A Basilar Membrane Resonator for an Active 2-D Cochlea

Tara Julia Hamilton, Craig Jin, André van Schaik
Computing and Auditory Research Laboratory
School of Electrical and Information Engineering
The University of Sydney, NSW 2006, Australia
Email: tara@ee.usyd.edu.au

Abstract—In this paper we present a Basilar Membrane Resonator design for an Active 2-D Cochlea. It incorporates some of the non-linear behaviour exhibited in the real cochlea by utilizing a quality factor control loop. This control loop varies the gain and the frequency selectivity of the resonator based on the amplitude of the input signal.

I. INTRODUCTION

The cochlea is a fascinating transduction organ that illustrates the ingenious way in which engineering problems are solved in nature. It has a dynamic range of approximately 120 dB [1] – allowing us to hear from the slightest whisper to the roar of a 747 flying overhead. For almost 20 years, since the first paper by Lyon and Mead [2], the cochlea has been the object of neuromorphic research. There have been many previous cochlea designs, however, for a wide variety of reasons – from the non-inclusion of the non-linear effects present in the real cochlea to the debilitating effects of noise and mismatch – there is still much work to do before we have results that can compare with the performance of the real organ.

II. AN ACTIVE SILICON COCHLEA MODEL

A. Silicon Cochlea Designs

The first Silicon Cochlea was published by Richard Lyon and Carver Mead [2]. This silicon cochlea used a cascade of 100 second-order low pass filter stages to represent the Basilar Membrane (BM). The quality factor (Q) values of the filters could be externally set but could not be automatically set by the chip. This design was followed by improvements in the modeling of cochlea mechanics and circuit design [3] - [5].

The most recent silicon cochlea incorporated the cochlea’s non-linear effects (shown in Figure 1) by modeling many of the cell structures of the Organ of Corti [5]. The mathematical model of this chip was very successful in simulations, however, the hardware implementation’s performance was severely degraded by transistor mismatch and noise ([5] pp. 174).

Figure 1. The effects of the non-linear behaviour of the Cochlea on Basilar Membrane Velocity (Adapted from pp. 97 [1])

B. The Model

Based on the performance of previous implementations we have chosen to take a more “high-level” approach to our active cochlea design. Clearly we do not have the resources available to us that the body has, where mismatch and noise appear to be averaged-out by sheer weight of numbers, so it seems impossible to copy biology exactly. For instance, there are over 3000 inner hair cells in the human cochlea and about 10 fibres connected to each of these [1]. This is several orders of magnitude greater than what we can currently achieve on a chip.

Figure 1. The effects of the non-linear behaviour of the Cochlea on Basilar Membrane Velocity (Adapted from pp. 97 [1])

The cochlea may be modeled by a resistive network with a number of resonators attached to it with logarithmically decreasing resonant frequencies (from base to apex) [6]. A simplified schematic of this is illustrated in Figure 2. Non-active models utilizing this structure give qualitative results that closely match those of biology for a passive cochlea (Figure 1) [4], [6]. We have followed this same model but included an automatic-Q control mechanism into our resonator design.

C. Automatic Q-Control

Inside the real cochlea low signal levels result in, not only an increase in the gain of the input signal, but also a sharpening in the tuning of the BM (see Figure 1). Thus, we have implemented Automatic Q-Control which allows us to control both the gain and frequency selectivity of the BM resonator. Frequency selectivity suppresses noise outside the
frequency band of interest, and this, along with an increase in gain greatly improves the resonator’s performance at low signal levels.

![Decision Circuit Operation](image)

Figure 4. Decision Circuit Operation

The control loop for implementing Automatic-Q Control is illustrated in Figure 3. The control loop consists of the BM resonator, a simple peak detector [7], a decision circuit, a ramp generator, and a wide-linear-range transconductance amplifier [8]. The control loop can be disabled allowing the Q-value to be set manually.

![Resonator with Automatic Q-Control Loop](image)

Figure 3. The Resonator with the Automatic Q-Control Loop

The level of the output signal from the BM resonator is measured by the peak detector and fed into the decision circuit. The decision circuit employs two current comparators – one sets the ceiling for the signal amplitude and the other sets the threshold. This is shown in Figure 4. The decision circuit employs hysteresis to avoid errors due to oscillations. A summary of the modes of operation of the decision circuit is given in Table I.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Q-Value</th>
<th>Control Signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal &gt; Ceiling</td>
<td>Q ↓</td>
<td>Vctrl = 0, Vctrl2 = 0</td>
</tr>
<tr>
<td>Threshold1 &lt; Signal</td>
<td>Q constant</td>
<td>Vctrl = 0, Vctrl2 = 1</td>
</tr>
<tr>
<td>Signal &lt; Threshold2</td>
<td>Q ↑</td>
<td>Vctrl = 1, Vctrl2 = 1</td>
</tr>
</tbody>
</table>

The Q-value of the BM resonator is controlled by the output current of the wide-linear-range transconductance amplifier. The magnitude of this current is controlled by the voltage from the ramp generator. A higher voltage generates a larger current and, hence, a larger Q-value. When the ramp generator output voltage, Vramp, is equal to the supply voltage VDD, the output current of the wide-linear-range transconductance amplifier is set to give the maximum Q-value.

![Diagram of BM Resonator](image)

Figure 5. A simplified 2-D cochlea model

The Basilar Membrane Resonator (BMR) was implemented using a second-order band-pass filter with the Automatic Q-Control loop setting an appropriate Q-value.

The second-order band-pass filter was implemented using two Tau Cell log-domain filters [9]. Figure 5 shows the schematic for the second-order band-pass filter and the transfer function for this filter is given in equation (1).

$$ I_{OUT} = \frac{s \tau}{s^2 \tau^2 + s \tau + 1} I_{IN} $$

where, $\tau$ is the time constant that determines the resonant frequency, given by, $\tau = \frac{C U_T}{I_o}$, and $C$ is the capacitance, $U_T$ the thermal voltage and $I_o$ the bias.

One of the advantages of using the Tau Cell for filter design is that the resonant frequency and Q-control can be configured in a variety of ways [10]. From Figure 1 we see that we want to maximize Q for low signal levels and have little to no Q for high signal levels. We configured the filter to have a Q-value which is governed by the following equation:

$$ Q = \frac{I_o}{2I_o - A_1 I_o} = \frac{1}{2 - A_1} $$

In equation (2), $A_1$ approaches 2 when the signal level is low and approaches 0 when the signal level is high.

We can deduce from this that we will obtain non-linear compressive effects as illustrated in Figure 1. The maximum Q-value is obtained using the Automatic Q-Control loop by setting the bias current of the wide linear range amplifier to be approximately $2I_o$. This bias can be set to its optimum level by turning off the automatic Q-control loop and varying the bias until the output amplitude is at its maximum. Errors in the bias current due to noise or mismatch result in a reduction in Q.

The right-most part of Figure 5 shows the multiplier cell which is used to set the Q-value of the filter. The multiplier is connected to $V_a$ and $V_b$ in the filter and to $I_q$ ($I_q = A_1I_o$) from the wide-linear-range amplifier.
In the multiplier cell we can have $Va$ connected to the drain and $Vb$ to the gate of the same transistor without desaturating it since the voltage swing on both these nodes is small in this type of log-domain circuit.

B. Automatic Q-Control Loop Circuits

Figure 6 shows the peak detector circuit. This circuit was adapted from [7]. It rectifies the input current, $I_{in}$, using the capacitor, C, to hold the peak voltage. A small leakage current ($I_{leak}$) is included so that the circuit can track changes in the input.

The decision circuit (Figure 7a) comprises of two current comparators (Figure 7b) and digital logic to facilitate the modes of operation described in Table I. The digital logic in Figure 7a simply adjusts the reference current to change the threshold level, between $Threshold1$ and $Threshold2$ (see Figure 4), required to implement the hysteresis. The output of the peak detector is mirrored into the current comparators ($I_{peak}$), as is the reference current ($I_{ref}$). The peak current is sourced into node $X$ (Figure 7b) and the reference is a current sink from node $X$. The voltage at node $X$ increases when the peak current exceeds the reference current. This causes a copy of the peak current to flow into node Y via $M3$, which subsequently flows back into node $X$ via $M2$. Hence, the increase in voltage at node $X$ is reinforced and the output, $V_{comp}$, goes low. The voltage at node $X$ decreases when the reference current is greater than the peak current. In this case the decrease in voltage at node $X$ is reinforced through the action of $M1$ and $M4$ and $V_{comp}$ goes high. This circuit was used since it responds quickly and decisively to changes in the peak current value and it implements hysteresis, improving noise immunity.

The ramp generator circuit is given in Figure 8. Based on the control signals, $V_{ctrl}$ and $V_{ctrl2}$, the capacitor, C, is either charged, held constant or discharged. As the capacitor is charged the output, $V_{ramp}$, increases linearly. $V_{ramp}$ decreases linearly when the capacitor is discharged. The speed that the ramp rises and falls can be controlled by changing the charge and discharge currents.

The wide-linear-range transconductance amplifier (Figure 9) is described in detail in [8]. It utilizes techniques such as bump linearization and well inputs to increase its linearity over a wide voltage range. In the Automatic Q-control loop we use the wide linear range transconductance amplifier as a voltage controlled current source. As the input, $V_{ramp}$, increases, the output current increases and vice versa. The current from the wide-linear-range transconductance amplifier ($I_{out}$) is bidirectional, however, $V_{ramp}$ never goes below the reference voltage, $V_{r-}$, and hence the circuit is always sourcing current.

IV. SIMULATION RESULTS

Figure 10 shows the effect of changing the Q-value of the BM Resonator. This was done by disabling the automatic Q-control loop and manually changing $I_q$. It shows both an increase in gain and frequency selectivity as is illustrated in Figure 1. Figure 1, however, shows much greater gain and steeper cut-off. This is because Figure 1 is illustrating the non-linear effects of an entire cochlea at one particular point along the BM rather than a single BM resonator as we are doing here.
Figure 10. Gain versus frequency for a Basilar Membrane resonator with varying Q

The result of a transient analysis of a single BM resonator is shown in Figure 11. Here we see the output current, \( I_{out} \), increase as a result of the ramp generator control signals, \( V_{ctrl} \) and \( V_{ctrl2} \), initially both being high. This causes the output of the ramp generator, \( V_{ramp} \), to increase and subsequently the Q-control current, \( I_q \), to increase. After 60ms \( V_{ctrl2} \) falls so that \( V_{ramp} \) and \( I_q \) are being held constant resulting in a constant output signal level. At 80ms the input signal increases resulting in the output current exceeding the ceiling and \( V_{ctrl} \) falling. This results in a decrease in \( V_{ramp} \) and \( I_q \) until 100ms. At this point \( V_{ctrl} \) goes high once again and \( V_{ramp} \), \( I_q \) and the output signal level are held constant.

Figure 11. Transient analysis of the BM resonator

The effect of varying the level of the input signal on the output is shown in Figure 12 with the automatic Q-control loop enabled and disabled. The output level between the dashed lines in Figure 12 represents the Target Amplitude (see Figure 4) set by the decision circuit.

From Figure 10 and Figure 11 we see that for low input signal levels, both the gain and the selectivity of the resonator tuning increase. Figure 12 shows that the BM resonator has a non-linear compressive effect on the gain which is dependent on input signal level.

V. CONCLUSIONS

In this paper we have presented a Basilar Membrane Resonator with Automatic Q-control for use in an Active 2-D Cochlea. Our design is a high-level implementation of what is currently understood of the biology of the human cochlea. We have incorporated the non-linearities of the cochlea into our BM resonator design so that it can be used to create an active 2-D cochlea.

Figure 12. Non-linear compressive gain effects on the input signal (in dB relative to 1 nA)

REFERENCES