Op Amps as Electrometers
or – The World of fA

The definition of an electrometer is not graced by complete agreement. However, it would seem to describe a system capable of measuring voltages or currents with leakages or resolutions somewhere in the range below 1 picoampere, and probably closer to 1 femotampere ($1\text{fA} = 10^{-15}$ A). The elements of the system include a transducer, a connecting cable (long or short), an input device, and some form of signal conditioning.

Today, op amp designers have introduced a number of devices capable of functioning as input devices and signal conditioners. A good example is the Analog Devices 310/311* family of parametric amplifiers, with bias currents less than 10fA. The essential advantage of such devices to the electrometer designer is that–if well made and capable of predictable performance–they remove one of the headaches from an exercise that exceeds Excedrin dimensions.

We offer here a few notes for the electrometer designer encompassing the factors to be considered in the choice of input device, and the considerations involved in interfacing it to the rest of the problem. A *non*electrometer-designer who is interested in low current measurements may also derive some ideas for extending his frontiers and an appreciation of the scope of the problems involved when performing measurements in "the world of fA."

THE PROBLEM

Nominally, the problem is either to transduce a current into a voltage, or to measure a voltage with negligible current drain. The basic configurations, familiar to all op amp users, are shown in Figures 1a and 1b.

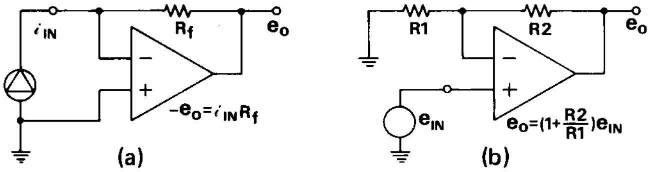

Figure 1. Basic low-level measurement circuits. (a) The operational amplifier develops e_O proportional to i_{IN}, offering a low dynamic impedance to the current source. (b) The operational amplifier unloads the voltage source, and provides voltage gain.

The basic configuration of 1a is typically used for gas chromatographs, ionization gages, and photomultipliers; the configuration of Figure 1b is typical for pH meters. In the limited space available, we will discuss largely the configuration of Figure 1a. Most of the considerations, except for the feedback resistor, will be applicable to Figure 1b, together with the added leakage and common-mode problems introduced by above-ground operation.

Figure 2 shows how the basic configuration of Figure 1a looks in the harsh light of reality. The two major sources of trouble are:

1. The circuit inside the triangle
2. The circuit outside the triangle.

INSIDE THE TRIANGLE

On the opposite page are tabulated a number of approaches to obtaining low-leakage high-impedance inputs for electrometers, with a comparison of their input current, voltage drift, and noise.

For new designs, one may dismiss the vibrating-capacitor electrometer as being too expensive and too good for most jobs, although it approaches the limits of resolution the most closely of all. One may also dismiss electrometer tubes, if any of the solid-state approaches will do the job, on the basis of the mechanical ruggedness and lower drift of the solid-state alternatives.

Among solid state designs, MOSFET's, though not yet proven, are just coming into use, where–if their dc drift and need for protection can be tolerated–they are most useful in applications calling for low leakage current over a wide range of temperature. (However, the increase in leakage of the protection diodes with temperature may somewhat dimish this apparent advantage.) Junction FETs have the virtue of simplicity, and they can be selected for low voltage drift, but even the best have leakage currents (10^{-13}A), that are difficult to offset.

Parametric op amps have stable, readily-predictable characteristics, and they have been reliably used in electrometer circuitry for a number of years. Their major weakness is the bandwidth limitation imposed by their input capacitance, and the excessive current noise developed by the voltage noise across the input capacitance, at frequencies above 1Hz.

OUTSIDE THE TRIANGLE

Feedback Resistor In the world of fA, some resistors look like capacitors; others look like filters: connected in a feedback circuit, their "Boella" effect can cause an amplifier's response (and noise) to peak. Correction of such noise peaking can be accomplished by connecting a short length of stiff wire to the output end of the feedback resistor and bending it to form an angle to the resistor body. The length of the wire and the angle can be experimentally adjusted

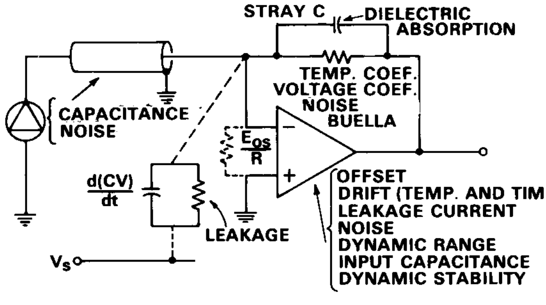

Figure 2. Some sources of error.

BIBLIOGRAPHICAL NOTE

"The Ubiquitous Electrometer," which appeared in *Industrial Research*, March, 1971 (pp 36-39), offers an articulate discussion of the present status of electrometry and a wealth of applications ideas for electrometers and "para-electrometers." Soft on MOSFET's, but well worth reading.

to eliminate peaking effects without appreciable bandwidth limiting (as compared to a single lumped feedback capacitor).

Dielectric absorption (in resistors), 1/f noise (in poor-quality resistors carrying current), resistance temperature- and voltage-coefficients, all can cause errors. Typical high-value resistors with acceptable properties that have been in use in recent years have been manufactured by such companies as Victoreen and Welwyn. A recent development is chip resistors; M.S.I. Company of North Attleboro, Mass., can supply values up to $2 \times 10^9 \Omega$ and beyond.

Resistive attenuators may be used in the feedback circuit to magnify the effective resistance (a 10:1 attenuation will make $10^{10}\Omega$ look like $10^{11}\ \Omega$) and decrease the shunt capacitance somewhat. However, they magnify voltage drift and low-frequency noise.

Input cable capacitance is important, because the amplifier's noise voltage develops a noise current proportional to the shunt capacitance. The cable should be rigid, because capacitance changes will cause changes in its charge (or current: $i = dQ/dt = d(CV)/dt = C\ dV/dt + VdC/dt$). Also, bending of the insulation can develop noise, in the form of friction-induced charges. Graphite-coated insulation helps. The input leads should be fixed in relation to the power supply, again because the motion of vibration can cause substantial $V\ dC/dt$ currents (capacitor microphone effect). e.g., for $dC/dt = 10^{-15}$ F/sec, i = 15fA. And don't forget the $C\ dV/dt$ term for ripple, or the dc leakage resistance.

Guard the input, but watch out for humidity! Especially transient humidity, i.e. "breath storms." Consider galvanic action, developed in the presence of moisture, between the gold plating on a TO-5 case and the Kovar leads.

Dielectric absorption can be important.
The circuit time constants are all so long, even with low-pF capacitors, that dielectric absorption, having comparable time constants, can hoodwink the unwary observer.

Teflon insulators should have minimal stresses, because they can generate currents up to 1pA, which gradually subside over periods of *hours*.

Thermal baffling. With $10^{10}\ \Omega$, 0.1pA will develop 1mV of signal. For best accuracy and lowest drift, the circuit should be kept in a thermally-baffled enclosure. It will respond to changes in temperature slowly, and be essentially immune to fast transient changes. Ovens having proportional temperature control may be used, but their elevated temperatures cause increased current offsets, and their regulation may not be close enough to make their use of more than incremental value. ▶▶▶

This article is based, in part, on a talk given by Analog's Bob Demrow at CECON '70, entitled "Low-Current Measurements"

KEY PARAMETERS OF INPUT ELEMENTS

INPUT CURRENT

METHOD	IDEAL LIMIT	REAL LIMIT	TYP VALUE Amperes	COMMENTS
Varactor Bridge (Model 310)	$\sim\Delta I_o\left(\frac{V_P}{k}\right)^2$	$\frac{\Delta E_{os}}{k} I_o$	2×10^{-15}	Design compromises possible by variation of pump voltage and pump frequency
Metal Oxide Semiconductor (MOS)	0	Insulation Resistance and Protective Device	10^{-14}	Input protection needed
Electrometer Tube	0	Insulation Resistance ION Currents and Photon Currents	10^{-14}	Drifts with time
Junction FET	I_0	Insulation Resistance	10^{-13}	Relatively high input current
Vibrating Capacitor	0	≈0	10^{-16}	Expensive

VOLTAGE DRIFT

METHOD	IDEAL LIMIT	REAL LIMIT	TYP VALUES	COMMENTS
Varactor Bridge (Model 310)	Work Function	Cost of Selection	20μV/Day 10/30μV/°C	———
Metal Oxide Semiconductor (MOS)	Work Function and Channel Resistance	Qss (Surface State Charge)	5mV/Day 150μV/°C	Qss is time, temp, bias, previous history, and $ dependent
Electrometer Tube	Work Function	Time Change of Work Function	2mV/HR	Rate is time dependent
Junction FET	Work Function and Channel Resistance	Cost of Selection	50μV/Day 10/50μV/°C	———
Vibrating Capacitor	Work Function	Materials Technology	100μV/Day	———

NOISE

METHOD	i_N (rms) @ 1Hz	C_{IN}	e_N (rms) @ 1Hz
Varactor Bridge (Model 310)	$1/4\ fA/\sqrt{Hz}$ (Shot Noise)	30pF	flat – $.1\mu V/\sqrt{Hz}$ $e_n \propto V_p$
Metal Oxide Semiconductor (MOS)	$1/4\ fA/\sqrt{Hz}$ Protective Device and Leakage Resistance	10pF (With Protection)	1/f ($3\mu V/\sqrt{Hz}$)
Electrometer Tube	$1/6\ fA/\sqrt{Hz}$ Leakage Resistance and Shot Noise	5pF	1/f ($½\mu V/\sqrt{Hz}$)
Junction FET	$1\ fA/\sqrt{Hz}$ Shot Noise and Leakage Resistance	5pF	1/f ($½\mu V/\sqrt{Hz}$)
Vibrating Capacitor	Johnson Noise	10pF	flat– ($½\mu V/\sqrt{Hz}$)