Noise Minimization in Electronic Circuitry

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Introduction:

  The detection of small currents at low frequency is impaired by the scientist's ability to reliably detect the signal above noise. Noise from circuit components and electronic pickup in a lab can bury valuable information in digitized buzz. Reducing noise in the frequency regime below 1 kHz is especially difficult due to flicker noise and harmonics from 60 Hz wall sockets in this work. The reduction of signal interference in sensitive current to voltage transimpedance amplifiers is investigated by characterizing the noise performance of components, varying amplifier configuration and incorporating low pass filters.

  Noise in electronic circuits has origins both inside and outside the system. External interference comes from 60 Hz wall sockets, cell phones, other experiments and many devices which transmit and collect signals. Often, these sources of interference can be identified and eliminated from the signal by shielding. Internal sources of noise are more difficult to eradicate and come from three main sources; thermal noise, shot noise and flicker noise.

  Thermal noise results from the random motions of charge carriers within a material. This intrinsically noisy property of molecules cannot be eliminated above 0K; therefore it is the theoretical lower limit of noise in electronic circuitry. The rms thermal noise voltage (v_N) is related to a material's resistance (R) and temperature (T). It is also affected by the bandwidth of the measured signal (Δf):

$$v_N{}^2 = 4TR\Delta f$$

This noise occurs over the entire spectrum and is independent of signal frequency. The equation indicates that a limited detection bandwidth will reduce noise from frequencies outside the region of interest. This is accomplished by adding low pass filters after the signal is amplified.

  Shot noise is created by random fluctuations of electric current due to the motion of charge carriers across a junction. The rms current from shot noise (i_N) is related to the DC current (I) passing through an interface by the following equation:

$$i_N{}^2 = 2qI\Delta f$$

Here, q is the charge on an electron (in Coloumbs) and Δf is the bandwidth of the detector. This quadratic relationship to DC current suggests that using small currents in the circuit can significantly reduce the shot noise contribution. The above relationship also reveals that shot noise is independent of signal frequency.

  Flicker noise exhibits an inverse relationship to signal frequency, it is often referred to as 1/f noise. The physical causes of flicker noise are not well understood. However, its effects in semi-conductor devices and transistor circuits are well documented. Noise in the frequency regime below 1 kHz (the region of interest) in these devices is generally dominated by flicker noise.

Motivation:

The purpose of this project is to develop low noise current to voltage transimpedance amplifiers to detect small signals at low frequency. The circuits are intended for use in rocket deployments to measure the current of atmospheric aerosols hitting a detector and laboratory experiments to measure the charge on a grain of dust.

The circuits currently in use are one stage operational amplifiers which use resistive feedback loops. The gain is determined by the ratio of feedback resistor (R_f) to input resistor (R_{in}).

$$g= R_f / R_{in}$$

In this configuration, an increase in gain requires adjusting the resistor values. The noise of a resistor increases with its resistance value. Therefore, there is a direct relationship between how much gain can be achieved and how much noise is present in the system.

To simultaneously increase sensitivity and decrease noise, a new system configuration was sought. The mathematics of electronic circuitry shows that the first component of an amplification system contributes the most noise. Therefore, a multi-stage amplification system whose first stage has a very low noise character is desired. A literature review provided inspiration; however, many of the novel systems do not match our specific requirements for low frequency and ultra-small signals. A circuit developed by S.F.Paul et al[1], was built, tested and altered to fit our needs.

Experimental Setup:

To reduce the effects of environmental interference, the circuits and components under examination were placed in a Faraday Box. The conductive Faraday Box shields the circuitry from ambient EM signals. The circuit connects to a following amplifier and oscilloscope by coaxial cable, whose braided metal shielding protects the signal from interference. The coaxial cable is grounded to the Faraday box. To prevent stray capacitances and ground loops, the Faraday box is taken to a common external ground with the circuit, power supply, scope and following amp. Each component rests on a metal grounding plate.

To characterize the noise, circuit output was taken through a x100 amplifier, then to a Textronix TDS 2012B oscilloscope. The scope's internal digitizer spans 20mV over 255 points, yielding a step size of 80microvolts. This introduces rounding errors within the data acquisition program for the sufficiently small (<80 microvolts) signals of interest. A following amplifier was used to increase the signal, reducing the effects of digitizing error. Another obstacle in data acquisition is scope noise. Early experiments showed that the circuit noise was extremely close to the internal noise of the oscilloscope. Random fluctuations could produce data sets where circuit noise appeared smaller than scope noise. This problem was rectified by adding a following amplifier to increase the circuit noise signal, so that scope noise could be subtracted reliably. The oscilloscope and following amplifier were powered by AC wall sockets. Their rms noise voltage remained constant and therefore did not interfere with circuit noise calculations.

The scope's digitized signal was sent to a National Instruments' Signal Express program for data collection. The rms noise voltage of each circuit and its Fast Fourier Transform were calculated using MathCAD software. The rms noise of the scope and following amplifier system was determined and averaged between open and closed

circuited cases. For all data reported, the system noise was subtracted from circuit noise as an uncorrelated error under a square root. The resultant noise figure is then divided by the gain (x100) of the following amplifier.

The Fast Fourier Transform of early noise data showed that the major contribution to noise over all tested circuits and components resulted from 60Hz wall sockets and their harmonics, despite the shielding provided by a Faraday box. The interference was caused by noise generated by the power supply which converts AC from the wall socket to DC. The inverting power supply was replaced by very low noise 9V batteries.

The rocket samples at 1000 samples/ sec. This corresponds to a maximum detectable frequency of 500 Hz by the Nyquist criterion. The circuit's bandwidth can then be reduced to the region of interest by incorporating a low-pass RC filter, RC=3.2E-4 with a roll-off frequency of 500Hz. The filter does not have a perfect roll-off, however, it reduces the contributions of high frequency noise in the circuit.


Fig. 1 Experimental Set-up

Method:

The most sensitive amplifier must have the least noisy components. The data sheets which accompany operational amplifiers and JFET components do not provide enough information to compare noise performance. Often, the noise voltages are quoted without stating the testing conditions, such as the bandwidth. Furthermore, the frequencies for which noise voltages are given are generally well above the region of interest (< 50 Hz). First, three operational amplifiers were chosen for comparison, the LF356, OPA129 and OPA627. Then, Four InterFET JFETs were tested, the 2N4416, IFN152, IFN147 and 2N6550. After determining the least noisy parts, a multi-stage op-

amp circuit[1] with JFET input was built in stages, tested separately and then assembled. The circuit (found in literature review) will be modified to fit the project's specific needs. The noise performance of each circuit was characterized by measuring the rms noise voltage from the circuit output with no input signal.

OP-Amps
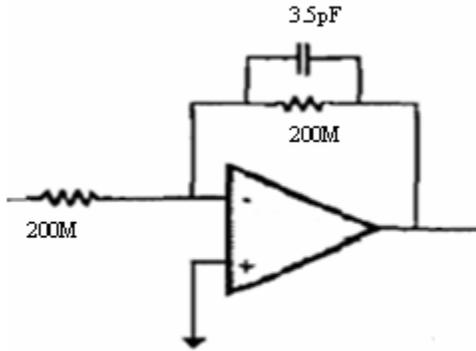
The noise performance of the LF356, OPA129 and OPA627 op-amps were assessed. An inverting amplifier with a gain of -1 was used to test the op-amps, depicted in Fig.2. The noise is characterized for an open circuit and closed circuit. Table 1 shows the rms noise voltage for the three OP-Amps.

Fig. 2

	LF356	OPA627	OPA129	Units
Open circuit	.177	.121	.160	mV
Closed circuit	.098	.030	.110	mV

Table 1 rms noise voltage from OP-Amps

In this study, the OPA627 is the least noisy operational amplifier. The Fast Fourier Transforms of the OP-Amp noise shows that there are no common frequencies which contribute significantly to noise. This means that there is mostly white noise, which is expected from semi-conductor devices.
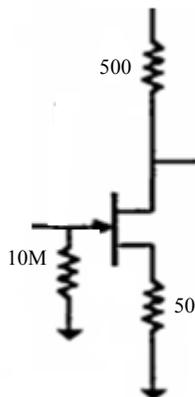
JFETs:

Four JFETs were considered in this study, the InterFET 2N4416, 2N6550, IFN147, IFN152. The 2N4416 is the only JFET studied that had a pin connecting to the case. This pin was connected to ground for testing. Otherwise, all the JFETs were tested in the same amplifying configuration, shown in Fig 3. Data was taken for a closed circuit and open circuit. The data indicates that the lowest noise JFET is the 2N4416.

Fig. 3

	2N4416	2N6550	IFN147	IFN152	
Open	4.6	12	10	7.3	μV
Closed	6.0	7.2	8.6	8.0	μV

Table 2   rms noise voltage from JFETs

Multiple-stage Amplifier:

      The full circuit can be seen in Fig. 4. This is an adapted version of the circuit developed by S. F. Paul, et al[1].
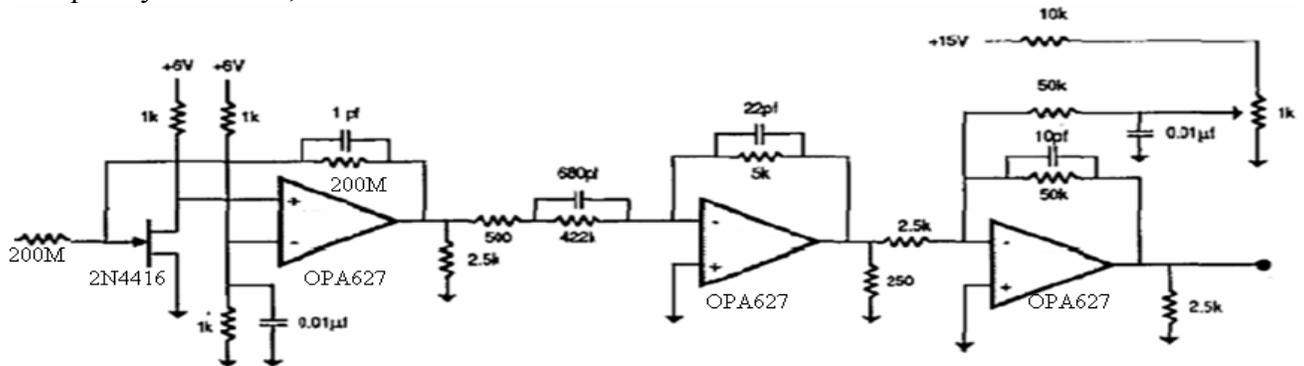

Fig. 4 multi-stage amplifier

      The first stage is essentially a low-noise current to voltage integrator with a JFET input. The first stage's RC time constant is 3E-4, which produces a low pass filter. The circuit was tested with a 200 MΩ input resistor, yielding a gain of 1.

      The second stage is a differentiating amplifier. The input RC combination of the second stage matches the RC time constant of the feedback impedance in the first stage. The second stage's feedback RC combination is smaller, 1.1E-7, which serves as frequency compensation. The second stage acts to restore the frequency response of the circuit. The third stage is a 20x amplifier with an adjustable DC offset.

      Each stage was tested separately. The rms noise data (shown in Table 3) was collected with no signal at the input. The three stages were tested both open and closed circuited.

	Stage 1	Stage 2	Stage 3	Full Ckt	
Open	56	43	1.5	21	μV
Closed	12	3.2	3.9	20	μV

Table 3 rms noise voltages from multi-stage amplifier

      The fully operational circuit's smallest detectable signal is 63 μV$_{p-p}$ with a signal to noise ratio of 3.

Works Cited:

1. S. F. Paul, et al. Low-noise photodiode detector for optical fluctuation diagnostics. Rev. Sci Instrum. 63 (10) October 1992