Noise and Interference, the Lock-In Amplifier, (and the IV-meetkast)

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FND group talk, modified to web-tutorial - 4 November 2004
Why look into this?

You measure much faster if you use the lock-in amplifier and the IV-meetkast options in the optimal way.

It takes very little time to do a critical evaluation of actual noise levels that show up.

It is more subtle than we like to admit, but worth spending some time on.
Outline

Nature of unwanted contributions to measured signals.

Why use a lock-in amplifier?

Concepts and guidelines for optimal use of lock-in amplifiers.

Evaluation of observed noise levels.
Unwanted contributions to measured signals

**Noise, drift:**
- Setup-made, intrinsic
- Often non-periodic
- Shielding and isolation does not help

**Interference:**
- Environment-made
- Often periodic
- Shielding and isolation helps

.........distinction sometimes artificial.
Ideal world

World with some reality

Johnson-Nyquist noise

intrinsic noise, drifting offset

I_{bias}

Volt meter
Spectrum of amplifier noise

INPUT VOLTAGE NOISE SPECTRAL DENSITY

Voltage Noise (nV/√Hz)

Frequency (Hz)

Taken from data sheet OPA627 (part of IV-meetkast)
For amplifiers in practice, this gives:
World with some more reality

Ideal world
What to do about?

Simple averaging = low-pass filtering works!

........but is inefficient and not always effective because of the 1/f character of the unwanted signals.
So, what about measuring at higher frequencies, and then band-pass filtering?
Good idea, but........

In practice it is not possible to realize ultra-narrow band-pass filters that are

- stable
- flexible

(this can work in software though \(\approx\) lock-in amplifier)
What does work real-time: A lock-in amplifier

Idea:

Control or bias at some high frequency.

Amplify the measured signal (full spectrum) up to a level where noise does not hurt it anymore.

Mix (multiply) it with a high-level reference signal at exactly the same frequency as the wanted signal.

Low-pass filter the mixed signal (can be realized ultra narrow).
\[ V_R = A_R \sin(\omega_R t) \]

\[ V_S(\omega_S) = A_S(\omega_S) \sin(\omega_S t + \theta(\omega_S)) \]

\[ V_M = V_S \times V_R \\
= \frac{1}{2} A_R A_S \cos(\omega_S - \omega_R + \theta) - \frac{1}{2} A_R A_S \cos(\omega_S + \omega_R + \theta) \]

After LPF, only for \( \omega_S = \omega_R \)

\[ V_{DCX} = \frac{1}{2} A_R A_S \cos(\theta), \text{ also } V_{DCY} = \frac{1}{2} A_R A_S \sin(\theta) \]
What you should **NOT** conclude now:

“If you use lock-in detection, there is little need to worry about interference and shielding etc.”

Because:

Heating of a sample results from the (total current through the sample)$^2$.

\[ V_{\text{max}} = I_{\text{peak-peak}} \times R \Rightarrow \text{sets “eV” energy scale in device.} \]

If you study **non-linear** behavior, you get higher harmonics of unwanted signals (as noise or apparent signal) in your desired signal.

If you study *variations in non-linear* behavior, you get a varying amount of higher harmonics of unwanted signals in your desired signal.
Non-linearities
Some hints for optimal use of lock-in amplifiers
Time constant and repetition time
Slope of LPF filter
Low-pass filtering: frequency domain

![Diagram of low-pass filter frequency response](image)

- $A_{LPF}$ represents the attenuation of the low-pass filter.
- The frequency $f_{-3dB}$ is where the attenuation is $-3$ dB.
- The x-axis represents frequency in Hz, ranging from 0 Hz to 50 Hz.
Low-pass filtering: time domain

Here data taken with $T_{Rep} \ll T_C$

For $T_{Rep} \ll T_C$ successive sampled data points are not independent, no new information.
<table>
<thead>
<tr>
<th>Filter slope (dB/oct)</th>
<th>ENBW</th>
<th>$T_{\text{Rep-1%}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>$1/(4\ T_c)$</td>
<td>$5\ T_c$</td>
</tr>
<tr>
<td>12</td>
<td>$1/(8\ T_c)$</td>
<td>$7\ T_c$</td>
</tr>
<tr>
<td>18</td>
<td>$3/(32\ T_c)$</td>
<td>$9\ T_c$</td>
</tr>
<tr>
<td>24</td>
<td>$5/(64\ T_c)$</td>
<td>$10\ T_c$</td>
</tr>
</tbody>
</table>

For 6 dB case, LPF is simple RC filter.

$$T_c = \text{RC-time} = \text{RC} \quad (\text{always defined for single filter!})$$

$$f_{-3dB} = 1/(2\pi RC)$$

ENBW = $1/(4RC) \quad (\text{for white Gaussian noise!})$
Example 6 dB vs 24 dB filter slope

Say \( f_{REF} = 1 \) kHz
Assume narrow-band noise contribution at 1.05 kHz
Assume noise = \( 10^4 \) times the signal (80 dB)
Like to see signal 1% accurate (-40 dB)
Need to LPF 50 Hz by 120 dB

\[
\begin{array}{c|c|c|c}
\text{Slope} & f_{-3dB} & T_c & T_{Rep} \\
6dB & 50 \mu Hz & 3000 s & 15000 s \\
24dB & 1.6 Hz & 100 ms & 1 s \\
\end{array}
\]

24 dB case is 15000 times faster than 6 dB!

Q: How does this work out for white noise?
LINE and SYNC filters

Look it up. In general, use it below 200 Hz!
Dynamic reserve
**Dynamic reserve:**

ratio between peak-peak voltage of total signal and *peak-peak* of wanted signal.

**Dynamic range:**

ratio between peak-peak voltage of total signal and *resolution* of wanted signal.
Use “Low noise” (0-124 dB)

Use “Normal” (0-154 dB)

Use “High reserve” (0-174 dB)

Note: Lock-in people use x10 = 20 dB
Offset and Expand

Use OFFSET and EXPAND (x10 or x100) if you have a small signal on top of a constant background.
Without OFFSET and EXPAND you see the AD conversion.
Evaluating noise levels
(measurement efficiency)

Are you at the noise level that is intrinsic to the setup? (can only be improved by averaging longer........)

Do measurement vs time, all control fixed.

Result from lock-in at certain $T_C, I_{bias},$ etc.

$V_{DCX}$

time
Observed Gaussian white noise with $f_{\text{REF}} = 20$ Hz

$V_{\text{DCX}}$

Observed $V_{\text{NSD}}$ at sample:

$V_{\text{NSD}} = \frac{V_{\text{RMS}}}{\text{Gain}} \sqrt{\frac{4T_C}{C}}$

Specified amplifier noise:

$V_{\text{NSD}} = \frac{V_{\text{RMS}}}{\text{Gain}} \sqrt{\frac{4T_C}{C}}$

Note units:

- $V_{\text{DCX}}, V_{\text{RMS}}, V_{\text{P-P}} \Rightarrow V$
- $\text{ENBW}, \text{Gain} \Rightarrow \text{Hz}$
- $V_{\text{NSD}} \Rightarrow V/\sqrt{\text{Hz}}$
What if you find 100 instead of 10 nV/$\sqrt{\text{Hz}}$?

a) Try to fix the problem

b) Just average longer

$$V_{\text{RMS}} = \text{Gain} \frac{V_{\text{NSD}}}{\sqrt{4T_C}}$$

4 days instead of 1 hour for some sweep!
**Conclusions**

The Lock-in is an effective averaging tool to beat 1/f part of the unwanted components in measured signals.

Improving your signal:noise ratio (in terms of amplitudes) x 10, means 100 times faster data taking: The difference between results and no results.
IV-meetkast

Next time:
  Why use the IV-meetkast?
  Shielding
  Ground loops
  Clean ground
  Inductive interference
  Capacitive interference