Fully Integrated OTA-C Filter Tunable by Controlled Transconductance Parameter
Adam Vrba and Roman Prokop

Abstract – This work deals with design of fully integrated 2nd-order tunable filters. These presented filters use transconductance amplifiers as the active components and they are tuned by controlling transconductance parameter of these OTA amplifiers. Cut-off frequency and quality of all the filters can be tuned independently. The introduced filters use voltage-tunable linear transconductor with two cross coupled differential pairs.

Keywords – OTA - C filter, gm - C filter, tunable filter, fully integrated filter

I. INTRODUCTION
The main advantage of using OTA as active component is that OTA - C filters can be simply tunable by controlling the DC bias voltage or current that changes transconductance parameter of the OTA amplifier. This allows us to tune electronically the filter parameters very simply. This capability is especially important for fully integrated tunable filters. Another advantage is the possibility to fabricate OTA - C filter and digital signal processing circuits on the same semiconductor chip even at digitally oriented technology. Resistor realization is impractical because they take up excessive chip area for resistance values usually called in this filters. OTA - C filters overcome utilization of resistors by circuits that use one or more transconductance amplifiers. This circuit is capable to realize equivalent grounded or floated resistor. Hence OTA - C filters mainly use only transconductance amplifiers and capacitors. Input dynamic range of transconductance amplifiers is mostly limited because of their non-linearity.

Filters described in this paper are supposed to be used in the sigma-delta modulation measuring system for filtering a digitally generated harmonic signal for biasing capacitive sensor. As can be seen in Fig. 1, the harmonic signal generator consists of ROM memory, low-pass sigma-delta first order modulator and analog low-pass filter. Content of ROM memory is a digital pattern of sine wave in 8-bit resolution.

Fig. 1. Block diagram of harmonic signal generator

For measurement of wide range of impedances (mostly capacitances of capacitive sensors) the biasing harmonic input signal at various frequencies must be generated, so tunable low-pass analog filter is needed. The full system for digital harmonic signal generation is described more deeply in [1], nevertheless, the understanding of the system is not necessary for design and analysis of the presented tunable filters.

As a suitable active device for tunable analog filters the transconductance stage with controlled $gm$ parameter seems to be one of the best choices.

II. TRANSCONDUCTANCE AMPLIFIER
Almost linear voltage-controlled CMOS transconductor is described in [2]. This transconductor is based on two differential pairs ($M_1M_4$ and $M_2M_3$) connected in cross-coupled configuration shown in Fig. 2. Just due the differential connection we are able to reach quite good linearity of the transconductor even with usage of highly non-linear CMOS tranzistors. Transistor $M_2$ is connected against the transistor $M_1$, so then the current $i_1$ is given by difference between transconductance parameters of transistors $M_1$ and $M_3$. Relationship between input differential voltage $v_d$ and output current $I_{OUT}$ is given by (1), where $k_n$ is the transconductance parameter and $V_A$ is the bias voltage defined in (2). Transconductance parameter is tunable by varying of the bias voltage $V_A$ and it is obvious that transconductance of amplifier goes to zero for bias voltage $V_A$ goes to zero. That allows realization of very small transconductances, which are important especially for low frequency filters.

![Cross-coupled differential pair of the OTA stage](image)

Cross-coupled configuration allows realization of transconductance amplifier with nicely linear dependence between the bias voltage $V_A$ and transconductance of the circuit. Linearity dependence is maintained as long as all devices remain in saturation region; this is fulfilled as far as input differential voltage meets the inequality (3) and (4).
\[
I_{\text{OUT}} = 2k_lV_dV_d \quad (1)
\]
\[
V_d = V_a - V_{SS} \quad (2)
\]
\[
| V_d | < 2 | V_r + V_a | \quad (3)
\]
\[
| V_d | < 2 | V_{SS} + V_r | \quad (4)
\]

If the terminal \( V_{SS} \) is grounded, the voltage applied at terminal \( V_a \) directly drives transconductance parameter. A suitable low-impedance voltage source for \( V_a \) voltage must be used for proper function of transistor \( M_2 \) and \( M_3 \). The convenient tunable voltage source with low output impedance was designed during this research whose nominal output resistance is less than 40 \( \Omega \) for whole bias range. Simulated result of the transconductance dependence on the controlling voltage \( V_a \) is presented in Fig. 3. From the graph is obvious that transconductance of the designed amplifier can be varied by a factor 15.

![Graph showing transconductance as a function of \( V_a \) voltage](image)

**III. OTA-C FILTER STRUCTURE**

Two universal structures described in this paper can realize at least two filter functions in dependence on different input and output positions. The third structure can realize only low-pass notch filter. Second order filters have been chosen for the reason of better cut-off frequency tuning and simpler design dependencies. High order filter can be realized utilizing cascade connection of more 2nd order filters. Independency of filter quality during cut-off frequency tuning is also suitable for proper harmonic generator function.

**A. Structure 1**

The circuit on Fig. 4 can realize low-pass and band-pass filter. Table 1 presents input and output connection for different filter functions. Filter consists of two grounded capacitors and two integrators in a single loop where one ideal integrator consists of \( g_1 \) and \( C_1 \) and the second lossy integrator consists of \( g_2 \), \( C_2 \) and \( g_3 \) transconductor, connected as grounded resistor with resistance of \( 1/g_3 \). Equation for filter quality

\[
Q = \frac{C_2}{g_3} \sqrt{\frac{g_2 C_2}{g_1 C_1}} \quad (5)
\]

and cut-off frequency

\[
\omega_0 = \frac{g_2 g_3}{\sqrt{C_1 C_2}} \quad (6)
\]

is the same for both filters types. Cut-off frequency can be tuned by transconductance parameter \( g_1 \) and \( g_2 \). It can be seen that the parameter \( \omega_0 \) can be varied as much as the transconductance parameter of one transconductor. Parameters \( Q \) and \( \omega_0 \) can be set independently. Tuning of \( \omega_0 \) without affection of \( Q \) is possible when rate \( \sqrt{g_2 g_3} / g_3 \) stay constant.

<table>
<thead>
<tr>
<th>Filter type</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>( V_{I1} )</td>
<td>( V_{O2} )</td>
</tr>
<tr>
<td>BP</td>
<td>( V_{I3} )</td>
<td>( V_{O1} )</td>
</tr>
</tbody>
</table>

**Fig. 4. Configuration of structure 1 filter**

![Image of the configuration of structure 1 filter](image)

Absolute values of capacitors cannot be controlled with any acceptable degree of accuracy. On the other hand the relative ratio between transconductances and especially between capacitances can be controlled much more accurate. Due to that we can exercise good control over the designed \( Q \) value but not over \( \omega_0 \).

**B. Structure 2**

The circuit on Fig. 5 can realize LP, HP, BP, LPN and HPN filter. Table 2 presents input and output connection for different filter functions. Filter consists of six transconductance amplifiers where two of them are connected as resistor. This circuit can realize low-pass notch filter from \( V_{O3} \) when \( V_{I1} = V_{I4} = V_{I14} \) meaning that \( V_{I1} \) and \( V_{I4} \) are connected together and providing input node. Low-pass notch filter is suitable for attenuation of harmonic components near the cut-off frequency.

\[
\omega_0 = \frac{g_2 g_3}{\sqrt{C_1 C_2}} \quad (7)
\]

\[
Q = \frac{g_2}{g_3} \sqrt{\frac{g_2 g_3 C_2}{g_1 g_6 C_1}} \quad (8)
\]

\[
a_2 = \frac{g_2}{g_5} \frac{g_5}{g_6 + g_3} \quad (9)
\]

Equation for filter quality \( Q \) (eq. 8) and cut-off frequency \( \omega_0 \) (eq. 7) is the same for all filter types. Parameter \( a_2 \) (eq. 9) defines ratio \( a_2^0 / a_2^0 \), where \( a_2^0 \) is angular frequency of zero. Main advantage of this configuration is independent cut-off frequency, quality and \( \omega_0 \) tuning. At the expense of that we must tune six transconductance parameters. For separate tuning of cut-off frequency the two
transconductance \( g_1 \) and \( g_2 \) must be tuned. Quality is not affected when the \( g_1/g_2 \) ratio is constant.

**Table 2: Structure 2 Filter Type**

<table>
<thead>
<tr>
<th>Filter type</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>( V_{i3} )</td>
<td>( V_{o1} )</td>
</tr>
<tr>
<td>HP</td>
<td>( V_{o35} )</td>
<td>( V_{o3} )</td>
</tr>
<tr>
<td>BP</td>
<td>( V_{i3} )</td>
<td>( V_{o2} )</td>
</tr>
<tr>
<td>BS</td>
<td>( V_{i4} )</td>
<td>( V_{o3} )</td>
</tr>
<tr>
<td>LPN</td>
<td>( V_{i34} )</td>
<td>( V_{o3} )</td>
</tr>
<tr>
<td>HPN</td>
<td>( V_{i46} )</td>
<td>( V_{o3} )</td>
</tr>
</tbody>
</table>

**IV. CONCLUSION**

Transconductance amplifier was designed in AMIS CMOS 0.7µm technology and simulated in Cadence design environment. Transconductance parameter can be easily varied by a factor 15 for acceptable DC bias currents. Lowest transconductance that can be realize is about 1µS. Simulated transfer function of the low-pass filter realized by structure 1 is shown in Fig.7. Cut-off frequency was tuned through 1.4 decade from 8.8 kHz to 220 kHz. All transconductance amplifiers have been tuned equally to keep constant quality \( Q \) of the filter which was designed as 0.7 for all cut-off frequencies.

\[
\omega_0 = \sqrt{\frac{g_1 g_2}{C_1 C_2 + C_i C_3}} \quad (10)
\]

\[
Q = \frac{(C_2 + C_i) g_1}{g_2 C_1} \quad (11)
\]

\[
a_2 = \frac{C_2}{C_2 + C_3} \quad (12)
\]

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