弱電気魚のジャミング回避行動モデルに基づくCMOS周波数比較器

A CMOS Frequency Comparator based on Jamming Avoidance Response of *Eigenmannia*

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Eigenmannia is an electric fish that generates sinusoidal voltages at their electric organ (electric organ discharge: EOD), to recognize the surrounding environment. When two individuals (fishes) each of which emits nearly the same EOD frequencies meet, the fishes shift their EOD frequencies away from each other, because the electrolocation ability is vulnerable to interference with the fish's own EODs. To execute this jamming avoidance response (JAR), a fish must discriminate a sign of the frequency difference (Df) between their own EOD (S_1) and the neighbor's one (S_2) [1].

Figure 1 shows a brief schematic of computation for JAR in *Eigenmannia*. Let us assume that a fish has electroreceptors at locations A and B on its body, and receives S_1 and S_2, as shown in Fig. 1(a). Because S_1 causes interference with S_2, and vise versa, the received signals at location A and B, which we denote S_A and S_B, would have a slight difference [Fig. 1(b)]. Then the fish compares S_A with S_B to obtain the phase difference ($\equiv H_\mathrm{A} - H_\mathrm{B}$) [Fig. 1(c)], and detects the highest amplitude of S_A and S_B. When values of the maximal amplitude ($|S|_\mathrm{A}$) and the phase difference are plotted in a 2-D plane, a circular trajectory appears, as shown in Fig. 1(d). Directions of the rotation reflect the sign of Df: clockwise for negative Dfs and counterclockwise for positive Dfs. By detecting the direction, a fish makes a decision to increase or decrease the EOD frequency. This mechanism is achieved by two types of electroreceptors (P- and T-units). A P-unit mainly detects amplitudes of the received signal, while a T-unit detects phases of the received signal. A P-unit emits spikes whose firing rate is proportional to the detected amplitude. A T-unit emits spikes only when the received signal's phase is equal to a certain value. In this report, we implement P- and T-units by analog CMOS circuits, and demonstrate that the proposed circuit have qualitatively the same characteristic as a model of *Eigenmannia* [1].

Figure 2 shows the proposed P-unit (a) and T-unit (b) circuits. The P-unit circuit generates spike currents I_pout when positive input current I_in is applied. As I_in increases, the number of output spikes (per unit time) increases. In the T-unit circuit, if $I_\mathrm{in} = 0$, V_T is high at the equilibrium ($\mathrm{M_{T3}}$ is turned on). Therefore, when the T-unit circuit accepts I_in (> 0), I_in is simply mirrored to the output node I_tout. Once nonzero I_in was given, V_T is decreased because parasitic capacitance of $\mathrm{M_{T1}}$ is discharged by the current of $\mathrm{M_{T2}}$ ($=I_\mathrm{in}$). Therefore, $\mathrm{M_{T3}}$ is turned off, and I_in is not mirrored to I_tout, which result in the spike generation.

We conducted SPICE simulations of the proposed circuits by assuming 0.35-μm standard CMOS process. The supply voltage and V_ref were set to 3 V and 0.45 V, respectively, and I_ref was set to 0.1 μA. Figure 3(a) shows input current I_in normalized by $S_1 + S_2 = \sin(2\pi \cdot 10^6 \cdot t) + \sin(2\pi \cdot 1.04 \cdot 10^6 \times t)$, *i.e.*, Df is positive. Figures 3(b) and (c) show time courses of the output currents of the P-unit and T-unit circuits, respectively. The P-unit's firing rate was increased (or decreased) when the input amplitude is high (or low), while the T-unit emitted spikes at a fixed phase of the input current. Figure 4 summarizes the results shown in Fig. 3. Figure 4(a) shows the P-unit's firing rate as a function of time with the same time scale as in Fig. 3. Figure 4(b) shows phase differences between two output spikes when the T-unit accepted modulated and unmodulated inputs. As expected in a model of *Eigenmannia*, a plot of the firing rate versus the phase difference in a two-dimensional plane yielded a circular trajectory rotating counterclockwise [Fig. 4(c)].

The results above encourage us to develop a low-power CMOS frequency comparator because i) all the MOSFETs circuits could be operated in their subthreshold region, and ii) the proposed circuits were very simple as compared with standard frequency comparators. We are going to implement a rotation detector based on a model of *Eigenmannia* which consists of simple neural networks with less wiring complexity [1].

References

[1] W.F. Heiligenberg, *Neural nets in electric fish,* The MIT Press.

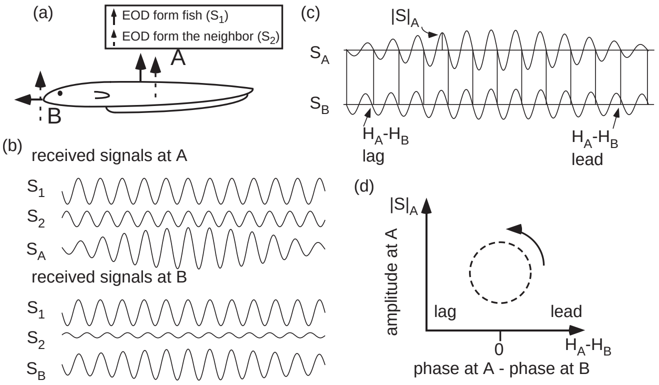
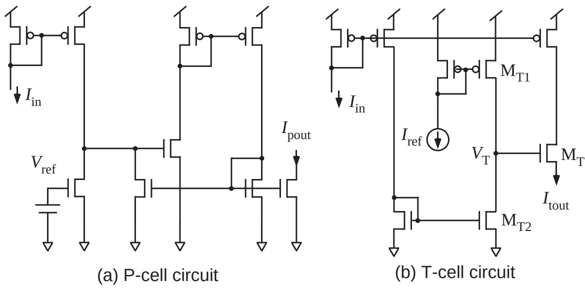


Fig. 1　Computation for JAR in *Eigenmannia*



(a) P-cell circuit　　(b) T-cell circuit

Fig. 2　Schematics of proposed P- and T-unit circuits.

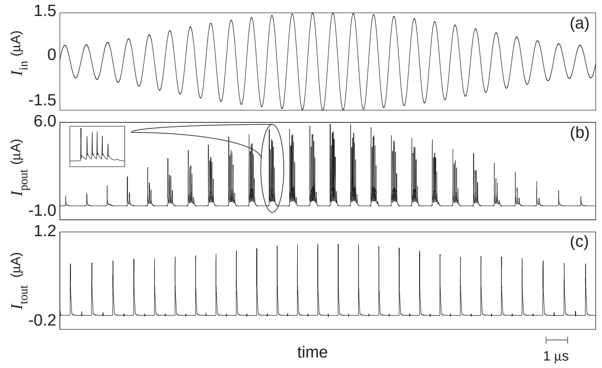


Fig. 3　Simulation results (P- and T-unit circuits).

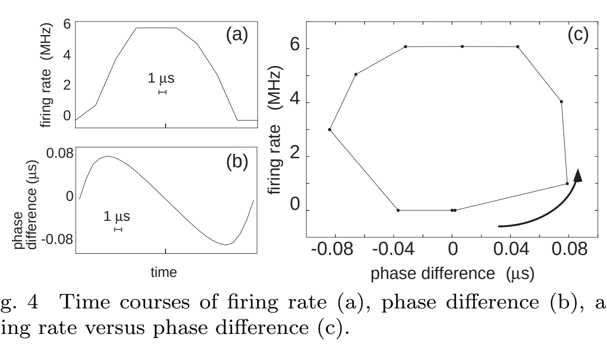


Fig. 4　Time courses of firing rate (a), phase difference (b), and firing rate versus phase difference (c).