# A CIRCUIT MODEL OF SENSORY RECEPTOR FUNCTION

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## ABSTRACT

The main objective of this work is the design of a circuit that can mimic the activity of sensory receptors. Several integrate-and-fire models have been proposed for a generic neuron: Lapicque's RC circuit, the Hodgkin and Huxley model, and various VLSI circuits. The first two models do not respond appropriately to time-varying stimuli. On the other hand, the problem with many VLSI circuits is that they are usually designed to demonstrate specific neural features, for a single neural pathway.

The firing rate of a periphery sensory neuron can be explained by using a theoretical model based upon information transmission along the nerve fiber [1]. This model accounts for varying neural firing rates, and adaptation/deadaptation effects. By modifying an integrate-and-fire circuit, one can mimic the equivalent behaviour of this theoretical model.

## INTRODUCTION

The firing activity of the sensory receptor can be described at two levels of detail. At the lower level, action potentials can be generated according to receptor potentials, ionic channel properties, and stimulus thresholds. However, the model proposed by this paper investigates firing activity at a higher level. At the higher level, changes in firing rates due to time-varying stimuli are taken into consideration.

In 1907, Lapicque used a RC circuit to model the firing of a nerve fiber [2]. The Lapicque model is often used as a first-order approximation of neural activity. The model only accounts for the action potential time constants when a fixed-voltage stimulus is used.

In 1952, Hodgkin and Huxley developed a model based on a squid axon. They constructed a theoretical model based on the voltage-dependent membrane conductances responsible for action potential generation. This model does relatively well in describing the events of an action potential, but it is difficult to realise because it requires non-linear resistive components. For steady current inputs, the isolated Hodgkin-Huxley patch responds with steady firing rates (without adaptation effects). Moreoever, as the intensity of the applied current is increased, the firing rate increases and the amplitude of each pulse decreases. One of the major criticisms of this model is that if the parameters are allowed to vary without restraint, then the model can be made to account for any phenomena. [3]

The previous two models attempted to describe action potentials at a low level of detail. High-level VLSI integrate-and-fire models have been proposed which have well-defined firing rates, and also take adaptation into account. [4] These circuits, however, are usually designed to demonstrate specific neural features, for a single neural pathway.

The circuit proposed by this paper is a direct adaptation of Norwich's work [5]. He showed that the firing rate of a periphery neuron can be modeled by the following equation [6]:

$$F(I,t) = \frac{1}{2} k \ln(1 + \frac{\square I^n}{t}) \quad \text{............} \ (1)$$

where **F** is the firing rate, **k** and **,** are constants, **I** is the stimulus intensity, **t** is time, and **n** is a constant.

If **t** is fixed, then the firing rate **F** will increase as the stimulus intensity **I** is increased. Hence, **F** will increase with increasing **I**. If **I** is fixed, **F** will decrease as time progresses. This is what is known as the temporal adaptation effect.

This equation was extended to encompass time-varying stimuli and a resting firing rate by Wong [1]:

$$F(I,t) = \frac{1}{2} k \ln(1 + \frac{\square(I + \square I)^p}{m(t)}) \quad \text{.........} \ (2)$$

where **‰I** is the internal noise generated by the receptor, **p** is a constant, and **m(t)** is a time-varying memory function

In addition to the resting firing rate, and deadaptation effects, the responsiveness to successive pulses of stimuli is also captured by Equation 2. For example, when two subsequent pulses of stimuli are applied, **m(t)** ensures that the second response will have a lower initial firing rate than the first.

## CIRCUIT MODEL

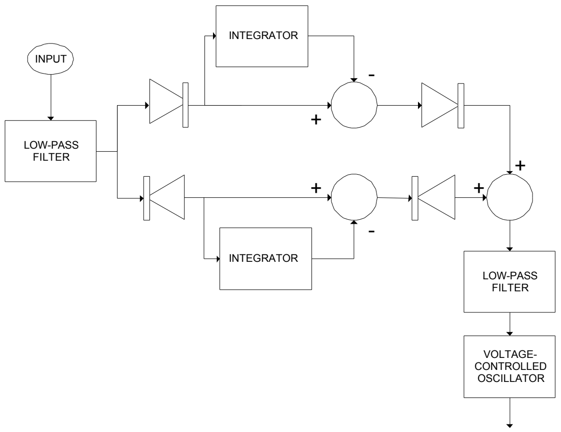

***Figure 1**- Simplified top-level circuit diagram.*

In the circuit, a low-pass filter was used to remove the high-frequency components of the signal. Afterwards, the positive and negative components of the signal were separated, and each component was integrated. The integration of each signal was subtracted from the original signal. This accounted for adaptation and deadaptation effects respectively. Finally, both the positive and negative signals were merged back together; the final firing rate was put through a low-pass filter and input into a voltage-controlled oscillator.

It should be noted that the input must not have a DC offset for the circuit to function properly. In the derivation of Equation 1, it was assumed that the receptor responded directly to the variance of the stimuli. The proposed circuit was designed to respond to variances about zero voltage.

## RESULTS

1. <u>Logarithmic Response</u>

A diode has the following I-V characteristics:

$$I = I_o(e^{\frac{V}{V_T}} - 1)$$

or

$$V = \frac{1}{V_T}\ln\left(1 + \frac{I}{I_o}\right)$$

The input was fed through diodes to ensure a logarithmic response. These diodes were also used to separate the positive and the negative components of the signal.

2. <u>Resting Firing Rate</u>

The firing rate output was input to a voltage-controlled oscillator. The oscillation frequencies were callibrated for different voltages using a linear mapping. A minimum frequency was programmed to ensure that the model always fired at a resting frequency during periods of non-stimulation. This minimum firing rate corresponded to ‰I in Equation 2.

3. <u>Memory</u>

The integrator circuit for both the positive and negative components consisted of a RC circuit across the feedback loop of an OpAmp. (see Figure 2) This circuit created an increasing time-delayed version of the input signal. The outputs of the integrator were subtracted from the original input signal to produce temporal adaptation and deadaptation effects for respective upsteps and downsteps of voltage (see Figure 3). Note the second "pulse" (in the FR) is lower in amplitude than the first "pulse", which is what is predicted by Equation 2.

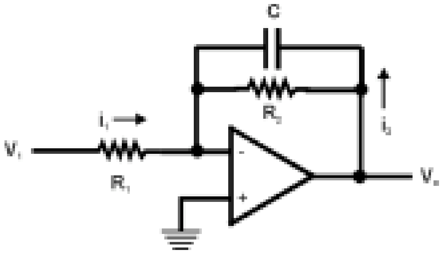

***Figure 2-*** *Integrator Circuit.*

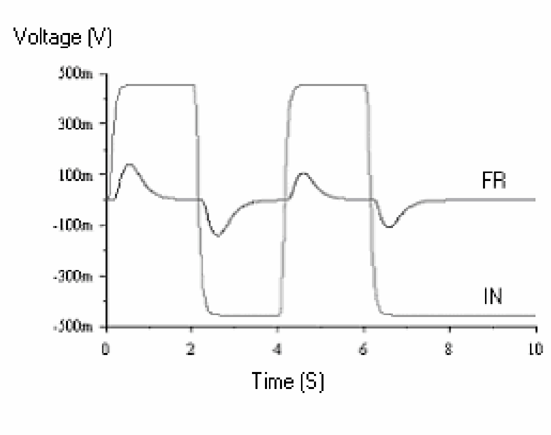

***Figure 3**- Adaptation and deadaptation effects. The firing rate is on the y-axis. FR is the output of the circuit. IN is the input stimulus.*

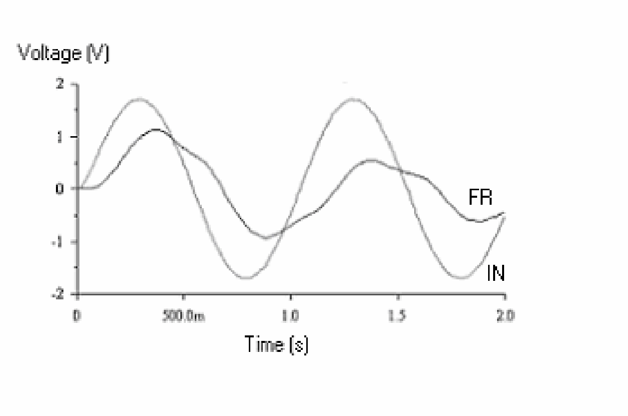

**Figure 4-** *Firing rate response (FR) when a sinusoid was used as an input (IN).*

In the integrator circuit (Figure 2), the large resistance $R_2$ across the capacitor allowed the capacitor to discharge slightly during periods of inactivity. This discharge allowed for full adaptation and full deadaptation after prolonged periods of inactivity. The discharge also increased the amount of time until the amplifier saturated.

This circuit was also tested with sinusoidal inputs. The circuit output was a phase-delayed sinusoid with increasing attenuation, as predicted by Equation 2 (see Figure 4). The output curve in this figure agreed with the expected result, but is not entirely satisfactory because of the non-linearities in the firing rate waveform.

## DISCUSSION

The aim was to create a general circuit that could mimic the activity of sensory receptors. The proposed circuit was tested with sinusoidal and rectangular inputs. Further work must be done to improve the output firing rate for sinuisoid stimuli. Some preliminary work was also conducted on adding RL circuits to the circuit model; these would help to improve the exponential rise and decay in the respective deadaptation and adaptation curves.

With the insight gained from these models, this circuit may be applicable in biological computing design. Since this circuit examines neural firing at a high level, future work could be done to interface it with a low-level model. For example, the firing rates predicted by the circuit could be input to the Hodgkin and Huxley model. The Hodgkin and Huxley model could then be responsible for action potential generation.

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