An analog-digital circuit for sound localization based on the biological auditory system

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***Abstract*:** In this study, we proposed the analog-digital circuit for sound localization based on the biological auditory system. The proposed circuit is constructed with the delay line and the comparator. The delay line was constructed with the simple analog circuits of current mode. The NOR circuit was used as the comparator. The current mode delay line was evaluated by the simulation program with integrated circuit emphasis (SPICE). The test circuit was fabricated by discrete metal oxide semiconductor (MOS) transistors on the breadboard. The result with SPICE and the measured results of the test circuit showed that the time for transmitting the signal of the current mode delay line becomes short when the sound of the target is large. When the sound of target is small, the time for transmitting the signal became long. The proposed circuit for sound localization was evaluated by SPICE. The result with SPICE showed that the circuit can generate the signal for detecting the position of the sound of the target. We can realize novel target tracking system by applying the novel circuit based on the biological auditory system to the previous proposed tracking system based on the biological vision system.

Keywords: sound localization, auditory system, tracking system, analog circuit, digital circuit,

I. INTRODUCTION

It is necessary for robotics vision, monitoring system and collision avoidance system to capture quickly the target in the center of the visual field. However, it is difficult for the typical systems using only vision system since the system can not detect the target when the target is not projected on the visual area. Both the vision system and the auditory system exist in the brain of the animal. The animal can capture the target in the center of the visual area by using auditory system which can process the sound information of the target and detects the position of the sound, even if the target is not projected on the visual area.

Recently, many researchers proposed and fabricated the simple circuit for target tracking system based on the biological vision system [1]-[3]. Since the circuits were proposed by mimicluing only the vision system, the system could not track the target when the target was not projected on the photodiode array which is input part. And the system could not track the target in the lightless situation since the dynamic range against light intensity of the circuit was small. If the circuit based on the vision system is connected with the circuit based on the auditory system, it is able to track the target in various situations. However, there are no simple circuits based on the auditory system.

L. A. Jeffress proposed the model for sound localization based on the biological auditory system [4]. The model is constructed with the delay line and the comparator.

In this study, we proposed the simple analog-digital circuit for sound localization based on the model by Jeffress. We tried to propose the simple analog circuit for delay line. We call the delay line the current mode delay line. The NOR circuit was used as the comparator. The results with the simulation program with integrated circuit emphasis (SPICE) and the measured result of the test circuit fabricated by discrete metal oxide semiconductor (MOS) transistors on the breadboard showed that the current mode delay line can operate normally. The results with SPICE showed that the proposed circuit can generate the signal for detecting the position of the sound of the target.

II. SOUND LOCALIZATION MODEL

Figure 1 shows the model for sound localization proposed by Jeffress [3]. The model is constructed with the delay line constructed with the delay neuron D and the comparator C. I_{right} and I_{left} are input signal generated by the right ear and the left ear, respectively. When the sound of the target is large, I_{right} and I_{left} become large. Inversely, I_{right} and I_{left} are small when the sound of the target is small. I_{right} is input to the delay line (right). I_{left} is input to the delay line (left). I_{right} transmits the delay line (right) from D_n to D_1. I_{left} transmits the delay line (left) from D_1 to D_n. Therefore, delay neurons output the signal sequentially. When I_{right} (I_{left}) is large, the delay time t_{delay} for transmitting the delay line (delay time) is short. When I_{right} (I_{left}) is small, the time t_{delay} is large. The delay times of the delay line right and left are t_{dright} and t_{dleft}, respectively. The comparator inputs the output signals of delay neurons. When both delay neurons output the signal, the comparator outputs the signal. The model can detect the position of the sound by detecting the position of the comparator which outputs the signal firstly.

When the sound of the target is located in the center of the model, I_{right} is equal to I_{left}. Then, the comparator located in the center outputs the signal, since t_{dright} is equal to t_{dleft}. When the sound of the target is located in the right of the model, I_{right} is larger than I_{left}. Then, the comparator located in the left outputs the signal since t_{dright} is shorter than t_{dleft}. When the sound of the target is located in the left of model, I_{right} is smaller than I_{left}. Then, the comparator located in the right outputs the signal. Thus, the model has the function of the sound localization. As shown in Fig. 1, we call the cell constructed with two delay neurons and one comparator the Unit.

Ⅲ. SOUND LOCALIZATION CIRCUIT

The unit circuit of the delay line is shown in Fig. 2.

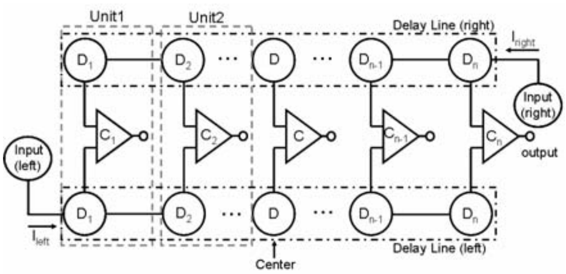


Fig.1. The model for sound localization by Jeffress.

Since the unit circuit is operated by the current mode, we call the delay line constructed with the unit circuits the current mode delay line.

The unit circuit is constructed with 9 MOS transistors and 1 capacitor. The unit circuit corresponds to the delay neuron in Fig. 1. I_{in} is the input current. I_{in} corresponds to I_{left} in Fig. 1, when the unit circuit is used as D_1 of the delay line (left). It is assumed that I_{in} (I_{right} and I_{left}) is the signal generated by the microphone. When the sound of the target is large and small, I_{in} is large and small, respectively.

I_{in} flows into the integration circuit constructed with the capacitor C_n and the nMOS transistor M_{n1}. The voltage V_C is represented by

$$V_C = \frac{I_{\mathrm{in}}}{C_n} t_d + V_0 \tag{1}$$

V_0 is the constant voltage, and V_0 is equal to 0 V. The t_d is equal to the delay time. The voltage V_{SW} is represented by

$$V_{SW} \cong \frac{V_{DD} - V_{th}}{V_C + (V_{DD} - V_{th})} V_{DD} \tag{2}$$

V_{th} is the constant voltage. When V_C is smaller than V_{DD}-V_{th}, V_{SW} is about the supply voltage V_{DD}. Then, the output current I_{out} is 0 since the pMOS transistor M_{p1} as the switch turns off. When V_C is larger than V_{DD}-V_{th}, V_{SW} is about 0. Then, I_{out} becomes I_{in} since M_{p1} turns on. I_{out} is transmitted to the neighbouring unit circuit, and I_{out} is used as the input current of the neighbouring circuit.

When I_{in} is large, the delay time t_d is short. When I_{in} is large, I_{out} is early equal to I_{in} since the delay time t_d which is the time for increasing V_C is short, as shown in eq. (1). When I_{in} is small, I_{out} is slowly equal to I_{in} because t_d is long. Thus, the proposed circuit in Fig. 2 can be used as the delay neuron.

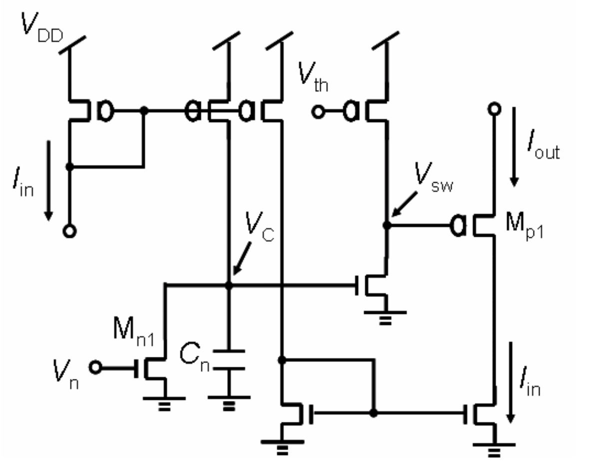


Fig.2. The unit circuit of the current mode delay line.

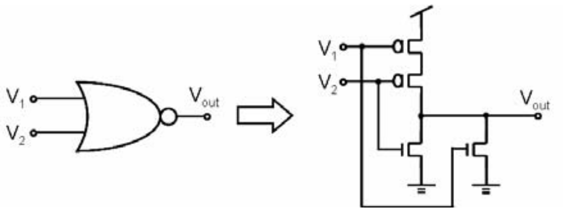


Fig. 3. The structure of the NOR circuit.

The NOR circuit was used as the comparator in Fig.1. The NOR circuit is shown in Fig. 3. The circuit is constructed with 4 MOS transistors. V_1 and V_2 is input voltage. V_{SW} of unit circuit used to the delay line (right) is connected with the terminal of V_1. V_{SW} of unit circuit used to the delay line (left) is connected with the terminal of V_2. V_{SW} became 0 when the signal is transmitted to the unit circuit. The circuit outputs the supply voltage V_{DD} in the only case that V_1 and V_2 are 0. By detecting the position of the comparator which outputs firstly V_{DD}, the proposed circuit can detect the position of the sound of the target.

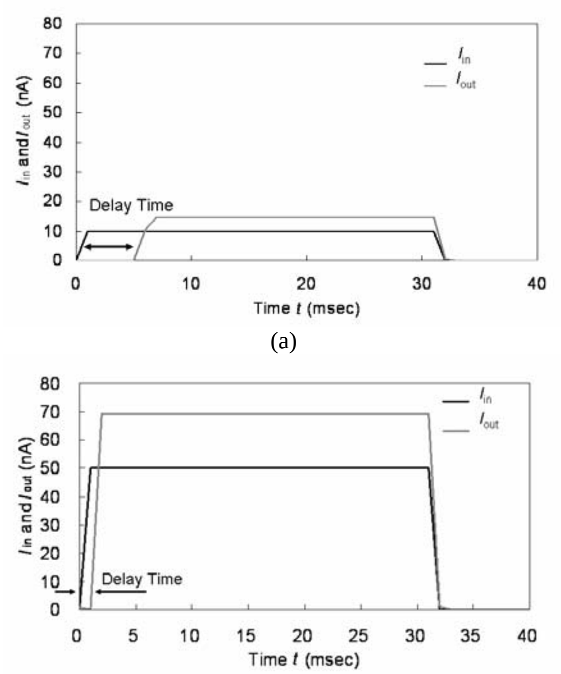
Ⅳ. SIMULATION AND EXPERIMENTAL RESULT

We investigated the proposed unit circuit in Fig. 2 by using SPICE. In all simulations, the model parameter of 1.5 μm CMOS process was provided. The channel length and channel width of all MOS transistors was 3.0 μm and 4.5 μm, respectively. C_n was set to 100 pF. V_{DD} was set to 5 V. V_{th} was set to 4.25 V. V_n was set to 0 V.

Figure 4(a) shows output current I_{out} when the input current I_{in} is 10 nA. The unit circuit outputted I_{out} after about 10 msec. The delay time was about 10 msec. Figure 4(b) shows the output current I_{out} when the input current I_{in} is 50 nA. The unit circuit outputted I_{out} after about 1 msec. The delay time was about 1 msec. Thus, the delay time became short when the I_{in} became large.

The current mode delay line constructed with 5 proposed unit circuits was evaluated by SPICE. Figure 5 shows the simulation results. I_{in} is the input current of the first unit circuit. I_{out} is the output current of the 5th unit circuit. I_{in} was set to 10 nA. After about 18 msec, the 5th unit circuit output I_{out}. The delay time was 18 msec. We understand that the current mode delay line can transmit the signal.

In order to investigate the current mode delay line, the test circuit was fabricated on the breadboard by using discrete MOS transistors (nMOS: 2SK1398, pMOS: 2SJ184, NEC). Figure 6 shows the photograph of the fabricated test circuit and the experimental equipment. The current mode delay line was constructed with 3 unit circuits in Fig. 2. V_{DD} was set to 5 V. V_{th} was set to 3.3 V. V_{in} was set to 1.4 V and V_n was set to 0 V.



(a)

(b)

Fig. 4. The simulation result of the unit circuit. (a) The result when I_{in} is 10 nA. (b) The result when I_{in} is 50 nA.

Figure 7 shows the measured results of the test circuit of the current mode delay line. Each V_{SW} in Fig. 2 is shown in Fig. 7. When V_{SW} becomes 0, the signal is transmitted to the unit circuit. The results in Fig. 7 showed that the test circuit can transmit the signal.

The proposed circuit for sound localization was evaluated by SPICE. 20 unit circuits were arranged in one-dimensionally. The construction is equal to that in Fig. 1. Figure 8(a) shows the output voltages of comparators when the input current I_{right} was equal to

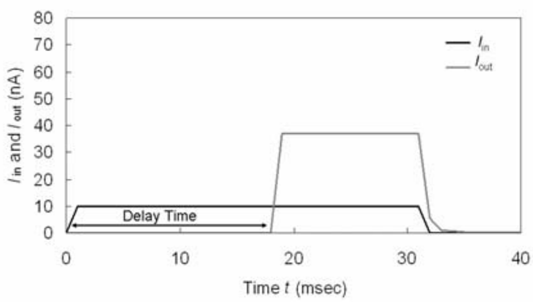


Fig. 5. The simulation result of the delay line.

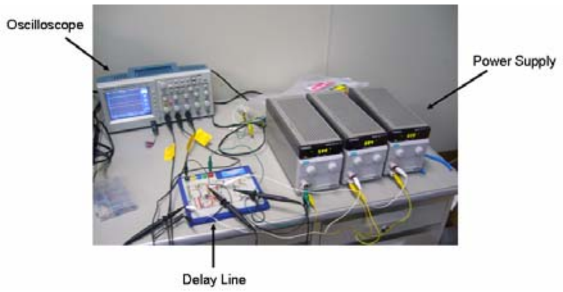
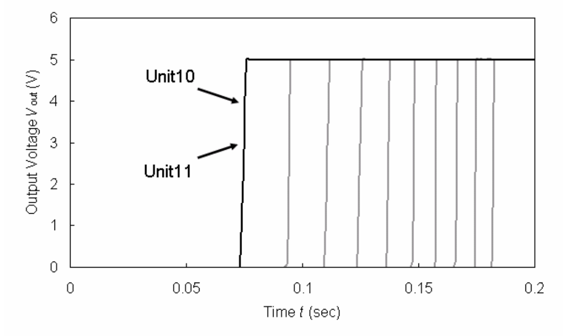


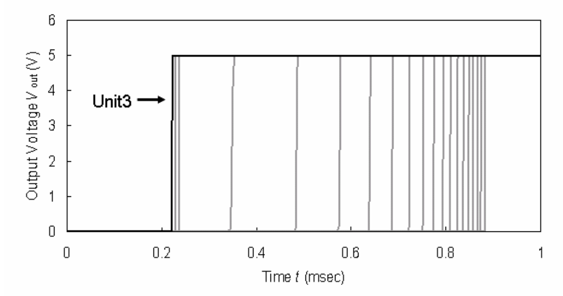
Fig. 6. The photograph of the fabricated test circuit and experimental.

the input current I_{left}. Then, the sound of the target was located in the center. I_{right} and I_{left} were set to 20 nA. The comparators of Unit10 and Unit11 located in the center firstly outputs the voltage.

Figure 8(b) shows the output voltage of comparators when I_{left} is smaller than I_{right}. Then, the sound of the target was located in the right side. I_{right} was set to 25 nA. I_{left} was set to 20 nA. The comparator of Unit3 located in the left side firstly output the voltage. The result with SPICE showed that the proposed circuit has the function of the sound localization.



(a)



(b)

Fig. 8. The simulation result of the circuit for sound localization. (a) Output voltages when the sound of the target was located in the center. (b) Output voltages when the sound of the target was located in the right side.

VI. CONCLUSION

In this study, we proposed the analog-digital circuit for sound localization based on the biological auditory system. The proposed circuit is constructed with the current mode delay line and the comparator. The NOR circuit was used as the comparator. The current mode delay line was evaluated by SPICE. The test circuit of the delay line was fabricated by discrete MOS transistors on the breadboard. The result with SPICE and the measured results of the test circuit showed that the delay time becomes short when the sound of the target is large. When the sound of target is small, the delay time became long. The result with SPICE showed that the proposed circuit can generate the signal for detecting the position of the sound of the target. We can realize novel target tracking system by applying the novel circuit based on the biological auditory system to the previous proposed tracking system based on the biological vision system.

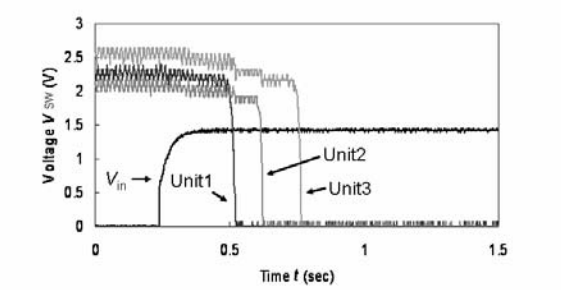


Fig. 7. Measured result of the test circuit of the current mode delay line.

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