameter of 20 mm on the polyimide film can be used as a film with an

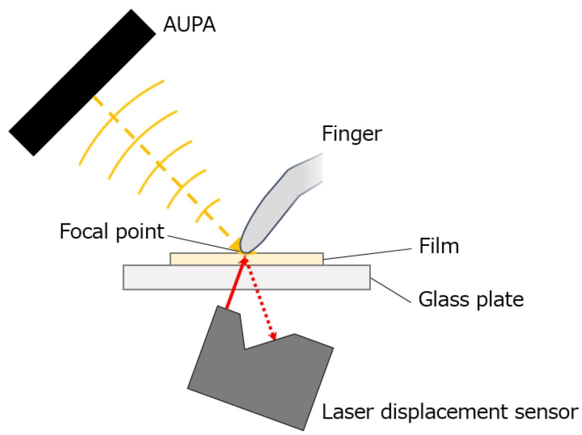

Fig. 8. Measurement of surface amplitude.

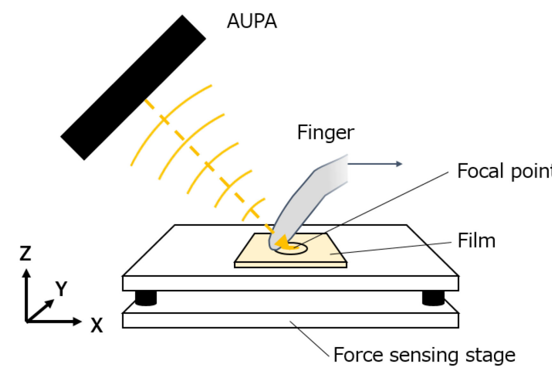

Fig. 9. Measurement of friction characteristics.

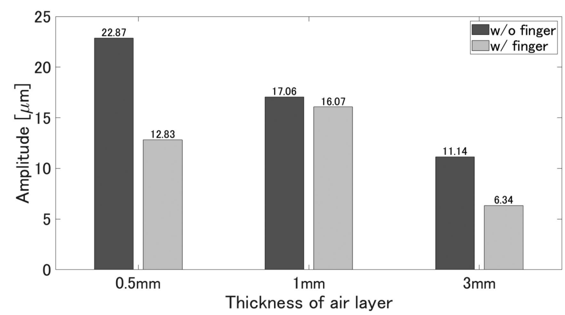

Fig. 10. 40 kHz component of surface amplitude in with-finger and without-finger conditions.

air layer behind it. Regarding the thickness of the air layer, five prototypes of 0.2 mm, 0.3 mm, 0.5 mm, 1 mm, and 3 mm were prepared in consideration of the influence of finger pressure, which was not considered in the simulation. Each surface was irradiated with convergent ultrasonic waves using AUPAs. In this study, six AUPAs were combined (aperture 570 mm $\times$ 300 mm, 1494 oscillators in total) and oriented at an angle of 45° with respect to the horizontal plane, as shown in Fig. 1. According to [15], the focal point is estimated to be 1 cm in diameter in this setup. In the experiment, each oscillator was driven at the maximum amplitude, and the presented force within an area of 1 cm^2 at the focal point was measured to be 27 mN.

A. Measurement

First, the surface displacement at the center of the film was measured using a laser displacement sensor (KEYENCE Co., Ltd., LK-H023). A schematic diagram of the settings for the displacement measurement is shown in Fig. 8. The prototype was fixed on a glass plate, and the laser beam was incident from the bottom in an oblique direction. The target area for measurement was manually adjusted such that displacements of objects other than the film, such as that of the glass surface, were not measured. The focal point of the ultrasound was generated at the center of the film, and measurement was performed under two conditions: one without a finger and the other with a finger. In the condition with the finger, one of the authors placed their right index finger on the central part of the film with a measured pressing force of approximately 0.3 N. Because the laser beam was applied to the center of the contact region from the opposite side of the finger, the amplitude just below the finger could be measured. The wavelength of the laser was 690 nm, the spot diameter was 25 μm, and the measurement was performed at a sampling rate of 392 kHz.

Next, the frictional force acting between the finger and the film surface was measured. We used a force sensing stage (Tactile Force Plate, Tech Gihan Co., Ltd., TF-2020) capable of measuring the vertical and horizontal components of the force acting between the finger and the film. As shown in Fig. 9, the prototype was fixed on the force sensing stage made of acrylic, and one of the authors traced the 20 mm diameter across the film from left to right with their right index finger. The vertical and horizontal components of the force were measured at a sampling rate of 10 kHz. The movement speed of the finger was approximately 4 $\mathrm{cm/s}$, and the angle between the finger and the film surface was maintained at 45°. The focal point of the ultrasound was generated at the center of the film. We also measured the force under the no ultrasound condition to investigate the effects of ultrasonic waves.

B. Result

The surface displacement results are shown in Fig. 10. For each film with different thicknesses, 40 kHz component of amplitude in surface displacement was calculated in two conditions: with and without a finger. Films with an air layer thickness of 0.2 mm and 0.3 mm were excluded from the measurement because the distance between the film and the acrylic plate was too small to measure correctly. The amplitude of the 40 kHz component was calculated as the maximum amplitude in the frequency band of 39.9–40.1 kHz, which was obtained by fast Fourier transformation of the observed signal.

At all thicknesses, the 40 kHz vibration corresponding to ultrasonic waves from AUPAs was observed, and the amplitude in the with-finger condition was smaller than that in the without-finger condition. However, note that the existence of the finger does not significantly attenuate the surface amplitude because the observed value is comparable in both conditions. It can also be seen that the surface vibrates with the largest amplitude at 0.5 mm thickness under the without-finger

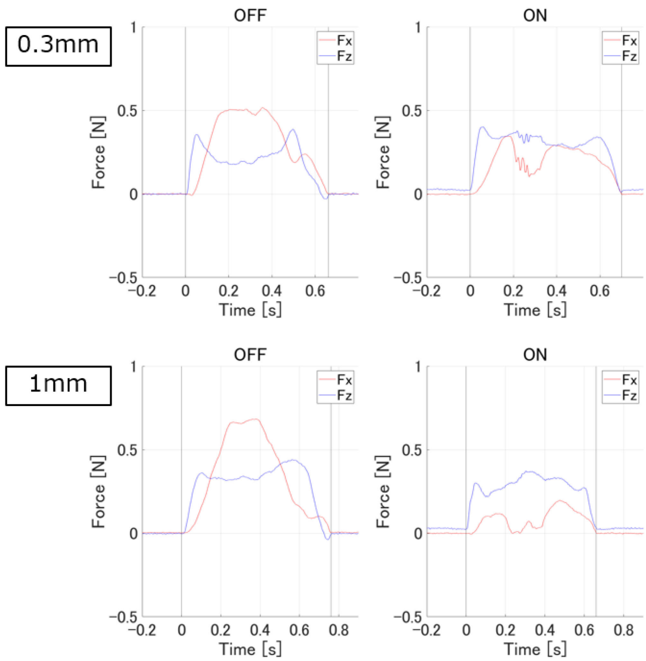

Fig. 11. Time variation of the vertical and horizontal force acting between the finger and the film (0.3 mm and 1 mm thicknesses). The two vertical lines represent the start and end of contact, respectively.

condition, whereas it vibrates at 1 mm thickness under the with-finger condition.

The friction characteristics are also shown. For each film, the vertical force F_z and the horizontal force F_x when touched with a finger was measured, and the averaged friction coefficient $\bar{\mu} = \bar{F}_x/\bar{F}_z$ was calculated, where $\bar{\cdot}$ is the averaged value of $\cdot$ from the start of contact to the end of contact. To remove noise owing to measurement, a moving average filter of 100 points was applied to the measured values.

Fig. 11 shows the representative temporal changes of F_z and F_x of one trial when the thickness of the air layer was 0.3 mm and 1 mm. F_x is obviously reduced under the ultrasound-ON condition in both thicknesses. However, it can be seen that the decrease in F_x is sharper with the 1 mm thickness than with the 0.3 mm thickness, which is the theoretical optimum value.

With the 1 mm thickness, comparing the two conditions, F_z in both conditions seems similar, but F_x is completely different from each other. Under the ultrasound-OFF condition, F_x is above the value of F_z near the center of the film, whereas under the ultrasound-ON condition, F_x is always well below the value of F_z. It can be observed that F_x is particularly small in the center of the film.

The same measurement was performed with different thicknesses of the air layer, and the average friction coefficient $\bar{\mu}$ was calculated. Fig. 12 shows the mean and standard deviation of friction coefficient in five stroking trials. We found that the friction was greatly reduced under the ultrasound-ON condition with thicknesses of 0.5 mm and 1 mm. This was a result that matched the subjective feeling when touching the film. The friction reduction was most noticeably perceived at 1 mm, followed by 0.5 mm and 3 mm, in this order. Conversely, it was perceived slightly for 0.2 mm and 0.3 mm.

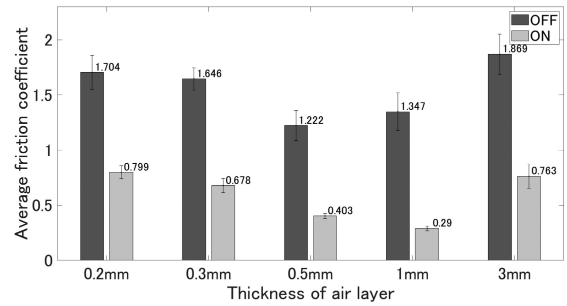

Fig. 12. Average coefficient of friction.

V. Discussion

In the simulation, the surface amplitude was maximized in the frequency band centered at 40 kHz. The average displacement amplitude at 40 kHz was more than 15 μm, which is sufficiently large compared to the reported threshold for ultrasonic friction reduction in a previous study [14]. However, note that the displacement is under the condition without a finger. In the design of the resonance frequency, only the motion in the direction normal to the film surface was considered, and the spatial vibration distribution was ignored. The effect of spatial distribution can be seen in the standing waves formed on the film surface. This is considered to be formed by the lateral propagation of the compression of the air and the tension of the film. Although there are many points on the film that appear to vibrate very little as a result of the standing wave, in practical applications, the contact area of the finger pad is larger than the interval of such nodes; thus, sufficient friction reduction can be perceived.

In the experiment using the manufactured prototype, we confirmed that the film surface vibrated by ultrasonic waves emitted from AUPAs under both conditions. It is notable that the amplitude did not decay significantly in the presence of the finger. In other words, the occlusion of ultrasound and the pressure imposed on the film by the finger had a small influence. This is probably because the ultrasonic waves irradiated at an oblique angle entered the gap between the finger and the film and oscillated the surface. In addition, it is also possible that the vibration of a part of the film not shielded by the finger propagated in the lateral direction. Additional study is required to elucidate the precise mechanism.

It is reasonable that the measured amplitude was the largest with a thickness of 0.5 mm under the without-finger condition because the thickness is close to 0.3 mm, which minimizes the acoustic impedance according to the design of the film-air resonance structure. The amplitude at 0.5 mm was larger than that in the simulation at 0.3 mm, which is considered to be due to the underestimation of the set sound pressure in the simulation. Conversely, under the with-finger condition, the amplitude at 1 mm was the largest, followed by 0.5 mm by a slight difference. This is consistent with the result of the measured friction coefficient because a larger amplitude leads to smaller friction according to previous studies [11]–[14]. In the case of the 1 mm-thickness, the measured amplitude was a considerably large value compared to the amplitude of the polystyrene foam surface in [7] (approximately 5 μm), confirming that sufficient friction reduction occurred on the film surface.

Regarding the friction properties, a significant reduction in friction was observed at thicknesses of 1 mm and 0.5 mm, indicating the possibility of practical application. Conversely, the friction was not significantly reduced at 0.3 mm, which is the optimum thickness in the theoretical design and numerical simulation. This might be because of the effect of finger pressure. In more detail, a thin air layer caused the finger to come into contact with the acrylic plate when touching the film, and evident friction reduction did not occur. From the same perspective, it is considered that the most remarkable friction reduction occurred at 1 mm because the center of the film was dented when pressed with the finger. Since the finger pressure was not assumed in the simulation, it is reasonable that the air layer should have a thickness of more than 0.3 mm if the concavity of the film is considered. The optimal shape and thickness considering the existence of a finger will be determined in our future work.

The results of subjective perception generally matched those of the measured friction coefficient, although perception was only evaluated by one person. However, although the decreases in the friction coefficient at thicknesses of 0.2 mm and 0.3 mm are almost the same as that at 3 mm, as shown in Fig. 12, friction reduction was not perceived much compared to the case of 3 mm. This can be attributed to contact between the finger and plate, as mentioned above. Therefore, it is possible that parameters other than the friction coefficient, such as the deformation of the finger, can also influence the perception of friction. Perceptual characteristics need to be elucidated through psychophysical experiments.

In terms of the application of the proposed method to touch panels, it is necessary to array the resonance structure to cover the entire screen. The array inevitably creates a boundary between the supporting part and the film on the air layer. One problem caused by the boundary is that it is visible and impairs the transparency of the device. The problem will be solved by making the sidewall of the supporting part flat and vertical to minimize the width of the boundary. Another problem is that the supporting part creates a dead zone where friction reduction cannot be perceived. Design to minimize the dead zone maintaining stable vibration will be future work.

VI. Conclusion

In this study, we proposed a film-type device that remotely reduces surface friction owing to the squeeze film effect using airborne ultrasound emitted from AUPAs. We designed a film-air resonance structure that can be excited by remote ultrasound emitters and confirmed through simulation that the surface amplitude increased at the driving frequency of AUPAs, 40 kHz. In addition, we measured the surface amplitude and friction characteristics using prototypes made with polyimide film. The amplitude of the film surface was sufficiently large for the squeeze film effect to occur even in the presence of the finger. We also confirmed that the surface friction noticeably decreased, indicating that the intended effect actually occurred on the film surface.

We conclude that the proposed system is applicable to friction control and has the potential to provide tactile sensation to various rigid plates, including touch panels that do not have an actuator for tactile feedback.

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