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Stochastic resonance aided tactile sensing

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SUMMARY
Stochastic resonance (SR) is one of the basic principles intrinsically possessed by any living thing to highly adapt to complicated environments including various disturbances. Although a noise is inevitably mixed by contact with an object and a sensor's movement on it in tactile sensing, a human being can evaluate the several micrometers of unevenness on the object surface by means of SR. We intend to apply SR to tactile sensing and to develop a tactile sensing system capable of measuring an object surface with high precision in not only a controlled environment like a precision measurement room but also in a living environment. First, we investigate the SR characteristic possessed by a Hodgkin–Huxley model capable of emulating squid's neuron activities. According to the simulation results, we develop a new electronic circuit capable of generating the SR. We perform the object surface scan using a linear stage equipped with a tactile sensor and the circuit. A series of object surface scanning tests is repeated while changing the intensity of applied noise, and the signal to noise ratio (SNR, hereafter) is calculated from the obtained measurement data to check the effect of the SR. In the experiment, striped textures with a height of $\delta = 5 \sim 30\,\mu$m are used as specimens. The SNR changes depending on the noise intensity, and the local maximum appears under a proper noise. It is found that the sensing accuracy is improved according to the aforementioned SR theory. Therefore, SR, which is usually applied to noisy environments, is effective for a tactile sensing system.

KEYWORDS: Tactile sensor; Complex systems science; Stochastic resonance; Hodgkin–Huxley model; Bio-mimetic processing.

1. Introduction

Stochastic resonance (SR, hereafter) is one of the basic principles intrinsically possessed by any living thing to highly adapt to complicated environments including various disturbances, and it attracts many researchers' attention because it is considered to be a source of such high adaptation capability as described in some survey papers.[1,2] A deterministic dynamics may be enhanced when fluctuation and random disturbance occur in a nonlinear dissipative system. According to this effect of SR, it is possible to detect a signal by superimposing a proper noise on an undetectable weak signal. SR phenomenon in a single neuron is observed in simulations of a numerical model[3,4] as well and is being examined in realms such as neuron neurophysics[5,6] and brain science.[7,8]

Although in tactile sensing, a noise is inevitably mixed by contact with an object and a sensor's movement on it, a human being can evaluate the several micrometers of unevenness on the object surface.[9,10] In addition to these experimental results, it has been found that a human being effectively utilizes SR in tactile sensation.[8] Therefore, it is expected that we can build a new tactile sensing system possessing high robustness for adaptation over environmental change and disturbance by mimicking biological information processing.

The purpose of the present research is to apply SR to tactile sensing. On the basis of the results, we intend to develop a tactile sensing system capable of measuring an object surface with high precision in not only a controlled environment like a precision measurement room but also in a living environment. It will be utilized in tactile sensor-mounted robots, which have been researched in the previous papers.[11,12]

There are some human tactile receptors emitting spontaneous immanency noise, and a mechanical noise occurs when we scan an object surface with our finger. Corresponding to both noises, we develop a system in which an immanency noise is generated by an electric circuit. The system consists of a strain gauge-type pressure sensor, a linear motor, and an analog circuit. We verify the system using a series of object surface scanning experiments. We perform the object surface scan using SR after we adjust the parameters of the system so its detection ability reaches the undetectable level for weak unevenness. We repeat an object surface scan while changing the intensity of applied noise and compute the signal to noise ratio (SNR, hereafter) from the obtained measurement data to check the effect of SR. In the experiment, striped textures with a height of $\delta = 5 \sim 30\,\mu$m are used as specimens.

2. Principle of SR

The concept of SR was originally put forward to explain problems such as periodically recurrent ice ages.[1] So far, phenomena related to SR have been found in fields such as physics, chemistry, biomedical sciences, and electronics.[2] In

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SR phenomena caused by nonlinear multistable systems, the noise dependence of SNR is written as

$$\mathrm{SNR} = \frac{A}{D^2} e^{-\frac{B}{D}}, \tag{1}$$

where A and B are constants depending on the systems. D denotes variance of input noise. Since Eq. (1) has a local maximum, it indicates that an appropriate value of D brings a maximum SNR.[2] Although A and B should be determined by a proper regression, they were determined by several numerical simulations in the subsequent chapters.

On the other hand, some researchers are trying to establish a model of SR to find whether the Hodgkin–Huxley model (HH model, hereafter)[13] can emulate the SR phenomenon.[3–5] The HH model is well known as a neuron model capable of emulating well a giant neuron of a spear squid.

In order to develop a new tactile sensing system enhanced by SR, we have investigated the HH model, which is a four-dimensional simultaneous nonlinear differential equation written as follows:

$$\begin{aligned} \frac{dV}{dt} &= -120m^3h(V-55) - 36n^4(V+72) \\ &\quad -0.3(V+49.387) + I(t) + \xi(t) \end{aligned} \tag{2}$$

$$\frac{dm}{dt} = \alpha_m(V)(1-m(V)) - \beta_m(V)m(V) \tag{3}$$

$$\frac{dh}{dt} = \alpha_h(V)(1-h(V)) - \beta_h(V)h(V) \tag{4}$$

$$\frac{dn}{dt} = \alpha_n(V)(1-n(V)) - \beta_n(V)n(V) \tag{5}$$

where

$$\alpha_m(V) = -\frac{0.1(35+V)}{e^{-(\frac{35+V}{10}+1)}+1}, \tag{6}$$

$$\beta_m(V) = 4e^{-(\frac{60+V}{18})}, \tag{7}$$

$$\alpha_h(V) = 0.07e^{-(\frac{60+V}{20})},$$

$$\beta_h(V) = \frac{1}{e^{-(\frac{30+V}{10})}+1}, \tag{8}$$

$$\alpha_n(V) = -\frac{0.01(50+V)}{e^{-(\frac{50+V}{10})}-1}, \text{ and} \tag{9}$$

$$\beta_n(V) = 0.125e^{-(\frac{60+V}{80})}. \tag{10}$$

In Eqs. (2)–(10), V and t are the membrane potential and time scaled in mV and ms, respectively. m, h, and n are nondimensional variables representing states of ionic channels of the neuron. $I(t)$ [μA] included in Eq. (2) represents the input signal provided by the other neuron through the axon. $\xi(t)$ is not included in the original HH model and is added in the present paper to represent SR. It denotes white noise and satisfies the following formulas:

$$\langle \xi(t) \rangle = 0, \tag{11}$$

$$\langle \xi(t_1)\xi(t_2) \rangle = D\delta(t_1 - t_2), \tag{12}$$

where $\langle\,\rangle$ and $\delta(\,)$ are mean operation and Dirac's delta function, respectively.

3. An Experimental Apparatus

In this chapter, we explain an experimental surface scanning apparatus shown in Fig. 1 developed for examining the SR effect capable of enhancing sensitivity while adding adequate noise into the input signal. The apparatus is composed of a strain gauge-type pressure sensor (This is the LM-A produced by KYOWA, Co. and is used as a tactile sensor. Hereafter, we call it the tactile sensor.), a z-stage (LZ632-S2, Tyuoh Seiki, Co.), and an automatic x-stage (ALS602H1M, Tyuoh Seiki, Co.) Acceptable maximum force and resolution of the tactile sensor are 20 N and 0.1 N, respectively.

Specimens with concave and convex textures formed by an etching process shown in Fig. 2 are attached to the automatic stage, and after the probe of the tactile sensor is compressed on the specimen's surface it scans the surface by means of the automatic x-stage. Width of both the concave and convex portions is 1 mm, and there are four kinds of specimens of 5, 10, 20, and 30 μm in step-height.

The following formula holds between stage velocity v (mm/s), wavelength of surface texture λ (mm), and frequency of surface texture f (s^{-1}):

$$v = f\lambda. \tag{13}$$

Since the texture length λ shown in Fig. 2 equals 2 mm, if the stage velocity v is assumed to be 6 mm/s, which is a

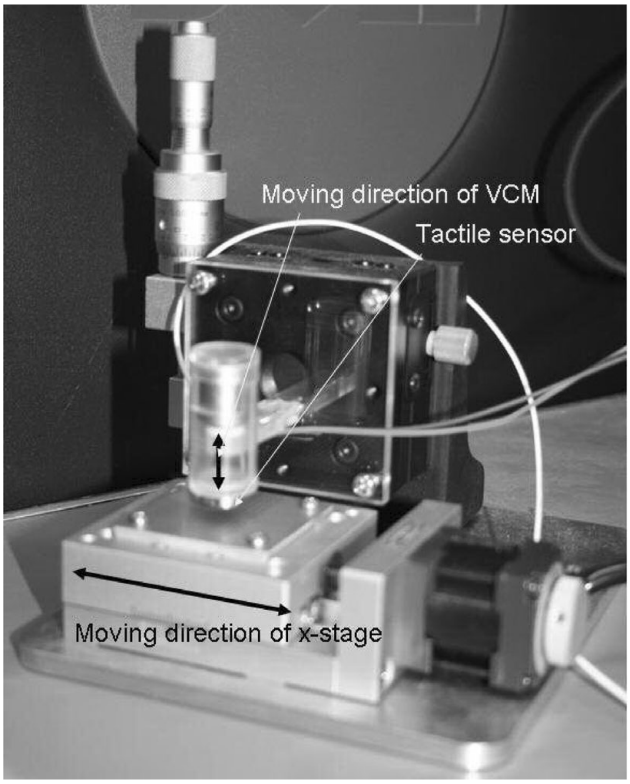

Fig. 1. Scanning testing machine equipped with tactile sensor.

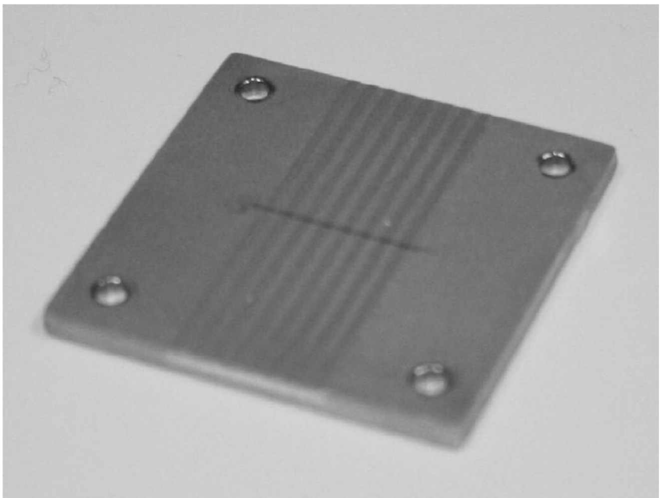

Fig. 2. Specimen with striped texture.

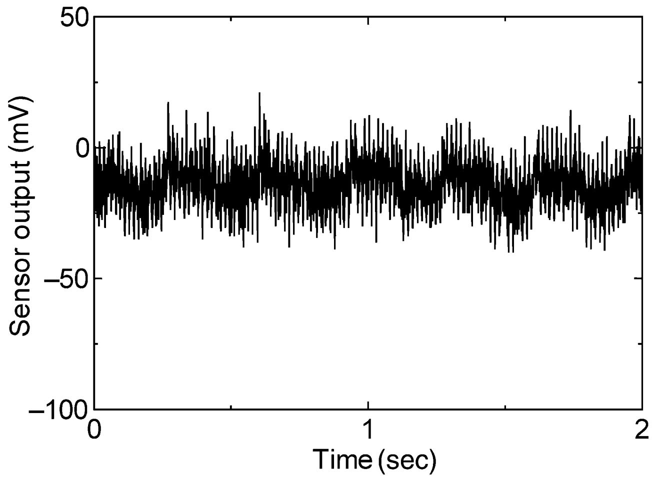

Fig. 3. Scanning result.

rather slow scanning speed for human being, the frequency is obtained as 3 s^{-1}.

Since a linear actuator (AB10, Act Giken; maximum force: 0.5 N) is attached on the backside of the tactile sensor in the present system, the compression load acting on the specimen is adjustable by means of controlling the current of the linear actuator. Since we estimated an optimum value of the compressive force as 0.3 N through several trials, force of 0.3 N is applied in the following experiments.

The variation in the tactile sensor's output under a scanning test of δ = 5 μm is shown in Fig. 3. If the probe of the tactile sensor goes up to the convex portion of the texture, the tactile sensor emits a high level signal as shown in Fig. 3. At the same time, we can see that noise is superimposed on the signal. The noise seems to originate from both an electronic circuit of the processing sensor signal and the mechanical contact between the sensor probe and the specimen surface. If we do not perform any additional signal processing, we cannot measure the surface morphology any more.

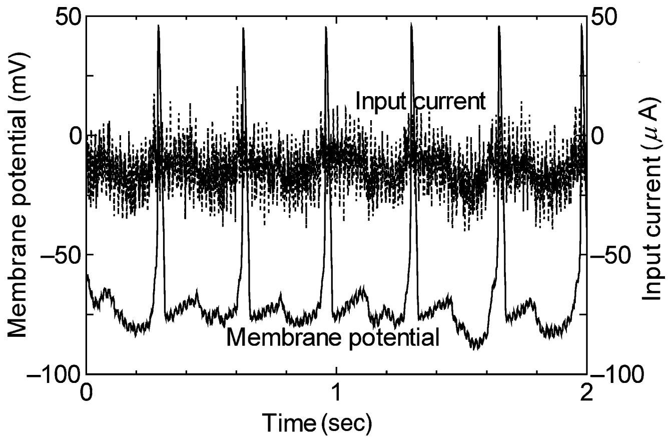

Fig. 4. Variation in membrane potential obtained by superimposing appropriate noise.

4. Simulation of HH Model

Since several researchers have reported the SR characteristic of the HH model so far,[5–7] we intend to first examine it in the case of surface texture sensing. We apply the output signal shown in Fig. 3 to the HH model of Eqs. (2)–(10). In this simulation, the unit of the output signal mV is transformed into μm to input it into the HH model. Since no pulses are emitted without any noise, Gaussian noise satisfying Eqs. (11) and (12) is superimposed on the input. Figure 4 shows the output of the HH model in the case of noise having deviation $\sqrt{D} = 5\ \mu$A. As shown in Fig. 4, pulses are emitted synchronously to the concave-convex wave of the surface. Therefore, it seems possible that an artificial SR system is established by implementing the HH model into the tactile data processing as software.

We examined the SR characteristics of the HH model within a rather wide $\sqrt{D}$ range to obtain the relationship between SNR and $\sqrt{D}$ shown in Fig. 5. A 9-point moving

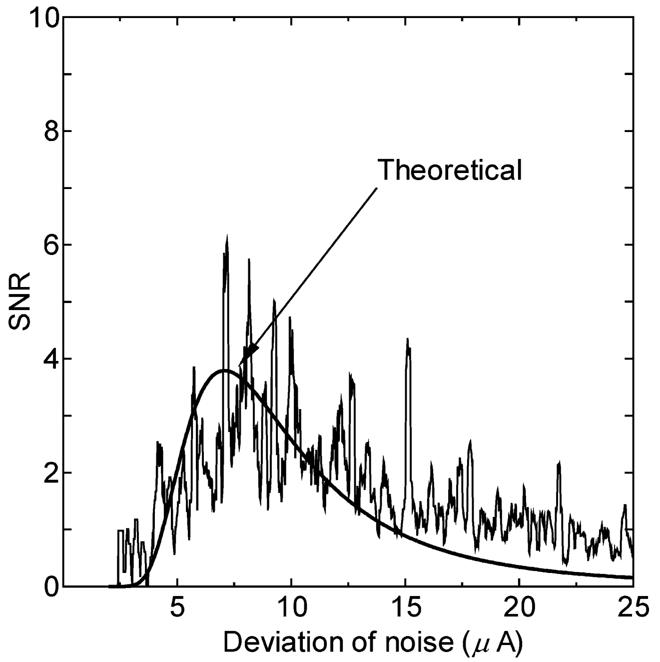

Fig. 5. Relationship between SNR and noise deviation for texture sensing test (δ = 5 μm).

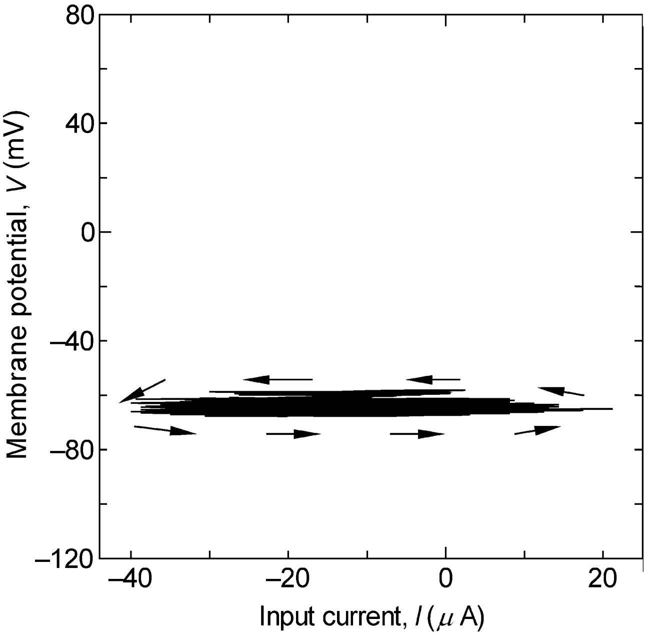

Fig. 6. Relationship between membrane potential and input current without noise.

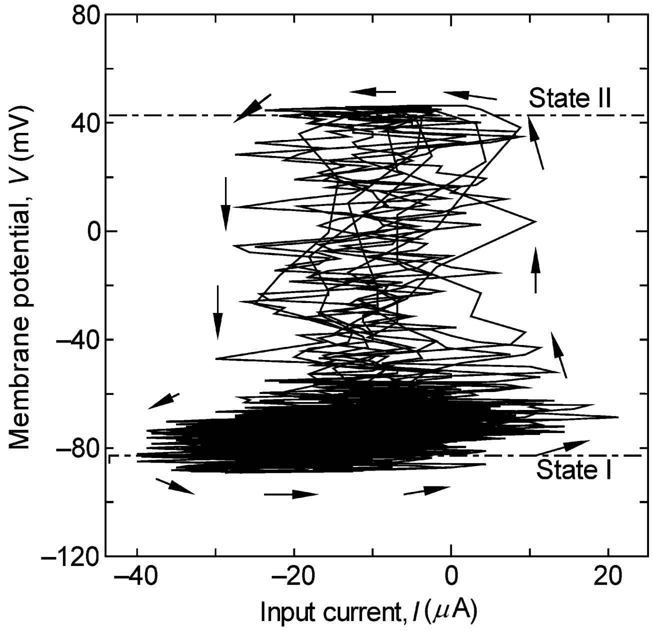

Fig. 7. Relationship between membrane potential and input current without appropriate noise.

average of SNR is shown in Fig. 5 because of the remarkable vibration of SNR. Even if the 9-point moving average is performed, marked variation in SNR is observed for small change in $\sqrt{D}$. In order to check whether an SR effect is caused in this simulation, we compare the simulated results with the theoretical result of Eq. (1) expressed by a thick solid line in Fig. 5. Although the difference between the simulated result and the theoretical result becomes slightly large in the large $\sqrt{D}$ region, the abscissa corresponding to the local maximum of the simulated result is almost the same as that of the theoretical result. As we discussed in the above paragraph, the HH model causes the SR phenomenon. This result has been observed by other researchers.[5–7] However, it is noted that the SNR is markedly varied even if a tiny deviation of input noise intensity is applied. There are no advantages if the HH model is incorporated into the tactile sensing system.

5. Experimental Tactile Sensing System

5.1. An electronic circuit emulating SR

Tactile sensors are composed of many sensing elements capable of detecting distributed pressure. Artificial SR tactile sensing, in which a neuron emulator such as the HH model is applied to each sensing element, is not always efficient from the viewpoint of computation cost.

On the other hand, it is well known that it is easy to make an artificial electronic circuit emulating the HH model.[9] Even if we succeed in producing such a kind of circuit, it has a problem related to the bumpy characteristic shown in Fig. 5. Hence we develop a new electronic circuit incorporating the essence of SR into itself.

In this section, we examine the SR phenomenon caused in the HH model. At first, we compare the state of SR occurring with that of SR not occurring. Figure 6 shows the state of SR not occurring. The relationship between membrane potential and input current moves almost along a single line in Fig. 6.

In contrast, in Fig. 7 showing the state of SR occurring, it can be seen that the relationship between membrane potential and input current shows a limit cycle. According to the limit cycle, if the membrane potential exceeds a threshold, the state moves from State I to State II. Then the state returns to State I after it emits a signal.

Since the HH model forms quaternary simultaneous equations, it is not easy to explain the relationship between the limit cycle and SR. A simple SR system such as the system represented by Eq. (1) is convenient for the present investigation. The quaternary simultaneous equations of the HH model are changed to dual simultaneous equations by means of omitting two minor variables, and the deducted dual simultaneous equations have similar characteristics to the physical system represented by Eq. (1).[4] In the physical system, it has a bi-stable characteristic and changes its physical state with external noise. The physical state is coming and going between two stable states by activation of noise. As a result, it causes the limit cycle and the SR phenomenon. Consequently, if we can develop an electronic circuit capable of emulating the limit cycle, we can artificially generate the SR.

On the basis of the above discussion, we developed the electronic circuit as shown in Fig. 8 and Appendix. The present circuit contains the Schmitt-trigger circuit, which generates the limit cycle.[2] The ordinary Schmitt-trigger circuit forms the symmetry limit cycle of the dashed line as shown in Fig. 9.

As we mentioned in Section 3, the convex-concave square wave is measured in the present system. The Schmitt-trigger circuit emits high and low level signals for convex and concave surface textures, respectively. The Schmitt-trigger circuit possesses higher and lower thresholds; if it accepts a low level signal below the lower threshold, it emits a high

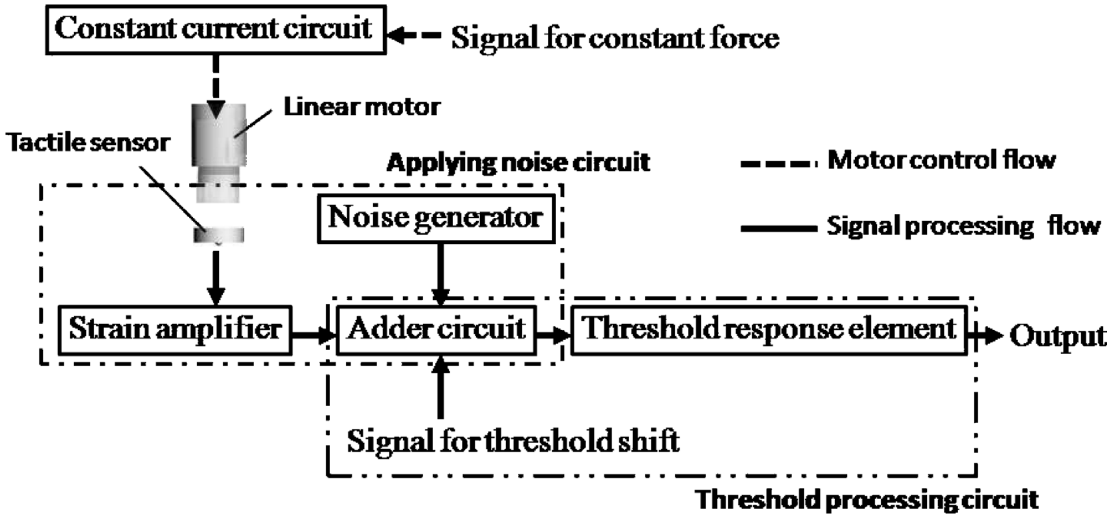

Fig. 8. Schematic block diagram of circuit generating SR.

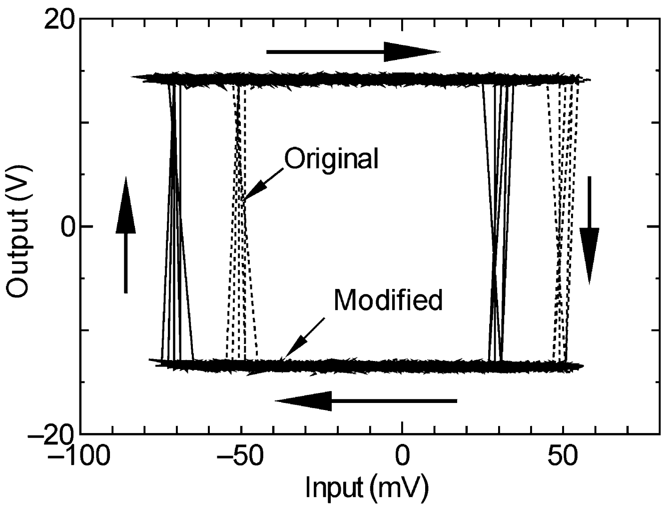

Fig. 9. Limit cycle obtained by Schmitt-trigger circuit.

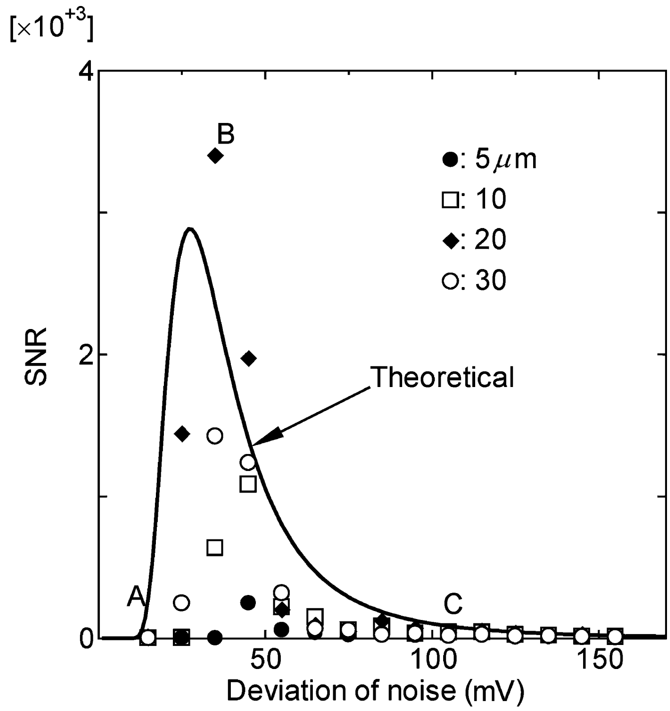

Fig. 10. Variation in SNR obtained by present circuit.

level signal and sets the higher threshold in itself; conversely, if it accepts a high level signal over the high threshold, it emits a low level signal and sets the lower threshold in itself. Due to the above mechanism, the signal from the tactile sensor is inversed before it is input to the Schmitt-trigger circuit. If noise is superimposed onto the weak input signal, the probability of the resultant input falling short under the lower threshold becomes larger. However, if the magnitude of the lower threshold coincides with that of the higher threshold as shown by the dashed line in Fig. 9, the probability of the resultant input exceeding the higher threshold becomes larger, and it seems to coincide with the probability of the resultant input falling short under the lower threshold. As a result, the output comes and goes between the low and high levels. To overcome this defect, the symmetry limit cycle of the Schmitt-trigger circuit is shifted as shown by the solid line in Fig. 9 to obtain the asymmetric loop. This shifting is performed by the added circuit demonstrated by "A" in Fig. 12 of appendix. Consequently, once the Schmitt-trigger circuit emits the high level, the output is latched onto the high level to maintain the high level until the next concave.

5.2. *Experimental result and discussion*

Texture recognition tests were performed using specimens possessing convex and concave fine strips $5 \sim 30$ μm in height on their surface to obtain the relationship between SNR and $\sqrt{D}$ as shown in Fig. 10. In Fig. 10, SNR is calculated by power spectrums of the noise and the ridge at $f = 3\ \mathrm{s}^{-1}$ corresponding to the ridge frequency of the surface texture. As shown in Fig. 10, SNR depends on noise intensity $\sqrt{D}$; it has a local maximum at about $\sqrt{D} = 35 \sim 45$ mV; in the region of high $\sqrt{D}$ SNR decreases with increase of $\sqrt{D}$.

They were moved by the motor-driven linear stage, and the probe was rubbed on the surface to obtain data of the convex and concave strips. Since the range frequency of a human tactile receptor was within several hertz, the speed of the linear stage was adjusted by taking into account the concave-convex interval of the texture. In Fig. 10, the solid curve shows the calculated results of Eq. (1). Since the theoretical curve fits the experimental results as shown in Fig. 10, the present circuit seems to possess an SR characteristic.

Output signal waves obtained at specific points are shown in Fig. 11 (a), (b), and (c) to examine precisely the above SR effect. The specific points correspond to symbols A, B, and C of 20 μm height in Fig. 10. In the case of point A, the circuit cannot respond to the input signal as shown in Fig. 11 (a). If an appropriate noise is added to the input signal, the output signal can follow the convex and concave texture of the specimen as shown in Fig. 11 (b). However, if the noise is too strong, output data are buried in the noise as shown in Fig. 11 (c).

It turns out that sensing accuracy is improved according to the aforementioned SR theory. Furthermore, the present system succeeds also in sensing the very subtle texture of $\delta = 5$ μm to obtain human-like tactile sensation. Therefore, SR, which is usually applied to noisy environments, is effective for a tactile sensing system.

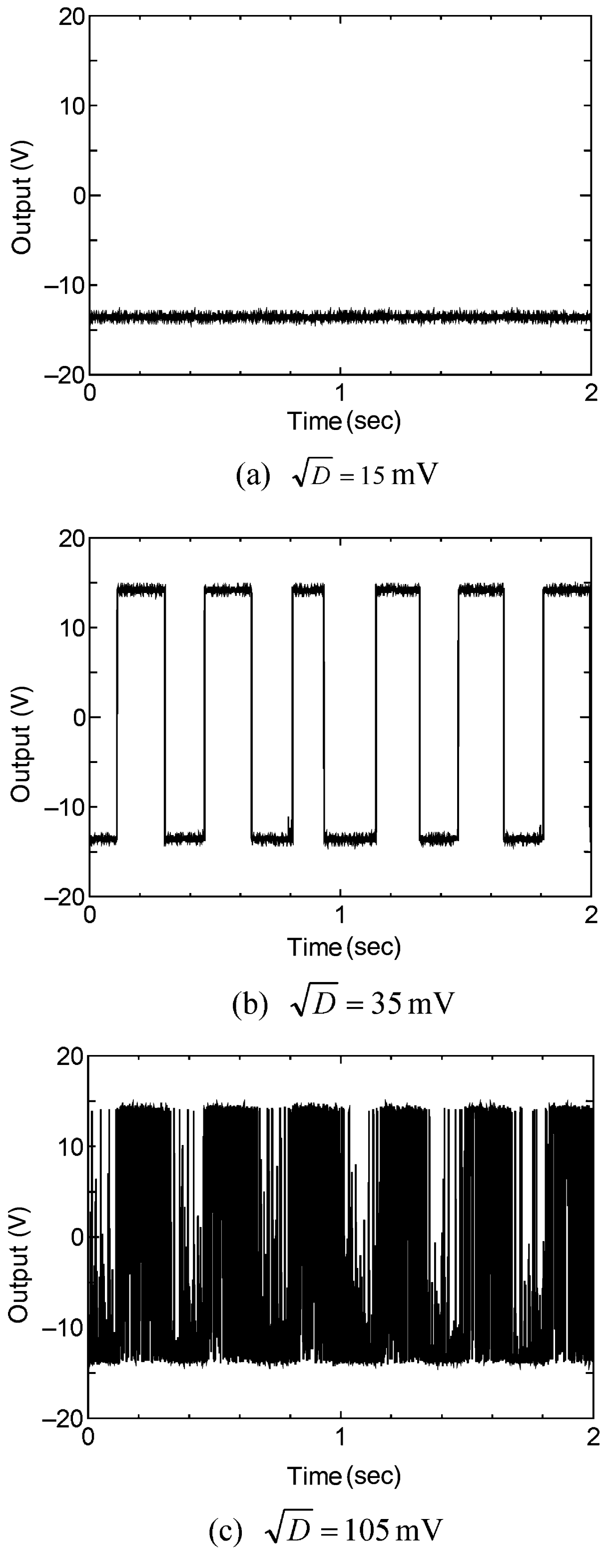

Fig. 11. Output of present circuit (a) $\sqrt{D} = 15$ mV, (b) $\sqrt{D} = 35$ mV, (c) $\sqrt{D} = 105$ mV.

6. Conclusion

In order to enhance the tactile sensing ability of robots by means of mimicking human tactile sensation, we developed a new electronic circuit capable of generating SR. We performed the object surface scan using a linear stage equipped with a tactile sensor and the circuit. A series of object surface-scanning tests was repeated while changing the intensity of applied noise and computing the signal to noise ratio (SNR) from the obtained measurement data to check the effect of SR. In the experiment, striped textures with a height of $\delta = 5 \sim 30$ μm were used as specimens. The SNR changed depending on the noise intensity, and the local maximum appeared under a proper noise. It was found that sensing accuracy was improved according to the aforementioned SR theory. Therefore, SR, which is usually applied to noisy environments, is effective for a tactile sensing system.

In future work, we will investigate more precisely the SR in human tactile sensation and intend to establish a new theory of the tactile sensing mechanism. In the investigation, we will elucidate the human tactile sensation function using psychophysical experiments, and produce a new neural network model on the basis of mimicking the human tactile sense function.

Acknowledgment

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Appendix

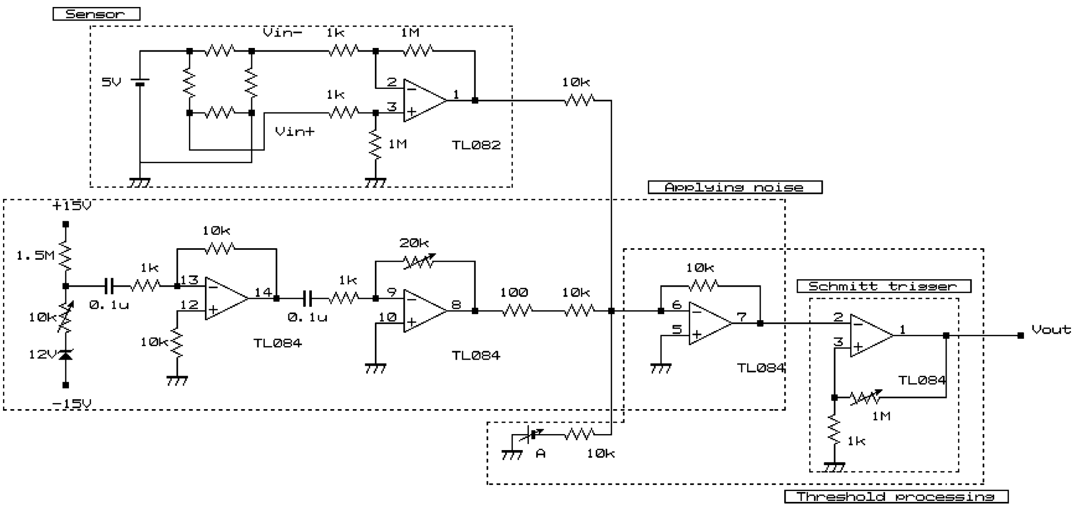

Fig. 12. Circuit generating SR including Schmitt trigger.