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Lateral Modulation of Midair Ultrasound Focus for Intensified Vibrotactile Stimuli

Ryoko Takahashi[1], Keisuke Hasegawa[2], and Hiroyuki Shinoda[3]

[1] Graduate School of Information Science and Technology, The University of Tokyo, Tokyo, Japan.,
takahashi@hapis.k.u-tokyo.ac.jp
[2] Graduate School of Frontier Sciences, The University of Tokyo, Chiba, Japan.
Keisuke_Hasegawa@ipc.i.u-tokyo.ac.jp,
[3] Graduate School of Frontier Sciences, The University of Tokyo, Chiba, Japan.
Hiroyuki_Shinoda@k.u-tokyo.ac.jp,

Abstract. In this paper, we propose a new modulation method of midair ultrasound focus named Lateral Modulation (LM), which provides significantly stronger vibrotactile stimuli on the skin surface compared to that provided by conventional Amplitude Modulation (AM) in the realm of midair ultrasound haptics. We experimentally validated the effectiveness of the LM method by showing that it significantly lowered the vibrotactile detection threshold compared with the AM method, for a wide range of modulation frequencies. The method was found to be valid both on the glabrous and hairy skins, and is expected to be applied to whole-body midair haptics. We demonstrate that the LM method relies on the characteristics of human perception of moving stimuli on the skin surface.

Keywords: Midair Haptics, Haptic Display, Human Perception

1 Introduction

Airborne Ultrasound Tactile Display (AUTD) [1][2] can present tactile stimulus on a human body surface without direct contact. AUTD creates an ultrasound focus at an arbitrary position in the workspace by controlling the phase shift and amplitude of the output emission of the ultrasound transducers. The focus presents tactile stimuli by applying acoustic radiation pressure, which pushes the skin surface inside the focal region. This display can superimpose tactile feedback onto 3D human-computer interfaces such as AR and VR systems. As examples of such aerial vibrotactile systems, an aerial touch panel with haptic feedback called HaptoMime[3] and a mutual real-time telepresence system called HaptoClone[4], which allows two users over a distance to simultaneously share a virtually identical three-dimensional workspace that includes visual and tactile information, have been developed so far, in addition to many other related technologies[5][6].

The standard method of presenting vibrotactile sensation with a current AUTD is temporally modulating the amplitude of the acoustic radiation pressure with a waveform so that it has vibration components of about 100 to 200 Hz. With this method, the presentation position is limited to the glabrous part of the skin (often a palm), which is the most sensitive region available for tactile stimulation for most cases.

This is because the maximum pressure that the device can generate is firmly limited by its specification, and consequently, it is highly difficult to present relatively low frequency vibration components lower than several tens of hertz as distinctly perceivable passive tactile stimuli. Although it is true that users can perceive those lower-frequency-modulated focus by actively and carefully moving their hands, in those cases, it is only possible to let the users feel smooth protrusion when they pay sufficient attention to it. The most straightforward solution for improving the focal intensity is to increase the presentation pressure by employing a larger number of AUTDs[7]. Nevertheless, it is not always desirable to emit such a strong ultrasound from the viewpoint of safety. In addition, for some applications, it may be difficult to assume a hardware configuration that occupies a large space. If we achieve clear tactile presentation to areas other than hairless skin, we can make full use of the intrinsic advantage of midair ultrasound haptics that stimulus can be presented at an arbitrary timing on any position on the body. For instance, new applications such as presentation of a trigger evoking the user's attention, presentation of midair trajectory, or instruction of specific body actions, can be realized for an unspecified number of users in a purely haptic manner.

In fact, haptic technology targeting the whole body is still under development, however, it is a field with great expectations in terms of practical application. The fundamental assumption among current whole-body haptic displays is that the users wear specific devices in touch with their bodies[8][9]. Those "wearable" methods are indeed promising for many potential applications. However, those devices have some inevitable inconveniences such as constrained body movement of the user and bulky device size due to the wiring and actuators. As for AUTDs, it can reliably apply force on the exposed body surface such as hands, arms, and face. It should be noted that successful stimulation of the skin under clothes is still difficult with the method proposed in this paper.

The conventional amplitude modulation (AM) method temporally modulates the ultrasound pressure, which means that the average output acoustic power is lower than the maximum non-modulated power. At the same time, a non-modulated spatially-fixed ultrasound focus, which yields temporally constant radiation pressure, cannot be felt as a vivid passive tactile sensation as described above even when the focal acoustic power is much greater than that of perceivable AM focuses.

The main idea of this research is that the temporally non-modulated focus yields vibrotactile sensation on multiple points on the skin when the focus is horizontally moving in a continuous manner, while employing the maximum possible output of the device. In other words, it is not the focal amplitude but the horizontal focal location that is modulated in the proposed method. We define this spatial modulation technique as Lateral Modulation (LM). Current

AUTD systems can locate ultrasound focus with a spatial resolution in the submillimeter range and a temporal refresh rate of 1,000 Hz, resulting in smooth focal movements on the skin. In addition, some researches have suggested the existence of somatosensory areas that are selectively activated by spatially moving stimuli[10], though its mechanism is still not completely understood. Therefore, with the LM method, it is expected that the resulting vibrotactile stimuli can be stronger owing to the fully utilized acoustic power and enlarged vibrated skin region, compared with conventional spatially fixed AM focus.

In this paper, we have experimentally clarified that the LM method is able to present subjectively stronger vibrotactile sensation to both the palm and the dorsal side on the lower arm, compared with the conventional AM method. In addition, we have also confirmed that this lowering of the detection threshold of vibrotactile stimuli with the LM method is observed among a wide range of modulation frequencies in the range of 50 to 200 Hz.

2 Principle

2.1 Tactile Stimulation by Ultrasound Focus

AUTD is a device containing ultrasound transducers arranged in a lattice pattern. The phase and amplitude of the output waveform of each transducer can be individually controlled. AUTD concentrates the acoustic power in a narrow area with a controlled set of output phase and amplitude. The maximum possible energy concentration is achieved when the acoustic pressure from all the transducers converge to one point. This is realized by setting the phase shifts of the transducers in such a way that they are proportional to the distance between the desired focal position and each transducer. Although it is possible to generate spacing patterns with multi focus instead of a single focus[11][12], we focus on presenting a single focal point in this paper, because it is the strongest possible acoustic field.

It is known that when an object blocks intense acoustic propagation, a quasistatic pressure proportional to the acoustic power is generated on its surface. This phenomenon is called acoustic radiation pressure[13], which is the fundamental physical principle of aerial ultrasound tactile presentation. Although the instantaneous ultrasound pressure varies with time, the time average value of the radiation pressure is proportional to the acoustic power on a macroscopic time scale. As a result, theoretically, the squared ultrasound waveform envelope is detected and perceived as vibrotactile stimuli[7].

Theoretically, the sound pressure distribution around the ultrasound focus created by transducers arranged in a lattice is given as a two-dimensional squared sinc function. Here, the focus refers to the region between two central zero-cross lines. The size of the perceivable focus can be narrowed down to about the wavelength depending on the distance from the emitting surface[2]. The AUTD used in this paper has transducers resonating at 40 kHz, and therefore it presents a spot of about 8.5 mm in size, which is equal to the wavelength. The acoustic power outside the focus is much lower, which contributes little to the perceivable vibrotactile stimuli.

Note that the ultrasound focus only generates pressure normal to the skin surface. Regardless of the modulation mode, no shear force is thought to be generated on the skin surface. Thus, the focal movement described in the following section does not include any tangential force such as friction. It includes only the spatiotemporal changes of the normal force on the skin.

2.2 Vibrotactile Presentation Method: Amplitude Modulation vs Lateral Modulation

Conventional Method: Amplitude Modulation From the earliest research stages of ultrasound midair haptics[1], it has been a common strategy to increase the subjective stimulus intensity by temporally modulating the ultrasound pressure. This method involves temporally varying the amplitude of the waveform while keeping the focal position fixed. In this paper, we define this method as "Amplitude Modulation," and hereinafter call it "AM." Note that what the AUTD directly controls is the exerted acoustic radiation pressure on a rigid target, and not its displacement. In presenting vibrotactile stimulation with sinusoidal AM, it is known that the identification threshold is the lowest for a modulation frequency of around 200 Hz when targeting the palm[7]. It is thought that this is because the vibrotactile detection threshold of the Pacini corpuscles has a minimum value around 200 Hz, and is superior in sensitivity to the other receptors. However, to the best of our knowledge, there are no examples of similar sensitivity curves for ultrasound stimulation in hairy parts without Pacini corpuscles. Nevertheless, it is empirically known that AM ultrasound focuses are difficult to perceive by hairy skin, especially when the modulation frequency surpasses 200Hz. As stated above, theoretically, a squared envelope of the waveform corresponds to the vibrotactile sensation. Nevertheless, we simply created the focal waveform so that the envelope of the (non-squared) waveform was sinusoidal. This is because of the simplicity in implementation, and we considered that this incongruity has little effect on the perceived stimuli.

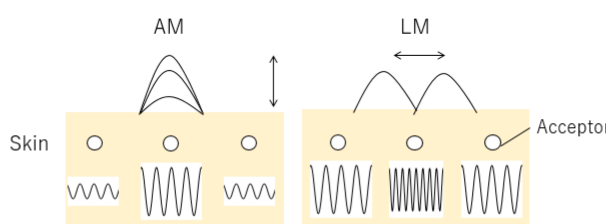

Fig. 1. Two vibrotactile presentation methods. The waveforms represent the strength and cycle of pressure given to the acceptors. The left figure shows conventional Amplitude Modulation, and the right figure shows Lateral Modulation.

Proposed Method: Lateral Modulation In this paper, we propose a new method of modulation. This method involves keeping the amplitude of the waveform constant while temporally changing the horizontal position of the focus in a periodic manner. We define this method as "Lateral Modulation," and hereinafter call it "LM." We switched the focal position at a refresh rate of 1,000 Hz. Fig.1 shows the concept of the two methods.

Here, we compare the time average of the acoustic power applied to the entire skin in AM and LM. Let ω_c be the carrier angular frequency of the ultrasound wave, $\omega_m(< \omega_c)$ be the AM angular frequency, and $p_{AM}(t)$ and $p_{LM}(t)$ be the instantaneous acoustic pressure at the focal point in AM and LM, respectively, with t denoting the time. In our setup, ω_c is $2\pi \times 40$ kHz. With a modulation index of 100%, the instantaneous acoustic pressure at the focal point is given as:

$$p_{AM}(t) = p_0 \sin(\omega_c t) \sin(\omega_m t),\ p_{LM}(t) = p_0 \sin(\omega_c t), \tag{1}$$

where p_0 is the maximum amplitude. We have the time-averaged acoustic powers P_{AM} and P_{LM} radiated from the phased array as:

$$P_{AM} = \frac{a}{T} \int_0^T (p_{AM}(t))^2\, dt,\ P_{LM} = \frac{a}{T} \int_0^T (p_{LM}(t))^2\, dt, \tag{2}$$

where $T = \frac{2\pi}{\omega_m}$, and a is a constant, concluding that $P_{LM} = 2P_{AM}$. Since the radiation pressure is proportional to the acoustic power [13], when the maximum output of the device is constant, LM can apply twice the acoustic power to the entire skin as that of AM in time average.

Next, we consider the fluctuation of pressure on a specific fixed spatial point on the skin. In this paper, we define LM as the horizontal sinusoidal movement of a focus with a fixed amplitude. Here, the LM frequency is defined as the frequency of the focal movement. The excitation waveform at a fixed point on the skin depends on the shape of the focus and the distance from the LM center. For instance, if the focus has an edgy power distribution, the resulting excitation waveform will correspondingly contain steep parts. Note that the excitation waveform is not always a sine wave with a single frequency. For example, at the center point of the LM, the skin surface is excited by a waveform having a frequency component double that of the LM frequency, because the focus crosses twice in one cycle. The existence of these harmonics and the vibration on multiple adjacent receptors with spatially dependent phase delays is what differentiates LM from AM.

3 Experiment

We constructed an experiment workspace with 4 AUTDs mounted on the ceiling of an aluminum frame(Fig.7). The ultrasound emitted from the AUTDs propagate downwards. All experiments were performed with this workspace.

3.1 Experiment 1: Measurement of acoustic radiation pressure

The first experiment was the waveform measurement of acoustic radiation pressure generated by the LM method with an electric condenser microphone (ECM) from Kingstate (KECG2738PBJ-A). The waveform was captured by an oscilloscope (PicoScope 4262). All the waveforms shown in this section were processed by the software low-pass filter of the PicoScope with the cut-off frequency set to 2,000 Hz so that it corresponds to the waveform of the acoustic radiation pressure. We verified how the LM vibrotactile stimuli varied spatially.

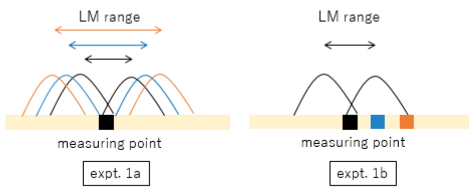

Fig. 2. Conceptual diagram of experiments 1a and 1b. In experiment 1a, the measurement position was fixed and the spatial amplitude was changed. In 1b, we fixed the spatial amplitude and changed the measurement position.

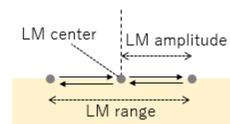

Fig. 3. Definition of LM terms. The circle in the figure indicates the focus position.

Procedures In this experiment, the LM frequency was set to 25 Hz, resulting in a period of 40 ms. Fig.2 shows the schematic descriptions of the two experiments, 1a and 1b. In both the experiments, the distance from the emission plane of the AUTD to the ECM was 230 mm.
(Experiment 1a): We fixed the ECM at the center of the workspace, which corresponded to the center of the generated LM focus. We measured the ECM outputs for sinusoidal LM amplitudes of 2, 4.5, and 7 mm. Here, we define LM amplitude as the halved horizontal swinging length of the LM focus (Fig.3).
(Experiment 1b): Next, we fixed the LM amplitude to 7 mm and measured the radiation pressure waveforms while shifting the horizontal position of the ECM with respect to the LM center by 0 to 9 mm in steps of 1 mm.

Results Fig.4 shows the ECM output waveform at the LM center. The blue, red, and green lines are the outputs for the LM amplitudes 2, 4.5, and 7 mm, respectively. In all the lines, two peaks are observed within one LM cycle (40 ms). These results agree with the theoretical speculation that the doubled frequency component is observed at the LM center. The variation of the ECM output is seen to increase with increase in the LM amplitude. Note that the focal size in the experiment was approximately 10 mm.

Fig.5 shows the ECM output waveforms for experiment 1b, when the measurement positions were set to 1, 3, 5, and 7 mm away from the LM center, with the LM amplitude fixed to 7 mm. Fig.5 shows that the interval between the two peaks varies depending on the measurement position. This is understood by calculating the timing when the focal center traverses the measurement point. The position of the focal center in the LM direction can be represented as $A\sin(\omega_{LM}t)$, where A is the LM amplitude, t is the time, and ω_{LM} is the LM

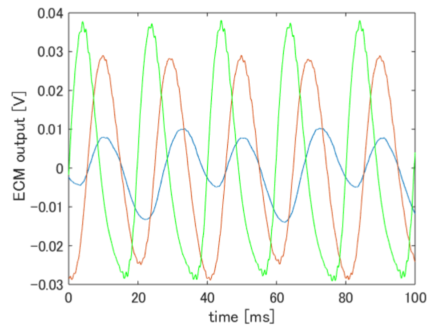

Fig. 4. Output voltages of the ECM installed at the LM center. The LM frequency was 25 Hz, and the blue, red, and green lines are for the LM vibration amplitudes of 2, 4.5, and 7 mm, respectively. Harmonics were observed in all the lines, and the ECM output amplitude became larger for larger lateral vibration amplitude.

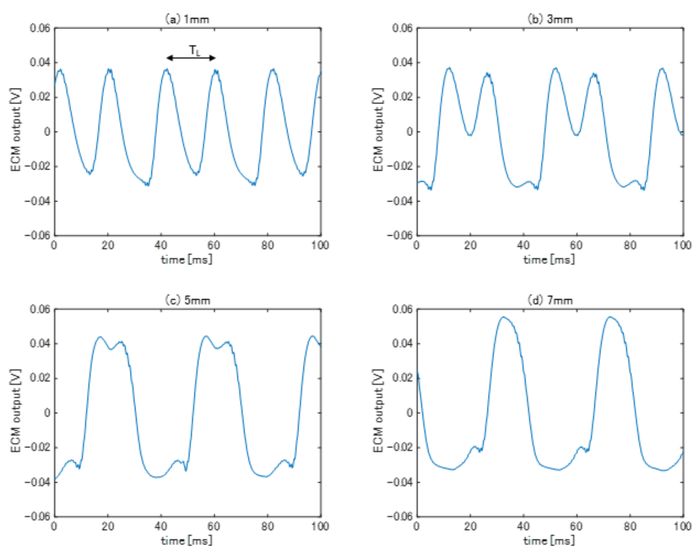

Fig. 5. Output voltages of the ECM for 25 Hz LM with a lateral vibration amplitude of 7 mm in experiment 1b. Figures a, b, c, and d are for the distances 1, 3, 5, and 7 mm between the ECM and the LM center, respectively.

angular frequency. The peaking time t of the radiation pressure at the measurement point x_0 is obtained by solving $x_0 = A\sin(\omega_{LM}t)$. For $x_0 > A$, the focal center does not cross during the LM cycle, where a single peak is expected in the LM cycle. However, small secondary peaks were seen in the graph of 7 mm. This is because of the secondary peak in the squared sinc function adjacent to the focal region.

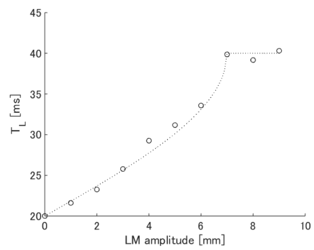

Fig. 6. Theoretical curve of T_L and the measured values.

We define the longer interval between the two peaks as T_L. Fig.6 shows the theoretical curve of T_L and the actually measured values along the measurement positions. The theoretical curve is consistent with the measured values of T_L, which indicates that current AUTDs could generate LM focus in a theoretically predictable way.

3.2 Experiment 2: Vibration detection threshold on hairless part

We experimentally obtained the vibration detection threshold of AM and LM stimuli on the palm with respect to several modulation frequencies and LM amplitudes.

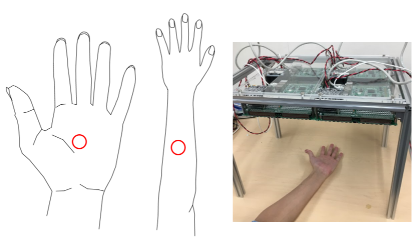

Fig. 7. Left figure shows the focus point in experiment 2, center figure shows the focus point in experiments 3 and 4, and right picture shows a view of the experiment.

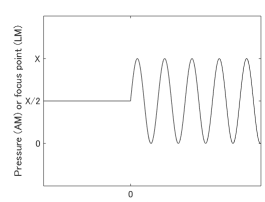

Fig. 8. Modulation of ultrasound pressure amplitude or focal position over time. The unmodulated acoustic radiation pressure is presented at the center of the workspace and the modulation starts with the sound of the signal (time = 0). X is the amplitude of each modulation.

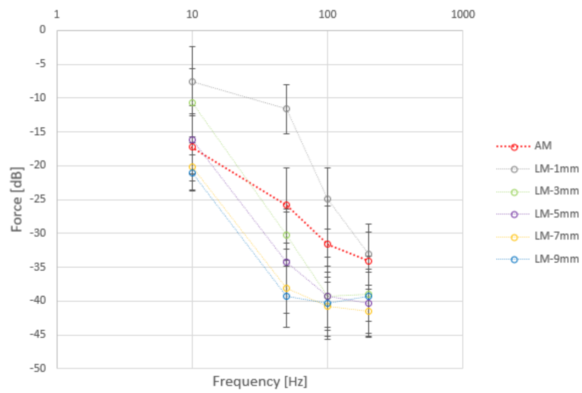

Fig. 9. Comparison of the average thresholds for AM and LM on hairless skin. 0 dB corresponds to the upper limit of the output ultrasound pressure of the device. Error bars indicates standard deviations. The cases in which vibration was not felt even at the maximum output were eliminated. 10 Hz AM stimuli could not be felt by one subject, and 1 mm and 10Hz LM stimuli could not be felt by two subjects. “LM-X mm” indicates the LM that has X mm LM amplitude.

Procedures Fig.7 shows a view of the experiment. We had five male and one female subjects, whose age ranged from 22 to 32. The subjects placed left hand on the center of the workspace, with the palm facing upward (Fig.7). During the experiment, the subjects wore headphones playing white noise to nullify auditory clues. In every trial, the subjects heard the cue sound as the stimuli was presented. Then, they answered whether they felt the vibrotactile sensation after the signal sound. We varied the stimulus intensity and obtained the detection threshold for each condition by using the method of limits. For each condition, the trial was done once. The distance from the emission plane of the AUTD to the palm was 270 mm.

Fig.8 shows the modulation waveform of the ultrasound amplitude in AM stimulation. Because negative radiation pressure cannot be produced, proper offset pressure was required. However, the DC offset caused static pressure and mass flow, called acoustic streaming. In order to get rid of these factors, which were irrelevant to the experiments, we presented a focus modulated with this DC offset for seconds prior to each time the AM focus was displayed. This DC offset was set to the 50% value in the waveform. A similar procedure was also done for LM stimuli: every trial started with presenting a still focus that lasted for seconds followed by an LM modulated focus. The intensity of stimuli in both AM and LM is defined as the maximum instantaneous output pressure from the AUTD. The maximum amplitude was varied with 51 levels. For both AM and LM stimuli, we set the modulation frequency to 10, 50, 100, and 200 Hz. The LM amplitude was set to 1, 3, 5, 7, and 9 mm.

Result Fig.9 shows the result. Here, 0 dB corresponds to the upper limit of the output ultrasound pressure of the device. 10 Hz AM stimuli could not be felt by one subject, and (1 mm, 10Hz) LM stimuli could not be felt by two subjects. The overall tendency in LM stimuli is that the increase in the LM amplitude lowers the detecting threshold. It can be observed that the LM stimuli with more than 5 mm amplitude was felt stronger than the AM stimuli. (1 mm, 50 Hz), (3 mm, 100 Hz), (5 mm, 50, 100, or 200 Hz), (7 mm, 50, 100, or 200 Hz), or (9mm, 50 Hz) LM stimuli were significantly different from the AM stimuli in the paired t-test ($p < 0.05$). This tendency is reasonably understood with the results in experiment 1.

3.3 Experiment 3: Vibration detection threshold on hairy part

Procedures Experiment 3 was performed in the same fashion as that of experiment 2, except that the stimulation position was changed to the center of the forearm hairy part (Fig.7). We presented both AM and LM stimuli. For LM stimuli, the LM amplitude was fixed to 7 mm. The modulation frequency was set to 10, 50, 100, and 200 Hz.The distance from the emission plane of the AUTD and the palm was 230 mm to 250 mm.

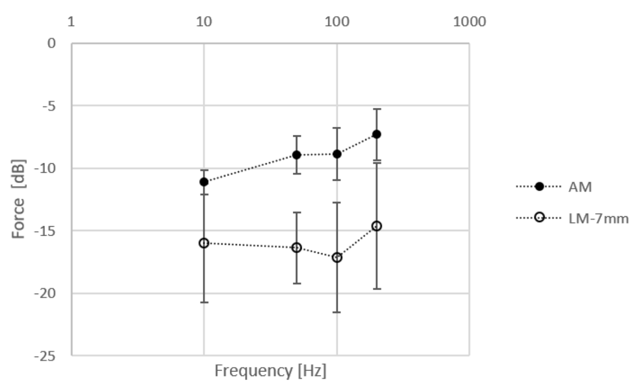

Fig. 10. Comparison of the average thresholds for AM and LM on hairy skin. 0 dB corresponds to the upper limit of the output ultrasound pressure of the device. Error bars indicate standard deviations. The cases in which vibration was not felt even at the maximum output were eliminated. 100 Hz AM stimuli could not be felt by one subject, and 200Hz AM stimuli could not be felt by two subjects.

Result Fig.10 shows the result. The result that the LM threshold takes lower values among all modulation frequencies is consistent with the result of the previous experiment. The difference is that thresholds are flatter among the modulation frequencies. This is due to the absence of Pacini corpuscles, which exhibit extreme sensitivity around a specific stimulation frequency. Since the AM threshold does not decrease as the modulation frequency increases, we conclude that the threshold decrease in LM stimuli is not because of the harmonics that LM contains. It is also worth noting that a drop in detection threshold of at most 10 dB was observed. The difference between AM and LM stimuli was significant in the paired t-test ($p < 0.05$), when the LM frequency was 50, 100, or 200 Hz.

3.4 Experiment 4: Subjective evaluation of two vibrotactile

In this experiment, the subjects evaluated the difference between AM and LM stimuli by subjective impressions of the stimuli. We presented AM vibrotactile and 7 mm LM vibrotactile at the maximum intensity on the middle of the hairy part of their forearm. For both the conditions, the modulation frequency was set to 50 Hz. After two stimuli, the subjects answered which stimulus was stronger. They were also asked to express how each of the vibration felt like. As a result, 100% of the subjects answered that LM was a stronger stimulus ($n = 5$). For both the stimuli, some subjects answered that they felt as if wind was blowing on their arm. This was presumably because of the wind caused by acoustic streaming. It should be clearly noted that what the subjects felt was not only the wind since the vibrotactile stimuli was surely felt as demonstrated in the above experiments.

4 Discussion

While an AM focus is thought to activate both shallow and deep receptors (Meissner and Pacini corpuscle), LM modulation can be considered to stimulate mainly shallow receptors. We expect this because the sum of the applied pressure in the region of LM range is constant, and the size of the receptive fields in these two receptors are different. Since deep receptors receive sums of stimuli on wider areas, they are unable to perceive the small spatial changes of the stimuli point. If selective stimulation of different mechanoreceptors is achieved with our method, it may be possible to present a variety of realistic tactile textures[14][15].

As stated above, the harmonics entailed by the LM focus was not the essential aspect of enhancement of vibrotactile stimuli. In addition, although the LM focus contains twice the acoustic power as that of the AM focus as stated above, the lowering of detection threshold cannot be explained merely by this effect. As referred to in the introduction, some researches refer to the activation of somatosensory areas by spatially moving the stimuli on the skin surface[10]. More detailed investigation about the perceptive effect of those spatial stimuli will lead to a more efficient way of subjectively intensifying the presented vibrotactile stimuli.

5 Conclusion

We proposed the lateral modulation (LM) method to present midair ultrasound vibrotactile stimuli. We verified the effectiveness of the LM method in terms of enhancing the subjective strength of the presented vibrotactile stimuli on the glabrous and hairy skin regions, compared with the conventional AM methods. We demonstrated that this effect was valid for modulations of 50 to 200 Hz with an LM amplitude of 5 mm and more. We also found that this effect cannot be explained by the harmonics caused by the LM focus, concluding that it is due to the characteristics of human perception of spatially modulated stimuli.

Our achievement will be utilized in realizing full-body haptic systems that are free from mechanical constraints as stated in the introduction. In future, we will investigate the underlying mechanism that causes the LM enhancement, as well as construct a practical system based on this method.

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