DYNAMICS DAYS SOUTH AMERICA 2010
International Conference on Chaos and Nonlinear Dynamics

INPE – National Institute for Space Research
São José dos Campos – SP – Brazil – July 26-30, 2010

EXCITABLE ELECTRONIC CIRCUIT AS A SENSORY NEURON MODEL

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keywords: Neuronal Dynamics, Stochastic Dynamics, Applications in Engineering.

According to recent works in statistical physics [1], enhanced dynamic range in sensory systems can emerge as a collective phenomenon of many excitable elements, each of which with small dynamic range. This effect would allow the construction of high sensibility sensors, made of simple components. This work proposes a simple excitable electronic circuit as a basic element in the construction of a high sensibility electronic sensor.

The circuit, composed only of an operational amplifier, a capacitor and resistors, has dynamics equivalent to that of the FitzHugh-Nagumo model for neuronal excitability, with one fast variable and one slow variable. We propose two models to describe the circuit and compare them to experimental data. One of the proposed dynamical systems is:

$$\begin{cases} \dot{v} = b - v + \dfrac{(a-b)}{1+e^{-(\alpha v - w)/x_0}} \\ \\ \dot{w} = \phi\left[\beta v + \gamma j - w\right] \ , \end{cases} \tag{1}$$

with $\phi \ll 1$ setting the ratio between the slow and fast time scales. The circuit non-linearity has its origins in the operational amplifier, whose dynamics is controlled by a function similar to the Heaviside function. Note that as $x_0 \to 0$ in equation (1), the v-nullcline becomes piecewise linear, corresponding to the behavior of an ideal operational amplifier (in which case the bifurcation diagram can be obtained analytically).

In neuronal systems, the response to a stimulus may change between samples, even if the stimulus intensity remains unchanged in different realizations. As sources to this variability we mention the randomness of the many biophysical process that controls the generation of spikes (like the opening of an ionic channel) and the stochastic nature of the stimulus (fluctuations in the concentration of odorant molecules that stimulates the olfactory sensory system, for example). To reproduce this effect in the excitable electronic circuit, we introduce noise generated from an analogical noise generator circuit. The intensity of the stimulus is controlled through a DC voltage, added to the noise. The statistics of the spikes generated by the excitable circuit corresponds approximately to that of a homogeneous Poisson process. We have, then, a very simple DC-Poisson converter, in which the intensity of a constant stimulus is converted to a Poisson rate. Figure 1 illustrates how the response changes as we change the stimulus intensity applied to the circuit. We measured the excitable circuit response (mean firing rate) to a constant DC voltage added to the noise and obtained a relation between the DC voltage and the Poisson rate. From this response curve the dynamic range of the excitable circuit could be calculated, resulting in a value of about one decade, which is in agreement with measurements performed in real neurons [2].

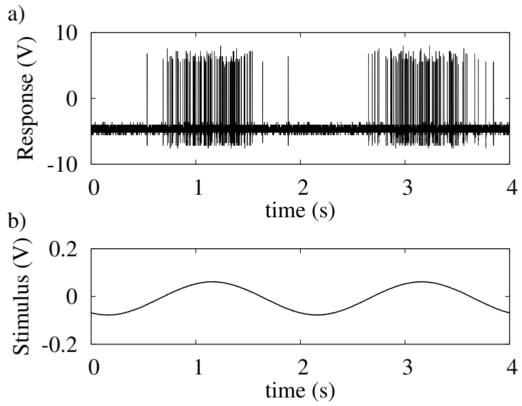

Figure 1 – Circuit response (a) to a sinusoidal stimulus (b). Note the stochastic nature of the response.

References

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