Preamplifiers

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Tech Talk
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Motivation

• Better understand daily used electronics
• Use measurement equipment better
Outline

• Basics about filters
• I to V converter (LNHS)
• Voltage Preamplifier (1201)
• Combination with Lock-in
Basics about filters

- Low-pass filter

\[ V_{out} = V_{in} \frac{1}{\sqrt{1 + \omega^2 R^2 C^2}} \]
Low-pass filter

\[ V_{out} = V_{in} \frac{1}{\sqrt{1 + \omega^2 R^2 C^2}} \]

\[ \omega = 2 \cdot Pi \cdot f \]

\[ \frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{2}} \]

\[ \frac{1}{\sqrt{2}} \]

\[ \tau = RC = 1 \]
Low-pass filter

• Decibel (dB) definition (for amplitudes):

\[ dB = 20 \cdot \log \left( \frac{A_1}{A_2} \right) \]

• For power:

\[ dB = 10 \cdot \log \left( \frac{P_1}{P_2} \right) \]
Low-pass filter

\[ V_{out} = \frac{V_{in}}{\sqrt{2}} \]

\[ dB = 20 \cdot \log\left(\frac{V_{out}}{V_{in}}\right) = 20 \cdot \log\left(\frac{1}{\sqrt{2}}\right) = -10 \cdot \log(2) \]

\[ dB = -10 \cdot \log(2) = -10 \cdot 0.301 \approx -3 \]

\[ f_{1/\sqrt{2}} = f_{-3dB} = f_{3dB} \]
Low-pass filter

First order filter

\[ f_{-3dB} \]

\[ \tau = RC = 1 \]
Low-pass filter

\[
\lim_{\omega \to \infty} \frac{V_{out}}{V_{in}} = \lim_{\omega \to \infty} \frac{1}{\sqrt{1 + \omega^2 R^2 C^2}} = \frac{1}{\omega R C}
\]

\[
\tilde{\omega} = 2 \cdot \omega
\]
\[
\tilde{V}_{out} = \frac{V_{out}}{2}
\]
\[
dB = 20 \cdot \log\left(\frac{\tilde{V}_{out}}{V_{out}}\right) = -6
\]

\[\text{−6 dB/octave}\]

\[
\tilde{\omega} = 10 \cdot \omega
\]
\[
\tilde{V}_{out} = \frac{V_{out}}{10}
\]
\[
dB = 20 \cdot \log\left(\frac{\tilde{V}_{out}}{V_{out}}\right) = -20
\]

\[\text{−20 dB/decade}\]
Low-pass filter

First order filter

\[ \tau = RC = 1 \]

**slop**e:

-6 dB/octave

-20 dB/decade
Low-pass filter

Higher order filters

\[ f_{-3dB} / f_{-6dB} \]

\[ \tau = RC = 1 \]

First order
-20 dB/decade

Second order
-40 dB/decade
Low-pass filter

First order filter

Time response:

\[ t_R = t_{90\%} - t_{10\%} \]
Low-pass filter

First order filter

\[ V_{out} = V_{in} \left( 1 - e^{-\frac{t}{RC}} \right) \]

\[ t_R = t_{90\%} - t_{10\%} = ln(9) \cdot RC \]

\[ = ln(9) \cdot \frac{1}{2\pi f_{3dB}} \]

N order filter

\[ t_R = \sqrt{(t_{R1})^2 + (t_{R2})^2 + \cdots + (t_{RN})^2} \]
I to V converter

- SP 983 with LSK389A
- SP 983 with IF3602
Offset Example

$I_{in} > 0 \quad \rightarrow \quad V_{out} > 0$

Positive Current into I/V  \quad \rightarrow \quad Positive output voltage
Block diagram
**Input Offset Voltage**

\[ V_{offset} = \pm 10V \quad \Rightarrow \quad V_{in} = (\pm 10V)/100 = \pm 100mV \]

- can take several minutes to stabilize
- add AC is also possible

\[ V_{in} \text{ stabilized (\pm} 10\mu V) \]
Input Offset Error

\[ V_{offset} = 0V \quad \rightarrow \quad V_{in} = V_{error} = (-15 \div 15)\mu V \]

- can be compensated with some \( V_{offset} \)
**Offset Example**

- $V_{in} = I_{in} = 0$
- $V_{offset} = +3V$
- $V_{out} = -30mV$

- INVERTED voltage at the output
- Output resistance: **22Ω**, connect to next stage inputs $>=10kΩ$
Input and Output Noise Voltage

\[ \text{Noise Gain} = 1 + \frac{R_f}{X_{in}} \]

\[ R_f \sim GAIN(V/A) \]

\[ U_{n_{tot}} = \sqrt{(U_n^-)^2 + (U_n^+)^2} \]

\[ U_{out_{noise}} = U_{n_{tot}}(1 + \frac{R_f}{X_{in}}) \]

\( (\omega = 2\pi f): \quad X_{in} = \frac{1}{j\omega C_{in}} \)

\[ U_{out_{noise}} = U_{n_{tot}}(1 + j\omega R_f C_{in}) \]

<table>
<thead>
<tr>
<th></th>
<th>@ f = 10 Hz</th>
<th>@ f = 30 Hz</th>
<th>@ f = 100 Hz</th>
<th>@ f = 1 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSK389A</td>
<td>4.3 nV/sqrt(Hz)</td>
<td>2.7 nV/sqrt(Hz)</td>
<td>2.2 nV/sqrt(Hz)</td>
<td>1.8 nV/sqrt(Hz)</td>
</tr>
<tr>
<td>IF3602</td>
<td>2 nV/sqrt(Hz)</td>
<td>1.5 nV/sqrt(Hz)</td>
<td>1.4 nV/sqrt(Hz)</td>
<td>1.2 nV/sqrt(Hz)</td>
</tr>
</tbody>
</table>
## Input Current Noise

<table>
<thead>
<tr>
<th>GAIN [V/A]</th>
<th>Current Noise @ 10 Hz [fA/sqrt(Hz)]</th>
<th>Current Noise @ 1 kHz [fA/sqrt(Hz)]</th>
<th>Theoretical Limit [fA/sqrt(Hz)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^9$</td>
<td>5.5</td>
<td>9.1</td>
<td>4.1</td>
</tr>
<tr>
<td>$10^8$</td>
<td>13.7</td>
<td>15.3</td>
<td>13</td>
</tr>
<tr>
<td>$10^7$</td>
<td>42</td>
<td>42</td>
<td>41</td>
</tr>
<tr>
<td>$10^6$</td>
<td>137</td>
<td>135</td>
<td>130</td>
</tr>
<tr>
<td>$10^5$</td>
<td>580</td>
<td>541</td>
<td>410</td>
</tr>
</tbody>
</table>

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<tr>
<th>GAIN [V/A]</th>
<th>Current Noise @ 10 Hz [fA/sqrt(Hz)]</th>
<th>Current Noise @ 1 kHz [fA/sqrt(Hz)]</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$10^9$</td>
<td>6.1</td>
<td>16.2</td>
<td>4.1</td>
</tr>
<tr>
<td>$10^8$</td>
<td>14</td>
<td>21</td>
<td>13</td>
</tr>
<tr>
<td>$10^7$</td>
<td>42</td>
<td>44</td>
<td>41</td>
</tr>
<tr>
<td>$10^6$</td>
<td>140</td>
<td>138</td>
<td>130</td>
</tr>
<tr>
<td>$10^5$</td>
<td>588</td>
<td>545</td>
<td>410</td>
</tr>
</tbody>
</table>

For $f = 1$ kHz, $GAIN = 10^9$, $U_{current} = U_{voltage}$ $\rightarrow C_{in} = 2nF$
Grounding sensitive samples by using this input switch is strongly recommended during manipulations on the I/V converter (e.g. changing gain, power on/off).

First release external switch, then **internal**, another sequence may destroy sample!
Be Careful!

“Do not touch input with your fingers or any object, since electrostatic discharge may damage the sensitive input J-FET”
Input resistance

\[ R_{IV} = \frac{R_f}{1 + G(f)} \approx \frac{R_f}{G(f)} = f \frac{R_f}{GBWP} \]

**IF3602**

Example of calculating the AC-input resistance:

- \( f = 1 \text{ kHz} \)
- \( \text{Gain} = 10^7 \text{ V/A} \)
- \( \text{GBWP} = 620 \text{ MHz} \)
- \( R_{prot} = 28 \Omega \)

\[ R_{in} = 28 \Omega + 1 \text{ kHz} \times (1E7 / 620E6) = 44 \Omega \]

**LSK389A**

Example of calculating the AC-input resistance:

- \( f = 1 \text{ kHz} \)
- \( \text{Gain} = 10^7 \text{ V/A} \)
- \( \text{GBWP} = 68 \text{ MHz} \)
- \( R_{prot} = 28 \Omega \)

\[ R_{in} = 28 \Omega + 1 \text{ kHz} \times (1E7 / 68E6) = 175 \Omega \]
“Overload is detected on the unfiltered output voltage”
# Rise/Fall time, Bandwidth

<table>
<thead>
<tr>
<th>GAIN [V/A]</th>
<th>Rise/Fall-Time (10%, 90%) [μs] typical</th>
<th>maximum</th>
<th>Bandwidth (-3 dB) @ 1 V [kHz] typical</th>
<th>minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^9$</td>
<td>203</td>
<td>270</td>
<td>1.6</td>
<td>1.2</td>
</tr>
<tr>
<td>$10^8$</td>
<td>14</td>
<td>15</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>$10^7$</td>
<td>3.6</td>
<td>3.7</td>
<td>94</td>
<td>90</td>
</tr>
<tr>
<td>$10^6$</td>
<td>1.1</td>
<td>1.2</td>
<td>308</td>
<td>300</td>
</tr>
<tr>
<td>$10^5$</td>
<td>0.61</td>
<td>0.62</td>
<td>569</td>
<td>500</td>
</tr>
</tbody>
</table>
Low-Pass Filter

2\textsuperscript{nd} order \((-40 \text{ db/decade})\)
Rise/Fall time, Bandwidth

Gain $10^5 \, V/A$

<table>
<thead>
<tr>
<th>$f_{cut}$ (Hz)</th>
<th>30 Hz</th>
<th>100 Hz</th>
<th>300 Hz</th>
<th>1 kHz</th>
<th>3 kHz</th>
<th>10 kHz</th>
<th>30 kHz</th>
<th>100 kHz</th>
<th>Full</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{r/f}$ (ms)</td>
<td>11.5 ms</td>
<td>3.44 ms</td>
<td>1.15 ms</td>
<td>344 μs</td>
<td>115 μs</td>
<td>34.4 μs</td>
<td>11.5 μs</td>
<td>3.44 μs</td>
<td>340 ns</td>
</tr>
</tbody>
</table>

Value from table are $\sqrt{2}$ smaller than theoretical prediction (look like $1^{st}$ order filter)
Voltage Preamplifier (1201)
Power

Battery charge rate selector switch
- C/25 Slow Charge Rate
- C/10 Fast Charge Rate
- BATT (C/25)

Input for external gating signal (or contact closure)

Remote programming option inputs/outputs

Low impedance (50 ohm) output, up to 25mA at any gain and over total frequency range.

600-ohm output (parallels front panel 600-ohm output)

Unity-gain (X1) output, up to 7mA over total frequency range.
Input connections

\[ E_{out} = (A - B) \times (1201 \text{ Gain}) \]
where A = voltage applied to A Input
B = voltage applied to B Input

Both Inputs at DC (differential mode)
Filters

• High pass filter (HPF)
  -6 dB/octave (1\textsuperscript{st} order)
  range: DC to 3kHz

• Low pass filter (LPS)
  -6 dB/octave (1\textsuperscript{st} order)
  range: 3Hz to 400kHz
Gain

- In **CAL** position, gain accuracy is ±1%
- Range: 10 to 25000
Overload can come from:
• Detector after first gain stage
• Detector after second gain stage
• Detector of excessive common mode signal
Specifications

INPUT IMPEDANCE
dc Coupled  Greater than 1 GΩ (100MΩ); Typically 5 GΩ (5000MΩ).
ac Coupled  100MΩ (each input BNC)

INPUT CURRENT
Less than 10pA, either input; less than 5 pA difference (offset) current.

INPUT FREQUENCY RESPONSE
<0.008Hz (ac Coupled) to 400 kHz

dc STABILITY (vs TEMPERATURE)
6 µV/°C max, referred to input; 300 µV/°C max, referred to output.

dc STABILITY (vs Time)
20 µV/24 hr r.t.i., non-cumulative, maximum, after ½ hour warm-up.

MAXIMUM INPUT, COMMON MODE
10 V. pk-pk: 200Vdc in ac mode.

MAXIMUM INPUT, DIFFERENTIAL OR SINGLE-ENDED
± of 750 mV (gains X10-X100); ±75 mV (gains of X200-X 10K)
## Specifications

**COMMON MODE REJECTION (Minimum)**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Gain &gt; 200</th>
<th>Gain &lt; 200</th>
</tr>
</thead>
<tbody>
<tr>
<td>dc – 100 Hz</td>
<td>125 dB</td>
<td>115 dB</td>
</tr>
<tr>
<td>1 kHz</td>
<td>105 dB</td>
<td>95 dB</td>
</tr>
<tr>
<td>10 kHz</td>
<td>85 dB</td>
<td>75 dB</td>
</tr>
<tr>
<td>100 kHz</td>
<td>65 dB</td>
<td>55 dB</td>
</tr>
<tr>
<td>200 kHz</td>
<td>55 dB</td>
<td>45 dB</td>
</tr>
<tr>
<td>400 kHz</td>
<td>50 dB</td>
<td>40 dB</td>
</tr>
</tbody>
</table>

Model 1201 Typical Common Mode Rejection
Noise density

**Noise figure**
Less than 0.4 dB at 1 kHz, with 1 M\(\Omega\) source impedance. Less than 0.04 dB at 1 kHz, with 1 M\(\Omega\) source impedance.

**Noise**
Less than 15 nV per Hz\(^{-1/2}\) at 10 Hz. Less than 7 nV per Hz\(^{-1/2}\) at 1 kHz. Less than 4 fA/\(\sqrt{\text{Hz}}\) below 100 Hz.
Combination with Lock-in

I/V converter → Lock-in

I/V output resistance: 22Ω
Combination with Lock-in

Noise calculation

Noise density:

$2.2 \text{nV/} \sqrt{\text{Hz}}$

$S = 4.8 \text{nV}^2/\text{Hz}$

For $f_m = 100 \text{Hz}$

Lock-in measure at $f_m = f_0$

$$V_{rms} = \sqrt{\int_{f_{min}}^{f_{max}} A(f, Q) \cdot S \cdot df}$$

For $Q = 1$, $V_{rms} = 49 \text{nV}$