CAPACITIVELY-COUPLED CURRENT CONVEYER SECOND-ORDER SECTION FOR CONTINUOUS-TIME BANDPASS FILTERING AND COCHLEA MODELING

David W. Graham and Paul Hasler

Georgia Institute of Technology
School of Electrical and Computer Engineering
Atlanta, GA 30332

ABSTRACT

The Capacitively-Coupled Current Conveyer Second-Order Section (C^4 SOS) is a continuous-time bandpass filter with electronically tunable corner frequencies and ±40 dB/decade or greater roll offs. The corner frequencies can be set independently of each other, and the bandwidth can therefore be tuned at will. Each corner can have its own Q peak, or, if the corners are brought close together, a very tight bandwidth with a single Q peak develops. This leads to further isolation of any given frequency and is thus useful for signal processing applications. An array of these C^4 SOS's with exponentially spaced center frequencies forms a good model of the human cochlea (inner ear) where signals are decomposed with filtering processes that have $Q \approx 30$.

In this paper, we present the Capacitively-Coupled Current Conveyor Second-Order Section (C^4 SOS) which is a continuous-time bandpass filter with ±40 dB/decade roll offs. This filter is based on the Capacitively-Coupled Current Conveyer (C^4) [1] and the Autozeroing Second-Order Section (AutoSOS) [2]. Figure 1 shows the schematic for the C^4 SOS. It is in a configuration similar to a Tow-Thomas filter, but it is composed of capacitive-based bandpass elements. The corner frequencies are electronically tunable and can be moved independently of one another.

Second-order sections are fundamental building blocks for creating higher-order filters on IC's, and they have been shown to be useful in forming models of the cochlea (inner ear) [3][4]. An array of these bandpass second-order sections can be used to create a silicon cochlea that is able to closely model the resonant properties of the human cochlea and can thus be used as a biologically-inspired audio signal processor in the continuous-time domain. The biases can be tuned to achieve a moderate Q peak, mirroring biology. The center frequencies can be exponentially spaced via either a resistive network or floating gates.

The data we present in this paper is from a circuit fabricated in a 0.5μm process available through MOSIS, and the power supply was set to $V_{DD} = 3.3V$. The W/L ratios were set to 1.5μm/4.8μm for the six transistors with external biases and 4.8μm/1.5μm for the other six transistors.

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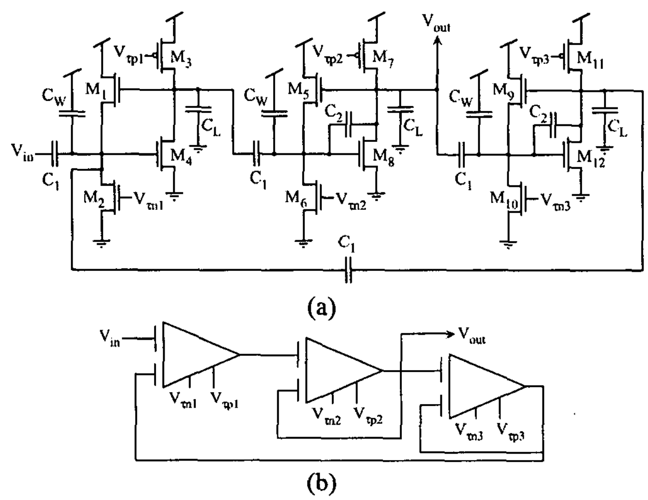
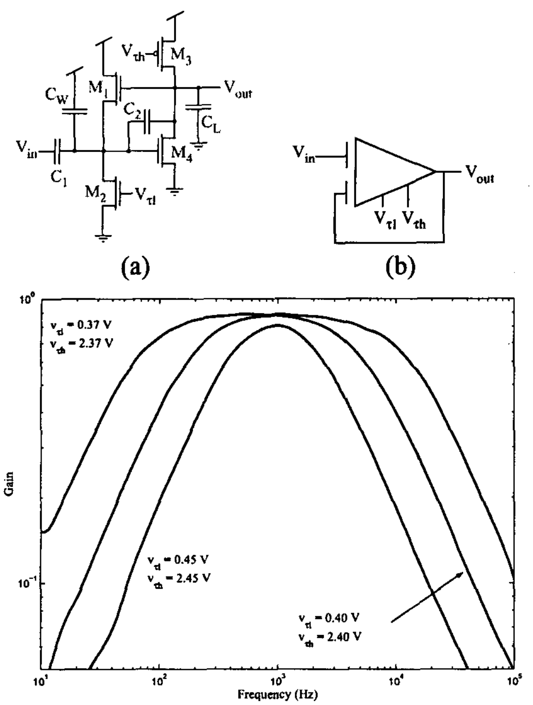


Fig. 1. (a) Circuit schematic for the C^4 Second-Order Section. This is a bandpass filter with ±40 dB/decade roll offs, and it is composed of three C^4's, each with a bandpass effect and ±20 dB/decade roll offs. The corner frequencies are electronically tunable and are independent of each other. The combination of the three biasing nFET's (M_2, M_6, and M_{10}) yields the low cut-off frequency, and the combination of the three biasing pFET's (M_3, M_7, and M_{11}) gives the upper cut-off frequency. (b) Shorthand notation of the C^4 SOS. This shows the amplification effects of the filters. The "extra" lines on the amplifier symbols emphasize the capacitive coupling for each of the amplifier stages.

I. BACKGROUND FOR THE C^4 SOS

The C^4 SOS bandpass filter, which is shown in Fig. 1, is based on the Diff2 second-order section structure [5]. It closely models the form of the AutoSOS [2] in which three autozeroing floating-gate amplifiers (AFGA) were used. In that case, the first filter acted as a high-gain amplifier, and the third filter had its time constant set so fast that it acted merely as an amplifier with a gain of -1. The C^4 SOS uses the configuration of the AutoSOS and replaces the AFGA's of the AutoSOS with bandpass filters. As a result, the operation of the C^4 SOS is much like the that of the AutoSOS [6]. Unlike the AFGA version, the assumption cannot be made that the time constants are far enough apart that the differentiation and integration regimes can be treated as isolated



(c)

Fig. 2. (a) Circuit diagram of a Capacitively-Coupled Current Conveyer (C^4). This is the basic building block for the C^4 SOS. The two corner frequencies (controlled by $v_{\tau l}$ and $v_{\tau h}$) can independently be moved and are electronically tunable. The slopes are first-order. (b) Shorthand notation of the C^4. (c) Data showing the basic operation of a C^4.

from one another.

The C^4 SOS is composed of three bandpass filters which are based on the Capacitively-Coupled Current Conveyer (C^4) shown in Fig. 2a. The C^4's corner frequencies are electronically tunable and can be set independently of one another. The frequency response of the C^4 is governed by

$$\frac{V_{out}}{V_{in}} = -\frac{C_1}{C_2}\frac{s\tau_l(1-s\tau_f)}{s^2\tau_h\tau_l + s(\tau_l + \tau_f(1-\frac{C_o}{\kappa C_2})) + 1} \quad (1)$$

where the time constants are given by $\tau_l = \frac{C_2 U_T}{\kappa I_{\tau_l}}$, $\tau_f = \frac{C_2 U_T}{\kappa I_{\tau_h}}$, and $\tau_h = \frac{C_T C_O - C_2^2}{C_2}\frac{U_T}{\kappa I_{\tau_h}}$. The total capacitance, C_T, and the output capacitance, C_O, are defined as $C_T = C_1 + C_2 + C_W$ and $C_O = C_2 + C_L$. The currents I_{τ_l} and I_{τ_h} are the currents through M_2 and M_3, respectively. With normal usage, τ_f is so fast that the zero it produces lies far outside of the operating range. Thus, the C^4 takes on the properties of a bandpass filter with first-order slopes and a bandpass gain set by the ratio of the two coupling capacitors as $A_v = -C_1/C_2$. The overall time constant of the filter, which gives the center frequency, is $\tau = \sqrt{\tau_l \tau_h}$. By tuning the filter such that $\tau_h > \tau_l$, resonance occurs, and the value

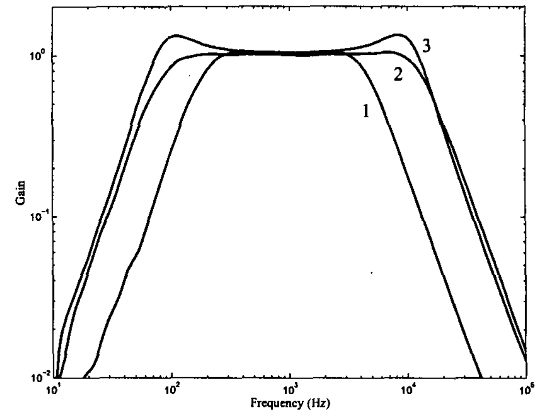


Fig. 3. This plot gives the frequency response of the C^4 SOS showing second-order behavior. The slopes outside the passband are 40 dB/decade. For each of the three traces, the third amplifier was set to $v_{\tau n3} = 0.2V$ and $v_{\tau p3} = 2.0V$. The other biases for curves 1-3 are: (1) $v_{\tau n1} = 0.41V$, $v_{\tau n2} = 0.42V$, $v_{\tau p1} = 2.45V$, $v_{\tau p2} = 2.41V$ (2) $v_{\tau n1} = 0.37V$, $v_{\tau n2} = 0.38V$, $v_{\tau p1} = 2.41V$, $v_{\tau p2} = 2.37V$ (3) $v_{\tau n1} = 0.33V$, $v_{\tau n2} = 0.42V$, $v_{\tau p1} = 2.37V$, $v_{\tau p2} = 2.41V$

of the Q peak is

$$Q = \sqrt{\frac{\tau_h}{\tau_l}}\frac{1}{1 + \frac{I_{\tau_l}}{I_{\tau_h}}(\frac{C_O}{\kappa C_2} - 1)} \quad (2)$$

The plot of Fig. 2 summarizes the response of the C^4.

II. CLASSICAL FILTER BEHAVIOR

The C^4 SOS is composed of three C^4's in the fashion of an AutoSOS. The feedback capacitor of the first-stage filter is removed in order to make that stage a high gain amplifier. For each of the other two stages, the capacitors were set to $C_1 = C_2$ in order to give unity gain.

The C^4 SOS can easily be placed into a mode of operation in which it produces second-order effects. More specifically, this filter can have a frequency response of any defined bandwidth, and outside that bandwidth, slopes of ±40 dB/decade occur.

In order to give this sort of response, the third amplifier is set to run "fast." In essence, the third amplifier is biased so that its corner frequencies are far enough outside the frequency range under consideration that this particular stage appears to simply yield a gain of -1 (since $C_1/C_2 = 1$) over the entire range of audible frequencies. The gain of -1 thus supplies the filter with negative feedback. To do this, the time constant set by $v_{\tau p3}$ is very fast, and the time constant set by $v_{\tau n3}$ is very slow. In other words, the current through M_{11} is a very large subthreshold current, and the current through M_{10} is a very small subthreshold current.

With the time constants of the third amplifier far out of the normal range of operation, a combination of the low-frequency and high-frequency time constants of the first two filters sets the overall low-frequency and high-frequency time

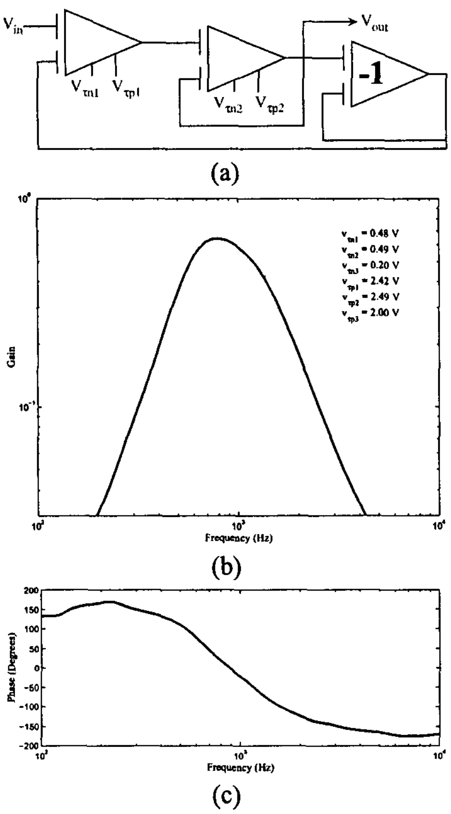


Fig. 4. (a) Simplification of the C[4] SOS when the third amplifier is set to run "fast." This yields a second-order response. (b) Magnitude frequency response for a tight bandpass filter and a small Q peak. (c) Phase response for the same bias conditions. The phase makes a sharp transition from 180° to −180° in the region of the center frequency.

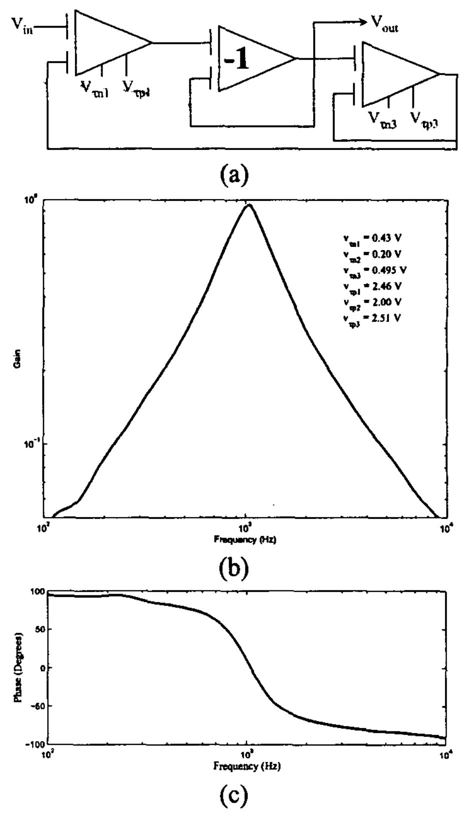


Fig. 5. (a) Simplification of the C[4] SOS when the middle amplifier is set to run "fast." This yields a first-order response. (b) Magnitude frequency response for a tight bandpass filter and a Q peak. (c) Phase response for the same bias conditions. The phase makes a sharp transition from 180° to −180° in the region of the center frequency.

constants of the C^4 SOS, respectively. By adjusting the relation of $v_{\tau n1}$ to $v_{\tau n2}$ or of $v_{\tau p1}$ to $v_{\tau p2}$, the response at either corner can be tuned to have a sharp transition or even a Q peak. The response at either corner is independent of the other, as long as the two corners are sufficiently far apart. Figure 3 shows representative curves of the C^4 SOS when the corners are separated. These responses have ±40 dB/decade roll offs.

The closer the two corners of the C^4 SOS are brought together, the narrower the bandwidth becomes until a very tight band with a Q peak develops. Figure 4 shows the frequency response for a case with a small Q peak. Also included is the phase response indicating the sharp transition.

In the same manner as was done in the previous case, the middle amplifier can be made to run "fast." Therefore, the middle amplifier virtually becomes a buffer with a gain of -1. This causes the third amplifier to be isolated from the first, and the capacitance varies less with frequency. Larger Q peaks for very narrow bandwidths are much easier to produce, but the cost is that the roll offs are only ±20 dB/decade, as is displayed in Fig. 5. The phase response is also given to show the very sharp transition. Third-order responses, or ±60 dB/decade slopes, can be achieved if the output of the C^4 SOS is taken as the output of the third amplifier.

III. C^4 SOS ARRAYS FOR COCHLEA MODELING

The basilar membrane of a cochlea detects the frequency components of a signal by locating where the membrane resonates. It can be thought of as a set of differently sized masses that are each free to resonate at their own specific frequency, as is shown in the illustration of Fig. 6a. Each of these masses on springs have second-order dynamics. Resonance is detected by the hair cells which then send signals to the Auditory Cortex via the Eighth Cranial Nerve. This resonance is in a fashion similar to a bandpass filter with a $Q \approx 30$. In consequence, an array of bandpass filters is a good model of the cochlea [5]. We therefore built an array of 32 C^4 SOS's, as is illustrated in Fig. 6b. We used six tapped resistive lines (one for each bias point) to space the center frequencies exponentially.

Figure 6c shows the response of the array with similar biasing conditions as were used in Fig. 4. Also included is Fig. 6d which shows the response of the array for the

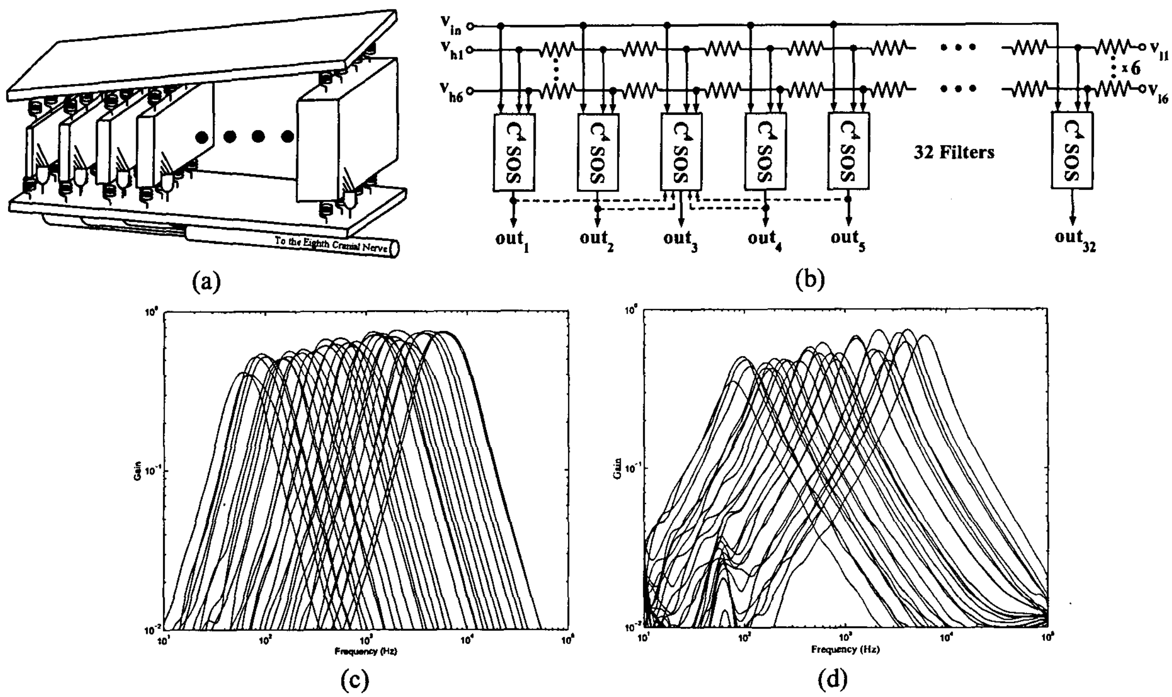


Fig. 6. (a) Illustration of the resonant properties of the cochlea. The basilar membrane can be thought of as a set of blocks on springs. Each block is of a different mass (slightly larger than the one preceding it), so each block resonates at a different frequency with second-order dynamics. Higher frequencies resonate smaller blocks (near the front) while lower frequencies resonate larger blocks (near the back). Hair cells sense the resonance and send signals down the eighth cranial nerve. Coupling occurs through the fluid. (b) Schematic of the array of the SOS's used for a cochlea model. This array is tuned from high frequencies to low frequencies. This is similar to a cochlea in which the higher frequencies are detected near the front and the lower frequencies are detected near the end. There are six resistive lines for exponentially biasing each C^4 SOS in the array. Future versions will implement floating gate elements instead of resistors to allow for programming and improved tuning. The dashed lines represent coupling among the different elements in the array. This is needed for phase accumulation, as in a real cochlea, and it also leads to improved rejection in the stopband (higher-order roll offs) for signal processing applications. This operation can be done with a computer, but it will be built into the circuit in future versions. (c) Frequeny response of the array with second-order slopes. (d) Frequency response of the array with first-order slopes.

same biasing conditions as in Fig. 5. The center frequencies for both of these modes are spaced monotonically. Both of these modes are legitimate methods of modeling cochlea. First-order slopes show the response of the cochlea before the effects of the hair cells, while the second-order case includes these effects. The advantage of the second-order responses is that potentially less coupling will be required to mimic human cochlea. This coupling, which will be present on future versions of this cochlea model, will help to represent the spatial dependence of the basilar membrane on itself. It will also help with phase accumulation and sharper cutoffs. Future versions will also replace the tapped resistive line with floating gate elements in order to better program each element in the array.

IV. CONCLUSION

The C^4 SOS is capable of Q peaks and ± 40 dB/decade roll offs which significantly aid in the isolation of any given frequency. In addition, second-order sections are the basis for most higher-order filters, so the C^4 SOS could be used as a basic building block for forming much higher-order and better continuous-time filters. Differential forms of the C^4 SOS could also be made for further increases in performance. Silicon cochlea models would become better approximations to biological cochlea, and analog signal processing would be able to improve drastically.

V. REFERENCES

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