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Neuron Circuits with Transverse Connections

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An analysis is made of neuron circuits with transverse connections using electronic neuron models both with the largest possible simplification and also more complicated ones described in [1] and [2] the subject matter of which is continued in this paper.

INTRODUCTION (SIMPLIFICATION OF THE MODEL)

The central nervous system contains many neurons with a great number of interconnections which may have a very heterogenous character. Consider a simple

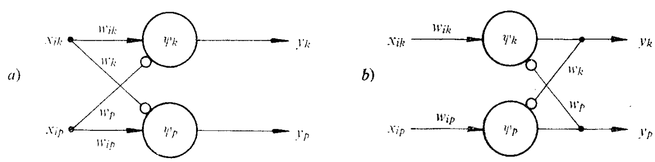

Fig. 1. Diagram of a neuron circuit with inhibitory transverse connections.

system of neurons with both types of synapses, the excitatory and inhibitory one, to be termed transverse connection net. Both neurons have separate inputs and outputs, and their interconnections are of the two-way type.

There exist two types of transverse connections, namely:

1. direct transverse connection (Fig. 1a),
2. feedback transverse connection (Fig. 1b).

These two types of connections have been treated by many authors mostly in connection with signal discrimination [3], [4], [5], [6], [7]. We are interested in the two-way inhibitory connection, although any combination of inhibitory and excitatory connections may be thought of.

Before starting the analysis, the model will be substantially simplified to bring out more clearly, the properties of the connection. The neuron model described in [2] is a system which treats a continuous postsynaptical input signal, the intermediate element being the frequency dependence $f_y(t) = \psi_f[x(t)]$ (i.e. (1) in [2]) simulating unit neuron activity. This system permits to compare the properties of the model with

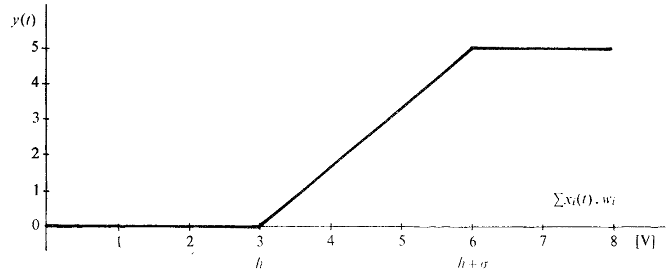

Fig. 2. Idealized shape of the dependence $y(t) = \psi[\sum_i x_i(t)\, w_i]$.

many neuron properties, but it should be conveniently simplified at the beginning to explain the properties of circuits of the type shown in Fig. 1a and 1b.

In this simplification, only the dependence of the postsynaptical output signal on the postsynaptical input signal will be noted, and the effect of the intermediary element — the voltage-frequency converter — will be neglected for the time being.

Assume a simplified neuron model with a characteristic (see (5) in [1] $y(t) = \psi[\sum_i x_i(t)\, w_i]$) expressed by the relationships:

$$\psi = \text{const} = 0 \quad \text{for} \quad x_i(t)\, w_i < h\,, \tag{1-A}$$

$$\psi = \psi^*[x_i(t)\, w_i - h] \quad \text{for} \quad h \leqq x_i(t)\, w_i \leqq \sigma + h\,, \tag{1-B}$$

$$\psi = \text{const} > 0 \quad \text{for} \quad x_i(t)\, w_i > \sigma + h\,. \tag{1-C}$$

The shape of this characteristic is shown in Fig. 2.

The gain of the system synapsis-neuron in the activity part of the character (1-B), expressed as the ratio between the increase in the output signal (or the ratio between the differential coefficients) is for each of the inputs

$$\frac{\Delta y(t)}{\Delta x_i(t)} \doteq \frac{\partial y(t)}{\partial x_i(t)} = \psi^* \,.\, w_1 \tag{2}$$

ψ^* being the neuron gain proper.

Consider again the circuits shown in Fig. 1a and 1b. For Fig. 1a the following equations may be written:

$$y_k = \psi_k^*(x_{ik}w_{ik} - h_k - x_{ip}w_p)\,, \tag{3}$$
$$y_p = \psi_p^*(x_{ip}w_{ip} - h_p - x_{ik}w_k)\,.$$

In order to illustrate the properties of the circuit shown in Fig. 1a, Fig. 3 shows an oscillographic record of the input and output signals for the employed neuron models with characteristics in accordance with Fig. 8 in [2].

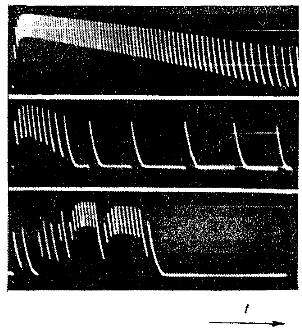

Fig. 3. The values of the weights of the connections are $w_{ik} = w_{ip} = w_k = w_p = 2$. Because the input signals are $x_{ip} > x_{ik}$, only the circuit ψ_k is excited and the second circuit is damped. But the input signal x_{ip} affects the initial reduction in the signal y_k.

CIRCUIT WITH FEEDBACK TRANSVERSE CONNECTION

As compared against the circuit in Fig. 1a, the Fig. 1b comprises a feedback connection which affects its properties to a substantial extent. The following equations hold for this circuit:

$$y_k = \psi_k^*(x_{ik}w_{ik} - h_k - y_pw_p)\,, \tag{4}$$
$$y_p = \psi_p^*(x_{ip}w_{ip} - h_p - y_kw_k)\,.$$

Making $x_{ik} = \text{const}$ and carrying out the relevant arrangements, one obtains in the interval (1-B) for y_k the equation of a straight line

$$y_k = \frac{\psi_k^* x_{ik}w_{ik} - h_p\psi_k^* + h_p\psi_p^*\psi_k^*w_p}{1 - \psi_k^*\psi_p^*w_kw_p} - \frac{\psi_k^*\psi_p^*w_{ip}w_p}{1 - \psi_k^*\psi_p^*w_kw_p}\,x_{ip} = b + kx_{ip}\,, \tag{5}$$

k being its line slope.

The product $\psi_k^* \psi_p^* w_k w_p$ may be termed *loop-gain* on the base of (2)

$$K_s = \psi_k^* \psi_p^* w_k w_p \geqq 0 \tag{6}$$

(total gain in the case of an open feedback loop).

On the other hand, the line slope

$$k = \frac{\psi^* \psi^* w_{ip} w_p}{1 - \psi_k^* \psi_p^* w_k w_p} = - \frac{\psi_k^* \psi_p^* w_{ip} w_p}{1 - K_s} \gtreqless 0 \tag{7}$$

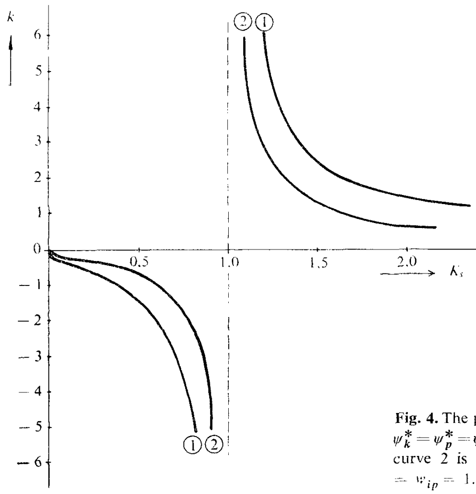

Fig. 4. The parameters are the values $\psi_k^* = \psi_p^* = \psi^*$. Curve 1 is for $\psi^* = 1$, curve 2 is for $\psi^* = 0.5$ at $w_{ik} = w_{ip} = 1$.

represents the gain of a circuit with feedback connection. It can be seen that the value k depends largely on the loopgain K_s and may attain negative and positive values.

The development of k as a function

$$k = f(K_s, \psi_k, \psi_p, w_k, w_p) \tag{8}$$

is shown in Fig. 4. A total of two areas can be distinguished:

$$k < 0 \quad \text{for} \quad K_s < 1 ,$$

$$k > 0 \quad \text{for} \quad K_s > 1 .$$

A special case is represented by $K_s = 0$, where $k \to \infty$. The loop-gain K_s is determined by the magnitude of the input signals and the shape of the dependence $y(t)$ on

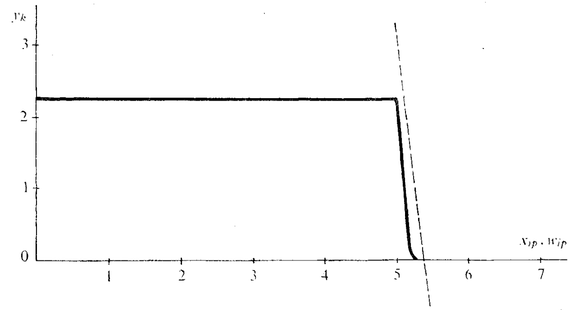

Fig. 5a. The full line illustrates the result measured for $\psi_k^* w_{ik} = \psi_p^* w_{ip} = \psi_k^* w_p = \psi_p^* w_k = 0.94$ at $w_{ik} = w_{ip} = w_k = w_p = 1$. The calculation for the idealized case in accordance with (5) is illustrated by the interrupted line.

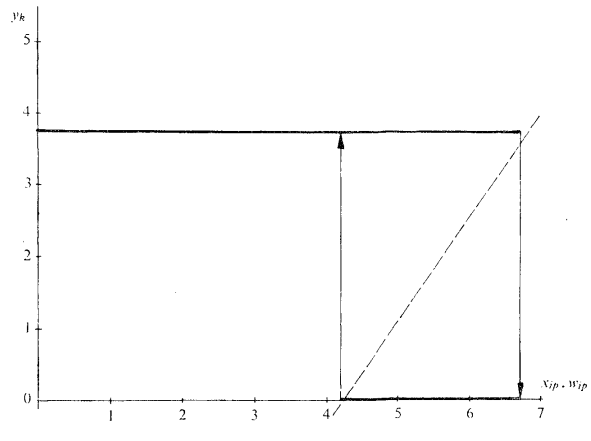

Fig. 5b. The full line illustrated the result measured for $\psi_k^* w_{ik} = \psi_p^* w_{ip} = \psi_k^* w_p = \psi_p^* w_k = 1.8$ for $w_{ik} = w_{ip} = w_k = w_p = 1$. The calculation for the idealized case in accordance with (5) is illustrated by the interrupted line.

$\sum_i x_i(t)\, w_i$. If there is $K_s > 1$ for a certain value of the input signal $\sum_i x_i(t)\, w_i$, there appears hysteresis caused by non-linearity ψ whose limits are determined by the value $K_s = 1$ where there occurs switching-over.

Fig. 5 shows results measured when using circuits whose characteristic is expressed by Fig. 2. Fig. 5 illustrates the dependence of the output signal y_k on the input signal x_{ip} for $x_{ik} =$ const. Fig. 5a expresses the dependence of y_k on x_{ip} for $K_s < 1$; Fig. 5b

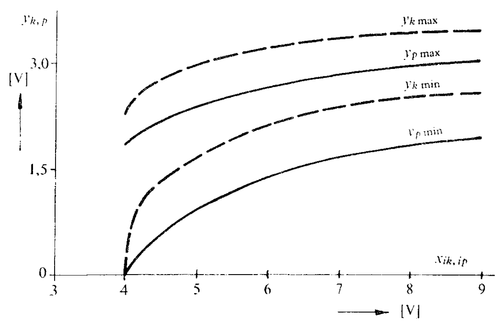

Fig. 6. Dependences $y(t) = \psi[\sum_i x_i(t)\, w_i]$ measured on two neuron models without adaptivity and paradoxical phase.

shows this dependence for $K_s > 1$ with visible hysteresis. The properties of the circuit for $K_s > 1$ are analogous to the properties of flip-flops [8].

If the obtained results are applied to the biological fact, one may conclude that under similar conditions in a biological system ($K_s > 1$) a weaker signal may decide the behaviour of a circuit if it arrives earlier than a stronger signal.

The output signal depends therefore not only on the magnitudes of the input impulses, but also on the time relationship existing between them. The information carrier is therefore not only the magnitude but also the time relationship between the signals.

Let us now return to the more complicated neuron model in accordance with Fig. 5 in [2] but, for the time being, without adaptivity and paradoxical phase. The dependence $y(t)$ on $x_i(t)$ and $f_y(t)$ on $x_i(t)$ of the thus modified neuron model for two actual cases are shown in Fig. 6. The measured shapes of hysteresis loops for two different values of the signal $x_{ip} =$ const in the circuit arrangement in accordance with Fig. 1b are shown in Fig. 7. It follows from the results that the minimum signal value (in our case $y_{k\min}$) is decisive for the inhibitory connection, but the maximum value $y_{k\max}$ (or $y_{p\max}$) becomes effective for the excitatory connection. The value k was not calculated because of being very complicated in view of non-linearity.

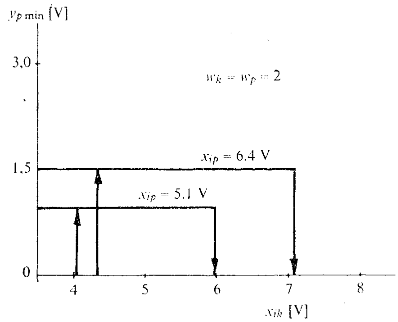

Fig. 7. Hysteresis loop for circuits with characteristics in accordance with Fig. 6.

RESULTS OF MEASUREMENT ON A COMPLETE NEURON MODEL

It follows from the above described results that the properties of the ciruit shown in Fig. **1b** are for $K_s > 1$ analogous to the properties of the flip-flops. But this analogy is complete only for the simplified model with a characteristic in accordance with Fig. 2. But if the model is more

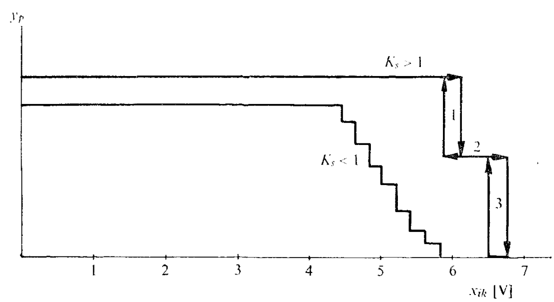

Fig. 8. Shapes of dependences $y_p(t) = f[x_{ik}(t)]$ of the circuit in accordance with Fig. 1b using neuron models with characteristics in accordance with Fig. 6 at two different values K_s.

complicated (Fig. 5 in [2]), many properties of the circuit shown in Fig. 1b are different, because the output signals depend not only on the average values of the input signals, but they are also a function of the frequency of the input signals (see Fig. 7 in [1]). We shall not go in more detail into these relationships which are intricate, only some results of measurement will be mentioned. If both inputs of the circuit (Fig. 1b) are fed with signals in the shape of a step function, and if they are time-shifted with respect to each other, the results are analogous to the results hitherto described. But if both signals arrive at the same moment $t = 0$, the behaviour of the circuit changes markedly. For a neural model without adaptivity the following results were registered: For slowly variable input signals at $x = 5.1$ V, $w_k = w_p = 1$ and $K_s > 1$, hysteresis was found for an input signal x_{ip} in the interval $\langle 5.5$ V; 6.7 V$\rangle$. After replacing the signals x_{ik} and x_{ip} by equally large signals in the shape of a step-function (speeking more accurately in the shape of

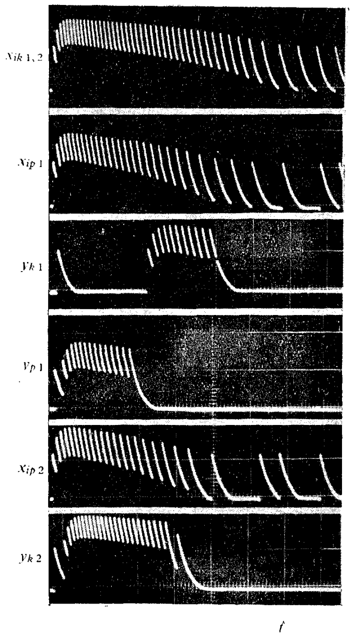

Fig. 9. For a signal $x_{ik1} = x_{ik2} = x_{ik1,2}$ at x_{ip1} the output is determined by the circuit ψ_p (Fig. 1b), at x_{ip2} it is the oppo-site case. The signal y_{p2} is zero.

rectangular pulses whose length exceeds many times the length of the sysle T_i of the output pulses), for x_{ip} with a constant amplitude and for x_{ip} with a gradually variable amplitude, the hysteresis area was slightly shifted and split into three partial areas (Fig. 8 for $K_s > 1$). The character of the lower and upper part remainds a hysteresis area, and in the central part there occurs mutual synchronizations of the output frequency of the two circuits f_y. For $K_s < 1$ there occurs only synchronization of the two circuits.

For small values of the adaptive component of the threshold $w_{0a}(t)$ there appears a similar situation like in circuits without adaptivity. But as $w_{0a}(t)$ increases, there appears a change because the signal conditions in the input of the excited circuit are strongly affected. The result is that the two circuits are alternatively excited.

Rather different results are obtained for out-put signals x_{ik} and x_{ip} in the shape according to Fig. 5 in [1]. If both input signals start simultaneously at the moment $t = 0$, hysteresis disappears even for $K_s > 1$ and there appears a quick transition from one limit state into the other. The oscillographic record of this phenomenon is shown in Fig. 9. For x_{ik} = const, the value x_{ip} at which the state of the circuit is changed is primarily determined by mutual time shifts of the input signals and by a delay in the transverse connections.

CONCLUSION

In conclusion it can be stated that the simplest neuron net or it s electronic equivalent can handle not only information carried by the signal magnitude but also by the time relationships between signals. If in a natural system it is possible to achieve values $K_s > 1$ then, under certain conditions, a weaker signal dominates a stronger one, and the system may respond incorrectly or with distortion. It follows from an experiment that there is a substantial difference between handling a signal with a small alternating component (which is a case similar to the operation of a great number of input signals with a small weight), and handling a signal with a large alternating component (small number of inputs with a large weight). In the second case for $K_s > 1$ the time relationships and character of the alternating signal component may affect the treatment of the signal in a decisive manner.

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REFERENCES

[1] P. Hiršl: Model neuronu. Kybernetika *1* (1965), 6, 539—550.
[2] P. Hiršl: Neuron model with electronic threshold circuit. Kybernetika *2* (1966), 6, 540—552.
[3] W. von Reichardt, G. Mac Ginitie: Zur Theorie der lateralen Inhibition. Kybernetik *1* (1962), 155—165.
[4] Deszö Varjú: Vergleich zweier Modelle für laterale Inhibition. Kybernetik *1* (1962), 5, 200 bis 208.
[5] P. Mueller, T. Martin, F. Putzrath: Biological Prototypes and Synthetic Systems. New York 4, 1962.
[6] W. Taylor: Pattern Recognition by Means of Automatic Analogue Apparatus. Proc. IEE *106 B* (1959), 26, 198—209.
[7] K. Küpfmüller, V. Jenik: Über die Nachrichtenverarbeitung in der Nervenzelle. Kybernetik *1* (1961), 1, 1—6.
[8] Л. А. Меерович, Л. Г. Зеличенко: Импульсная техника. Москва 1954.

Neuronové obvody s příčnými vazbami

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V tomto článku, který je pokračováním práce [1] a [2] je proveden podrobný rozbor obvodů s příčnými vazbami, složených z elektronických modelů neuronu. Pozornost je věnována obvodu, v němž inhibiční příčné vazby tvoří obvod kladné zpětné vazby. Jsou uvedeny výsledky dosažené na soustavě dvou modelů neuronu s příčnou vazbou za různých signálních podmínek na vstupu. Je zdůvodněna nutnost vzniku hysteréze při určitých hodnotách smyčkového zesílení ($K_s > 1$). Z počátku jsou pro osvětlení otázky uvedeny výsledky se zjednodušenými modely neuronů, je provedena analogie s klopnými obvody a dále jsou uvedeny výsledky pro modely složitější.

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