Reproducing Fine Textures on Touch Displays Using Band-Limited White Noise Vibrations

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***Abstract*—In this paper, perceived roughness of different band-limited white noise vibrations was evaluated on a tactile display. In the previous study, white noise vibrations without a specific cut-off frequency were found suitable while rendering fine textures. In that study, some participants reported that low frequency content of the noise vibrations were not plausible when they were touching the fine textures to rate the similarity between them. Therefore, the motivation of this work is to improve the perceptual capacity of white noise vibrations by adjusting its character according to the surface roughness of fine textures. Two essential factors can be used to adjust the character of noise vibrations: Frequency content and intensity level. In this study, a perceptual test is conveyed to scale the congruence between fine textures and band-limited noise vibrations with different high pass filters and intensities. In total, four cut-off frequencies (30 Hz, 60 Hz, 90 Hz and 120 Hz) and three intensity levels were tested to seek their best combination with respect to three fine textures with the grit sizes of 0.05 mm, 0.1 mm and 0.2 mm. Based on the analysis of the collected data, cut-off frequency is found as a primary factor to create plausible fine texture sensation on a display. On the other hand, vibration intensity has no significant effect on perceived similarity when the vibration intensity changes less than 3 dB.**

Keywords–Haptic; Texture; Rendering.

I. INTRODUCTION

The field of haptic augmented reality has experienced rapid growth using touch displays recently. Touch displays are rapidly emerging apparatus since they are programmable input devices. Besides their programmability, integration of haptic feedback to touch displays made them indispensable devices for users. With the enhancement of haptic feedback, not only blind [1], but also old or young people can have easier control on touch surfaces [2]. In the last decade, haptic touch devices have been already prototyped using different surface actuation mechanisms [3], [4], and there is even a commercialized touch product [5]. Thanks to haptic feedback, humans can experience cues, such as texture, shape and stiffness [6]-[9]. Particularly, texture cues provide fundamental haptic information about the objects on 2-D space. Hence, texture rendering has been considered as the first step on enhancing haptic dimension of touch devices.

So far, immense amount of researches have been conducted to produce texture sensation on displays by reproducing different texture dimensions, such as roughness and friction. These two cues have been simulated on touch displays using different approaches, such as electrostatic force, ultrasonic vibrations and vibrotactile feedback [8]-[10]. On the other hand, in recent years, some of the researchers introduced significant studies on measurement-based rendering techniques which enabled creating realistic haptic textures [9]. However, since such methods simply plays back the captured immense data from the surfaces, limited capabilities of tactile receptors [11] is unavoidably ignored [12]. Besides that, perception mechanisms of fine and coarse textures are different from each other as explained in the duplex theory of tactile texture perception [13]. Based on this theory, vibrations occurring from the spatial pattern of a surface can be only perceived when texture is not too fine. For fine textures, the effect of induced vibrations on the perception is not clear, but vibrotactile encoding ability of sensory receptors take place to perceive them [14], [15]. Based on the study of Tiest [16], it was reported that complex vibrations induced when a finger moves over fine textures are not identical to surface roughness while it is identical for coarse textures. In the seventies, the studies of Lederman [17]-[20] and Johnson [21]-[23] brought significant contributions to texture perception. According to their studies, spatial cues can contribute to roughness perception if the spatial size of bumps are larger than 0.1/0.2 mm. Afterwards, Bensmaia and Hollins asserted that waveform variations on complex vibrotaction can change the perception of texture, and vibrotactile encoding is sufficient itself to perceive fine textures [24]. Furthermore, another study claimed that active surface exploration with finger with varying speed can activate different tactile receptors with different selective frequencies [13].

As mentioned, the data-driven approach (playing back captured surface data) proposes tactile vibration for fine and coarse textures with similar complexity resolution. Moreover, played back recorded vibrations can contain non-perceivable frequency components, which are below the human vibration detection threshold. According to the former study [12], it was observed that recorded texture vibrations were too complex for coarse textures while fine textures were simulated best with complex vibrations. However, actual physical representation was not necessary to render fine textures since white noise vibrations were found as efficient as recorded vibrations. So far, not enough researches have been done on perception-based texture modelling [25], [26]. Accordingly, the aim of this study is to propose a simple and perceptually efficient fine texture rendering strategy. Therefore, white noise vibrations will be elaborated based on perceived roughness of fine textures which have different spatial densities. This elaboration procedure will be explained in section 2. With the proposed strategy, capturing surface data process, which is cumbersome and time consuming process, can be eliminated. This aim will be investigated by assessing the congruence between several sand papers and band noise vibrations with different cut-off frequencies and intensities. The fine sand papers are selected so as to have grit sizes of 0.05 mm, 0.1 mm and 0.2 mm. For the perceptual investigation, four cut-off frequencies and three intensity levels (reference, -3 dB reduced and +3 dB increased levels) were tested. Investigation process will be described in detail in Section 3. Before the main experiment session, perceived intensities of the band noise vibrations were equalized via a preliminary test to investigate the effect of the frequency clearly. Based on the results of the evaluation, cut-off frequency is found as a significant factor to have an effect on perceived roughness. On the other hand, changing the intensity level as much 3 dB is not found as a significant factor on the suitability of the band-limited white noise vibrations. In the following section, creation process of tactile stimuli, experimental setup and experimental method are explained.

II. EXPERIMENTAL SETUP

A. *Creation of Vibrotactile Feedback*

The band-limited white noise vibrations were produced at MATLAB with the sampling frequency of 44100 Hz. In total, 4 different high pass filters were applied to the white noise signals with the order of 6. The cut-off frequencies are 30 Hz, 60 Hz, 90 Hz and 120 Hz. In addition, a low pass filter with 1000 Hz cut-off frequency was applied to the band-limited noise signals to eliminate non-perceivable high frequencies. Note that the cut-off frequencies were selected considering the just noticeable difference of frequency [11]. During the preliminary research phase, 150 Hz cut-off frequency was also tested, but it was found similar with the vibration with Fc 120 Hz. The profiles of four types of band noise signals are schematically illustrated in Figure 1.

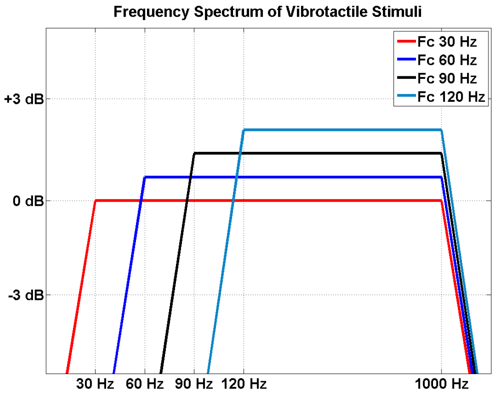

Figure 1. In the figure, frequency spectrum of prepared band-limited white noise signals are illustrated to show the spectral characteristics of each band noise vibrations.

Furthermore, intensity levels of the vibrations with different Fc values were equalized based on perceived vibration intensity. This process was done by conducting a preliminary test in which 5 subjects tuned the power amplifier until 4 types of vibrations have same perceived intensity. Thus, the peak magnitude difference between the signals are explicitly illustrated in Figure 1. After equalizing the perceived intensities of the vibrations, four types of vibrations were also produced at reduced (-3 dB) and increased (+3 dB) intensity levels.

B. *Test Setup*

To carry out a similarity evaluation on a display, an experimental apparatus was built as seen in Figure 2. A touch display monitor (Gechic HD 1102H) was assembled on top of an electrodynamic shaker (RFT Messelektronik), and the control interface was designed to contain scaling bar and play button for driving the vibrotactile stimuli. The tactile feedback was played for 5 seconds after the subjects clicked the play button on the interface, and a closed-back headphone (beyerdynamics DT-770) was used to prevent the potential interference of the sound of the electrodynamic shaker.

Figure 2. The experimental setup and the evaluation interface are seen above. During the evaluation, the participants touched the sand papers under the wood cover.

As shown in Figure 3, three sand papers with different grit sizes were utilized in the perceptual study to examine the relation between the spatial density of fine textures and the frequency content of white noise. The image demonstrates the sand papers from left to right with increasing grit sizes. Note that the sand papers have regular spatial distributions.

Figure 3. From left to right, the sand papers have 0.05 mm, 0.1 mm and 0.2 mm grit sizes.

Before the experiment started, tactile feedback generation system was validated as follows: Intensity level of the band noise vibrations at actual intensity on the display was perceptually set to be similar with the perceived roughness magnitude of 0.1 mm sand paper by tuning the power amplifier. This process was repeated for each participant. Therefore, the effect of altering the intensity level on the perceived roughness similarity can be examined. Moreover, the subjects were told to move their fingers in the central area of the display where the characteristic of vibrations was calibrated. In addition, the participants were requested to slide their fingers gently over the touch screen to avoid changing vibration intensity on the display considerably.

III. EXPERIMENTAL METHOD

In the evaluation, similarity tests were conducted based on Rohrmann scaling method [27] since it is a practical approach to evaluate similarity of a stimuli on linear one dimensional scale. In total, four band-limited white noise vibrations with cut-off frequencies of 30 Hz, 60 Hz, 90 Hz, and 120 Hz were judged in three different intensity levels. It means that there are 36 stimulation cases (4 vibrations x 3 intensity levels x 3 sand papers) when the subjects evaluate the vibrotactile stimuli for each texture. In total, 12 subjects, 9 male and 3 female aged between 24 and 39 years, participated in the experiment.

The evaluation consists of two consequent steps which are exploring the vibrations and textures, and the rating process. When the participants clicked the play button from the evaluation interface, the vibrations were driven one by one on the touch display. Then, the participants were requested to move their fingers on the display at a constant speed during the stimuli inspection. Also, the participants were allowed to repeat each vibrotactile stimulus until they are ready for the rating process. Afterwards, the subjects scaled the similarity of the each vibrotactile feedback with respect to each sand paper using verbal labels. The verbal labels are "not at all", "little bit", "middle", "very much" and "fully", placed on the continuous equal interval scale from 0 to 100 at the experiment interface. Also, the participants were allowed to rate anywhere in between two labels using the slider. Furthermore, before the main rating process, training session took place so that the subjects were trained to be familiar with the evaluation procedure and the types of vibrotactile stimuli before the main experiment. The data of the training session were not used for analysis of the test. The main test aimed to collect the subjective evaluation data with respect to all combinations of the vibrotactile stimuli and the textures. All participants completed the evaluation including the training session below 30 minutes.

IV. RESULTS

In the perceptual test, the similarity of the vibrotactile stimuli were judged by the subjects. The collected data for each vibrotactile stimulus were normally distributed. To begin with the investigation of the experimental data, similarity ratings of the vibrotactile stimuli were plotted for each texture as seen in Figure 4. In the figure, it is observed that there is a distinct differences between the ratings of the vibrations with different cut-off frequencies. In addition, when intensity level of the vibrotactile stimuli was reduced and increased, the ratings of the vibrations increased for 0.05 mm and 0.2 mm textures, respectively. This shows that the participants well-tuned the perceived intensity of the vibrations according to 0.1 mm sand paper. To analyze the effect of each factor (Cut-off frequency, intensity and texture) on the perceived roughness similarity, a three-way ANOVA test was performed. This test was carried on for 432 values (4 types of vibrations x 3 intensity levels x 3 sand papers x 12 subjects) using all similarity ratings as the dependent value. In conclusion, the cut-off frequency (F(3, 431) = 19.351, p = .0001) and the grit sizes of the fine textures (F(3, 431) = 5.268, p = .005) were found to have significant effects on the perceived similarity.

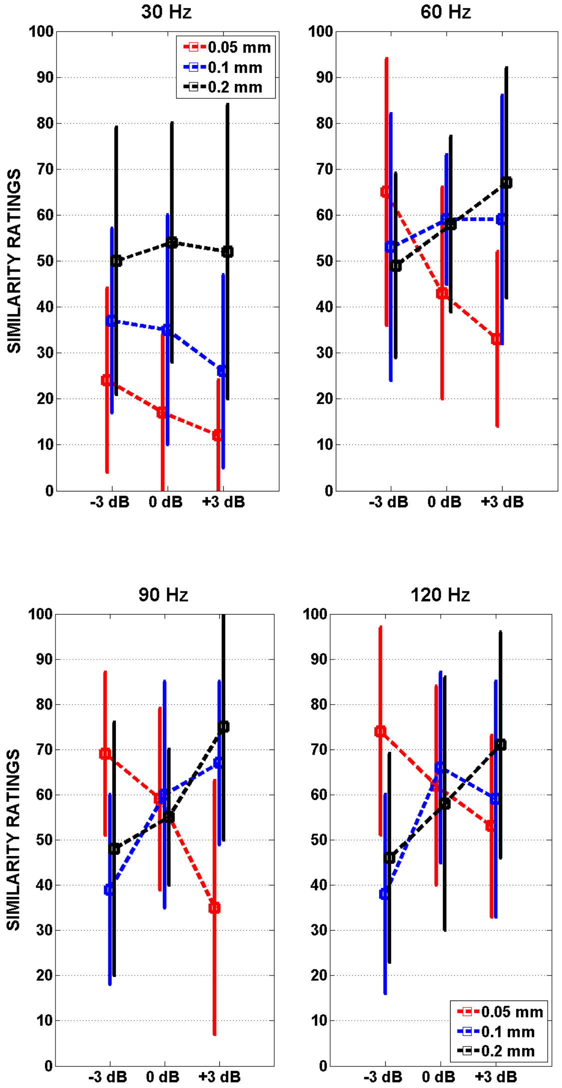

Figure 4. Similarity ratings of three texture vibrations are concluded as above. On the top, the ratings of fc = 30 Hz and fc = 60 Hz, on the bottom, fc = 90 Hz and fc = 120 Hz cases are plotted.

Apart from individual analysis of the independent factors, significant interaction effects were found between the factors of cut-off frequency and texture (F(3, 431) = 5.346, p = .0001), the intensity and the texture (F(3, 431) = 20.079, p = .0001), and all three together (F(3, 431) = 1.691, p = .045). The interaction among the three factors demonstrates that creating plausible band noise vibrations for fine textures depends on all three factors together, but primarily frequency content. On the other hand, although intensity was not found to have a significant effect on the ratings, it might have been significant if intensity level would have been altered more than 3 dB. Furthermore, Post-hoc t-tests with a Bonferroni procedure was performed to make pairwise comparisons for each factor. As a result, significant differences were found for 5 pairwise comparisons out of 12 comparisons: “ f_c = 30 Hz - f_c = 60 Hz”, “f_c = 30 Hz - f_c = 90 Hz”, “f_c = 30 Hz - f_c = 120 Hz”, “0.05 mm texture - 0.2 mm texture” and “0.1 mm texture - 0.2 mm texture”.

V. DISCUSSION

In this study, the suitability of the band-limited white noise vibrations are evaluated according to three different fine textures. The goal of this evaluation was to detect the most plausible frequency band and the vibration intensity level according to grit sizes of the fine textures. Therefore, a perception-based fine texture rendering model can be attained as an alternative to data driven method. With this method, data capturing process can be discarded, and texture rendering process can be simplified. This idea was developed after testing the suitability of white noise vibrations, recorded vibrations and simple sinusoids with respect to the fabric textures in the previous study. Since suitability ratings of white noise were found similar with the recorded vibrations for fine textures, it was considered that plausibility of white noise can be augmented by removing redundant frequency components. In addition, different vibration intensity levels were tested in the evaluation so that the roles of both cut-off frequency and vibration intensity on perceived similarity can be figured out in one test. According to the results, the cut-off frequency was found as a primary factor to create congruent texture vibrations. However, it is likely that vibration intensity could have had more impact on the similarity ratings if the intensity level would be increased or decreased more than 3 dB.

According to the collected similarity ratings, the band noise vibrations with 30 Hz cut-off frequency was found as the most unsuitable vibrotactile stimuli for the fine textures, as expected. Even altering the vibration intensity did not increase the ratings considerably. However, when the cut-off frequency was 60 Hz, the similarity ratings for the finest and the mid-fine textures increased with the confidence interval of 95%. This event demonstrates the effect of cut-off frequency on the suitability of the white noise vibrations. When the cut-off frequency of the tactile stimuli became 90 Hz, the mean ratings were maximum for 0.1 mm and 0.2 mm textures (at increased intensity level) with the confidence interval of 80%. For 0.05 mm texture, The maximum mean rating was attained when the cut-off frequency became 120 Hz (at reduced intensity level). For the F_c 90 and 120 Hz cases, altering vibration intensity changed the means of the ratings with the confidence interval of 95%. This demonstrates that the effect of vibration intensity on perceived roughness can be only observed if frequency content of the vibration is set to be congruent with respect to a reference texture.

Another point attained from the statistical analysis is that 0.05 mm and 0.1 mm textures were found significantly different than the 0.2 mm texture, but they were not found significantly different from each other. Possibly, it shows that different cutaneous perception processing might have occurred for 0.2 mm texture compared to 0.05 mm and 0.1 mm textures. This outcome agrees with the previous studies conducted by Lederman and Johnson arguing that spatial cues can contribute to roughness perception if the spatial size of a surface is more than 0.1/0.2 mm.

The perceived intensity of four band-limited noise vibrations were equalized at the preliminary test. It is because the human vibration detection threshold depends on the frequency of the vibration. Balancing the perceived intensity allowed to perform a reliable judgment on the effect of the cut-off frequency. Furthermore, the reason why the grit sizes of the sand papers were chosen as 0.05 mm, 0.1 mm and 0.2 mm is to analyze relation between the roughness of fine textures and the the factors comprehensively.

The maximum ratings of the vibrotactile feedback, which are resembling the roughness, were clustered between 70% and 80%. The reason why the ratings did not reach 100% is because the tactile texture perception consists of four main dimensions, and roughness is one of the dimension in texture perception. Therefore, lacking of other dimensions (hardness, friction and heat capacity) might have limited the subjective evaluation.

VI. CONCLUSION

With the results of this study, the effect of frequency and vibration intensity on the perceived magnitude of roughness is investigated. Hence, the primary and second factors affecting the suitability of created texture vibrations is figured out. On the other hand, the state of art for reproducing textures has been measurement-based approaches, but perception-based rendering algorithms will likely draw more attention in near future. It is because perception-based methods can provide plausible texture sensation on displays with simpler vibrations and rendering processes, as observed in the previous study [12]. These advantages can be particularly crucial for tactile internet technology, which aims rapid data transmission between smart haptic devices for extremely low latency [28]. Namely, texture rendering approaches which drive only perceptually perceivable amount of data with high perceptual capacity can be the most useful technique. As a future work, an extended study will be conducted to compare the perceptual capacities of perception-based and data-driven approaches, and this test will be carried out with more participants for more reliable statistical analysis.

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