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A Novel Nonlinear Small-Signal Detection Circuit using Divergence Properties of Second-Order Linear Differential Equations

S. Yamakawa [1], K. Ando [2], M. Akai-Kasaya [2,3] and T. Asai [2]
[1] Graduate School / [2] Faculty of Information Science and Technology, Hokkaido University, Sapporo, Japan
[3] Graduate School of Science, Osaka University, Osaka, Japan
Tel.: + 81-11-706-7147
E-mail: yamakawa.soichiro.c6@ist.hokudai.ac.jp

Summary: There are already technologies for detecting signals, but there are no small-signal detecting sensors that are small size enough to be implanted in a living body yet. If such a sensor could be developed, it could serve as an interface between humans and devices and contribute to the development of various fields. We propose a new signal detection method that focuses on detection rather than measurement. Unlike conventional methods that amplify signals, the proposed method achieves detection by converting the input signal into changes of oscillator frequency. Its main advantage is the possibility of greatly reducing the circuit size and power consumption compared to conventional methods. To verify the proposed method, we performed a simple implementation experiment. Consequently, pulse signals were successfully detected using the proposed method. We believe that the circuit can detect many types of signals with appropriate implementation.

Keywords: Sensor, Non-linear circuit, Oscillator, Small signal, Differential signal.

1. Introduction

There are a lot of technologies for signal detection. However, large equipment is required for detecting small signals such as action potentials of neurons [1, 2]. This is because such equipment was developed for high spatio-temporal resolution and accuracy, which are required in the study of neuronal function. In this study, we propose a method that differs from conventional signal measurement sensors and have the potential for further miniaturization; a sensor targeting signals with small amplitude and small pulse width can be achieved by focusing on the function of detection instead of signal measurement. Studies that have used entropy-based complexity evaluation methods include the analysis of small signal time-series data to perform machine fault diagnosis and the classification of EEG signals [3-5]. By using the proposed method, there is the potential to collect data more easily than before and contribute to development of different fields. Therefore, we evaluate the effectiveness of the proposed method for signal detection with a simplified implementation.

2. Proposed Method

Instead of amplifying the differential input signals, we propose a method that involves converting them into oscillator frequency changes for detecting them.

The proposed method is achieved using the following linear dynamics:

$$\begin{pmatrix} \dot{V_1} \\ \dot{V_2} \end{pmatrix} = \alpha \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}, \tag{1}$$

where α is a real constant. V_1 and V_2 are potentials. Equation (1) can be expressed in terms of a second-order linear differential equation as follows:

$$\begin{cases} \ddot{V_1} - 2a\dot{V_1} = 0 \\ \dot{V_2} = a(V_2 - V_1). \end{cases} \tag{2}$$

If we define the initial state of V_1 and V_2 as

$$\begin{cases} V_1(0) = V_{\mathrm{in1}} + V_{\mathrm{noise}} \\ V_2(0) = V_{\mathrm{in2}} + V_{\mathrm{noise}}, \end{cases} \tag{3}$$

with differential inputs ($V_{\mathrm{in1}}, V_{\mathrm{in2}}$) and noise ($V_{\mathrm{noise}}$), the solution to equation (1) is as follows:

$$\begin{cases} V_1(t) = \frac{1}{2}\{(V_{\mathrm{in1}} - V_{\mathrm{in2}})e^{2\alpha t} + V_x\} \\ V_2(t) = \frac{1}{2}\{(V_{\mathrm{in2}} - V_{\mathrm{in1}})e^{2\alpha t} + V_x\} \\ V_x = V_{\mathrm{in1}} + V_{\mathrm{in2}} + 2V_{\mathrm{noise}} \end{cases}. \tag{4}$$

This equation shows that the behavior of V_1 and V_2 in this system follows noise without divergences when there is no differential input, and they diverges in either the positive or negative direction when there is a differential input. Here, under the condition that both V_1 and V_2 are set to zero when one of them exceeds a certain threshold value, the system oscillates as long as the differential input exists. Furthermore, the time required the value to exceed the threshold depends on $|V_{\mathrm{in1}} - V_{\mathrm{in2}}|$, as indicated by equation (4). Consequently, the oscillation frequency of the system depends on the input amplitude.

The above suggests that we can detect the presence or absence of differential inputs implementing the linear dynamics shown in equation (1) in a circuit.

3. Experimental Results

We performed experiments to determine whether the signals can be detected using the proposed method. Equation (1) can be implemented directly on a circuit, as shown in Fig. 1 [6]. To verify whether the proposed method can detect the input signal, it is sufficient to confirm that the oscillation frequency changes depending on the input; as can be seen from equation (4), the input does not necessarily have to be a differential input for the verification of the principle, since divergence can also occur if it is not a differential input. Thus, in the circuit shown in Fig. 1, we investigated the input amplitude dependence of the output oscillation frequency by giving a single-ended input.

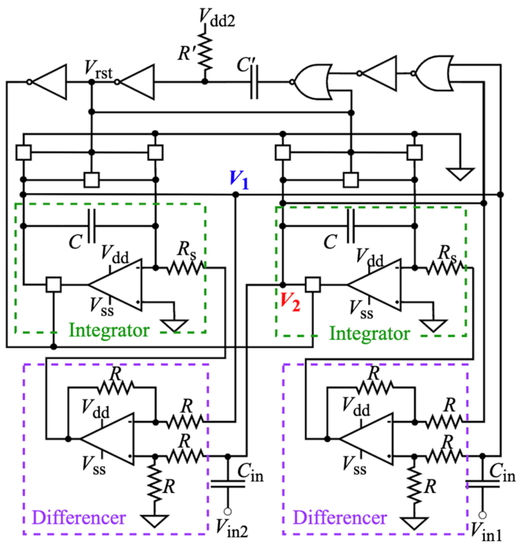

Fig. 1. Signal detection circuit.

Pulse signals (frequency: 200 Hz, amplitude: 0 to 1 V) were provided via the input terminal V_{in2} and we investigated the oscillation frequency for each of them. The input terminal V_{in1} is connected to 0 V(GND). Fig. 2 shows V_{rst} , V_1 , V_2 , and V_{in2} when the amplitude of the input signal is set to 0 V. Similarly, each potential changes as shown in Fig. 3 when the amplitude of the input signal is 1 V. Focusing on V_{rst}, V_1 and V_2 in Fig. 2, we can confirm the following behavior that; iv) reset operation for a certain period of time; i) reset ends; ii) V_1 and V_2 diverge; iii) reset is triggered because V_1 exceeds the threshold value, and the behavior becomes iv) again. Similarly in Fig. 3, i)' to iv)' are shown. The time it takes for V_1 to exceed the threshold value when the amplitude of V_{in2} is 1 V is shorter than when the amplitude of V_{in2} is zero. Similarly, we performed ten measurements and calculated the average output frequency from the average of those time. At each input amplitude, we also performed ten measurements and calculated the average frequency in the same way. The results are illustrated in Fig. 4. Fig. 4 shows that the frequency changes in dependence on the input amplitude and we demonstrated that the pulse signal input can be converted into a change in oscillation frequency. We believe that implementing the proposed method in an appropriate circuit can enable the realization of an effective circuit for detecting small signals, such as neural signals.

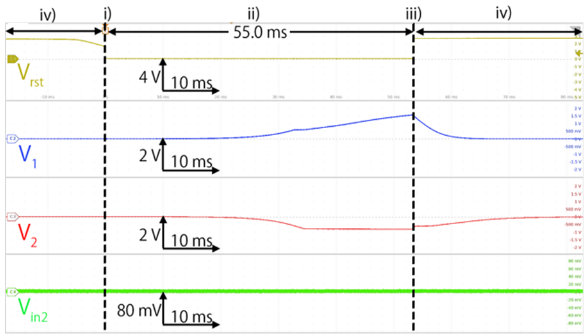

Fig. 2. Result when the amplitude of V_{in2} is zero.

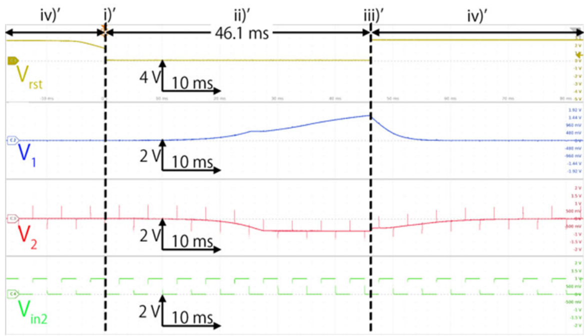

Fig. 3. Result when the amplitude of V_{in2} is 1 V.

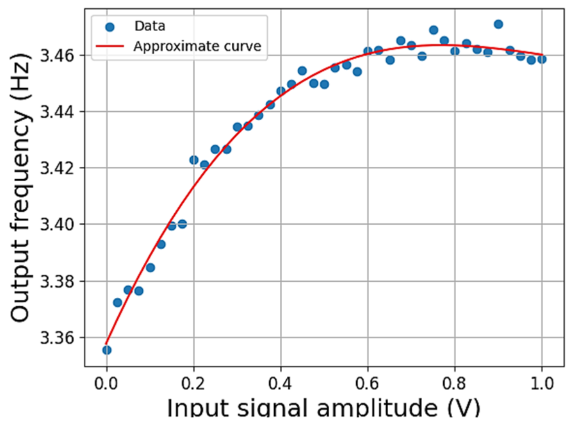

Fig. 4. Input amplitude dependence of frequency.

4. Conclusions

In this paper, we proposed a signal detection method that has the potential to be implemented in a compact and low-power-consumption package. Verification results revealed that the potential change provided by the input signal can be converted into a frequency change of the oscillator, and we confirmed that signal detection can be realized using this method. The accuracy and resolution of the proposed method depend on the implementation approach, and we believe that the proposed method can be applied to many fields by implementing it as a circuit suitable for the signal to be detected.

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