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Improvement of tactile sensitivity by stochastic resonance effect - Applications to surgical grasping forceps -

Yamato Sueda[1], Minoru Hattori[2], Hiroyuki Sawada[2], Hiroyuki Egi[2],
Hideki Ohdan[2], Jun Ueda[3], Toshio Tsuji[4], and Yuichi Kurita[4]

Abstract— **This paper reports experimental results on a surgical grasping forceps with a vibration actuator that enhances a tactile perception ability. A short-time exposure of tactile receptors to sub-sensory white-noise vibration is known to improve perception ability. This phenomenon, called stochastic resonance (SR) in the somatosensory system, is expected to enhance the sense of touch when the weak vibration is applied to a fingertip, and thereby improve associated motor skills. A lead zirconate titanate (PZT) actuator was attached on the grip of surgical grasping forceps. A passive sensory test has been conducted for healthy subjects to confirm the efficacy of the device. Statistical significance has been observed when appropriate noise is applied. To investigate the effect of the noise intensity, a summing network of FitzHugh-Nagumo model neurons was built. The simulation results showed that a network with relatively large units can improve the detection capability of the input signal.**

I. INTRODUCTION

Stochastic resonance (SR) is known to improve the sensitivity of a nonlinear system to weak stimuli in the presence of noise[1], [2], [3]. SR has been observed in the mechanoreceptors of animals such as crayfish, toads and rats[4], [5], [6]. It has been reported that the sensitivity of human's somatosensory receptors can be improved by a short-time exposure to sub-sensory white-noise vibration in visual and auditory systems[7], [8]. SR also enhances tactile and haptic abilities. Kurita et al. has reported the concept of a sensorimotor enhancer and shown the improvement in the tactile sensitivity[9]. In their work, a compact lead zirconate titanate (PZT) stack actuator was placed at a fingertip and a small vibration was given to the tactile receptors inside the fingertip. The developed sensorimotor enhancer is expected to assist persons who require dexterous skills. Kurita et al. have also applied their concept to a medical instrument[10]. The PZT actuator was attached on surgical grasping forceps, which are used in a minimally invasive surgery, and the vibration was transmitted to a subject's finger via the grip of the forceps. They have reported the improvements in tactile sensation through passive and active sensory tests.

Interestingly, the experimental results we have conducted in previous studies[9], [10] suggest that not only the maximum sub-sensory noise, which is just below the perception threshold and considered the optimal intensity, but also much smaller or even supra-sensory noise enhances the tactile sensitivity. Collins et al. have shown that noise does not significantly degrade the signal detection ability when the supra-sensory noise is applied based on the system response of a summing network of excitable units[11]. In this paper, we consider a summing network model of tactile receptors to investigate how the signal detection ability changes depending on the intensity of the noise.

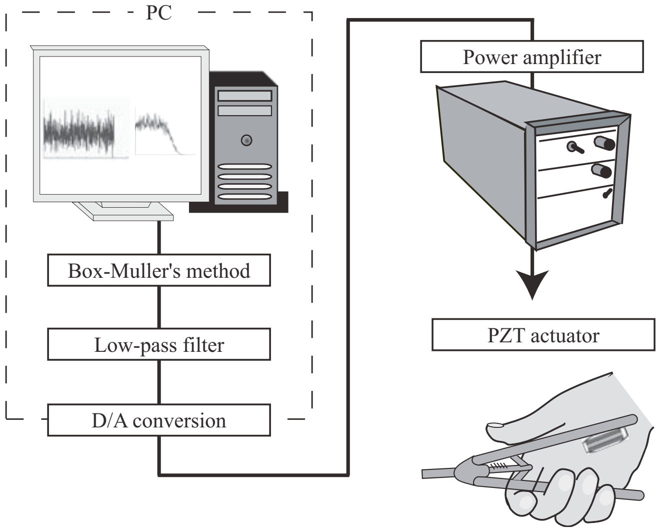

Fig. 1. System overview of the PZT actuator control

II. PASSIVE SENSORY TEST FOR HUMAN SUBJECTS

A. Experimental system

Fig.1 shows the system overview to generate vibration. The system was composed of a PZT actuator as a vibration source, surgical grasping forceps, which is used in a minimally invasive surgery, a power amplifier, and a computer to control the vibration. Fig.2 shows the developed forceps with the PZT actuator. The PZT actuator was attached at the grip of the forceps, and it generates a low-pass filtered white-noise vibration. Taking the frequency response characteristics of the tactile mechanoreceptors into account, vibration with a cutoff frequency of 300 [Hz] was applied to the hand. White noise signal $X(t)$ was generated based on Box-Muller's method defined by Eq. (1) with the standard deviation of σ:

$$X(t) = \sigma\sqrt{-2\ln\alpha(t)} \cdot \sin 2\pi\beta(t) \qquad (1)$$

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[1] Graduate School of Engineering, Hiroshima University, Hiroshima, Japan

[2] Institute of Biomedical Sciences, Hiroshima University, Japan

[3] George W. Woodruff School of Mechanical Engineering Georgia Institute of Technology

[4] Institute of Engineering, Hiroshima University, Hiroshima, Japan

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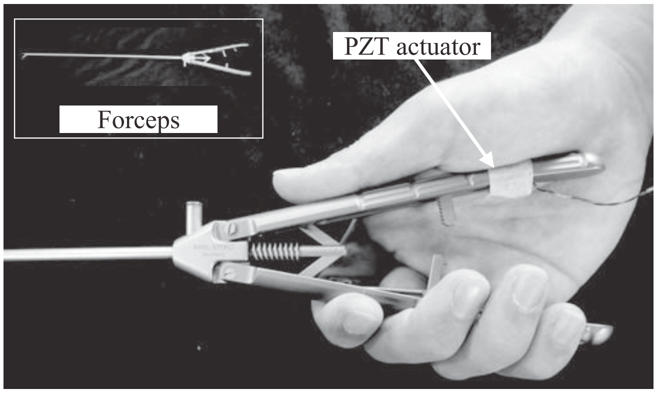

Fig. 2. Grasping forceps with the PZT actuator at the grip

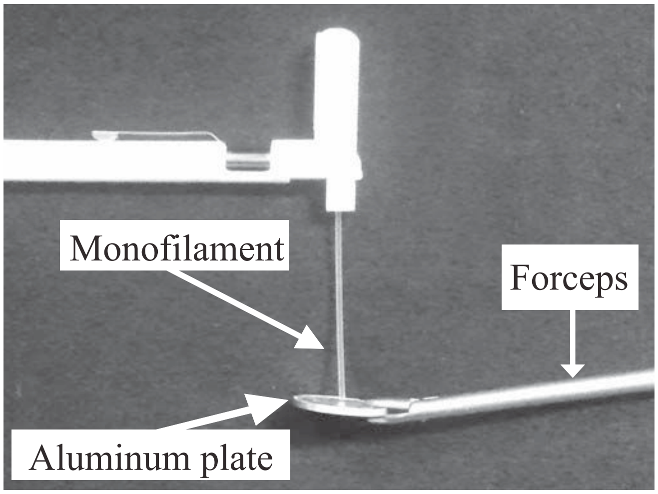

Fig. 3. Passive sensory test with the developed forceps

where $\alpha(t)$ and $\beta(t)$ are uniform pseudorandom numbers, and t is time.

B. Experiment

1) Detection of the perceptual threshold: In order to confirm the improvement in tactile sensitivity when using the forceps, we conducted a passive sensory test with human participants. 12 male healthy subjects aged 22-24 years old participated in the experiment. Prior to the experiment, the threshold of vibrarion perception was detected for each subject. Each subject was asked to grasp the grip of the forceps with his dominant hand. During the experiments, the torso and the non-dominant hand of the subject were in a relaxed state to minimize unwanted movement.

The vibration produced by the PZT actuator was transmitted to the subject's hand, in particular, his base of the thumb via the grip of the forceps. The subject was asked to report if he felt the vibration when the signal intensity changes. The maximum intensity that the subject could NOT feel, i.e., the maximum sub-sensory threshold, was recorded by an experimenter.

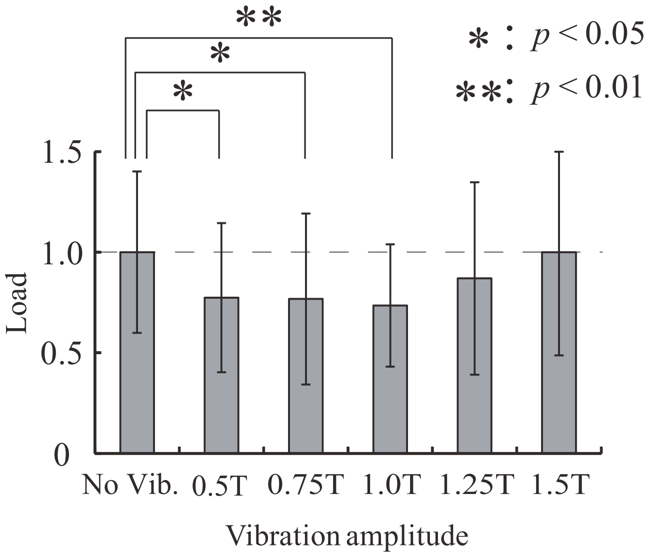

Fig. 4. Experimental results of the passive sensory test

2) Passive sensory test: In the following experiments, no-vibration and five different noise intensity conditions (50, 75, 100, 125 and 150 [%] of the perception threshold, denoted as 0.5T, 0.75T, 1.0T, 1.25T and 1.5T respectively) were conducted in a random order. All subjects gave informed consents before participating.

The subject was asked to grasp the forceps and close his eyes. The hand with the forceps was placed on a table. The experimenter pressed a monofilament against an aluminum plate pinched by the tip of the forceps until buckling occurred, held it for approximately 1.0 [sec], and then removed the monofilament. The subject was asked to report if he could feel the filament in contact. A total of 10 Semmes-Weinstein monofilaments (Touch-Test Sensory Evaluator): 0.008, 0.02, 0.04, 0.07, 0.16, 0.4, 0.6, 1.0, 1.4 and 2.0[g] were used under the aforementioned six conditions. Each subject performed four trials for each vibration condition. The subjects were not informed of the vibration intensity. The average of the answers in the four trials was recorded as the minimal load the subject can sense. The overview of the experiment is shown in Fig.3.

C. Result

The experimental results are shown in Fig.4. The horizontal axis is the vibration intensity that determines σ in Eq.(1). The vertical axis of the figure is the normalized minimal load against the minimal load measured in the no-vibration (No vib.) case. A smaller load indicates a better tactile sensitivity. The results showed that the minimal loads for the controlled cases of 0.5T, 0.75T, 1.0T, and 1.25T were smaller than that of the no-vibration case. A one-way analysis of variance (ANOVA) detected a significance main effect of vibration intensity ($p < 0.01$). The post-hoc Dunnett test detected significant differences against the no-vibration case for the cases of 0.5T and 0.75T ($p < 0.05$) and 1.0T ($p < 0.01$).

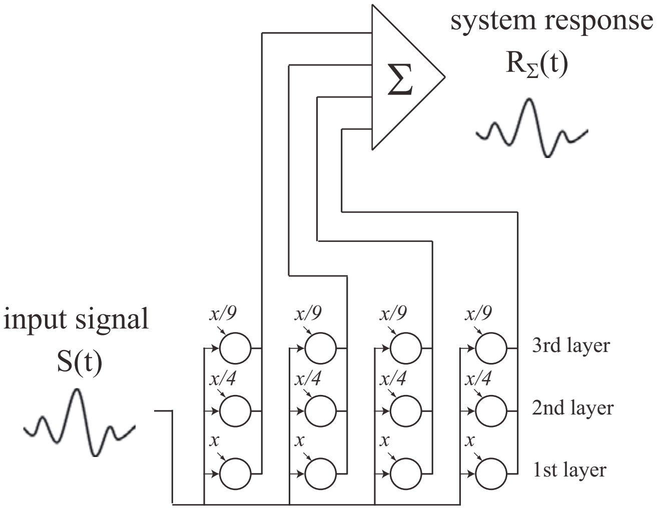

Fig. 5. A summing network of FitzHugh-Nagumo nueron models. In this figure, the three-layered network is shown. The noise given to each neuron is attenuated according to the square of the layer depth.

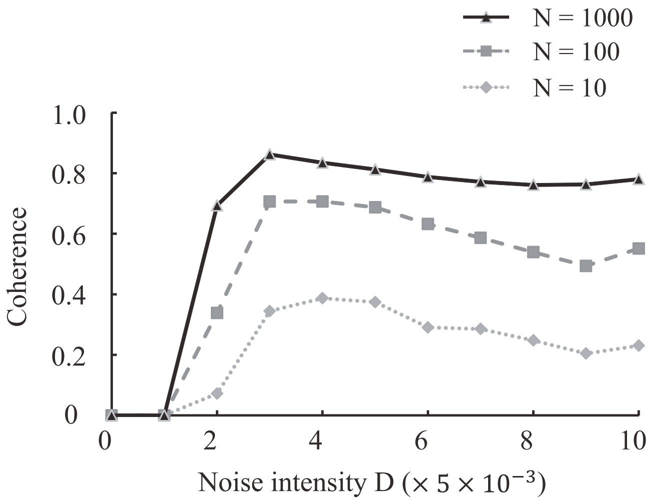

Fig. 7. Coherence C calculated against the noise intensity based on Eq.(4) for N=10, 100, and 1000, respectively

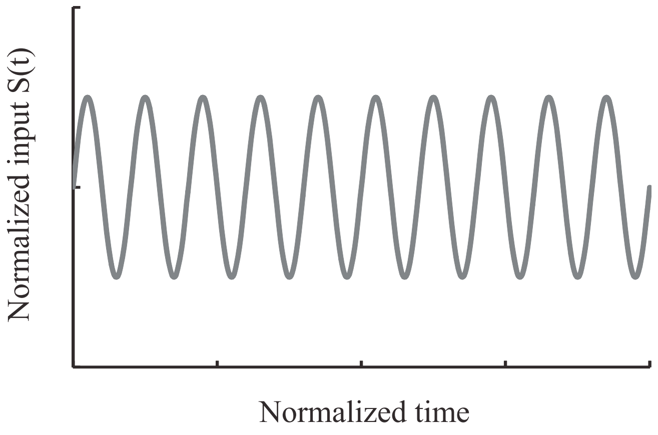

Fig. 6. Input signal (external stimuli) given to each neuron.

III. SIMULATION BY A SUMMING NETWORK MODEL

A. Summing network model of excitable units

A summing network of excitable units that correspond with tactile receptors inside a hand was considered based on [11], [12] to investigate the effect of the noise intensity. The schematic is shown in Fig.5. Each excitable unit is a FitzHugh-Nagumo model neuron[13] governed by the following equations:

$$\varepsilon \dot{V} = V(V-a)(1-a) - W + S + \xi \tag{2}$$

$$\dot{W} = V - W - b \tag{3}$$

Where V is a voltage variable, W is a recovery variable, ξ is Gaussian white noise given to each neuron with zero mean, S is an external stimuli (input signal), and $a = 0.5, b = 0.15, \varepsilon = 0.005$ are constants. The network has N excitalbe neurons in total and a multi-layered structure. In this study, the network has 10 layers; each layer has $N/10$ neurons. Considering the viscoelastic property of a hand, the noise intensity transmitted to the neurons was attenuated with the assumption that the attenuation increases as the square of the distance from a vibration source. Sinusoidal wave, which is shown in Fig.6, was given to the system as the input signal.

The equations were solved by a fourth-order Runge-Kutta method by using a MATLAB function. The obtained voltage V was converted to spike trains that corresponds to the firing of each unit. Then, the spike trains were converted to a mean firing rate (MFR) signal $R(t)$ for each unit, which means the number of spikes per second produced by each unit. The summation of the MFR signal of each neuron gave the resultant MFR signal $R_\Sigma(t)$ of the system.

The correlation between the input signal (external stimuli) $S(t)$ and the resultant MFR signal $R_\Sigma(t)$ was calculated by the normalized power norm given by [14]:

$$C = \frac{\overline{(S(t) - \overline{S(t)})(R_\Sigma(t) - \overline{R_\Sigma(t)})}}{\overline{[S(t) - \overline{S(t)}]^{1/2}}\,\overline{[R_\Sigma(t) - \overline{R_\Sigma(t)})]^{1/2}}} \tag{4}$$

We conducted the simulations 50 trials for each case of $N = 10$, 100, and 1000 with different noise.

B. Result

The mean resultant MFR signal of the system with $N = 10$, 100 and 1000 are shown in Fig.7, respectively. The vertical axis is the correlation value C given by Eq.(4). The horizontal axis is the noise intensity, which determines the noise given by $x = D \times \mathrm{randn}()$ where randn() is a MATLAB function.

As the correlation approaches to 1, the coherence between the input signal $S(t)$ and the system response $R_\Sigma(t)$ is maximized. The system responses with the noise intensity around $D = 4$ had relatively high correlation for any network size, Fig.8 and Fig.9 show the system responses with $N = 10$ and $N = 1000$ at the noise intensity of $D = 4$, respectively. The response of the system with $N = 1000$ was apparently closer to the input signal than that of the system with $N = 10$.

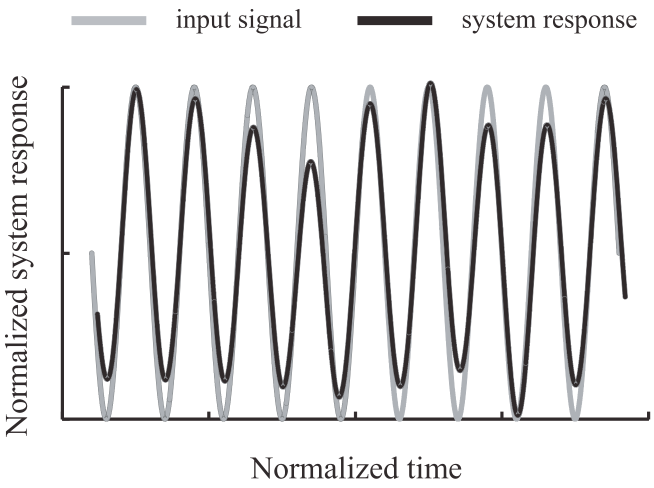

Fig. 8. Sytem response of the summing network with N=1000

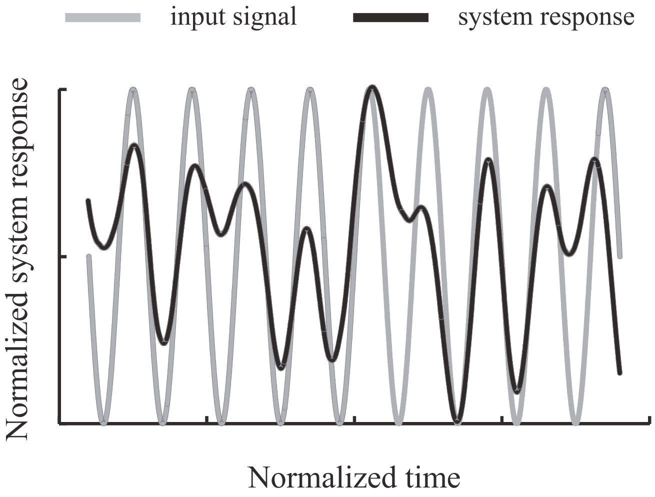

Fig. 9. Sytem response of the summing network with N=10

C. Discussion

The experimental results suggest that the network with relatively large units can improve the detection capability of the input signal. Importantly, the large network extended the range of the noise intensity that enhances the coherence. Fig.4 shows that not only the noise intensity of 1.0T, which is considered the optimal intensity because it is the maximum sub-sensory threshold, but also 0.5T and 0.75T intensity improve the tactile sensitivity. Our previous studies[9], [10] also showed that noise can improve the tactile sensitivity even if the intensity is not theoretically optimal. It is known that a human's hand has tens of thousands of tactile receptors. Our experiment and simulation show that such a large sytem does not require the the rigorous optimization of the noise to improve the sensitivity.

IV. CONCLUSION

For the purpose of exploring the medical application of stochastic resonance effect, we developed a surgical grasping forceps with a vibration actuator. A passive sensory test with the developed forceps showed that the tactile sensitivity is improved when the vibration with the intensity of 50%, 75%, and 100% of the perception threshold are applied. A summing network of FitzHugh-Nagumo neurons was built in order to investigate the system response when white noise is added to the neurons. The noise was assumed to be attenuated depending on the distance from the vibration source. The simulation results suggested that a network with relatively large neurons extends the range of the noise intensity where the perception sensitivity is enhanced.

Future work includes considering better designs of vibration actuators. Actual vibration transmissibility characteristics are also needed for the further investigation of stochastic resonance of signals occured inside a human hand.

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