An Alternative Analog VLSI Implementation of the Meddis Inner Hair Cell Model

Alistair McEwan and André van Schaik

School of Electrical and Information Engineering
University of Sydney
Sydney, NSW 2006, Australia

ABSTRACT

A circuit implementation of a model of the inner hair cell based on the Meddis inner hair cell model is presented. The model and implementation are alternatives of a previously presented exact implementation of the Meddis hair cell model. Models of the IHC are becoming more computationally intensive and require substantial analogue circuits to allow full implementation. The alternative model is more compact, less complex and more biologically plausible. The current mode circuit uses a modified differential pair input stage, translinear multiplier and translinear first order low pass filters to create large time constants with small capacitors.

1. INTRODUCTION

Inner hair cells (IHCs) are the mechanical to neural transducers located within the inner ear that convey sound wave energy from the cochlea to the auditory nerve [1]. Previous electronic models of the auditory pathway are capable of modeling the main characteristics of the IHC but fail with more complex stimuli [2]. Recently the most widely used computational model of the IHC, the Meddis IHC model [3], [4] has been successfully implemented in analogue VLSI [5]. Tests of the Meddis IHC circuit could be performed in real time and reveal characteristics about the model that appear to be redundant [5]. Hence the design of a less complex and more biologically plausible IHC circuit has been pursued. This circuit may be used the construction of sensors based on auditory physiology.

2. THE MEDDIS IHC MODEL

An important characteristic of the IHC, required for amplitude modulation detection [6] among other complex stimuli, is adaptation. The amount of available chemical neuro-transmitter in the IHC drops each time some is released, reducing the probability of transmitter release following further stimulation. Transmitter is slowly regenerated or reprocessed, which replenishes the available transmitter. Post release models of hair cell functions attempt to simulate adaptation; the most widely accepted being the Meddis model. This model has been shown to produce post stimulus time histograms that resemble physiological measurements of the auditory nerve fibre of the cat producing a clear adaptation effect (Figure 1). The probability of the auditory nerve firing is proportional to the amount of transmitter in cleft of the synapse. The Meddis model uses three differential equations to describe a recycling mechanism of transmitter from a supply pool, released through the permeable cell membrane into the synaptic cleft. Some of the transmitter is lost, while the remainder is taken back up into the cell and stored while it awaits recycling. The Meddis model is unique in its proposal of recycling, or re-uptake, of transmitter. However, this concept is also supported by the evidence of glutametric re-uptake by supporting cells in the hair cell synapse [6].

Figure 1: Post stimulus time histograms of a single auditory nerve fibre in response to repeated simulations in the cat, (a) and as predicted by Meddis’ hair cell model (b).

3. DIRECT CURRENT MODE CIRCUIT

The Meddis model was first implemented directly in a circuit to demonstrate a method of mapping systems of differential equations to translinear circuits [5]. Subthreshold CMOS circuits were used for their translinear behavior and low voltage swings that provide the ability to tune for long time constants without using excessively large capacitors. The results of a fabricated chip showed that the circuit agrees with the Meddis model and the biological model on eight tests of IHC function. The circuit consisted of a half wave rectification function (HWR), a multiplier (MULT), four variable gain current mirrors (\( g_{m1}, g_{m2}, g_{m3}, g_{m4} \)), and three first order low pass filters, (CLEFT, STORE and POOL), with respective time constants, (\( \tau_x, \tau_y, \tau_z \)).

The nature of the variable parameters of the model was investigated to determine how the model could be improved in size or complexity (Table 1). The time constants in the feedback path can be isolated. \( \tau_x \) and \( \tau_y \) control the rate of adaptation while \( \tau_z \) performs low pass filtering of the input. Also from Table 1, \( g_x \) and \( g_y \) appear to offer no additional useful control over adaptation than is possible with \( g_y \) and therefore appear to be redundant. This removes the need for two of the three gain controls making the model less complex.

0-7803-8251-X/04/$17.00 ©2004 IEEE  
IV - 928
ISCAS 2004
Figure 2. A direct current mode implementation of the Meddis model [5].

<table>
<thead>
<tr>
<th>Time Const.</th>
<th>Parameter Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_y$</td>
<td>Time constant of slower adaptation</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>Time constant of rapid adaptation</td>
</tr>
<tr>
<td>$\tau_v$</td>
<td>With little effect on adaptation, this filter is responsible for removing the 1kHz carrier wave of the stimulus, as it is a low-pass filtered with a cut-off below 1kHz.</td>
</tr>
</tbody>
</table>

Gains

$g_a$
- Increases effect of slow adaptation.
- Limits the amount of transmitter manufactured in the factory, which in turn offsets the slow adaptation of transmitter in the pool.

$g_b$
- Decreases effect of rapid adaptation.
- Determines the effect of transmitter recycled through the store, which in turn offsets the fast adaptation of transmitter in the pool.

$g_c$
- Same effect as $g_b$ on adaptation.
- Directly controls the size of the output signal and has little effect on adaptation.

$g_d$
- Same effect as $g_b$ on adaptation.

Table 1. Investigation of the model parameters.

4. ALTERNATIVE IHC MODEL

These observations lead to the notion that only a single 1kHz low pass filter is needed for many different IHC modules. The cleft filter may be removed from the feedback loop and placed before the multiplier, as it appears to only be required to low pass filter the input signal. The resulting model is more biologically plausible [3], with the IHC membrane providing the low pass filtering of the input signal, and adaptation being controlled by the synaptic cleft and store filters. The store filter may be represented in biology by a supporting cell [7].

Figure 3. An alternative, less complex current mode implementation of the Meddis IHC model.

The new model also results in savings in the number of filters required to represent hair cell transduction. A single membrane filter may be used to synapse to many spiral ganglion cells that are part of the auditory nerve as is found in real hair cells [8]. Each interface would then be required to contain only two filters rather than three.

5. ALTERNATIVE CURRENT MODE CIRCUIT

The block diagram of the new model, transformed to the current domain, is shown in Figure 3. For comparison the direct model is shown in Figure 2. The cleft filter has been removed from the feedback loop and placed with the membrane function to provide low pass filtering of the input signal at about 1kHz. This also removes the need for the gain block, $g_c$, as the signal level can be controlled by the half wave rectification function (HWR). The circuit details are shown in Figure 4. The HWR block is a modified differential pair input stage that converts the voltage input to a half wave rectified current. First order translinear [9] or logdomain [10] low pass filters are used to implement the time constants and a translinear multiplier provides multiplication of the stimulus and feedback ($I_q I_{stim}$), and normalizes the output by the constant current $I_{max}$. The gain blocks are implemented using variable gain current mirrors where the expected gain is programmed into the size ratio of transistors and the source of the output transistor is connected to an external pin to allow trimming after manufacture. The redundant gain parameter, $g_d$, remains to enable control of adverse effects caused by mismatch in the current mirrors and translinear circuits.

6. MEASUREMENT RESULTS

A prototype of the circuit implementation of the alternative model has been fabricated and measured with encouraging results, (Figure 5), that are similar to the PST Histograms of the original Meddis model, (Figure 1). Adaptation to the repeated stimulus of an onset can be seen and a recovery to spontaneous rate of approximately 30ms. The cut-off frequency of the input filter was tuned to be close to 1kHz. Figure 5 (c) shows that the response to tones at 5kHz has a diminished a.c. response.
7. SIMULATION RESULTS

An important well reported auditory nerve property in response to tone-burst stimuli for which electrophysiological data exists is the rate intensity function. Rate intensity functions are plots of firing rate response versus stimulus intensity and indicate the dynamic range of the model. The method of Smith and Zwislocki [11] is used to find the rate intensity functions. Firstly a stimulus level is found where the onset and steady state rates are zero. This zero-dB level is the reference level. Responses are recorded for 300ms tone bursts in steps of 10dB to 40dB above the reference. The rise time of the signal and the duration of the recording interval are the same as those used by Meddis as these parameters effect the shape of the onset rate intensity function [12].

Three rates are identified in the response, shown in Figure 6. The spontaneous rate represents the response in the absence of stimuli. The onset rate is the firing rate averaged over the first 1ms while the steady state rate is the response averaged over the last 30ms of a 200ms tone burst. The onset rate is seen to increase monotonically with stimulus level and shows little or no sign of saturation. The steady state rate is independent of stimulus level in the Matlab simulation (Figure 7), however it increases slightly with stimulus in circuit simulations (Figure 8). The results by Meddis and physiological results report a steady state rate nearly independent of stimulus [12] level. The discrepancy in the circuit simulation is likely to be due to poor...
choice of parameters. Unfortunately the circuit simulations are quite lengthy and hence it is prohibitive to search the parameter space by circuit simulation. These measurements have yet to be made with the fabricated prototype. However, the parameters on a fabricated chip can be changed in real time and hence it is expected that a closer parameter set to that used by Meddis may be found with the chip. This was the case with the previous, direct current implementation of the Meddis IHC model (Figure 8), for which we did find a better choice of bias values for the fabricated chip than for the SPICE circuit simulations.

8. CONCLUSION

A more compact, less complex circuit implementation of the Meddis inner hair cell model has been designed. The model has only two filters in the feedback path to control adaptation and requires less parameter controls. Placing the 1kHz filter with the membrane circuit is more biologically plausible and leads to a smaller design as one membrane can be connected to many cells of the auditory nerve by multiple synapses.

Figure 7. Matlab simulations of the rate level functions.

Figure 8. Circuit simulations of the rate level functions for the alternative circuit.

9. REFERENCES