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INVESTIGATION OF HUMAN TACTILE STOCHASTIC RESONANCE DEPENDING ON FREQUENCY EFFECT

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Abstract-Stochastic Resonance (SR) is a significant concern for design of robotic tactile sensors because of its considerable enhancement of sensitivity of human tactile sensation. In the last few decades, researchers have found that noise previously considered detrimental in fact provides the benefit of SR phenomena. However, there are no experimental results for dependence on vibrotactile frequency, which issued as basic data for robotic tactile sensors. In this paper, we investigated the influence of the SR phenomena on human tactile sensation in the context of frequency-dependence of

absolute thresholds (AT). We developed a system composed of an experimental apparatus and a computer program based on psychophysics in order to measure the AT of human vibrotactile sensation. We performed three series of psychophysical experiments using normal vibration, 8-mm-sized stimulus point and the continuous sinusoidal signals of 32, 50 and 75 Hz to obtain the AT variation in frequency. The results show that since normal ATs decrease with appropriate noise, SR is observed in normal stimuli tests in the frequency range from 32 to 70 Hz. Since the inclination of the curve of AT in a double logarithmic graph is around -1 in both with-noise and without-noise conditions, SR is caused by the FA-I mechanoreceptive unit in the range of frequency.

Index terms*:* Tactile sensation and sensors, Stochastic resonance, Psychophysical experiment, Continuous sinusoidal signal, Mechanoreceptive units.

I. INTRODUCTION

In advanced robotics, since robots must sense tactile feelings, the development of tactile sensors and their data processing are crucial for allowing robots to explore and handle objects. Recent research shows that there is significant concern related to the study of stochastic resonance (SR), which has considerable influence on human tactile sensitivity and the nervous system involving random noise processes [1]-[4]. SR is a counter intuitive phenomenon observed in many non-linear and multi-stable systems; SR is caused through the addition of random noise, which makes an undetectable weak signal become more easily detectable to enhance the precision of the interpretation of the signal information. In the last two decades, it has attracted significant attention of numerous researchers. Recently, it has been shown that SR can enhance the detection and transmission of weak signals in certain nonlinear and multi-stable systems by using noise [5][6]. If we can incorporate SR into not only the robotic tactile sensors [7][8] but also haptic displays [9]-[11], they can take advantage of it because tactile sensing accepts the external noise inevitably arising from touching an object surface. Thus, we investigate SR of human tactile sensing in this paper. The human mechanism of tactile SR can aid us in producing new designs for robotic tactile sensors and displays.

The most prominent works investigating the influence of SR in human tactile sensation are by Collins et al. [12][13]. They performed a series of psychophysical studies of tactile sensation and found that an individual absolute threshold for a tactile stimulus could be significantly enhanced by a proper level of noise. However, further works are required to elucidate its mechanism and the effect on tactile sensation because the trapezoidal single wave used as a stimulus in their study was inadequate for examining frequency dependence of tactile SR. If the frequency of the single wave is over 10 Hz, human subjects cannot feel the stimulus. The frequency dependence is important for discussing which mechanoreceptive unit is activated in SR.

On the other hand, sensational thresholds presented by vibrotactile stimuli on the skin have been studied [14]-[23]. So far, it has been found that there are four kinds of mechanoreceptive units in human skin: the fast adaptive type I unit (FA-I), fast adaptive type II unit (FA-II), slowly adaptive type I unit (SA-I), and slowly adaptive type II unit (SA-II). Basic characteristics of mechanoreceptive units have been reviewed in our previous paper [24]. Miyaoka et al. demonstrated that the sensitivity of a mechanoreceptive unit depends on stimulus direction, stimulus size and the frequency [21][22]. According to these studies, although FA-I detects normal vibration without dependence on stimulus size, FA-II detects both normal and tangential vibration with dependence on stimulus size. In addition, SA-I detects normal low frequency vibrations and static pressure, and SA-II detects tangential vibration without dependence on stimulus size.

Based on the previous studies, we investigated the influence of the SR phenomenon on human tactile sensation to elucidate the mechanism of SR. Our previous works [24][25] show that tactile sensing precision is enhanced by proper noise; also, neither normal nor tangential difference threshold is significantly affected by stimulus point size in the low frequency condition. Moreover the characteristics of SR with normal vibration are quite different from tangential vibration. Since we used a single half sinusoidal signal as the signal in experiments, we could not discuss the dependence of tactile SR on frequency in the same way as Collins' works.

In this paper, we performed experimental studies of the frequency-dependence of absolute thresholds (AT) for the perception of vibration by applying noise. We investigated the influence of the SR phenomena on human tactile sensation in terms of the frequency-dependence of AT using method of limit, which is one of the psychophysical experiments. In this study, we carried out three series of psychophysical experiments using the continuous signals at sampling frequencies of 32, 50 and 70 Hz.

II. PSYCHOPHYSICAL EXPERIMENT

a. Experimental Set Up

Since we measure the vibrotactile thresholds presenting normal vibration to the human hand in this study, we used the experimental system developed in the previous study and coded a computer program based on the method of limit. In the following, the experimental system and its revised portions are briefly explained.

The system is comprised of a personal computer, a multilayer piezoelectric actuator (ASB680C801*P0, NEC/TOKIN), a function generator (WF1974, NF Corporation) to generate the signal and the noise, and a piezodriver (HJPZ-0.15P, Matsusada) to drive the actuator. The actuator is installed in a stainless steel box and equipped with a contactor 8 mm in diameter (Fig. 1). The box is insulated from the vibration of the actuator with a rubber cushion. We used a continuous sinusoidal signal as a tactile stimulus and a Gaussian white noise superimposed on the signal.

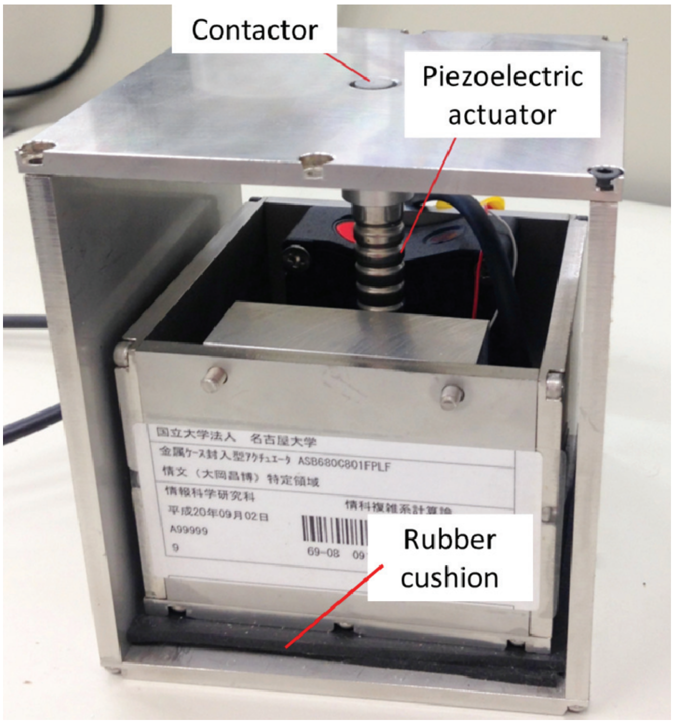

Figure 1. Vibration stimulator box

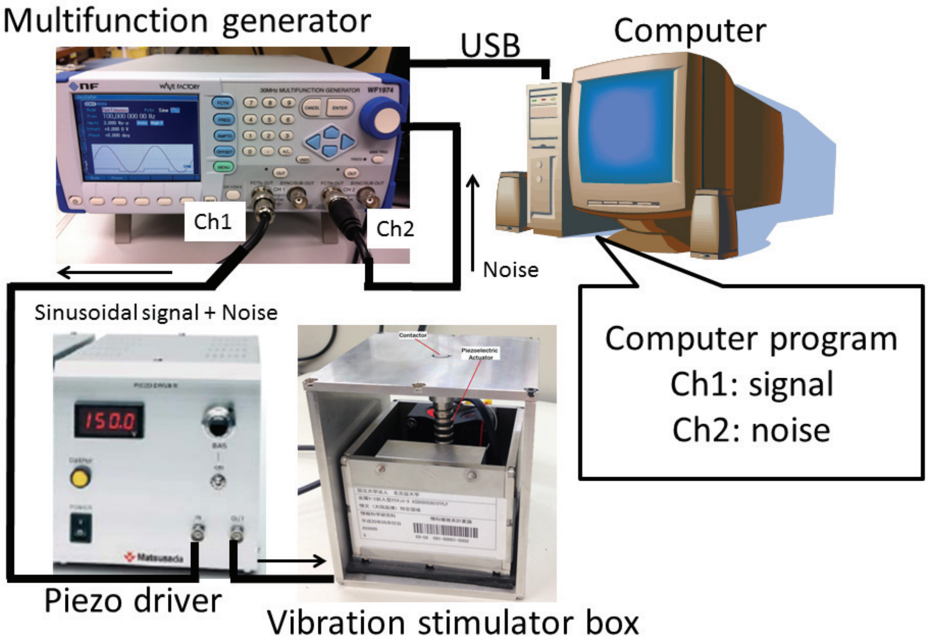

Figure 2. Schematic block diagram of experimental system

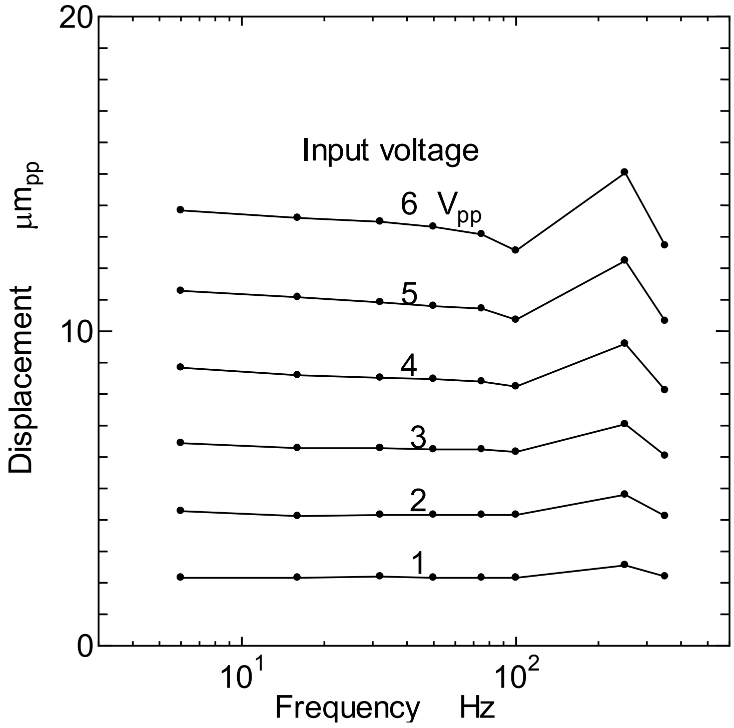

Figure 3. Calibration tests

The multifunction generator can generate different types of electrical waveforms over a wide range of frequencies in order to generate the signal mixed with or without noise. It has two channels: Ch 1 is used for sinusoidal generation and Ch 2 is used for noise generation in this experiment. Output of Ch 2 on the front panel is sent to the input terminal of Ch 1 on the rear panel to mix the signal and noise using the mixing function of the multifunction generator. The mixed waveforms are sent from the output terminal of Ch 1 on the front panel to the piezo driver to provide power to the actuator. The function generator is controlled by a personal computer; several commands such as changing amplitude, frequency and noise intensity (rms) are sent to the computer via USB (Fig. 2) according to user programs produced by VBA (Visual Basic for Applications) installed in Excel of Microsoft Office.

Since the piezoelectric actuator has non-linearity on the relationship between the applied voltage and the displacement, calibration tests were performed before the psychophysical experiments. Figure 3 shows the results of calibration tests, which were performed to examine the relationship between input volume amplitude and output displacement amplitude under different frequencies. In the tests, the displacement was measured by a laser displacement gauge. Although the graphs show peak values at 250 Hz, they almost keep constant under variation in frequency except for the peak values. In particular, the peak takes 13.3% larger value than the constant under 2-V_{pp} input voltage, which corresponds to around 4-μm_{pp} output displacement. Since as shown in Chapter 3 almost all experiments were performed under 4-μm_{pp} output displacement (2-μm_{0p} output amplitude), we assume that the apparatus produces constant displacement amplitude under different frequencies from 0 to 350 Hz.

b. Method of Limit

Since our goal is to determine the absolute threshold of human subjects in this study, we adopted the method of limits technique in the psychophysical experiments. The method of limits is perhaps the most frequently used technique for determining sensory threshold [26]. The determination of absolute threshold by method of limits used in this psychophysical experiment is exemplified in Table 1. Symbols A and D show the ascending and descending series, respectively.

In the method of limits, the stimuli are operated in either ascending series or descending series. The experiment starts by presenting a stimulus well above or well below threshold, and the stimulus intensity is changed by a small amount until reaching the border sensation. The experiment is terminated when the human subject reports the presence and disappearance of the sensation for ascending and descending series using Yes-No answers, respectively. Transition points are obtained for each series, and the average of these values is calculated as an absolute threshold in the experiment [25].

Table1. Example of method of limits in psychophysical experiments

	Response of Human Subjects(Y:Yes N:No)									
Stimulus Intensity (μm_{0p})	A	D	A	D	A	D	A	D	A	D
3		Y								
2.8		Y				Y				
2.6		Y		Y		Y				
2.4		Y		Y		Y		Y		
2.2		Y		Y	**Y**	Y		Y		Y
2	**Y**	Y		Y	N	**N**	**Y**	Y		Y
1.8	N	Y	**Y**	**N**	N		N	**N**	**Y**	Y
1.6	N	**N**	N		N		N		N	**N**
1.4	N		N		N		N		N	
1.2	N		N		N		N		N	
1	N		N				N		N	
0.8	N		N						N	
0.6	N		N							
0.4	N		N							
0.2	N									
0	N									
Transition Points	1.9	1.7	1.7	1.9	2.1	2.1	1.9	1.9	1.7	1.7
Mean Threshold Value	1.86 (μm_{0p})									

c. Experimental Procedure

Six healthy male subjects (average age: 23.5; standard deviation (SD): 0.84) in their twenties participated in the psychophysical experiment. The temperature of the room was maintained at 26^{o}C during the experiments for all human subjects. Subjects were seated and wore ear muffs to isolate them from environmental sound for better concentration. Their left hands were placed on the contactor (Fig. 4). Normal continuous sinusoidal vibrations were transmitted to the distal pad of the left index finger. Stimuli were controlled by the experimenter using a personal computer, and the intensity of the signals was changed using the computer program based on the method of stimuli [26]. The subjects judged the stimuli and were asked whether they felt the vibration (Yes-No answer).

There were two practice trials to allow the subjects to adapt to the apparatus and the environment of the experiment before each subject started the actual experiment. Each experiment was comprised of 10 trials as shown in Table 1, and each trial took about 1-3 minutes depending on the initial value and the termination value, which varied from subject to subject. Each subject took a one-minute rest between trials and a five-minute rest between experiments.

Based on the above procedure, five experiments were performed with different noise intensity levels. To get the influence of the super imposed noise on the signal, five noise intensity levels (0, 0.04, 0.09, 0.13, and 0.18 μm_{rms}) were applied to the continuous sinusoidal signal of the stimuli.

Figure 4. Scene of psychophysical experiment

Although the vibrotactile sensation depends on the frequency of the signal, we performed three series of psychophysical experiments to investigate the stochastic resonance effect on human tactile sensation depending on the frequency based on the above experimental procedure. We adopted three frequencies of 32, 50 and 75 Hz as frequency condition. In these experiments, we adopted a normal directional vibration case and 8-mm-sized stimulus point.

In each of these series of experiments, the subjects have to finish the 12 trials including the practice trials at different noise intensity levels, and the entirety of trials for each subject was 60. In all cases, it took 180-210 minutes for each subject to complete a series of psychophysical experiments.

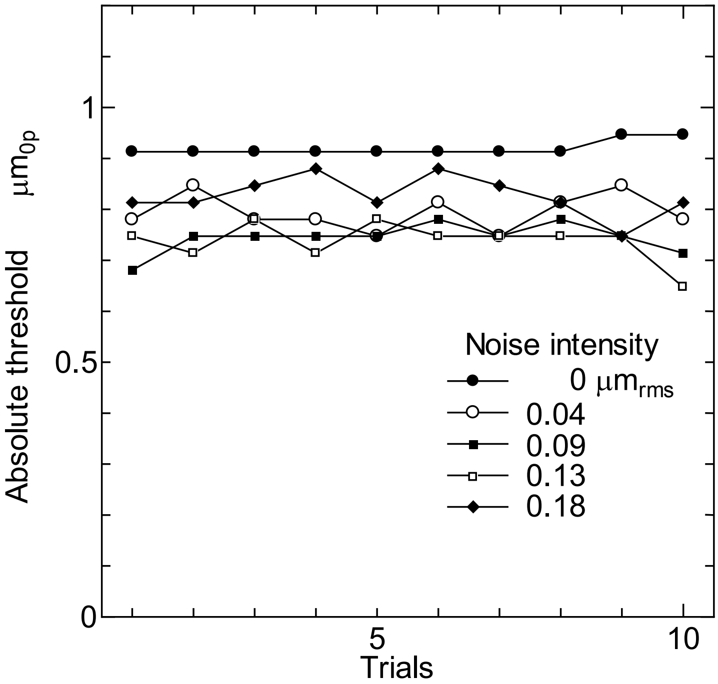

Figure 5. Example of experiment result obtained from human subject A (50 Hz)

III. EXPERIMENTAL RESULTS AND DISCUSSION

a. Experimental Results

In this study, we have carried out three series of psychophysical experiments and measured the vibrotactile thresholds presenting normal vibration to the distal pad of the left index finger of the human hand. Absolute thresholds (AT) of touch for six human subjects (A, B, C, D, E and F) were measured. Figure 5 illustrates the experiment with an example that shows the variation of the AT in the case of five noise intensity levels for 10 trials obtained from subject A.

Table 2 (a), (b) and (c) show the data for 35, 50 and 75 Hz, respectively. The mean value of the AT and the standard deviation of the mean obtained from 10 trials were calculated to discuss the results.

Table 2. Results of the experimental data that show the average value (Mean: μm_{0p}) and standard deviation of the value (SD) in six noise intensity levels for six subjects (A, B, C, D, E, F).

(a) Frequency: 32 Hz

Applied Noise (μm_{rms})	**Human Subjects**											
	A		**B**		**C**		**D**		**E**		**F**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	1.6	0.18	1.25	0.19	0.9	0.12	1.7	0.12	1.69	0.19	1.09	0.11
0.04	1.18	0.24	1.13	0.26	0.84	0.13	1.51	0.12	1.75	0.3	0.89	0.12
0.09	1.2	0.26	1.32	0.11	0.8	0.14	1.44	0.14	1.76	0.29	0.74	0.12
0.13	1.44	0.16	1.16	0.15	0.66	0.14	1.38	0.13	1.53	0.35	0.78	0.11
0.18	1.45	0.09	1.24	0.15	0.72	0.11	1.52	0.12	1.8	0.29	0.84	0.07

(b) Frequency: 50 Hz

Applied Noise (μm_{rms})	**Human Subjects**											
	A		**B**		**C**		**D**		**E**		**F**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	0.92	0.01	0.91	0.03	0.76	0.08	0.68	0.02	1.29	0.07	0.88	0.06
0.04	0.79	0.04	0.78	0.03	0.66	0.05	0.64	0.02	1.15	0.07	0.73	0.05
0.09	0.74	0.03	0.77	0.03	0.64	0.04	0.62	0.03	1.07	0.08	0.78	0.07
0.13	0.73	0.04	0.73	0.05	0.57	0.03	0.44	0.05	1.06	0.06	0.66	0.08
0.18	0.83	0.04	0.84	0.06	0.68	0.04	0.4	0.03	1.14	0.09	0.75	0.08

(c) Frequency: 75Hz

Applied Noise (μm_{rms})	**Human Subjects**											
	A		**B**		**C**		**D**		**E**		**F**	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0	0.83	0.07	0.79	0.1	0.81	0.07	0.7	0.02	1.25	0.09	0.9	0.09
0.04	0.66	0.04	0.7	0.06	0.66	0.04	0.66	0.02	1.08	0.15	0.74	0.06
0.09	0.67	0.04	0.64	0.04	0.63	0.04	0.66	0.05	1.1	0.11	0.72	0.08
0.13	0.64	0.06	0.59	0.06	0.59	0.03	0.57	0.03	1.04	0.1	0.65	0.05
0.18	0.72	0.06	0.59	0.07	0.64	0.06	0.61	0.04	1.09	0.15	0.72	0.07

Figure 6 illustrates the relationship between the AT and the applied noise intensity. According to Fig. 6, the AT values at no noise intensity level (0μm$_{rms}$) are around 1.37 μm$_{0p}$, 0.91μm$_{0p}$ and 0.88 μm$_{0p}$ for 32, 50 and 75 Hz, respectively. These graphs show a shallow U-shape and have a local minimum demonstrated by the elliptic in Fig. 6.The local minimum AT value is 1.16μm$_{0p}$, 0.70μm$_{0p}$ and 0.68μm$_{0p}$ for 32, 50 and 75 Hz, respectively.

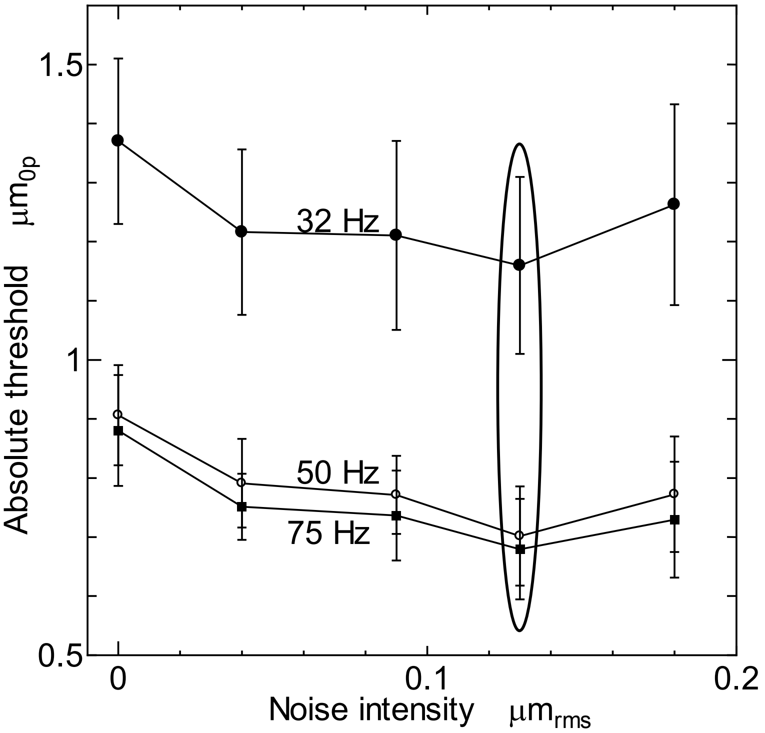

Figure 6. Average threshold curves; vertical bars are standard errors.

If the noise intensity, which is larger than 0.18μm$_{rms}$, is added to the sinusoidal signal, no human subject could identify the signal buried in noise. Thus, we did not perform any examination with noise intensity of more than 0.18 μm$_{rms}$. This means that AT increases very rapidly after 0.18-μm$_{rms}$ noise intensity. Consequently, the tactile sensitivity of humans is enhanced with an appropriate level of noise.

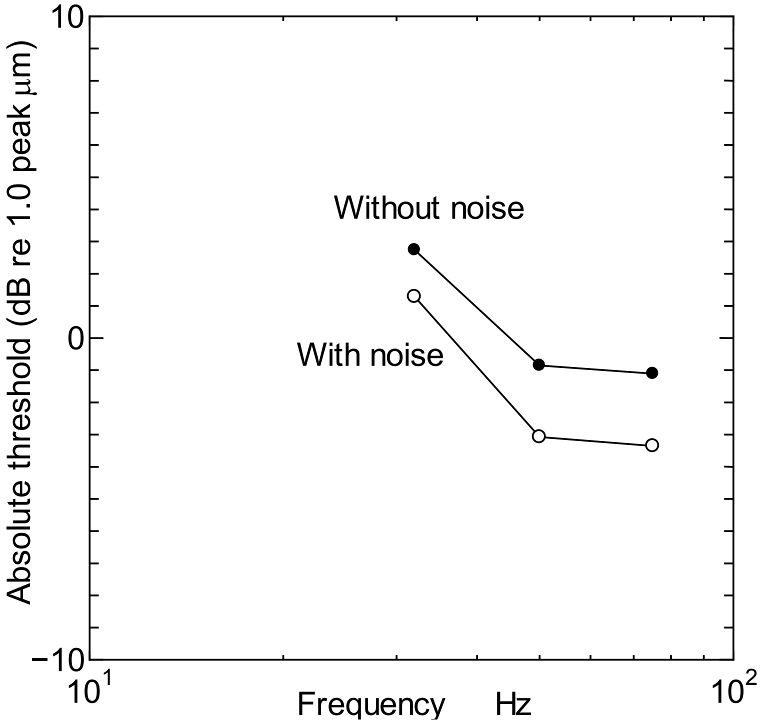

Figure 7. Relationship between threshold and frequency, which is affected by applied noise level

Figure 7 shows relationships between minimum AT and frequency, which are obtained in Fig. 6. There are two curves: one of them is without noise and the other is with noise. The AT curves decrease with increase of frequency. If the curve with noise is shifted to the vertical direction with 2-3 dB, it is almost over lapped to the curve without noise. This means that sensitivity of the mechanoreceptive unit is enhanced by the appropriate noise. Since the inclination of the curve of AT obtained by 35- and 50-Hz data is around -1 (-20 dB/dec) in both noise and without noise conditions, SR is caused by the FA-I mechanoreceptive unit in the range of frequency.

b. Discussion

First, we discuss the reliability of the experimental results. Since in this study we examine AT in the limited region of frequency 32-75 Hz, we will introduce the result obtained by Miyaoka et al. [21][22], which examined human AT of vibrotactile sensation in a wide range. Dotted lines show AT of FA-I and FA-II obtained from Miyaoka's data. Since the present human subjects'sensitivity is larger than that of the human subjects in Miyaoka's experiments with around 5 dB, the dotted lines are shifted to the inverse vertical direction.

Although the two points of the no-noise condition (32 Hz and 50 Hz) coincide with Miyaoka's FA-I data, the point of 75Hz is not on FA-II of Miyaoka's data. The reason we obtained this result relates to FA-II's sensitivity affected by temperature. While Miyaoka et al. took care of the temperature by using a special heater to heat the contactor, we did not do that. Since FA-II is very affected by temperature, AT of FA-II is shifted in the direction of the arrows in Fig. 8 when we did not attend to the temperature characteristic of the mechanoreceptive unit. Consequently, AT of FA-I peaks at 75 Hz in Fig. 8. Although the value of AT at 75 Hz seems to be larger than the usual vibrotactile data, FA-II's sensitivity is simply decreased in this experiment.

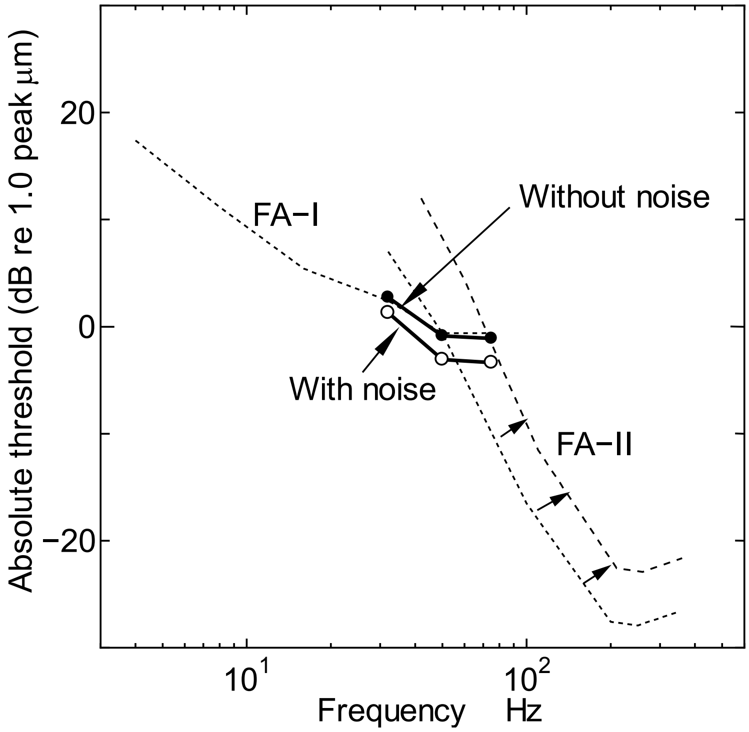

Figure 8. Relationship between threshold and frequency, which is affected by applied noise level.

Finally, since the two curves with and without noise have similar variation in frequency, the effect of SR seems to be generated in FA-I. However, since in our study we examined it in the limited frequency range, we cannot completely conclude that SR is one of the phenomena caused atthe receptor level yet. Further experimental data are required.

IV. CONCLUSION

In this study, we investigated the influence of the SR phenomenon on human tactile sensation in the context of frequency-dependence of absolute thresholds using aseries of psychophysical experiments with the method of limit. Experimental results indicated that, with the help of noise, the absolute thresholds decreased, indicating that SR occurred with AT variation in frequency from 32 to 75 Hz. Thus, human vibrotactile sensation is enhanced by an appropriate level of noise. Moreover, according to the result of the AT variation in frequency, the tactile SR in the frequency is almost similar, and SR observed in this test is caused by the FA-I mechanoreceptive unit.

However, since the prior and present studies are not sufficient to elucidate the characteristics of SR on mechanoreceptive units, we consider that further experimental studies in the high-frequency condition are required. Since the tactile SR seems to be generated in the mechanoreceptor, we intend to incorporate the SR mechanism not into computer software but into tactile sensor hardware if we apply the present study's results to robotics.

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