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NOISE ANALYSIS AND GAIN CONSIDERATIONS IN SELECTING THE RIGHT CURRENT PREAMPLIFIER

DL INSTRUMENTS

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INTRODUCTION

Current preamplifiers are used to match signal sources to lock-in amplifiers or other instrumentation. They are widely employed for two reasons. First, they yield much better frequency response and phase accuracy in the presence of shunt stray capacitance, which is the reason they are often found in photomultiplier applications or impedance measurements setups. Second, they provide extended linearity in conjunction with otherwise non-linear transducers such as semiconductor photovoltaic diodes.

The noise performance of the preamplifier, rather than the equipment it feeds, usually but not always determines the noise floor of the measurement system. It thus establishes speed and resolution that can be achieved in the acquired data, as explained in IAN 49 "Speed/Accuracy Tradeoff When Using A Lock-In Amplifier to Measure Signal in the Presence of Random Noise". The diagram below depicts the equivalent circuit for analysis of random noise effects in a current preamp. The sources include the input noise of the op amp, the thermal (Johnson) noise in the transconductance feedback resistor, the thermal noise of the source impedance and the source noise in excess of Johnson noise, such as generation-recombination or shot noise. Also included is the effect of the input voltage noise of the stage following the current preamp (e.g., the shorted input self noise of the lock-in amplifier). Under some circumstances, such as low values of R_f this can be a substantial or even dominant contribution to the overall noise.

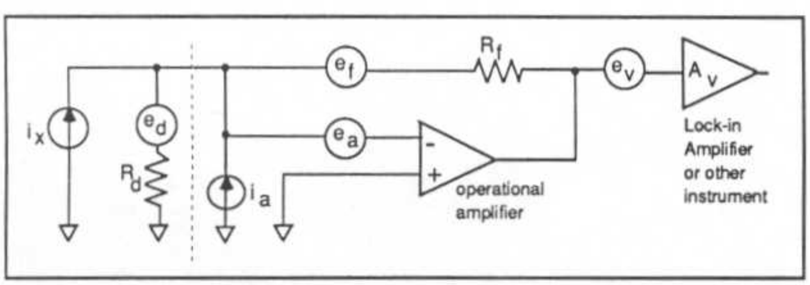

Figure 1 Current Amplifier Noise Model

e_v = voltage noise of stage following current preamp, Vrms/$\sqrt{Hz}$

e_a = op-amp voltage noise, Vrms/$\sqrt{Hz}$

i_a = op-amp current noise, A rms$\sqrt{Hz}$

i_x = source "excess" (non-thermal) noise, A rms/$\sqrt{Hz}$

R_d = Source dynamic impedance, ohms

e_d = thermal noise due to R_d, Vrms/$\sqrt{Hz}$ ($= \sqrt{4KTR_d}$)

R_f = preamp transimpedance, ohms (gain, volts/amp)

e_f = thermal noise due to R_f, Vrms/$\sqrt{Hz}$ ($= \sqrt{4KTR_f}$)

K = Boltzmans constant, 1.38×10^{-23} Joules/°K

T = absolute temperature, 300°K at ambient conditions

ANALYSIS *

We have the following superposed contributions to the overall voltage noise, e_n, referred to the input of the voltage amplifier (A_v).

$$\text{(due to } e_a) = e_a$$

$$\text{(due to } i_a) = i_a R_f$$

$$\text{(due to } R_d) = e_d \frac{R_f}{R_d} = R_f \sqrt{\frac{4KT}{R_d}}$$

$$\text{(due to } R_f) = e_f = \sqrt{4KTR_f}$$

$$\text{(due to } i_x) = i_x R_f$$

$$\text{(due to } e_v) = e_v$$

The random noise components, in general, will be uncorrelated and thus are summed as the square root of the sum of the squares. Dividing by R_f to obtain the preamp referred-to-input current noise, we have:

* Ignores source capacitance effects. See Appendix A.

$$ (i)\quad i_n = \frac{e_n}{R_f} = \sqrt{\overbrace{\left(\frac{e_a}{R_f}\right)^2}^{\text{op-amp voltage noise}} + \overbrace{i_a^2}^{\text{op-amp current noise}} + \overbrace{\frac{4KT}{R_d}}^{\text{source thermal noise}} + \overbrace{\frac{4KT}{R_f}}^{\text{transimpedance thermal noise}} + \overbrace{i_x^2}^{\text{source excess noise}} + \overbrace{\left(\frac{e_v}{R_f}\right)^2}^{\text{LIA input noise}}} $$

Note: Op-amp current noise i_a and op-amp voltage noise e_a usually will be partially correlated (coefficient ~ 0.7). For a worst-case analysis one could assume unity correlation and use$(e_a/R_f + i_a)^2$ in place of $(e_a/R_f)^2 + i_a^2$.

The apparent current noise density, i_n, contains both preamplifier and source noise contributions. For purposes of analysis, it is useful to lump these two contributions as defined below:

$$ (ii)\quad i_p = \sqrt{\left(\frac{e_a}{R_f}\right)^2 + i_a^2 + \frac{4KT}{R_f}}, $$

preamplifier noise

$$ (iii)\quad i_e = \sqrt{i_x^2 + \frac{4KT}{R_d}}, $$ external noise

therefore:

$$ (iv)\quad i_n = \sqrt{i_e^2 + i_p^2 + i_v^2}, $$ overall noise

where:

$i_v = e_v / R_f$, voltage amp noise referred to current preamp input

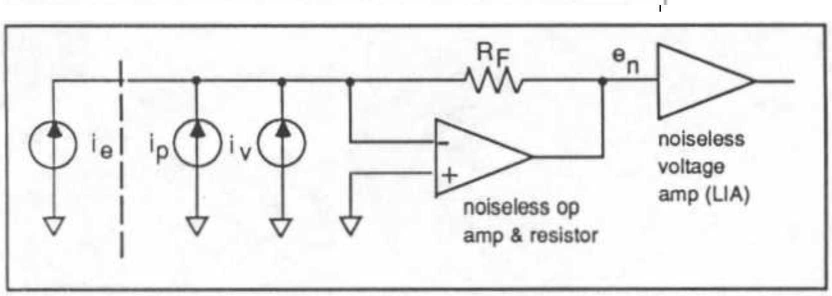

Figure 2 Overall Noise Contributions

The open circuit noise, i_p, is often specified directly for commercial preamps (e.g. ITHACO Model 164/1641). Alternatively the manufacturer may specify i_a and e_a and you must calculate i_p according to (ii) using the chosen transimpedance value, R_f. The value i_p represents the best theoretical noise performance of the preamp using an ideal current source input. Actual performance will be degraded due to finite values of R_d and due to excess noise, the combined effect of which can be viewed as an external noise source, i_e, operating in parallel with the amplifier self-noise, i_p.

DETERMINING SOURCE NOISE

The source noise, i_e, may be specified by the manufacturer of the input transducer. For example, the Noise Equivalent Power (NEP) of a photodetector may be given, in which case i_e = R NEP, where R is the detector responsivity in Amperes per watt illumination. See ITHACO IAN 41 "Lock-In Amplifier Digital Techniques for D* Signal-to-Noise Characterization of Infrared Detectors", or IPB0128 "Lock-In Amplifier D* Characterization of IR Detectors" for more details. In other cases the noise may be purely thermal, in which case equation (iii) applies with $i_x = 0$. If the noise is unknown, a lock-in amplifier can measure first the combined LIA and open circuit current preamp noise, $\sqrt{i_p^2 + i_v^2}$, then the noise with the source connected, i_n, from which i_e can be calculated using equation (iv). A technique for measuring noise with a lock-in is described in IAN 36 "Digital Techniques for Random Noise Measurement with Lock-In Amplifiers", IAN 38 "Method for Lock-In Amplifier Noise Measurement Using Digital Integration" and IAN 41.

Often the source dynamic impedance R_d is not given for the transducer. In the case of non-linear sources, its value can be measured experimentally as follows. If you can operate the detector under normal conditions of excitation and bias to obtain a linear voltage output, E_1, then place a trial shunt resistance R_x across the source to obtain a loaded output voltage, E_2) you can calculate $R_d = R_x (E_1 - E_2)/E_2$. If instead, you are able to place a trial resistor in series with the source transducer in conjunction with a current preamp, then $R_d = R_x E_2/(E_1 - E_2)$.

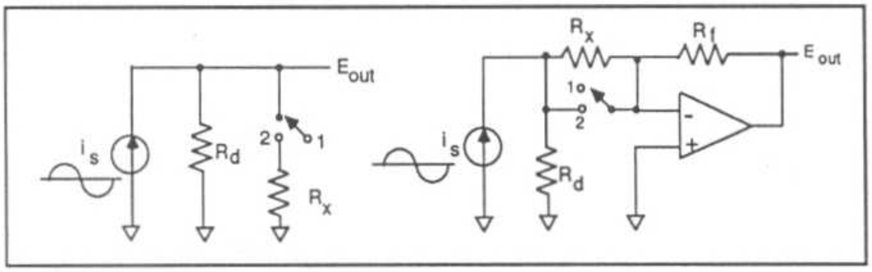

Figure 3 Determination of Dynamic Impedance

Figure 4 illustrates how to measure R_d for a photovoltaic detector. One would use low level illumination to achieve a linear output voltage (e.g., 1 mV), then select R_x to roughly halve the LIA reading.

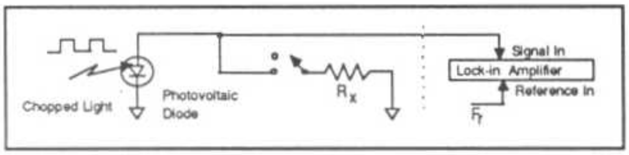

Figure 4 Voltage Mode Measurement of Photovoltaic Diode Dynamic Impedance

Another way of determining dynamic impedance is to use a curve tracer to observe the slope of the current-voltage characteristic at the operating point.

SELECTING THE RIGHT PREAMP AND GAIN

To achieve the fastest and most accurate measurements, one must strive to attain the highest overall signal-to-noise ratio (i.e., must minimize i_n). This is particularly true when the signal falls to a low level and approaches the noise floor of the system. As a general rule, the *larger* we can make R_f, the better the SNR. For example, take the simple case in which the source noise is purely thermal due to R_d and the preamp noise is due primarily to the thermal noise of R_f. Inspection of equation (i) shows that we want to select the preamp gain (transimpedance, R_f) to be significantly larger than the source dynamic impedance, R_d, to keep the preamp from adding substantially to the source noise. The equation also shows that increasing R_f decreases the effects of the op-amp voltage noise, e_a, and the voltage amp (LIA) self-noise, e_v).

This is not the whole story, however. There are limits on how high we can make R_f without compromising performance in other respects. First of all, R_f should not be made so large that the highest signals of interest would overload the LIA input (e.g. 1 V rms max.). Also allowance should be made for the expected interference passing through the preamp - that is, you must accommodate the dynamic reserve of the lock-in (e.g., 100 mV rms maximum signal for 40 dB interference headroom, assuming a 10 V rms overload level). Be aware that in general the current preamp operates at a fixed gain which suffices for the entire dynamic range of the signal, while the LIA voltage gain is switched to attain the proper full scale sensitivity of the composite system. This means that at the lowest expected signal, you must take care that R_f produces a large enough voltage output that the LIA can "see" it at its highest sensitivity. Given the option, try to keep the preamp output as high as possible to lessen grounding and shielding problems.

Other considerations come into play as we increase R_f. First, the frequency response drops off, which could lead to signal measurement error. Second, the system will become more microphonic. Any current preamp is inherently susceptible to acoustic pickup, which may necessitate putting it on an optical bench, taping down the input cables, etc., at R_f values above 10^6. Third, the effects of source excess noise or op-amp current noise will eventually make the further increases in R_f futile, per equation (i), as the quantity $\sqrt{4KT/R_f}$ falls below i_x or i_a.

In choosing a preamp one should pay attention to the following factors:

1. Does it have a selectable gain? If R_f is fixed, you may get stuck in an unworkable gain / noise / bandwidth / dynamic reserve bind.

2. Is it remote mounted or installed in the lock-in? Being able to place it near the transducer lessens interference pickup problems and reduces cable capacitance. The ITHACO Model 1641 and 1642 modular preamplifiers answer this need.

   Excess input capacitance can cause a number of problems, including microphonic pickup by the cable and preamplifier instability, as manifested by ringing (or even oscillation in extreme cases). This problem is worst at low gain levels (e.g. 10^3 or 10^4 V/A), where the preamp has the widest bandwidth.

The ability to remotely install the preamp also alleviates the microphonic problems at high gain levels (e.g. 10^8 V/A) by allowing the user to put it in a low vibration environment, such as on an optical bench.

3. If noise is specified in terms of op-amp noise and current (e_a, i_a) make sure you get the right model. Designers can decrease e_a at the expense of i_a and *vice versa*. Prefer a model with high e_a and low i_a (e.g., 15 nV, 0.01 pA), for high impedance sources (1 megohm and above). Prefer a model with low e_a and high i_a (e.g., 3 nV, 0.4 pA) for low impedance sources (1 kilohm and above).

4. Instrumentation noise will get worse at low frequencies due to increased amplifier voltage noise, both from the current preamp op-amp and the LIA voltage input amplifier. It can be many times worse for a modulation frequency of 10 Hz than it would be above the typical 1/f noise corner at 1 kHz.

   For low gain settings a similar low frequency rise in preamp current noise may occur. For high gain settings, the current preamp noise will tend to rise with increasing frequency. See typical curves in IPS 55, ITHACO Model 1642 Current Sensitive Preamplifier product brochure.

5. Do you need d.c. current nulling? Do you need detector d.c. biasing? Do you need extremely high gain (e.g., 100 gigohms)? Do you need filtering (risetime control) to suppress noise? Is the actual input impedance critical (it never will be exactly zero and increases at high R_f values)? Do you need battery operation to circumvent serious ground loop problems? Do you need extremely high dynamic range, gain stability, or input offset stability? Do you need to gate out recurring overloads due to excitation pulses? If the answer to any of these questions is yes, then you may need an instrument-grade current preamp such as the ITHACO Model 1211.

APPLICATION EXAMPLE

ITHACO MODEL 397EO LOCK-IN AMPLIFIER CURRENT PREAMP

e_a = 10 nV, typical
i_a = 0.01 pA, typical
e_v = 15 nV, typical
R_{f1} = 10^3 (X100 mode)
R_{f2} = 10^5 (X1 mode)

For the X100 current range:

$$i_p\,(10^3) = \sqrt{(10\text{ nV}/1\text{K})^2 + (0.01\text{ pA})^2 + 4KT/1\text{K}}$$

$$= \sqrt{\underset{(\text{due to } e_a)}{(10\text{pA})^2} + \underset{(i_a)}{(0.01\text{pA})^2} + \underset{(\text{due to } R_f)}{(4.07\text{pA})^2}} = 10.8\text{pA}$$

$i_v\,(10^3)$ = 15nV/1K = 15 pA, due to LIA voltage amp

The combined LIA current noise is $\sqrt{10.8^2 + 15^2}$ pA = 18.5pA/$\sqrt{}$ Hz for the X100 current range, primarily due to the input voltage noise of the LIA and the voltage noise of the current op amp. This is the noise equivalent of the 48 ohm resistor shunted across the preamp input, which implies that sources of this impedance or lower will suffer at worst a 3 dB SNR degradation due to the lock-in (3 dB noise figure at 48 Ω).

For the X1 range:

$$i_p\,(10^5) = \sqrt{(10\text{nV}/100\text{K})^2 + (0.01\text{pA})^2 + 4KT/100\text{K}}$$

$$= \sqrt{\underset{(\text{due to } e_a)}{(0.1\text{pA})^2} + \underset{(i_a)}{(0.01\text{pA})^2} + \underset{(\text{due to } R_f)}{(0.407\text{pA})}} = 0.419\text{pA}$$

$i_v\,(10^5)$ = 15nV/100K = 0.15pA due to LIA voltage amp

The combined LIA current noise is 0.445 pA/$\sqrt{\text{Hz}}$ for the X1 range, due primarily to R_f. The equivalent source impedance for a 3 dB noise figure would be 84K.

The main purpose of the 10^3 range is to accommodate large signal levels. While the noise figure may be far from optimal when used with clean high impedance sources, the source noise tends to be so small compared to the signal that the SNR degradation due to the preamp has negligible consequences.

A SPECIFIC CASE

As a practical example, let's assume we are using a photovoltaic detector and wish to measure vanishingly small signals. If NEP = 1pw/$\sqrt{Hz}$ and R = 1 A/W, then

i_e = R NEP = 1 pA/$\sqrt{Hz}$

This is equivalent to a source Johnson noise generator of

R (equivalent noise source) = $4KT/(i_e)^2$ = 16.5KΩ

Using the 397EO X1 current mode, as we have seen, yields an 84K amplifier noise equivalent, and thus the amp will have only a tiny effect ($\sqrt{1 + 16.5/84}$ = 1.094 or 0.8 dB) on overall noise. NEP represents approximately the smallest signal measurable by the detector. At this 1 pw limit, the preamp signal output will be P x R x Rf = 100 nV. The 397EO at maximum sensitivity and at Expand x10 gain mode has a full scale sensitivity of 1μV (10pA), so this represents a readily observable signal (10% of full scale). According to IAN 49 "Speed/Accuracy Tradeoff When Using a Lock-In Amplifier to Measure Signal in the Presence of Random Noise", if we use the maximum time constant settting of 25 seconds, the measurement reproducibility σ_x will be:

$$\sigma_x = \frac{e_n}{e_s\sqrt{8T}} = \frac{i_n}{i_s\sqrt{8T}} = \frac{1pA/\sqrt{Hz}}{1pA\sqrt{8x25sec}}$$

σ_x = .0707 (±21% 3σ fluctuation)

The LIA will require 8 x 25 = 200 seconds to settle when the input changes. This speed/accuracy limit is set by the detector NEP figure of merit and the maximum LIA time constant.

Better accuracy would be obtained by sampling once every 100 seconds and averaging the results (reproducibility error decreases proportional to $\sqrt{1/N}$).

If the signal were to increase to 10μA (140 dB above the noise floor of 1 pA/$\sqrt{Hz}$), you would finally reach the LIA input overload point on the 1V X1 sensitivity range and have to switch to the X100 current mode (R_f = 10^3).

APPENDIX A

INPUT CAPACITANCE EFFECTS ON NOISE

A frequency dependent current noise component due to preamplifier input voltage noise reacting with the input capacitance often will be significant. The capacitive noise effect is given by:

i_c = $e_a 2\pi fc$, A/$\sqrt{Hz}$
c = total capacitance
f = frequency

This noise current will be 90° out of phase relative to the resistive component e_a/R_f. Their combined effect will be $\sqrt{i_c^2 + (e_a/R_f)^2}$.

Thus the first term of equation (i) and (ii) would become:

$$[(2\pi fc)^2 + (1/R_f)^2]\, e_a^2$$

The input capacitance includes preamplifier, cable and source components. Estimation of the effect of i_c on total noise is difficult for two reasons. First, the self capacitance of a current preamplifier can be difficult to measure. Second, the partial correlation of e_a and i_a makes the calculation of the combined current and voltage noise effect a matter of considerable uncertainty. The noise component due to external capacitance adds linearly to the internal capacitive component, the sum of which adds vectorially to the e_a/R_f noise. These add quasi-vectorially to the op amp current noise. The composite of all of the above then add vectorially to the Johnson noise of the feedback resistor.

Total instrumentation noise, i_i, can be measured by determining the source capacitance, then substituting an actual capacitor of the same value and taking a noise reading. Then the increased noise, i_n, when the source is subsequently reconnected will be due solely to source noise. The contribution due to source noise, i_e, can be calculated readily using:

$$i_e = \sqrt{i_n^2 - i_i^2}$$

Moral, when dealing with high source capacitance and/or high frequencies, prefer a current preamplifier with a low input voltage noise, e_a, such as ITHACO Model 1642 (7nA/$\sqrt{Hz}$).