A Fully Integrated 0.5-7Hz CMOS Bandpass Amplifier.

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Case of study: Signal conditioning circuit for a piezoelectric accelerometer which is part of a rate adaptive pacemaker.

Objective:
1<sup>st</sup> - To realize the continuous time circuit without using external elements.
2<sup>o</sup> - To reduce as much as possible power consumption, area, and noise.

First stage of the signal chain: 2<sup>nd</sup> order bandpass amplifier.
Contents: A Fully Integrated 0.5-7Hz CMOS Bandpass Amplifier.

- Circuit specifications, analysis and difficulties.
  - Series-Parallel OTAs with very low transconductance and extended linear range.
  - Bandpass-amplifier architecture and measurements.
- Conclusions.
Circuit Specifications
### Specifications: Sensor

<table>
<thead>
<tr>
<th>Specs</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Sensitivity [pC/g]</td>
<td>1.4</td>
<td>1.9</td>
<td>2.4</td>
</tr>
<tr>
<td>Capacitance</td>
<td></td>
<td>550 pF</td>
<td></td>
</tr>
<tr>
<td>Transverse Response</td>
<td></td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Resistance (25°C)</td>
<td>10GΩ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance (150°C)</td>
<td>100MΩ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanic Resonance</td>
<td></td>
<td>9kHz</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram of sensor with 3.5 mV/g]
$V_{IN}$

580MΩ at 0.5Hz!

Some kind of virtual ground or DC bias is required!
## Specifications: System

<table>
<thead>
<tr>
<th>Specification</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Voltage</td>
<td>2.8 - 2.0 V</td>
</tr>
<tr>
<td>Accelerations range</td>
<td>0.007 - 0.34 g&lt;sub&gt;peak&lt;/sub&gt;</td>
</tr>
<tr>
<td>Input Voltage Range</td>
<td>(24 μV&lt;sub&gt;peak&lt;/sub&gt; - 1.2 mV&lt;sub&gt;peak&lt;/sub&gt;) ± 3.5mV gravity step</td>
</tr>
<tr>
<td>Current Consumption</td>
<td>&lt; 2μA</td>
</tr>
<tr>
<td>Frequency Response.</td>
<td>Bandpass 0.5-7Hz, 40 dB/dec</td>
</tr>
<tr>
<td>Input Noise.</td>
<td>&lt; 12μV&lt;sub&gt;rms&lt;/sub&gt;</td>
</tr>
<tr>
<td>Input Offset.</td>
<td>&lt; 13μV</td>
</tr>
<tr>
<td>Gain.</td>
<td>400</td>
</tr>
<tr>
<td>Others</td>
<td>No external elements (i.e. R, C)</td>
</tr>
<tr>
<td></td>
<td>Relaxed tolerance in transfer function</td>
</tr>
</tbody>
</table>
Main challenges:

• Transducer with a very high output impedance.
• Small signal in reverse in much higher gravity steps.
• Low noise, micropower.

• Sub-Hz filter without the aid of external resistors or capacitors.
**Selected Circuit Technique:** $G_m$-$C$ continuous-time.

Extremely low transconductors or large capacitors are required for low frequency filters.
Series-Parallel division OTAs:
**OTAs: Basic Series-Parallel OTA.**

- Very simple circuit ⇒ less area, power consumption.
- Do not introduce much excess noise or offset.
- Easy to reuse layout.

- Fabricated and tested OTAs up to 35nS (30GΩ) and 1V linear range.
**OTAs:** Example $G_{m6} = 100 \text{pS} \ (10 \text{G}\Omega)$

- Measured
- $G_{m6} \cdot V_{IN}$

Par linealizado:

Output Current $I_{Out}$ [nA]

Input Voltage $V_{IN}$ [Volts]
**OTAs:** Example $G_{m5} = 2.58\,nS$ \((380\,M\Omega)\)
# OTAs: Measured/estimated characteristics

<table>
<thead>
<tr>
<th>OTA</th>
<th>Transc. [^{[a]}]</th>
<th>Linearity $V_{\text{Lin}}$ [mV]</th>
<th>Input noise. $\mu V_{\text{rms}}$ [^{[a]}]</th>
<th>Input Offset $\sigma_{\text{Voff}}$ [mV]</th>
<th>Current Cons. [nA]</th>
<th>Area [mm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{m1}$</td>
<td>110(110)nS</td>
<td>60</td>
<td>5 (4)</td>
<td>1.1</td>
<td>14</td>
<td>.019</td>
</tr>
<tr>
<td>$G_{m2}$</td>
<td>2.35(2.58)nS</td>
<td>150</td>
<td>42</td>
<td>4.4</td>
<td>43</td>
<td>.040</td>
</tr>
<tr>
<td>$G_{m3}$</td>
<td>35(33)pS</td>
<td>150</td>
<td>163(130)</td>
<td>2.1</td>
<td>42</td>
<td>.092</td>
</tr>
<tr>
<td>$G_{m4}$</td>
<td>21nS</td>
<td>150</td>
<td></td>
<td></td>
<td>47</td>
<td>.051</td>
</tr>
<tr>
<td>$G_{m5}$</td>
<td>2.4(2.8)nS</td>
<td>500</td>
<td></td>
<td>9.1</td>
<td>44</td>
<td>.18</td>
</tr>
<tr>
<td>$G_{m6}$</td>
<td>89(100)pS</td>
<td>500</td>
<td></td>
<td>6.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[^{[a]}\] Linear characteristics as measured or estimated.
0.5-7Hz Filter-Amplifier
**Bandpass-Amplifier 0.5-7Hz**

Preamplifier maximum possible gain $G=46.4$

- $V_{Bias} = 700\text{mV}$
- $C_2=50\text{pF}$
- $550\text{pF}$ sensor capacitance used in the filter
- $V_{lin}=\pm 5\text{mV}$
- $C_3=50\text{pF}$
- $C_4=250\text{pF}$

Gain Stage $G_2=8.3$

$V_{lin}=\pm 500\text{mV}$

Output $V_{Out2}$

$G=385$
Bandpass-Amplifier 0.5-7Hz

Gain 2nd stage:
G2 = 8.3

Preamplifier Gain: G1 = 46.4
**Bandpass-Amplifier 0.5-7Hz:** Critical aspects.

- **$G_{m1}$:** noise is critical
- **$G_{m3}$** minimum possible transconductance.
- **$C_2 = 50\text{p}$**
- **$C_3 = 250\text{p}$**
- **$C_4 = 50\text{p}$**
- **$V_{IN}$**
- **$V_{OUT1}$**
- **$V_{OUT2}$**

- **$G_{m5,6}$** minimum offset.
- **$G_{m5,6}$** $\pm 500\text{mV}$ linear range.
- **$C_3$** as big as possible.
Bandpass Measurements: Gain - Frequency.

$G_{\text{máx}} = 390$

Frequency [Hz]: 1.8 Hz
Measurements: Qualitative response w/sensor.

- External 42nA reference current
- Mechanical shaking at approx. 2Hz
## Filter-Amplifier Measurements: Characteristics

<table>
<thead>
<tr>
<th>Specification</th>
<th>Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass-band frequency</td>
<td>40db/dec 0.5-7Hz</td>
</tr>
<tr>
<td>Gain</td>
<td>390</td>
</tr>
<tr>
<td>Input noise</td>
<td>2.1µV&lt;sub&gt;rms&lt;/sub&gt;</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>2.0 - 2.8 V</td>
</tr>
<tr>
<td>Current Consumption</td>
<td>230nA</td>
</tr>
<tr>
<td>Area</td>
<td>0.78mm&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Input Offset</td>
<td>18µV</td>
</tr>
</tbody>
</table>
**Conclusions:**

**Series-parallel Division OTAs:**

- Excellent trade-off solution regarding linearity, noise, occupied area, power consumption.
- OTA designed and tested up to the equivalent of 30Ω resistor and up to 1V linear range.

**Filter Design:**

- 0.5-7Hz, 40db/Dec, Gain 400, bandpass filter has been presented.
- Remarkable low power consumption, and input noise.

*No external elements have been employed!*