Non-Vibratory Pressure Sensation Produced by Ultrasound Focus Moving Laterally and Repetitively With Fine Spatial Step Width

Tao Morisaki, Masahiro Fujiwara, *Member, IEEE*, Yasutoshi Makino, and Hiroyuki Shinoda, *Member, IEEE*

***Abstract*—Focused airborne ultrasound provides various noncontact spatiotemporal pressure patterns on the skin. However, the presentation of static force remains an untouched issue because the static radiation force by ultrasound is too weak for the human hand to perceive. Hence, creatable sensations have been limited to vibrations or some dynamically changing feelings. This study demonstrates that a non-vibratory pressure sensation is presented by low-frequency Lateral Modulation (LM) with a fine spatial step width. LM is a pressure modulation method that moves a single ultrasound focus laterally and repetitively along the skin surface. The produced sensation in this study was not perfectly static, but the vibratory perception contained in the stimulus was significantly suppressed under a condition while maintaining its intense perception. We found the condition was 5 to 15 Hz in the LM frequency with a motion step width of less than 1 mm. In a comparison test in the most vibration-suppressed case, the participants reported 0.21 N as an equivalent force to the LM stimulus, significantly higher than the 0.027 N force physically applied by the ultrasound. The statistical analysis also showed that the step width of the LM had a significant effect on its vibratory sensation but not on the intensity of the evoked pressure sensation.**

***Index Terms*—Static pressure sensation, mid-air haptics, focused ultrasound.**

I. Introduction

Weakness of the displayed maximum force has been a significant limitation of ultrasound mid-air haptics. An airborne ultrasound tactile display (AUTD) [1] originating from previous studies [2]–[4] can transmit haptic sensation in a noncontact manner and potentially cover the applications of general haptics technology such as computer games [5], symbolic information transmission [6], and remote communication between humans [7]. AUTDs have a high spatiotemporal controllability of pressure distribution compared to other mid-air haptics using an air flow [8], [9]. Utilizing the controllability, a mid-air touchscreen [10], interaction systems with stereoscopic images with a touch sensation [7], and noncontact motion guidance using tactile sensation [11] have been demonstrated.

However, the static pressure sensation was excluded from the displayable sensations in these applications. This is because the perception threshold of physically static pressure is often higher than the ultrasound radiation pressure that can be provided [3], [12]. Therefore, temporal modulation is necessary to intensify the perception, which limits the displayed sensations to vibrotactile sensations. An exception is the static haptic image presented by Inoue *et al.* [13] in which a static ultrasonic field was created. However, the participants must always move their hands themselves to generate vibrations and feel the tactile sensation of the distribution.

To intensify the perception, two vibrotactile presentation methods–Lateral Modulation (LM) [14], [15] and Spatiotemporal Modulation (STM) [16]–have been proposed. In LM and STM, a single ultrasound stimulus point moves along the skin surface. Takahashi *et al.* proved that the tactile perception of LM stimulus is more intense than that of Amplitude Modulation (AM) stimulus, where the ultrasound amplitude changes at a fixed point on the skin [14], [15]. Although the applied force with LM and STM is temporally constant, the perception displayed is dynamic and vibratory. The limitation of the sensation displayed is a major disadvantage of ultrasound mid-air haptics because the static pressure sensation by slowly adaptive type-I (SA-I) receptors has the highest spatial resolution [17] and is indispensable in human tactile sensations in daily life.

In this study, we experimentally found the condition of an ultrasound low-frequency LM stimulus wherein the stimulus was clearly perceived, and the vibratory sensation was significantly suppressed. As a condition, a focus, i.e., a single point ultrasound stimulus, was laterally and periodically moved by several millimeters at a frequency of 5-15 Hz with a fine step width of less than 1 mm. As the authors' subjective comment, the stimulus was felt as a type of static pressure, where the stimulation was not perfectly static and was slightly moving; however, it was clearly different from "vibration." In the experiments, we changed the step width of the focus movement of the LM stimulus from 3 to 0.2 mm and evaluated their vibratory sensation. In

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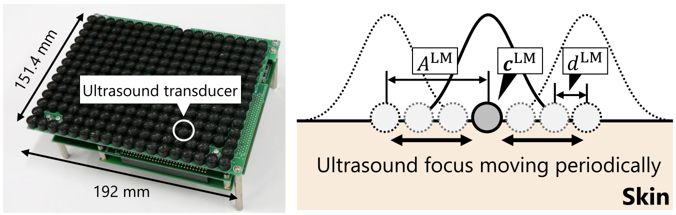


Fig. 1. Left: Airborne ultrasound tactile display used in this paper. Right: Schematic illustration of ultrasound Lateral Modulation (LM) stimulus.

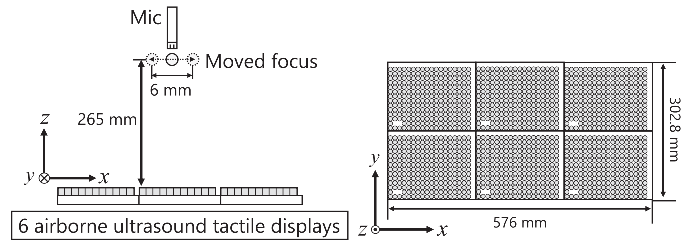


Fig. 2. Setup for measuring change in sound pressure of LM stimulus.

addition, to evaluate their perceived intensity, we quantitatively compared the perceived force with physical contact to a force gauge and evaluated the perception threshold. Frier *et al.* examined the relationship between the step width and perceived intensity in STM [18], where they drew a circle tactile pattern with a circumference of 100, 150, 200 mm by moving a single focus. They also investigated the effect of circle drawing frequency on the perceptual intensity. However, no study has examined the relationship between the step width of the focus movement and the vibratory sensation.

Some studies on contact-type haptic displays have presented static pressure sensation without using real static pressure. Makino *et al.* reported that suction pressure provides a static pressure sensation [19]. Kajimoto *et al.* reported that cathodic electrical stimulation provides a pressure sensation and low-frequency vibratory sensations [20]. Konyo *et al.* reported that vibrations below 5 Hz produce a pressure perception [21]. For ultrasound, the perception threshold of an AM stimulus at 5 Hz is comparable to or sometimes less than the maximum output from the device [22].

II. Principle

A. Airborne Ultrasound Tactile Display (AUTD)

An AUTD, a tool for mid-air haptics, is a device that comprises an array of airborne ultrasound transducers whose amplitude and phase can be individually controlled [3], [4]. By controlling each phase, an AUTD can focus ultrasound at arbitrary positions, and the localized sound pressure distribution is then generated at these positions. The localized pressure causes acoustic radiation pressure. It is a nonnegative pressure and proportional to the acoustic energy density [23]. Therefore, the radiation pressure varies according to the envelope of the presented sound wave. The diameter (pressure distribution) of the ultrasound focus generated by AUTDs can theoretically be narrowed to the wavelength of the ultrasound [3].

In this study, we used six AUTD units allowing the participants to clearly perceive all stimuli and evaluate them. We also aimed to realize the change in perception within a wide dynamic range of radiation force to evaluate the perception threshold and confirm the tactile feeling for a strong ultrasound stimulation. The AUTDs we used were equipped with 249 ultrasound transducers operating at 40 kHz (TA4010A1, NIPPON CERAMIC CO., LTD.) [24], [25]. Fig. 1-left shows the single AUTD unit. Because the frequency is 40 kHz, the diameter of the focus created by the AUTD is theoretically 8.5 mm. The AUTDs were connected to a Windows PC (Panasonic Let's Note CF-SZ6) via EtherCat, and were synchronously controlled.

B. Lateral Modulation (LM) Stimulus of Ultrasound

LM stimulus was originally proposed to present a vibrotactile stimulus using an AUTD with a lower perceptual threshold [14], [15]. Fig. 1-right shows a schematic of the LM used in this study. In LM, the position of the ultrasound focus is periodically and laterally moved by several millimeters.

Herein, we formulate the LM stimulus used in this study. The LM center $\boldsymbol{c}^{\mathrm{LM}} \in \mathbb{R}^3$ is the center position of the focal trajectory in the LM. The LM amplitude A^{LM} is half of the movement width of the ultrasound focus. The LM step width d^{LM} is the spatial step width of the focus movement. The LM direction $\boldsymbol{u}^{\mathrm{LM}} \in \mathbb{R}^3 (\|\boldsymbol{u}^{\mathrm{LM}}\| = 1)$ is the direction vector of the focus movement. $\phi^{\mathrm{LM}}(t) \in [-1, 1]$ is the periodic function that changes the focus position, and its frequency is the LM frequency f^{LM}. t denotes the elapsed time. From these definitions, the focus position $\boldsymbol{p}^{\mathrm{LM}}(t) \in \mathbb{R}^3$ in the LM is written as follows:

$$\boldsymbol{p}^{\mathrm{LM}}(t) = \boldsymbol{c}^{\mathrm{LM}} + \boldsymbol{u}^{\mathrm{LM}} A^{\mathrm{LM}} \phi^{\mathrm{LM}}(t), \tag{1}$$

We discretized the elapsed time and used it to drive an actual AUTD. The discretized elapsed time is defined as $t_i \in \{t_1 = 0, \ldots t_N < \frac{1}{f^{\mathrm{LM}}}\}$. $i \in \{1, \ldots N = \frac{4A^{\mathrm{LM}}}{d^{\mathrm{LM}}}\}$ corresponds to the number of focus positions $\boldsymbol{p}^{\mathrm{LM}}$ per cycle of the LM, where $4A^{\mathrm{LM}}$ is the total moving distance in one cycle. Because d^{LM} is constant, t_i satisfies the following conditions:

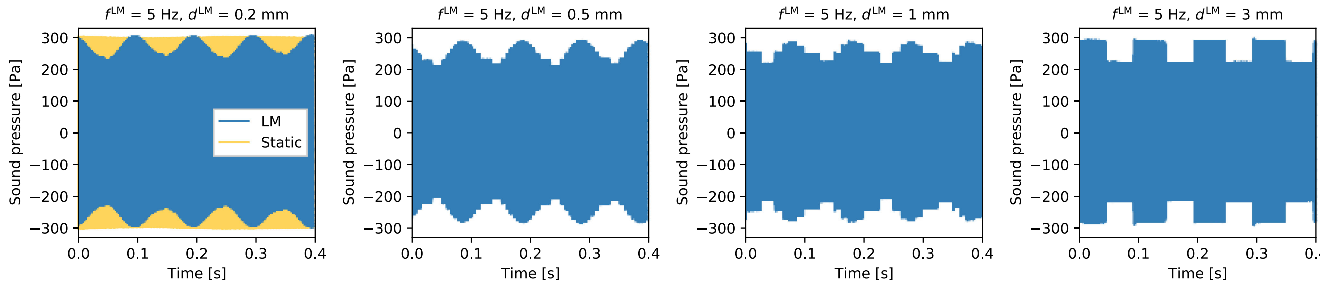
$$d^{\mathrm{LM}} = \|\boldsymbol{p}^{\mathrm{LM}}(t_i) - \boldsymbol{p}^{\mathrm{LM}}(t_{i-1})\|. \tag{2}$$

III. Physical Measurement of LM Stimulus

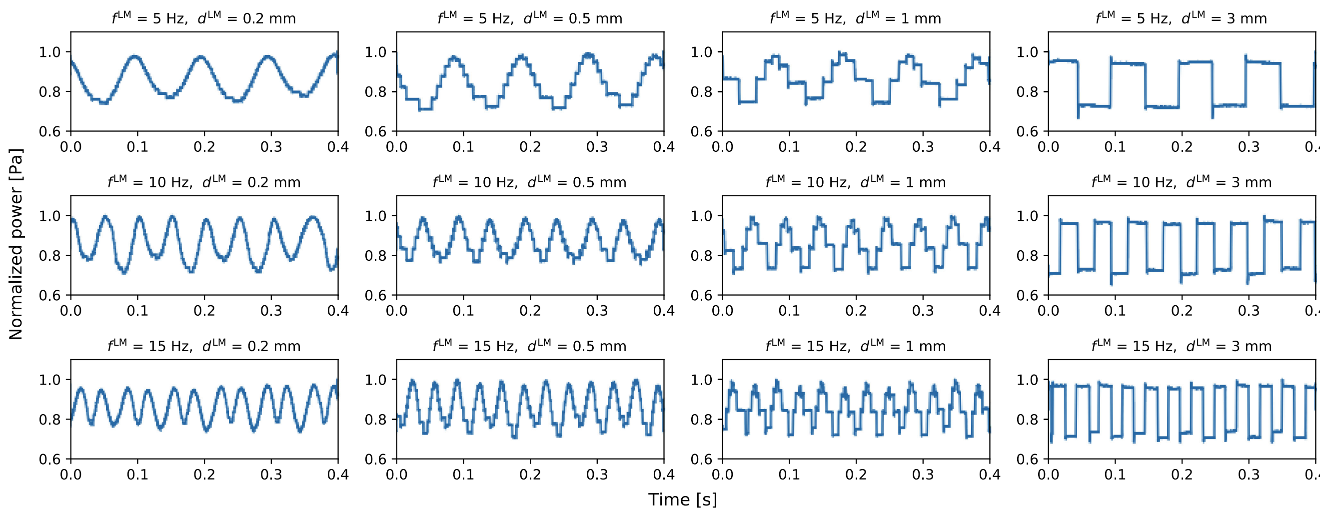
A. Change in Sound Pressure at $\boldsymbol{c}^{\mathrm{LM}}$

We measured the sound pressure of the LM stimulus at $\boldsymbol{c}^{\mathrm{LM}}$ to confirm whether the AUTDs presented an intended stimulus.

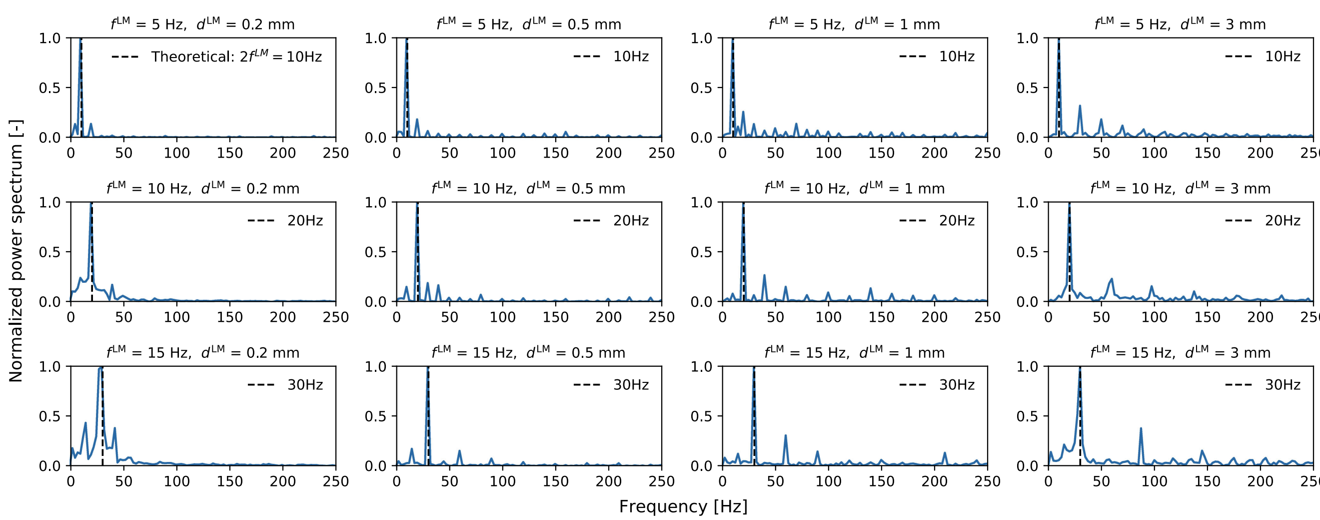
Fig. 2 shows the experimental setup and the coordinate system, which is a right-handed system with an origin at the lower left of the AUTDs. The AUTDs were placed upward. They presented LM stimuli at $\boldsymbol{c}^{\mathrm{LM}} = (288, 151.4, 265)$ mm. We set $d^{\mathrm{LM}} = 0.2, 0.5, 1, 3$ mm, $f^{\mathrm{LM}} = 5, 10, 15$ Hz, $A^{\mathrm{LM}} = 3$ mm, and $\boldsymbol{u}^{\mathrm{LM}} = (1, 0, 0)$, and ϕ^{LM} was a sinusoidal wave following the original study on the LM stimulus [14]. The sound pressure at the $\boldsymbol{c}^{\mathrm{LM}}$ was measured using an electric condenser microphone (Brüel & Kjær TYPE 4138-A-015). The AUTDs also presented an unmodulated stimulus at the $\boldsymbol{c}^{\mathrm{LM}}$ (corresponding



(a) Measured sound pressure of LM stimulus at $f^{\mathrm{LM}} = 5$ Hz with $d^{\mathrm{LM}} = 0.2, 0.5, 1, 3$ mm and unmodulated stimulus. They were measured at the $\boldsymbol{c}^{\mathrm{LM}}$.



(b) Envelope of measured sound pressure. The envelope was calculated by applying a 30 kHz low-pass filter to the squared waveform of the measured sound pressure.

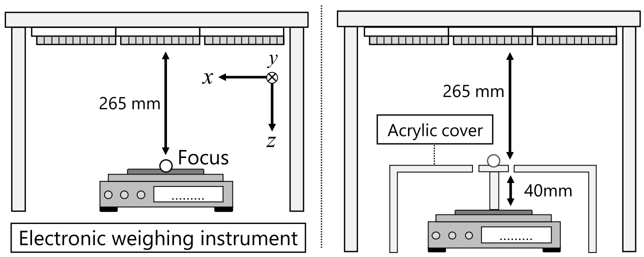


(c) Normalized frequency spectrum of calculated envelope (0 Hz components were deleted). The theoretical peak frequency $2f^{\mathrm{LM}}$ is plotted by a dotted line.

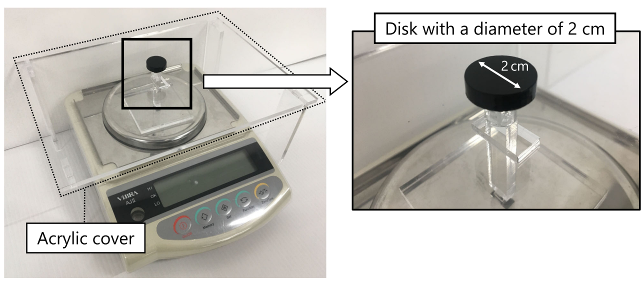
Fig. 3. Result of measuring sound pressure of LM stimulus.

$\phi^{\mathrm{LM}} = 0$), and its ultrasound pressure was measured using the microphone. The AUTDs' output was 2.7% of the maximum value, such that the output sound pressure was not beyond the measurement limit of the microphone (168 dB).

Fig. 3(a) shows the measured sound pressure of the unmodulated stimulus and LM stimuli at $f^{\mathrm{LM}} = 5$ Hz. Fig. 3(b) shows the normalized envelope of the sound pressure of the LM stimulus, and Fig. 3(c) shows its normalized frequency spectrum. The envelope was calculated by applying a low-pass filter to the squared waveform of the sound pressure. The cut-off frequency of the filter was 30 kHz, which was lower than the frequency of the ultrasound we used (40 kHz).



(a) Left) Measurement by the whole plate of the electronic weighing instrument with a diameter of 11.8 cm. Right) Measurement by an acrylic disc with a diameter of 2 cm. An acrylic cover was used to remove the side-lobe of the focus.



(b) Photograph of the acrylic cover removing the side robe of ultrasound focus.

Fig. 4. Setup for measuring radiation force of unmodulated stimulus.

Fig. 3(c) indicates that our AUTDs presented the desired LM stimulus because the envelope of every presented LM stimulus has a peak at twice a f^{LM}. Note that a focus in LM stimulus passes through $\boldsymbol{c}^{\mathrm{LM}}$ twice in one cycle. The theoretical peak frequency $2f^{\mathrm{LM}}$ is plotted by a dotted line in Fig. 3(c).

The envelopes with respect to d^{LM}, shown in Fig. 3(b), is also consistent with the theory. As the d^{LM} becomes finer, the acoustic power change becomes more continuous. When d^{LM} equals A^{LM} (3 mm), the envelope is a square wave.

B. Radiation Force

We measured the radiation force of the unmodulated ultrasound focus using a force sensor.

Fig. 4(a) shows the measurement setup. The AUTDs were fixed downward. The AUTDs presented an unmodulated focus at $\boldsymbol{c}^{\mathrm{LM}} = (288, 151.4, 265)$ and their radiation force was measured by an electronic weighing instrument (SHINKO DENSHI ViBRA AJ II) that can measure up to 6.1 N (620 gf) at a resolution of 0.01 mN (0.001 gf). The diameter of the scale pan of the weighing instrument was 11.8 cm. To exclude the contribution of the side-lobe, we placed an acrylic cover over the weighing instrument, shown in Fig. 4(b), and measured the force applied to an acrylic disk with a diameter of 2 cm.

The side-lobe is a radiation force distribution that appears extensively from a few millimeters from the focus position [3]. The diameter of an acrylic disc is determined so that the focus is surely included on the disc. We preliminary calculated the effective sound pressure distribution of the focus at the $\boldsymbol{c}^{\mathrm{LM}}$ in the measurement setup. The calculation result is shown in Fig. 5. The measurement area of the acrylic disc is also shown in this figure as a white circle. The result shows that the diameter in the y-direction of the focus is 1.7 cm and the diameter in the x-direction is 1 cm in the measurement setup. The calculated focus size indicates that some of the side-lobe were included in the disc but its contribution to the measured force was less than 5%.

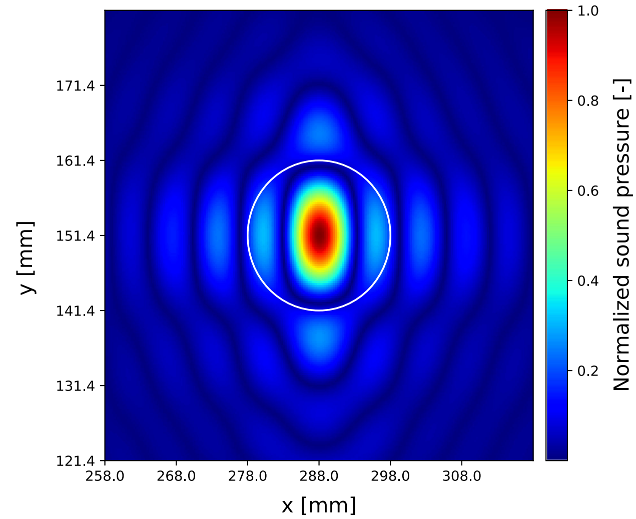


Fig. 5. Simulated sound pressure distribution of focus at the $\boldsymbol{c}^{\mathrm{LM}}$. The white circle indicates the acrylic disk with a diameter of 2 cm measuring the radiation force provided by the focus.

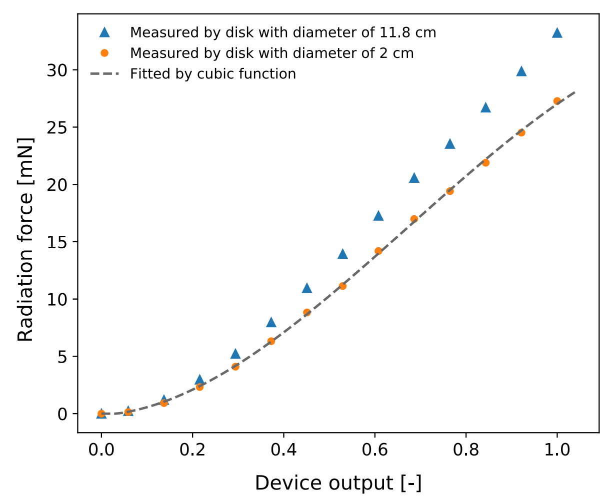


Fig. 6. Measured radiation force of unmodulated stimulus.

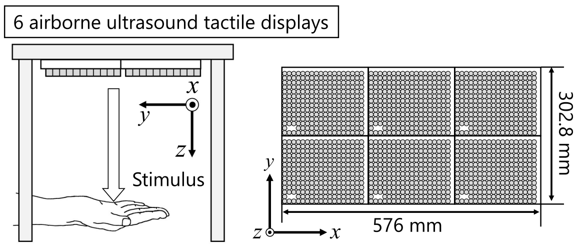
The measured forces are shown in Fig. 6. The maximum radiation force measured by the scale pan was 0.033 N, and that measured by the small acrylic disc was 0.027 N. We also fitted the cubic function to the force measured by the acrylic disc. The fitted function

$$F(G) = \begin{cases} 0 & (F < 0), \\ -24G^3 + 49G^2 + 2.2G - 0.13 & (\text{otherwise}), \end{cases} \tag{3}$$

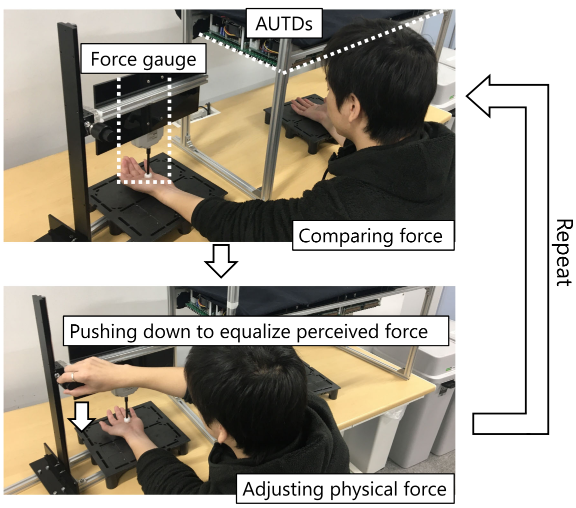
is plotted in Fig. 6, where F [mN] is the radiation force and $G \in [0, 1]$ is the device output of our AUTDs.

IV. Experiment 1: Vibratory Sensation

In this experiment, we explored the relation of the vibratory sensation to the LM step width d^{LM} and LM frequency f^{LM}.



(a) Schematic illustration of AUTDs and participants' hand.



(b) Flow of evaluating perceived force.

Fig. 7. Setup to evaluate vibratory sensation and perceived intensity.

A. *Experimental Setup*

The experimental setup is illustrated in Fig. 7(a). The six AUTDs were fixed downward. The AUTDs were driven at the maximum output. The participants placed their right palms to face the radiation surface of the AUTDs such that an ultrasound stimulus was presented at the center of the right palm. For all experiments conducted in this study, the participants heard white noise through a headphone to block external noise.

In this experiment, we presented LM stimulus whose ϕ^{LM} was a sinusoidal wave with $d^{\mathrm{LM}} = 0.2, 0.5, 1, 3$ mm, A^{LM} = 3 mm, $f^{\mathrm{LM}} = 5, 10, 15$ Hz, $\boldsymbol{u}^{\mathrm{LM}} = (1, 0, 0)$, $\boldsymbol{c}^{\mathrm{LM}} = (288, 151.4, 265)$ mm. For comparison, an unmodulated static pressure was presented. All stimuli were presented in random order.

B. *Procedure*

Ten males (23-28 years in age) participated in this experiment. All procedures conducted in this study were in accordance with the Declaration of Helsinki (2008), and the participants provided written informed consent prior to the study. First, the LM stimulus was presented on the right hand. The participants were instructed not to move their right hand while the stimulus was being presented. Second, to evaluate the vibratory sensation, the participants answered the following question with a rate of $0\% - 100\%$: **Q. How intensely did you perceive a non-stationary sensation compared to a static pressure sensation in the presented stimulus?** The participants were instructed to answer the question with 100% if they felt only a non-stationary sensation and 0% if they felt only static pressure. The participants were also instructed to consider "non-stationary sensation" to imply any kind of non-constant component, including a vibratory sensation. After answering the question, the participants proceeded to the next trial. Each participant conducted two experimental sets; thus, there were (4 resolutions $\times$ 3 frequencies + 1 unmodulated pattern) $\times$ 2 sets = 26 trials.

C. *Result*

Fig. 8(a) shows the reported non-stationary sensation rate. The result of the unmodulated stimulus is plotted to the left end of each figure. We applied the Shapiro-Wilk test to the obtained data and found that 6 out of the 13 data followed a normal distribution ($p > 0.05$). The conditions following the normal distribution are $\{d^{\mathrm{LM}} = 1, 3$ mm at $f^{\mathrm{LM}} = 5$ Hz$\}$, $\{d^{\mathrm{LM}} = 1, 3$ mm at $f^{\mathrm{LM}} = 10$ Hz$\}$, and $\{d^{\mathrm{LM}} = 1, 3$ mm at $f^{\mathrm{LM}} = 15$ Hz$\}$.

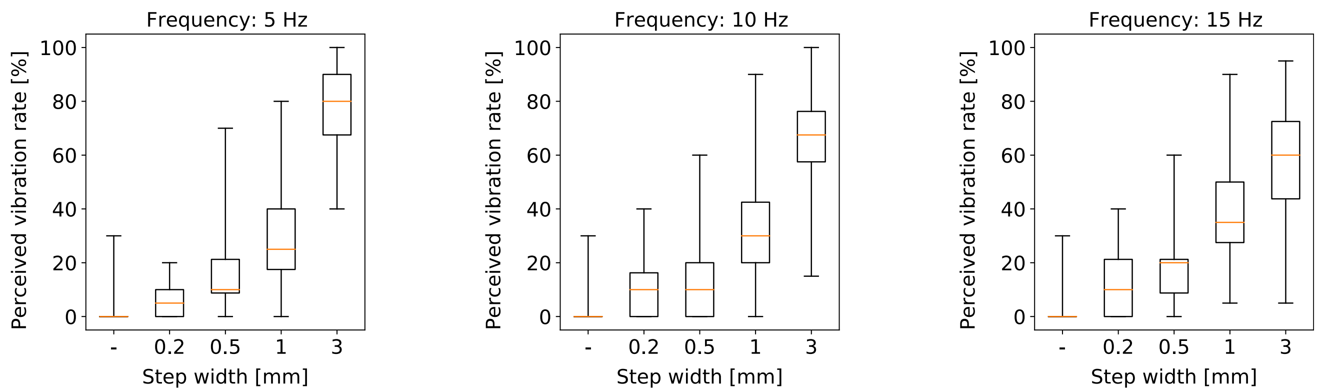
The maximum rate of non-stationary sensation of the LM stimulus was 80% with $d^{\mathrm{LM}} = 3$ mm and $f^{\mathrm{LM}} = 5$ Hz, and the minimum rate was 5% with $d^{\mathrm{LM}} = 0.2$ mm and $f^{\mathrm{LM}} = 5$ Hz. The rate of the unmodulated stimulus was 0%. The Wilcoxon signed-rank test showed that the unmodulated stimulus' rate was not significantly lower than the minimum rate ($p = 0.057 > 0.05$). We also applied the Wilcoxson signed-rank test to all d^{LM} pairs with Bonferroni correction. The analysis showed that all d^{LM} pairs had a significant difference ($p < 0.05$) except for two pairs between d^{LM} = 0.2 and 0.5 mm, at f^{LM} = 10 ($p = 2.2$), 15 Hz ($p = 0.49$). Among the pairs with significant differences, the pair with the maximum p-value was $\{d^{\mathrm{LM}} = 1$ and 3 mm at $f^{\mathrm{LM}} = 15$ Hz$\}$ ($p = 0.046$), and the pair with the minimum p-value was $\{d^{\mathrm{LM}} = 0.5$ and 3 mm at $f^{\mathrm{LM}} = 5$ Hz$\}$ ($p = 1.14 \times 10^{-5}$). Finally, we applied two-way ANOVA to the results with three factors: LM step width d^{LM}, LM frequency f^{LM}, and an interaction between them. The ANOVA results showed that d^{LM} ($F(3, 228) = 107.3$, $p = 0.024 \times 10^{-41} < 0.0001$), and the interaction ($F(6, 228) = 2.58$, $p = 0.019 < 0.05$) had a significant effect on the non-stationary sensation rate. f^{LM} had no significant effect ($F(2, 228) = 0.104$, $p = 0.9 > 0.05$).

V. Experiment 2: Equivalent Physical Force

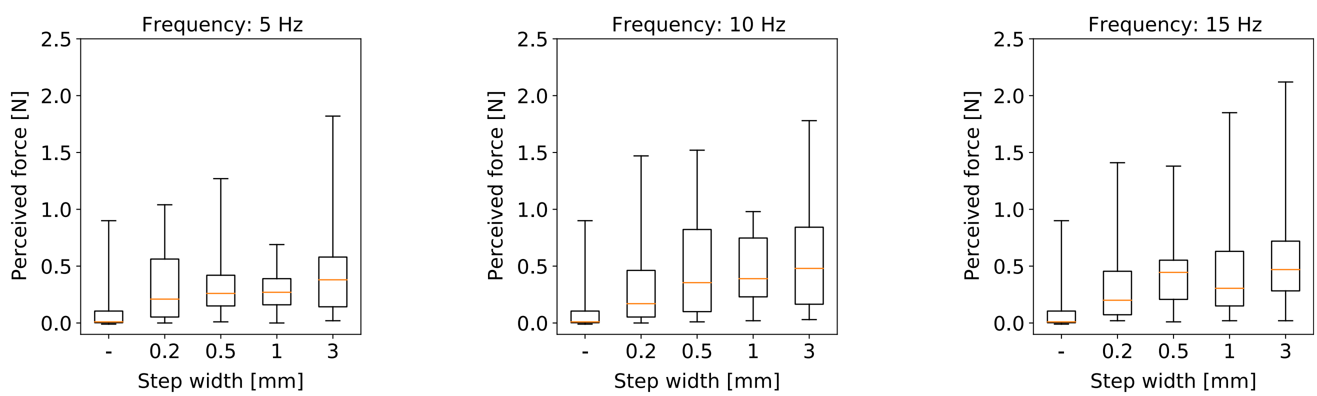
In this section, we evaluate the equivalent physical contact force of the LM stimulus with the spatial fine step width. The stimuli presented in this section were the same as those used in Section IV.

A. *Experimental Setup*

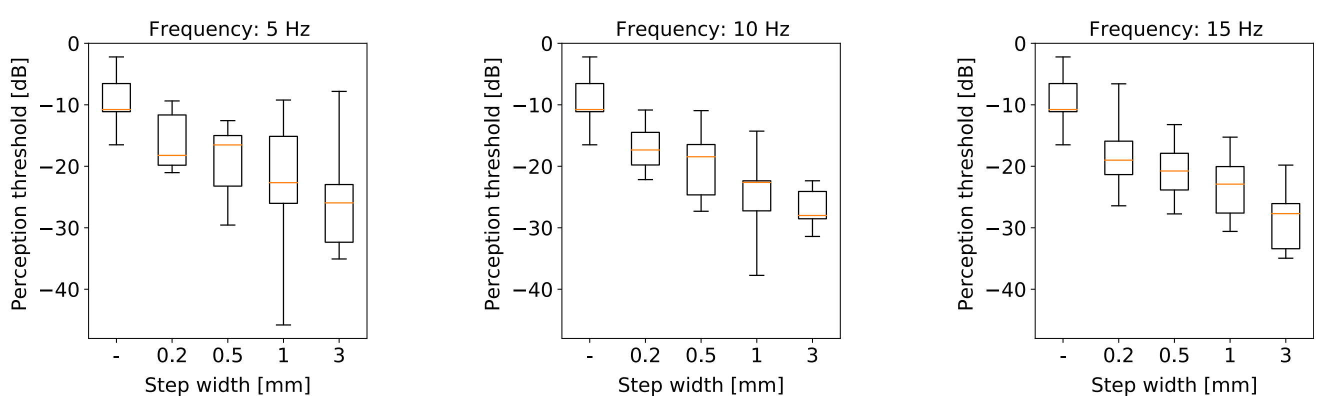
The experimental setup is shown in Fig. 7(b). The six AUTDs and a force gauge (IMADA ZTS-50 N) were fixed downward in mid-air. The force gauge can measure applied force up to 50 N (5.1 kgf) at a resolution of 0.01 N (1 gf). The AUTDs were driven at the maximum output. The force gauge was attached to a uniaxial stage, and its height could be



(a) Rate of non-stationary sensation.



(b) Perceived force.



(c) Perception threshold (dB re. 0.027N).

Fig. 8. Results of subjective experiment. "-" written on the horizontal axis indicates the result of unmodulated ultrasound stimulus corresponding to $\phi^{\mathrm{LM}} = 0$.

changed by turning its dial. A foamed styrol sphere with a diameter of 2 cm was attached to the edge of the force gauge such that the contact area was similar to the pressure area of the AUTDs. The participants placed their right palm facing the radiation surface of the AUTDs and their left palm facing the foamed styrol sphere.

B. Procedure

Ten males (24-28 years in age) and four females (23-25 years in age) participated in this experiment. First, the LM stimulus was presented on their right hand. The participants then adjusted the height of the force gauge by using their right hand such that the left hand contacted the foamed styrol sphere and perceived a contact physical force that was subjectively equal to the perceived LM stimulus. After moving the right hand back under the AUTDs, the participants compared the physical force and the LM stimulus and started adjusting the height again. They also kept both hands stationary during the comparison. They could adjust the height any number of times. When the participants judged that these stimuli were equalized, they orally reported. After this report, the participant maintained the contact status, and we recorded the median value of the 3 seconds data measured by the force gauge; subsequently, the LM stimulus was terminated. The participants adjusted the height so that their right hand did not touch the force gauge and proceeded to the next trial. There were (4 resolutions $\times$ 3 frequencies + 1 unmodulated pattern) $\times$ 1 set = 13 trials.

C. Result

The perceived force evaluated by the force gauge is shown in Fig. 8(b). We applied the Shapiro-Wilk test to the obtained data and found that 3 out of the 13 data followed a normal distribution ($p > 0.05$). The conditions following the normal distribution are $d^{\mathrm{LM}} = 1$ mm with $f^{\mathrm{LM}} = 5$ Hz and $d^{\mathrm{LM}} = 1, 3$ mm with $f^{\mathrm{LM}} = 10$ Hz.

The maximum perceived force of the LM stimulus was 0.48 N with $d^{\mathrm{LM}} = 3$ mm at $f^{\mathrm{LMM}=10}$ Hz and the minimum was 0.17 N with $d^{\mathrm{LM}} = 0.2$ mm at $f^{\mathrm{LM}} = 10$ Hz. The force of the unmodulated stimulus was 0.01 N. Two-way ANOVA with d^{LM} ($F(3, 156) = 1.45, p = 0.23 > 0.05$), f^{LM} ($F(2, 156) = 0.98,\ p = 0.38 > 0.05$), and the interaction ($F(6, 156) = 1.33, p = 0.99 > 0.05$) showed that no factor had a significant effect on the force.

To evaluate the difference in the force between the LM and the unmodulated stimulus (real pressure), we applied the Wilcoxon signed-rank test to the evaluated force. The results showed that all forces of the LM stimulus were significantly higher than that of the unmodulated stimulus ($p < 0.05$). The maximum p-value is 0.01 with $d^{\mathrm{LM}} = 0.2$ mm at $f^{\mathrm{LM}} = 5$ Hz and the minimum p-value is 1.2×10^{-4} with $d^{\mathrm{LM}} = 0.5$ mm at $f^{\mathrm{LM}} = 5$ Hz.

VI. Experiment 3: Perception Threshold

In this section, we evaluate the perception threshold of the LM stimulus with the spatial fine step width. Takahashi *et al.* reported the threshold of LM stimulus but did not explore the relationship between the threshold and the LM step width d^{LM} [14], [15]. The stimuli presented in this section were the same as those used in Section IV.

A. Procedure

The experimental setup was the same as that shown in Fig. 7 (a). Seven males (24-28 years in age) and two females (23-24 years in age) participated in this experiment. We used the staircase method to evaluate the perception threshold of the LM stimulus. To change the presented radiation force, we changed the device output G of the AUTDs from zero to 1 at 256 levels. The radiation force F changes according to eq. 3. The highest force corresponds to the maximum G, and the lowest force corresponds to the null output. First, the LM stimulus was presented at the center of their right hand with the null output, and its intensity increased automatically by one level per 100 ms. The participants pressed a specific keyboard key when they first perceived the stimulus. After pressing the key, the intensity started to decrease automatically. When they could not perceive the stimulus for the first time, the participants pressed the key, and the output started to increase again. The participants conducted this process until the key was pressed six times. The average radiation pressure at the key-pressed timing was recorded as the perception threshold. There were (4 resolutions $\times$ 3 frequencies + 1 unmodulated pattern) $\times$ 1 set = 13 trials.

B. Result

Perception thresholds are shown in Fig. 8(c). The 0 dB was the maximum radiation force $F(1) = 0.027$ N which was calculated by eq. 3. One of the male participants could not perceive the unmodulated stimulus; thus, its result was excluded from Fig. 8(c). One female participant reported that she could not answer correctly at $d^{\mathrm{LM}} = 3$ mm with f^{LM} = 5 Hz thus, the results were also excluded. We applied the Shapiro-Wilk test to the obtained data and found that 9 out of the 13 data followed a normal distribution ($p > 0.05$). The conditions following the normal distribution are $\{d^{\mathrm{LM}} = 0.5, 1$ mm with $f^{\mathrm{LM}} = 5$ Hz$\}$, $\{d^{\mathrm{LM}} = 0.2, 0.5, 3$ mm with $f^{\mathrm{LM}} = 10$ Hz$\}$, $\{d^{\mathrm{LM}} = 0.5, 1, 3$ mm with $f^{\mathrm{LM}} = 15$ Hz$\}$, and unmodulated stimulus.

The minimum threshold of the LM stimulus was -28 dB with $d^{\mathrm{LM}} = 3$ mm at $f^{\mathrm{LM}} = 10$ Hz, and the maximum was -16.52 dB with $d^{\mathrm{LM}} = 0.5$ mm at $f^{\mathrm{LM}} = 5$ Hz. The threshold of the unmodulated stimulus was -10.78 dB, and the Wilcoxon signed-rank test showed that it was significantly higher than the thresholds of all LM stimuli ($p < 0.05$). The maximum p-value is 0.012 with $d^{\mathrm{LM}} = 0.2$ mm at $f^{\mathrm{LM}} = 5$ Hz and the minimum p-value is 0.0039 with $d^{\mathrm{LM}} = 0.2$ mm at $f^{\mathrm{LM}} = 10$ Hz. We did not test the threshold with $d^{\mathrm{LM}} = 3$ mm at $f^{\mathrm{LM}} = 5$ Hz in which one participant did not answer collectedly in the experiment. Two-way ANOVA with d^{LM} ($F(1, 129) = 31.1, p = 1.37 \times 10^{-7} < 0.001$), f^{LM} ($F(1, 129) = 2.35, p = 0.12 > 0.05$), and their interaction ($F(1, 129) = 0.15, p = 0.69 > 0.05$) showed that only d^{LM} has a significant effect on the threshold.

VII. Discussion

A. Vibratory Sensation and Perceived Force

The results indicate that the low-frequency LM stimulus with the fine d^{LM} provided tactile stimulus with almost no vibration, which was perceived to be significantly stronger than the unmodulated stimulus. Under all f^{LM} conditions, when the d^{LM} was 1 mm or less, the vibratory sensation was lower than 35% and the participants pushed up the edge of the force gauge with 0.17 N or more. Moreover, through all experiments, six of the participants could not perceive the unmodulated stimulus, and all participants could perceive all LM stimuli.

1) Adaptation of Tactile Receptors: Some participants reported an extremely high equivalent force for the presented LM stimulus, which caused a large variance in the result of the equivalent force. For example, at the most vibration-suppressed condition ($d^{\mathrm{LM}} = 0.2$ mm and $f^{\mathrm{LM}} = 5$ Hz), the reported maximum force was 1.04 N, and the median value was 0.21 N. We conjectured that the extremely high force was attributed to the adaptation and the comparison timing. The tactile receptors of the participants were considered to be

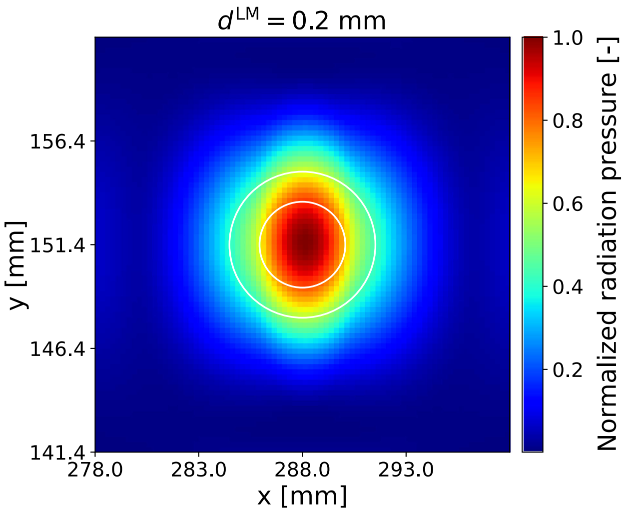


Fig. 9. Simulation of time-averaged radiation pressure distribution presented by LM stimulus with $d^{\mathrm{LM}} = 0.2$ mm. The white circles indicate the calculated contact areas between the formed styrol sphere and the participant's hand with the pushing force of 0.21 and 1.04 N, respectively.

adapted to the stimulus by the force gauge while adjusting the height of the force gauge [17]. When a static pressure is applied to a hand for a certain duration, the receptors of the hand adapt to the stimulus, and its perceived intensity gradually weakens. Therefore, the participants who evaluated the presented LM stimulus for a certain period of time after touching the force gauge tended to report a higher equivalent force. We did not control the time for touching the force gauge, but the participants completed the comparison within 5-10 seconds after adjusting some time in the first trial. Although the results include extremely high forces for this reason, we conclude that the results provide solid evidence that the perceived intensity of the LM is significantly higher than the physical radiation pressure. The results of the unmodulated stimulus are also informative. Only 36% of the perceived intensity of the unmodulated stimulus was higher than the radiation pressure, whereas 86% of the perceived intensity of the LM stimuli was higher than the radiation pressure. In future work, the contact motion of the reference object should be computer-controlled by some mechanical stage.

2) Difference in Stimulation Area: In the equivalent force experiment, the stimulation area of the LM stimulus was constant but the contact area on the styrol sphere changed according to the pushing force. As the stimulation area, we calculated the time-averaged acoustic radiation pressure distribution in one cycle of the LM. The pressure distribution with $d^{\mathrm{LM}} = 0.2$ mm is shown in Fig. 9. The contact area between the styrol sphere and the palm was also calculated assuming the Hertzian contact between them and flatness of the skin surface. We set the Young's modulus of the palm to 0.136 MPa and the Poisson's ratio to 0.48, referring to the previous study [26]. The results showed that the contact radii were 2.07 and 3.52 mm when the gauge was pushed in at 0.21 and 1.04 N, respectively. These pushing forces correspond to the median and maximum values of the reported forces at $f^{\mathrm{LM}} = 5$ Hz with $d^{\mathrm{LM}} = 0.2$ mm, respectively. The calculated contact areas are superimposed in Fig. 9 as white circles. The results indicate that when the styrol sphere was pushed up at 0.21 N (the median value), the contact area was less than 50% of the LM stimulation area, which would have decreased the equivalent force since a more concentrated force feels stronger. In the future, to future clarify the effect of the contact area, we will conduct the equivalent force experiment using multiple styrol spheres with different radius.

3) Mechanisms of Non-Vibratory Sensation: Herein, we discuss the mechanisms of both the strong perceived intensity and the suppressed vibration of low-frequency LM stimulus with fine d^{LM}. First, the strong intensity is considered to be due to the SA-I property, which response more strongly to the vibration of a few hertz than to static pressure [12]. Second, we conjecture that the vibration suppression occurred because the harmonic component of the presented radiation pressure was decreased by narrowing d^{LM}. Fig. 3(b)-3(c) show that when d^{LM} is decreased, the harmonic component of the envelope decreased. A low-frequency LM stimulus without harmonic components can evoke the pressure sensation as Konyo *et al.* reported that a vibration below 5 Hz evoked a pressure sensation [21]. On the other hand, the vibratory sensation remained for all LM stimuli. In the future, we will evaluate the tactile feeling of the remaining vibration by comparing it with a vibrotactile stimulus (e.g., LM stimulus of 50 Hz or AM stimulus of 200 Hz). As the authors' subjective comment, the quality of the remaining non-stationary component was clearly different from the vibration felt at 50 or 200 Hz.

B. Perception Threshold

The results shown in Fig. 8(c) indicate that the perception threshold of the LM stimulus significantly increased when its d^{LM} was fine. The increased thresholds were consistent with the results of the suppressed vibratory sensation shown in Fig. 8(a) because the perception threshold of static pressure was higher than that of a vibrotactile stimulus [12].

As the author's subjectivity, the pressure sensation evoked by the low-frequency fine-step LM stimulus was strongly perceived but, its perception threshold was higher than that of high-frequency LM stimulus with the same A^{LM} as our experiment evaluated by Takahashi *et al.* [14], [15]. They presented a high-frequency LM stimulus ($f^{\mathrm{LM}} = 50, 100, 200$ Hz) using four AUTDs and showed that its threshold at $A^{\mathrm{LM}} = 3$ mm was lower than -25 dB. In our experiment, we used six AUTDs and the threshold of the LM stimulus with $d^{\mathrm{LM}} = 0.2$ mm was higher than -20 dB.

The trend of change in the perception intensity obtained in this study is consistent with the trend obtained in a previous study conducted by Frier *et al.* [18]. They drew a circle tactile pattern with a circumference of 100, 150, and 200 mm by moving a single ultrasound focus. They also changed the number of the spatial sampling points of the circle pattern and evaluated the perceived intensity of the circle. Their results showed that when the sampling point increased (in other words, the motion step width of a focus decreased), the perceived intensity decreased like our results. They also reported that the perceived intensity was reduced when the number of sampling points was extremely small (e.g., four points). However, the tactile patterns they presented are significantly different from the pattern we presented. They presented a large circular pattern spanning the palm while we presented a short line pattern that is perceived as a single point stimulus [14].

C. Spatiotemporal Pattern of Focus Movement

In this study, we adopted a sinusoidal motion pattern in which the spatial step width was constant. It is also conceivable that the stimulation point is shifted with a constant time interval or follows a triangular motion pattern with a constant step in both time and space. A comparison among them is future work.

VIII. Conclusion

In this study, we verified that the vibratory sensation of an LM stimulus by focused ultrasound at 5-15 Hz was significantly suppressed by narrowing the step width of a moving ultrasound focus. In the LM with the fine step width, the perceived force of the LM stimulus was still clearly perceived and had a significantly higher intensity than that of the unmodulated stimulus, that is, real static pressure. In the experiments, the participants reported that the vibratory sensation rate was 5% in the presented LM stimulus at 5 Hz with a 0.2 mm step width. At the condition, the perceived force of the LM was equivalent to the physical stimulation when the edge of the force gauge pushed the hand of the participants at 0.21 N on average, whereas the unmodulated applied force with the same AUTD power was 0.027 N measured by an electronic weighing instrument.

We conclude that focused airborne ultrasound can present a non-vibratory tactile sensation. It was not a completely static force but the vibratory component was significantly suppressed compared with the total perception intensity. In the future, we will evaluate the small difference from the perfect static pressure and elucidate the mechanism of the suppression of the vibratory sensation.

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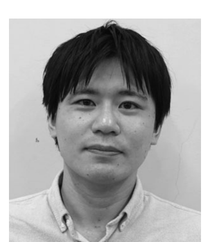

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