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MINIMIZATION OF NOISE IN OPERATIONAL AMPLIFIER APPLICATIONS

Precision Monolithics Inc.

APPLICATION NOTE 15

INTRODUCTION

Since operational amplifier specifications such as Input Offset Voltage and Input Bias Current have improved tremendously in the past few years, noise is becoming an increasingly important error consideration. To take advantage of today's high performance op amps, an understanding of the noise mechanisms affecting op amps is required. This paper examines noise contributions, both internal and external to an op amp, and provides practical methods for minimizing their effects.

BASIC NOISE PROPERTIES

Noise, for purposes of this discussion, is defined as any signal appearing in an op amp's output that could not have been predicted by DC and AC input error analysis. Noise can be random or repetitive, internally or externally generated, current or voltage type, narrowband or wideband, high frequency or low frequency; whatever its nature, it can be minimized.

The first step in minimizing noise is source identification in terms of bandwidth and location in the frequency spectrum; some of the more common sources are shown in Figure 1, an 11-decade frequency spectrum chart. Some preliminary observations can be made: noise is present from DC to VHF from sources which may be identified in terms of bandwidth and frequency. Noise source bandwidths overlap, making noise a composite quantity at any given frequency. Most externally caused noise is repetitive rather than random and can be found at a definite frequency. Noise effects from external sources must be reduced to insignificant levels to realize the full performance available from a low noise op amp.

EXTERNAL NOISE SOURCES

Since noise is a composite signal, the individual sources must be identified to minimize their effects. For example, 60Hz power line pickup is a common interference noise appearing at an op amp's output as a 16ms sine wave. In this and most other situations, the basic tool for external noise source frequency characterization is the oscilloscope sweep rate setting. Recognizing the oscilloscope's potential in this area, Tektronix® manufactures an oscilloscope vertical amplifier with variable upper and lower −3dB points, which allows quick noise source frequency identification. Another basic identification tool is the simple low pass filter as shown in Figure 2, where the bandpass is calculated by:

$$(1)\quad f_O \cong \frac{1}{2\pi RC}$$

With such a filter, measurement bandpass can be changed from 10Hz to 100kHz (C = 4.7μF to 470pF), attenuating higher frequency components while passing frequencies of interest. Once identified, noise from an external source may be minimized by the methods outlined in Table 1—the external noise source chart.

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FIGURE 1: Frequency Spectrum of Noise Sources Affecting Operational Amplifier Performance

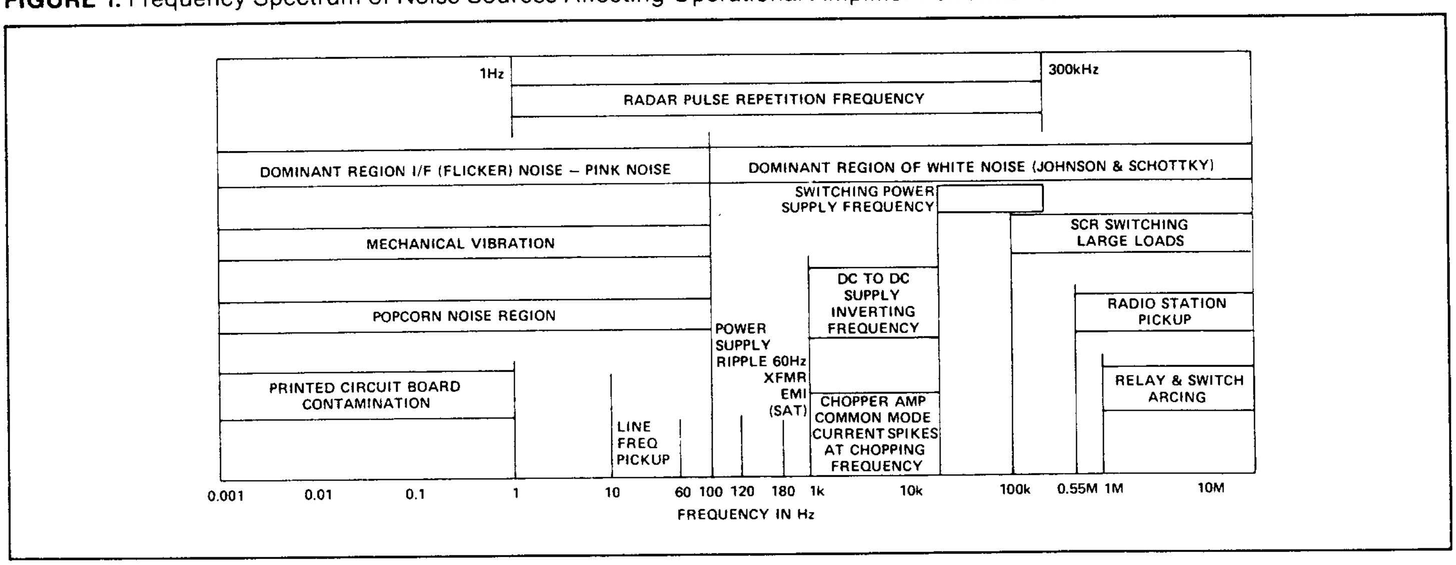

TABLE 1: External Noise Source Chart

Source	Nature	Causes	Minimization Methods
60Hz	Repetitive Interference	Powerlines physically close to op amp inputs. Poor CMRR at 60Hz. Power transformer primary-to-secondary capacitive coupling.	Reorientation of power wiring. Shielded transformers. Single point grounding. Battery power.
120Hz Ripple	Repetitive	Full wave rectifier ripple on op amp's supply terminals. Inadequate ripple consideration. Poor PSRR at 120Hz.	Thorough design to minimize ripple. RC decoupling at the op amp. Battery power.
180Hz	Repetitive EMI	180Hz radiated from saturated 60Hz transformers.	Physical reorientation of components. Shielding. Battery power.
Radio Stations	Standard AM Broadcast Through FM	Antenna action anyplace in system.	Shielding. Output filtering. Limited circuit bandwidth.
Relay and Switch Arcing	High Frequency Burst At Switching Rate	Proximity to amplifier inputs, power lines, compensation terminals, or nulling terminals.	Filtering of HF components. Shielding. Avoidance of ground loops. Arc suppressors at switching source.
Printed Circuit Board Contamination	Random Low Frequency	Dirty boards or sockets.	Thorough cleaning at time of soldering followed by a bakeout and humidity sealant.
Radar Transmitters	High Frequency Gated At Radar Pulse Repetition Rate	Radar transmitters from long range surface search to short range navigational—especially near airports.	Shielding. Output filtering of frequencies $\gg$ PRR.
Mechanical Vibration	Random < 100Hz	Loose connections, intermittent contact in mobile equipment.	Attention to connectors and cable conditions. Shock mounting in severe environments.
Chopper Frequency Noise	Common Mode Input Current At Chopping Frequency	Abnormally high noise chopper amplifier in system.	Balanced source resistors. Use bipolar input op amps instead. Use premium low noise chopper.
Switching Power Supply	Repetitive High Frequency Glitches In Supply And Ground	Improper ground return. Radiated noise from switching circuit.	Analog ground return to AC return. Shield power supply. Liberal power supply bypass at the op amp.

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FIGURE 2: Noise Frequency Analysis RC Low Pass Filter

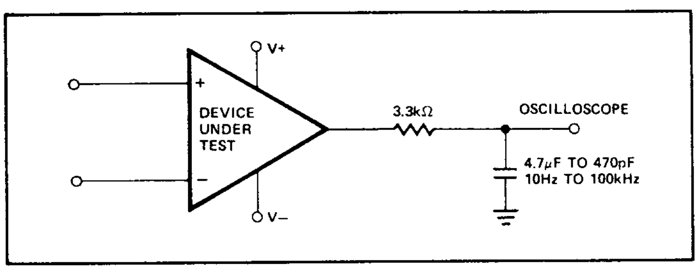
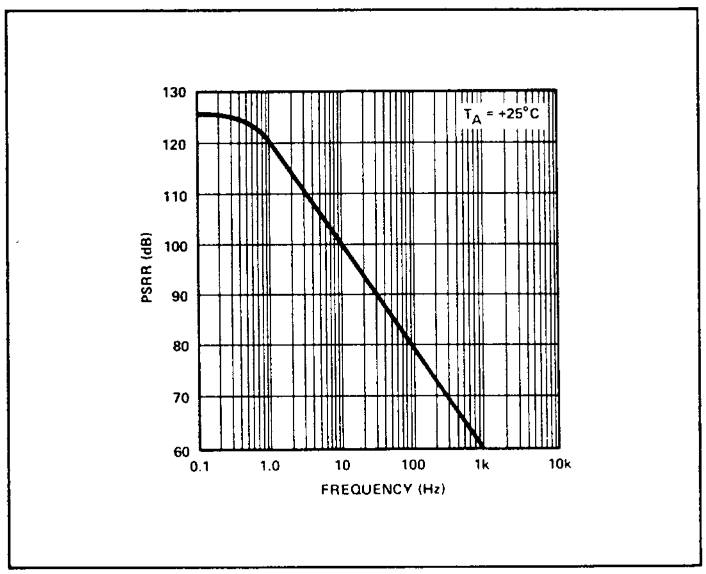


FIGURE 3: PSRR vs Frequency (OP-77)



Power Supply Ripple

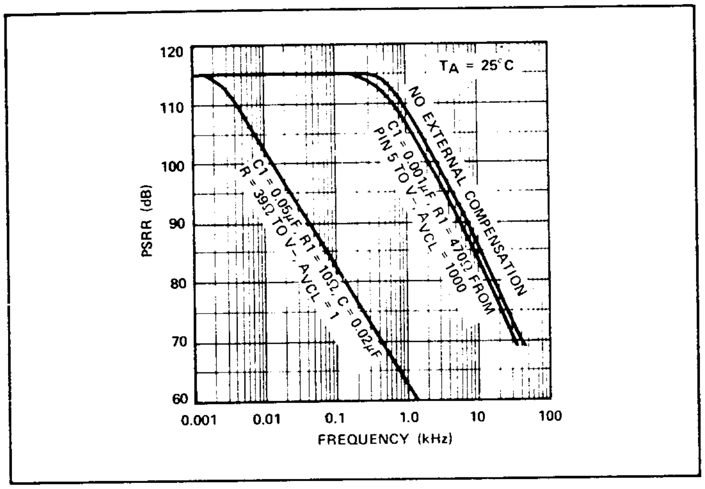
Power supply ripple at 120Hz is not usually thought of as a noise, but it should be. In an actual op amp application, it is quite possible to have a 120Hz noise component that is equal in magnitude to all other noise sources combined, and, for this reason, it deserves a special discussion.

To be negligible, 120Hz ripple noise should be between 10nV and 100nV referred to the input of an op amp. Achieving these low levels requires consideration of three factors: the op amp's 120Hz power supply rejection ratio (PSRR), the regulator's ripple rejection ratio, and finally, the regulator's input capacitor size.

PSRR at 120Hz for a given op amp may be found in the manufacturer's data sheet curves of PSRR versus frequency as shown in Figure 3. For the amplifier shown, 120Hz PSRR is about 76dB, and to attain a goal of 100nV referred to the input, ripple at the power terminals must be less than 0.6mV. Today's IC regulators provide about 60dB of ripple rejection; in this case the regulator input capacitor must be made large enough to limit input ripple to 0.6V.

Externally-compensated low noise op amps can provide improved 120Hz PSRR in high closed-loop gain configurations. The PSRR versus frequency curves of such an op amp are shown in Figure 4. When compensated for a closed-loop gain of 1000, 120Hz PSRR is 115dB. PSRR is still excellent at much higher frequencies allowing low ripple-noise operation in exceptionally severe environments.

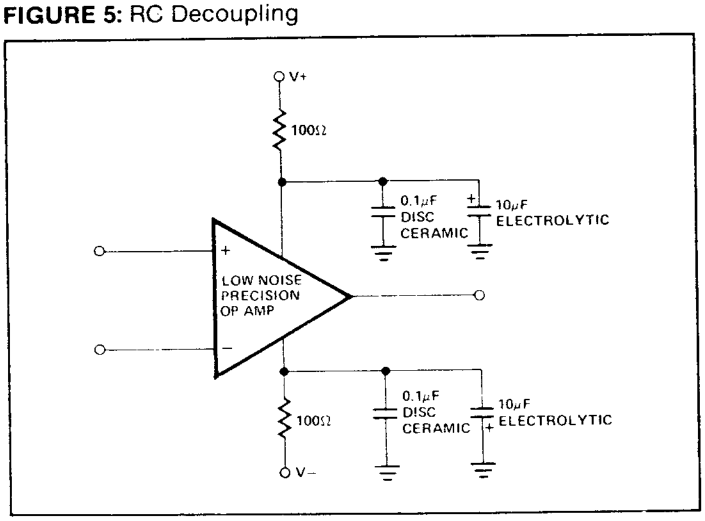
FIGURE 4: PSRR vs Frequency (OP-06)



Power Supply Bypassing

Usually, 120Hz ripple is not the only power supply associated noise. Series regulator output typically contain at least 150μV of noise in the 100Hz to 100kHz range; switching types contain even more. Unpredictable amounts of induced noise can also be present on power leads from many sources. Since high frequency PSRR decreases at 20dB/decade, these higher frequency supply noise components must not be allowed to reach the op amp's power terminals. RC decoupling, as shown in Figure 5, will adequately filter most wideband noise. Some caution must be exercised with this type of decoupling, as load current changes will modulate the voltage at the op amp's supply pins.

FIGURE 5: RC Decoupling



Power Supply Regulation

Any change in power supply voltage will have a resultant effect referred to an op amp's inputs. For the op amp of Figure 3, PSRR at DC is 126dB (0.5μV/V) which may be considered as a potential low frequency noise source. Power supplies for low noise op amp applications should, therefore, be both low in ripple and well-regulated. Inadequate supply regulation is often mistaken to be low frequency op amp noise.

When noise from external sources has been effectively minimized, further improvements in low noise performance are obtained by specifying the right op amp and through careful selection and application of the associated components.

OPERATIONAL AMPLIFIER INTERNAL NOISE

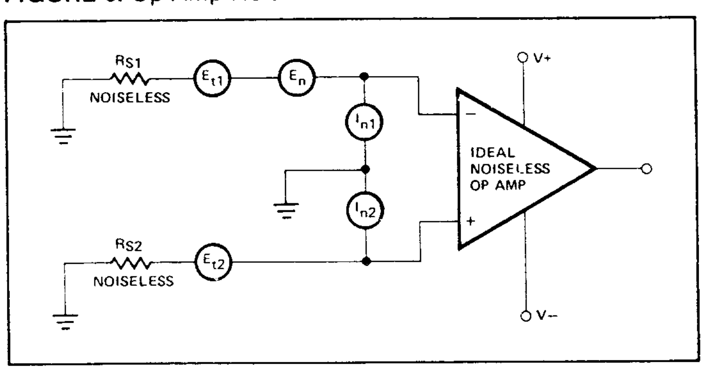
Most completely specified low-noise op amp data sheets specify current and voltage noises in a 1Hz bandwidth centered on 10Hz, 100Hz, and 1kHz, as well as low frequency noise over a range of 0.1Hz to 10Hz. To minimize total noise, a knowledge of the derivation of these specifications is useful. In this section, the reader is provided with an explanation of basic op amp-associated random noise mechanisms and introduced to a simplified method for calculating total input-referred noise in typical applications.

Op amp-associated noise currents and voltages are random in nature. They are aperiodic and uncorrelated to each other; and typically have Gaussian amplitude distributions, with the highest noise amplitudes having the lowest probability. There is a statistical relationship between the peak-to-peak value of random noise and its rms value. Where the amplitude distribution is Gaussian, the rms value may be multiplied by six to yield a peak-to-peak value that will not be exceeded 99.73% of the time (this is a handy rule-of-thumb for noise calculations).

Noise Model of Op Amps

In the calculation of op amp circuit noise, it is customary to refer all noise to the input. Figure 6 completely models the input-referred noise sources. In the model, the internal white and flicker noise sources are combined into three equivalent input noise generators, E_n, I_{n1}, and I_{n2}. The noise current generators produce noise voltage drops across their respective source resistors, R_{S1} and R_{S2}. The source resistors themselves generate thermal noise voltages, E_{t1} and E_{t2}. Total rms input-referred voltage noise, over a given bandwidth, is the square root of the sum of the squares of the five noise voltage generators over that bandwidth.

FIGURE 6: Op Amp Noise Model



(2) $E_n(f_H, f_L) = \sqrt{E_n^2 + (I_{n1} \cdot R_{S1})^2 + (I_{n2} \cdot R_{S2})^2 + E_{t1}^2 + E_{t2}^2}$

Equation 2 describes, in total, all noise sources of an op amp circuit. It will be used throughout this application note.

Minimization of total noise requires an understanding of the mechanisms involved in each of the five generators. First, the white noise mechanisms, thermal and shot, are discussed, followed by other low frequency noise mechanisms, flicker and popcorn.

Noise Mechanisms of Op Amps

The two basic types of op amp-associated noises are white noise and flicker noise (1/f). White noise contains equal amounts of power in each hertz of bandwidth. Flicker noise is different in that it contains equal amounts of power in each decade of bandwidth. This is best illustrated by spectral noise density plots such as in Figures 7 and 8. Above a certain corner frequency, white noise dominates; below that frequency, flicker (1/f) noise is dominant. Low noise corner frequencies in conjunction with a low white noise magnitude distinguish low noise op amps from general purpose devices.

FIGURE 7: OP-77 Noise Voltage

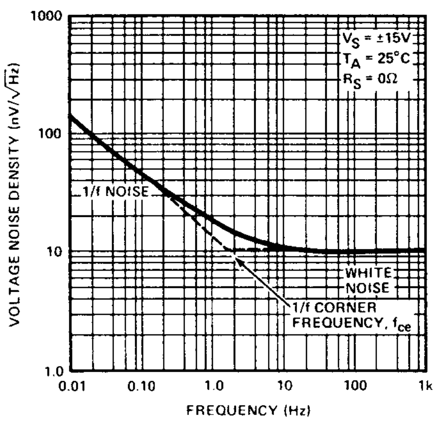
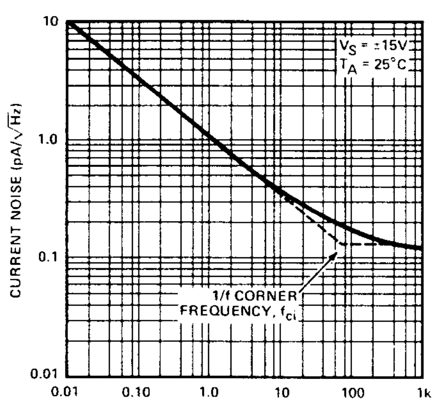


FIGURE 8: OP-77 Noise Current



Mathematically, noise spectral density may be expressed as:

(3a) $e_n^2 = \frac{E_n^2}{\Delta f}$ (3b) $i_n^2 = \frac{I_n^2}{\Delta f}$

Where: e_n, i_n = Spectral noise density of voltage and current, respectively

E_n, I_n = Total rms voltage and current noise in a frequency band, respectively

Δf = Bandwidth of 1Hz

From Equation 3, the total rms noise in a frequency band from f_L to f_H is then,

(4a) $E_n^2 = \int_{f_L}^{f_H} e_n^2\, df$ (4b) $I_n^2 = \int_{f_L}^{f_H} i_n^2\, df$

Where: f_H = Upper frequency limit of interest

f_L = Lower frequency limit of interest

Equation 4 means that three things must be known to evaluate total voltage noise (E_n) or current noise (I_n): f_H, f_L, and a knowledge of noise behavior over frequency.

White Noise

White noise contains many frequency components and is so named in analogy to white light which is made up of many colors. The important point to remember is that white noise has equal noise power in each hertz of bandwidth. In other words, the noise spectral density of white noise is **constant** with varying frequency. Thus, Equation 4 may be rewritten to describe white noise over a frequency band.

(5a) $E_{nW} = e_{nW}\sqrt{f_H - f_L}$ (5b) $I_{nW} = i_{nW}\sqrt{f_H - f_L}$

When $f_H \geq 10 f_L$, the white noise expressions may be reduced to:

(6a) $E_{nW} = e_{nW}\sqrt{f_H}$ (6b) $I_{nW} = i_{nW}\sqrt{f_H}$

Flicker Noise

Unlike white noise, flicker (1/f) noise is not constant with respect to frequency, but has a power spectral density that is inversely proportional (K_e, K_i) to the frequency of interest as described in Equation 7.

(7a) $e_{nF}^2(f) = \frac{K_e^2}{f}$ (7b) $i_{nF}^2(f) = \frac{K_i^2}{f}$

or,

(8a) $e_{nF}(f) = \frac{K_e}{\sqrt{f}}$ (8b) $i_{nF}(f) = \frac{K_i}{\sqrt{f}}$

Where: K_e, K_i are constants of proportionality.

The constants of proportionality depend on a number of parameters internal to the amplifier. It will be shown later that the constants will drop out mathematically.

In order to calculate total voltage and current noise, the concept of corner frequency is useful. Referring to the graphs of e_n or i_n versus frequency as in Figures 7 and 8, we can see that it is a composite of a zero-slope line (white noise) summed with a line f slope −1/2 (1/f noise, or flicker noise). The projected ntersection of these lines occurs where the two noise powers re equal, at a frequency called the *corner frequency*. Therefore, follows that at the corner frequency, f_{ce} or f_{ci},

(9a) $e_{nW}^2 = e_{nF}^2(f_{ce}) = \frac{K_e^2}{f_{ce}}$ (9b) $i_{nW}^2 = i_{nF}^2(f_{ci}) = \frac{K_i^2}{f_{ci}}$

earranging,

(10a) $K_e^2 = e_{nW}^2 \cdot f_{ce}$ (10b) $K_i^2 = i_{nW}^2 \cdot f_{ci}$

ubstituting in Equation 7,

(11a) $e_{nF}^2(f) = e_{nW}^2 \cdot \frac{f_{ce}}{f}$ (11b) $i_{nF}^2(f) = i_{nW}^2 \cdot \frac{f_{ci}}{f}$

r,

(12a) $e_{nF}(f) = e_{nW} \sqrt{\frac{f_{ce}}{f}}$ (12b) $i_{nF}(f) = i_{nW} \sqrt{\frac{f_{ci}}{f}}$

We can find the rms flicker noise in a band as follows:

$$(13a) \quad E_{nF}^2 = \int_{f_L}^{f_H} e_{nF}^2(f)\, df = e_{nW}^2 \cdot f_{ce} \cdot \ln\left(\frac{f_H}{f_L}\right)$$

$$(13b) \quad I_{nF}^2 = \int_{f_L}^{f_H} i_{nF}^2(f)\, df = i_{nW}^2 \cdot f_{ci} \cdot \ln\left(\frac{f_H}{f_L}\right)$$

Typical bipolar op amp corner frequencies for voltage noise are n the range of 1 to 20Hz; and for current noise, 10 to 1,000Hz. In comparison, FET input op amps have voltage noise corner frequencies in the range of 100Hz to 500Hz. Still higher are CMOS op amps whose corner frequencies are typically on the order of 1kHz.

Now that we have the mathematical expressions describing white noise and flicker noise, we can sum (by root-sum-square method) the two components to yield a total spectral density expression.

(14a) $e_n^2 = e_{nW}^2 + e_{nF}^2(f)$ (14b) $i_n^2 = i_{nW}^2 + i_{nF}^2(f)$

substituting from Equation 11,

(15a) $e_n = e_{nW} \sqrt{1 + \frac{f_{ce}}{f}}$ (15b) $i_n = i_{nW} \sqrt{1 + \frac{f_{ci}}{f}}$

Equation 15 is an expression frequently used to describe noise (voltage and current) curves seen in op amp data sheets.

The rms noise in a band is then:

$$(16) \quad E_n(f_H, f_L) = e_{nW} \sqrt{f_{ce} \cdot \ln\left(\frac{f_H}{f_L}\right) + (f_H - f_L)}$$

$$(17) \quad I_n(f_H, f_L) = i_{nW} \sqrt{f_{ci} \cdot \ln\left(\frac{f_H}{f_L}\right) + (f_H - f_L)}$$

Where: e_{nW} = White noise voltage spectral density
i_{nW} = White noise current spectral density
f_{ce} = Voltage noise corner frequency
f_{ci} = Current noise corner frequency
f_H = Upper frequency limit of interest
f_L = Lower frequency limit of interest

The two most important internally-generated noise minimization rules are derived from Equation 16 and 17: a) limit the circuit bandwidth, and b) use operational amplifiers with low white noise specifications in conjunction with low corner frequencies. So far we have derived the noise voltage (E_n) and noise current (I_n) components (Equations 16 and 17) for the first three terms of Equation 2, which is reproduced below.

$$(2) \quad E_n(f_H, f_L) = \sqrt{E_n^2 + (I_{n1} \cdot R_{S1})^2 + (I_{n2} \cdot R_{S2})^2 + E_{t1}^2 + E_{t2}^2}$$

In the next section, the last two terms of the equation, which are the thermal noise voltages generated by the external source resistances, are derived.

Thermal Noise

Thermal (Johnson) noise is a white noise voltage generated by random movement of thermally-charged carriers in a resistance; in op amp circuits, this is the type of noise produced by the source resistances in series with each input. Its rms value over a given bandwidth is calculated by:

$$(18) \quad E_t = \sqrt{4kTR \cdot (f_H - f_L)}$$

Where: k = Boltzmann's constant = 1.38×10^{-23} joules/K
T = Absolute temperature, kelvin
R = Resistance in ohms
f_H = Upper frequency limit in hertz
f_L = Lower frequency limit in hertz

At room temperature, Equation 18 simplifies to:

$$(19) \quad E_t = 1.28 \times 10^{-10} \sqrt{R \cdot (f_H - f_L)}$$

To minimize thermal noise (E_{t1} and E_{t2}) from R_{S1} and R_{S2}, large source resistors and excessive system bandwidth should be avoided.

Thermal noise is also generated inside the op amp, principally from r_{bb}', the base-spreading resistances in the input stage transistors. These noises are included in E_n, the total equivalent input voltage noise generator.

All the component noise sources of Equation 2 have now been derived. Total noise of an op amp circuit may be easily calculated using the equation. In the next sections, examples using several precision op amps will be calculated to illustrate the noise minimization techniques as well as to contrast the different noise performance of these devices.

TOTAL NOISE CALCULATION

With data sheet curves and specifications, and a knowledge of source resistance values, total input-referred noise may be calculated for a given application. To illustrate the method, noise information from the Precision Monolithics OP-77A and OP-27A data sheets are reproduced in Figure 9. The first step is to determine the current and voltage noise corner frequencies so that the E_n and I_n terms of Equation 2 may be calculated using Equations 16 and 17.

Corner Frequency Determination

In the input spot noise versus frequency curves of Figure 9, it may be seen that voltage noise ($R_S = 0$) begins to rise at about 3Hz. Lines projected from the horizontal (white noise) portion and the sloped (flicker noise) portion intersect at 2Hz, the voltage noise corner frequency (f_{ce}). In the center curve, excluding thermal noise from the source resistance, current noise multiplied by 200kΩ is plotted as a voltage noise. Lines projected from the horizontal portion and sloped portions intersect at 80Hz, the current noise corner frequency (f_{ci}).

FIGURE 9A: OP-77 Input Spot Noise Voltage vs Frequency

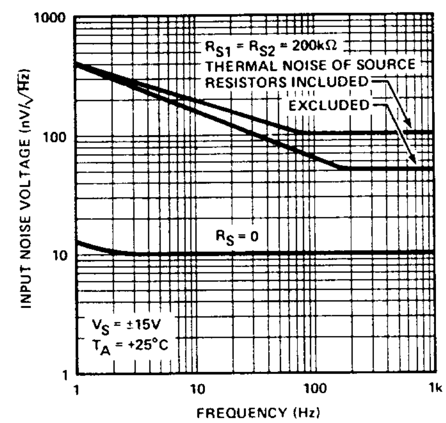


FIGURE 9B: OP-77/OP-27 Ultra-Low Offset Voltage Op Amps

ELECTRICAL CHARACTERISTICS at $V_S = \pm15V$ and $T_A = 25°C$, unless otherwise noted.

PARAMETER	SYMBOL	CONDITIONS	OP-77A MIN	OP-77A TYP	OP-77A MAX	OP-27A MIN	OP-27A TYP	OP-27A MAX	UNITS
Input Noise Voltage	e_{np-p}	0.1Hz to 10Hz	—	0.35	0.6	—	0.08	0.18	μV_{p-p}
Input Noise Voltage Density	e_n	f_O = 10Hz	—	10.3	18.0	—	3.5	5.5	nV/√Hz
		f_O = 100Hz	—	10.0	13.0	—	3.1	4.5	
		f_O = 1000Hz	—	9.6	11.0	—	3.0	3.8	
Input Noise Current	i_{np-p}	0.1Hz to 10Hz	—	14	30	—	—	—	pA_{p-p}
Input Noise Current Density	i_n	f_O = 10Hz	—	0.32	0.80	—	1.7	4.0	pA/√Hz
		f_O = 100Hz	—	0.14	0.23	—	1.0	2.3	
		f_O = 1000Hz	—	0.12	0.17	—	0.4	0.6	
Input Offset Voltage	V_{OS}		—	10	25	—	10	25	μV
Input Offset Voltage Drift	TCV_{OS}	$-55°C \le T_A \le +125°C$	—	0.1	0.3	—	0.2	0.6	μV/°C
Long Term Input Offset Voltage Stability	V_{OS}/Time		—	0.2	1.0	—	0.2	1.0	μV/Mo
Input Offset Current	I_{OS}		—	0.3	1.5	—	7	35	nA
Input Bias Current	I_B		—	±1.2	±2.0	—	±10	±40	nA

INPUT NOISE VOLTAGE (e_{np-p})
The peak-to-peak noise voltage in a specified frequency band.

INPUT NOISE VOLTAGE DENSITY(e_n)
The rms noise voltage in a 1Hz band surrounding a specified value of frequency.

INPUT NOISE CURRENT (i_{np-p})
The peak-to-peak noise current in a specified frequency band.

INPUT NOISE CURRENT DENSITY (i_n)
The rms noise current in a 1Hz band surrounding a specified value of frequency.

Equations 16 and 17 also require e_{nW} and i_{nW} for calculation of E_n and I_n. To find e_{nW} and i_{nW}, use the data sheet specifications a decade or more above the respective corner frequencies; in the case of the OP-77A, e_{nW} is $9.6V/\sqrt{Hz}$ (1,000Hz), and i_{nW} is $0.12pA/\sqrt{Hz}$ (1,000Hz). At this time, it should be noted that the noise current, $0.12pA/\sqrt{Hz}$, is a value that has been incorrectly derived from the standardized, commonly-used test method on virtually ALL commercially available op amps. The value is off by a factor of $\sqrt{2}$. Therefore, in order to calculate the correct total noise, the data sheet current noise value should be multiplied by a correction factor of $\sqrt{2}$. Thus, for the noise calculation of the OP-77A, the value e_{nW} is $9.6nV/\sqrt{Hz}$ (1,000Hz), and i_{nW} should be $0.17pA/\sqrt{Hz}$ (1,000Hz).

OP-77 Bandwidth of Interest

To be summed correctly, each of the five noise quantities must be expressed over the same bandwidth, f_H to f_L. For calculation purposes, assume f_H to be the highest frequency component that must be amplified without distortion. Note that e_n, i_n, corner frequencies are independent of actual circuit component values. When doing noise calculations for a large number of circuits using the same op amp, these numbers only have to be calculated once.

OP-77 Typical Application Example

Figure 10A shows a typical ×10 gain stage with a 10kΩ source resistance. In Figure 10B, the circuit is redrawn to show five noise voltage sources. To evaluate total input-referred noise, the values of each of the five sources must be determined.

FIGURE 10A: Noise Analysis Circuit

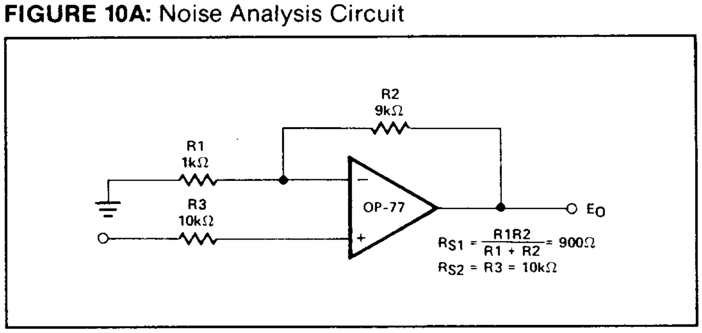
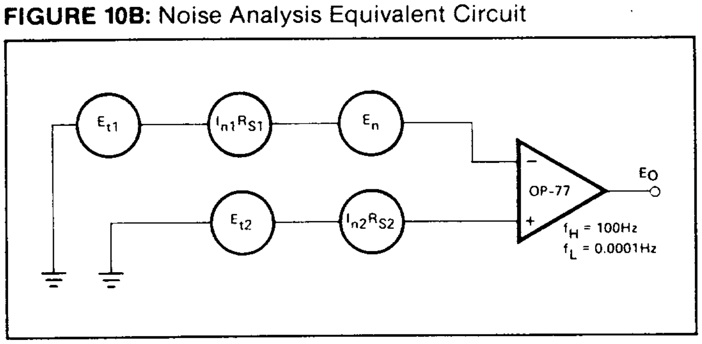


FIGURE 10B: Noise Analysis Equivalent Circuit



Using Equation 19: $E_t = 1.28 \times 10^{-10} \sqrt{R \cdot (f_H - f_L)}$

$E_{t1} = 1.28 \times 10^{-10} \sqrt{(900\Omega)\ (100Hz)} = 0.04\mu Vrms$

$E_{t2} = 1.28 \times 10^{-10} \sqrt{(10k\Omega)\ (100Hz)} = 0.128\mu Vrms$

Next, calculate I_n using Equation 17:

$$I_n = i_n \sqrt{f_{ci} \cdot \ln\left(\frac{f_H}{f_L}\right) + f_H - f_L}$$

$$= 0.17pA \sqrt{80 \cdot \ln\left(\frac{100Hz}{0.0001Hz}\right) + 100 - 0.0001}$$

$$= 5.9pArms$$

and:

$I_{n1} \cdot R_{S1} = 5.9pA \cdot (900\Omega) = 0.0053\mu Vrms$

$I_{n2} \cdot R_{S2} = 5.9pA \cdot (10k\Omega) = 0.059\mu Vrms$

Finally, E_n from Equation 16:

$$E_n = e_n \sqrt{f_{ce} \cdot \ln\left(\frac{f_H}{f_L}\right) + f_H - f_L}$$

$$= 9.6nV \sqrt{2 \cdot \ln\left(\frac{100Hz}{0.0001Hz}\right) + 100 - 0.0001}$$

$$= 0.108\mu Vrms$$

Substituting in Equation 2:

$$E_n(f_H - f_L) = \sqrt{E_n{}^2 + I_{n1}{}^2\, R_{S1}{}^2 + I_{n2}{}^2\, R_{S2}{}^2 + E_{t1}{}^2 + E_{t2}{}^2}$$

$$= \sqrt{(0.108\mu V)^2 + (0.0053\mu V)^2 + (0.059\mu V)^2 + (0.04\mu V)^2 + (0.128\mu V)^2}$$

$$= 0.18\mu Vrms$$

Total input-referred noise = 1.08μV peak-to-peak (0.0001Hz to 100Hz).

Notice that of the five terms in the equation, the first and the last terms dominate. Since the first term is the total rms noise voltage inherent of the amplifier, nothing can be done by the system designer to lower its noise other than to choose a device having inherently low noise characteristics. As can be seen in Equation 16, two key parameters determine the total rms noise of an amplifier—low white noise density and low noise corner frequency.

Notice that the thermal noise voltage (last term) of Equation 2 is determined by the 10kΩ value selected for R3. Had the value been reduced to 1kΩ, the thermal noise voltage would have been 0.04μVrms instead of 0.128μVrms. As a result, total rms noise voltage would have become 0.122μV, a remarkable 32% reduction in total noise.

Indeed, low noise design requires the system designer not only to choose an amplifier with low noise characteristics, but also to pay close attention in selecting appropriately low source resistances in the input circuit.

741 Calculation Example

The preceding calculation determined total noise in a given bandwidth using a low noise op amp. To place this level of performance into perspective, a calculation using the industry-standard 741 op amp in the circuit of Figure 10 is useful. Once again the starting point is corner frequency determination, using the data sheet curves of Figure 11: $f_{ce} = 200Hz$; $f_{ci} = 2kHz$; $e_n = 20nV/\sqrt{Hz}$; $i_n = (\sqrt{2}) \cdot (0.5pA/\sqrt{Hz}) = 0.71pA/\sqrt{Hz}$.

Using these corner frequencies and noise magnitudes, E_n and I_n are calculated to be 1.07μVrms and 118pArms respectively. Multiplying this noise current by the source resistance gives terms 2 and 3 of Equation 2 as shown below:

$$(2) \quad E_n(f_H, f_L) = \sqrt{E_n^2 + I_{n1}^2 R_{S1}^2 + I_{n2}^2 R_{S2}^2 + E_{t1}^2 + E_{t2}^2}$$

substituting in the equation:

$$E_n(f_H, f_L) = \sqrt{(1.07\mu V)^2 + (0.106\mu V)^2 + (1.18\mu V)^2 + (0.04\mu V)^2 + (0.128\mu V)^2}$$

$$= 1.6\mu Vrms$$

Total input-referred noise = 9.6μV peak-to-peak (0.0001Hz to 100Hz). This is more than 8 times that of the low noise OP-77 example. Notice further in this example, the third term of the equation becomes an additional dominant term. It is due to a higher noise current flow in the 10kΩ source resistance.

The calculation examples illustrate four rules for minimizing noise in operational amplifier applications:

Rule 1. Use an op amp with low noise characteristics.

Rule 2. Use an op amp with low noise corner frequencies.

Rule 3. Keep source resistances as low as practical.

Rule 4. Limit circuit bandwidth to signal bandwidth.

FIGURE 11A: Input Noise Voltage as a Function of Frequency

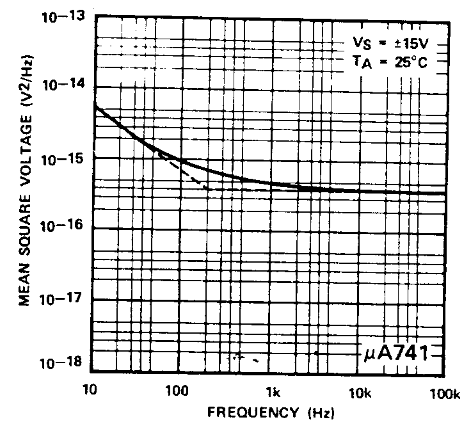
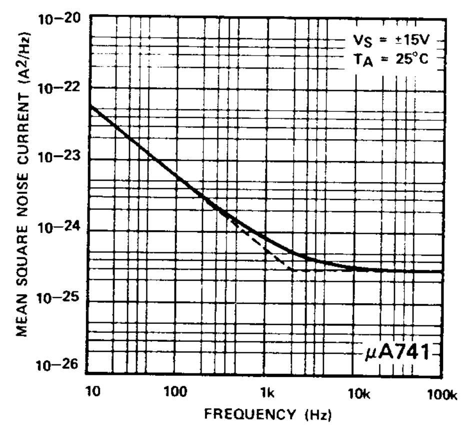
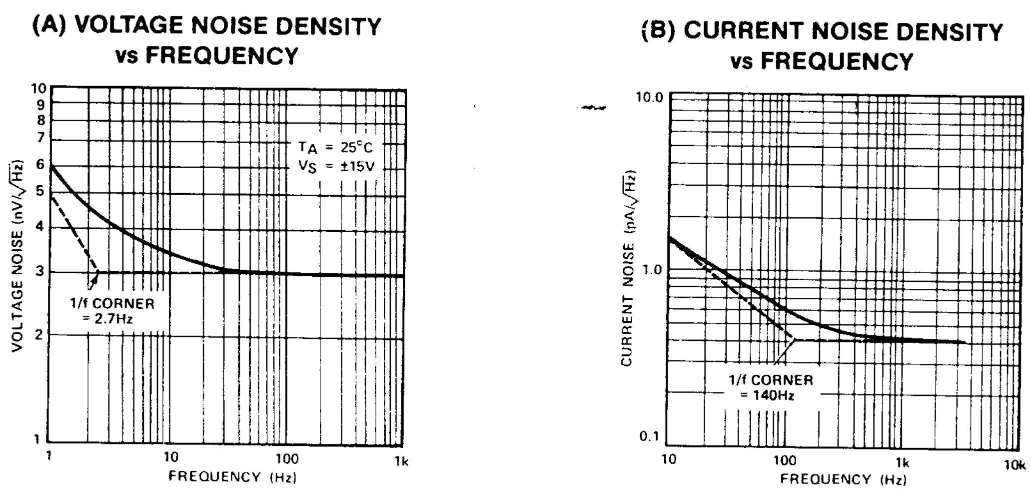


FIGURE 11B: Input Noise Current as a Function of Frequency



AN-15

FIGURE 12: OP-27, OP-37, and OP-227 Noise Voltage and Current as a Function of Frequency



OP-27/OP-227/OP-37 Noise Optimization Design

In this example, a low noise, high speed op amp is examined. Using the circuits in Figures 10A and 10B, and using the data sheet curves of Figures 12A and 12B:

$f_{ce} = 2.7\text{Hz};\ f_{ci} = 140\text{Hz};\ e_n = 3.0\text{nV}/\sqrt{\text{Hz}};$

$i_n = (\sqrt{2}) \cdot (0.4\text{pA}/\sqrt{\text{Hz}}) = 0.57\text{pA}/\sqrt{\text{Hz}}$

Using these corner frequencies and noise magnitudes, E_n and I_n are calculated to be 0.035μVrms and 25.7pArms, respectively. Multiplying the noise currents by the source resistances yield terms 2 and 3 of Equation 2 as shown below:

$$E_n(f_H, f_L) = \sqrt{E_n^2 + I_{n1}^2 R_{S1}^2 + I_{n2}^2 R_{S2}^2 + E_{t1}^2 + E_{t2}^2}$$

$$= \sqrt{(0.035\mu V)^2 + (0.023\mu V)^2 + (0.257\mu V)^2 + (0.04\mu V)^2 + (0.128\mu V)^2}$$

$$= 0.293\mu\text{Vrms}$$

Total input-referred noise = 1.76μV peak-to-peak (0.0001Hz to 100Hz).

Contrary to expectation, these supposedly lower noise amplifiers produce a circuit that has higher total noise than the previous OP-77 design. A closer analysis reveals again that the 10kΩ source resistance is the primary contributor to the two dominant terms (terms 3 and 5) of the total noise equation. The resulting noise generated swamped the excellent noise performance of these devices.

For the purpose of noise optimization, the 10kΩ source resistance is reduced to a balanced 910Ω resistance to preserve the inherently low input offset error of the amplifier. Recalculating Equation 2,

$$E_n(f_H, f_L) = \sqrt{(0.035\mu V)^2 + (0.023\mu V)^2 + (0.023\mu V)^2 + (0.04\mu V)^2 + (0.04\mu V)^2}$$

$$= 0.074\mu\text{Vrms}$$

Total input-referred noise is now a respectable 0.44μV peak-to-peak (0.0001Hz to 100Hz).

It is clear from this optimization that the system designer can achieve both a balance of low noise and low input offset voltage performance with these amplifiers. It is also obvious that one can optimize noise further by using, say, a 10Ω source resistance; in which case, the resulting total rms noise voltage is now 0.058μV, and a peak-to-peak noise is 0.35μV. This translates to a net noise reduction of 20% compared to the design using 1kΩ balance source resistance.

LIMITING BANDWIDTH TO MINIMIZE NOISE

Effective circuit bandwidth must not be much greater than signal bandwidth or amplification of undesirable high frequency noise components will occur. Throughout the preceding calculations, an assumption of "bandwidth-of-interest" was made, while in actual application the amplifier's bandwidth must b considered.

In Figure 13, the OP-77 frequency response curves show rolloff of 20dB/decade; integration of the area under the curv will show the effective circuit noise bandwidth to be 1.57 time the 3dB bandwidth. In most closed-loop gain configuration the amplifier's bandwidth may be greater than required, an output filtering, such as in Figure 14, could be used. As a alternate to output filtering, an integrating capacitor may b connected across the feedback resistor. Bandwidth may also b limited in some applications by overcompensating an externall compensated low noise op amp, such as the OP-06.

FIGURE 13A: OP-77 Open-Loop Frequency Response

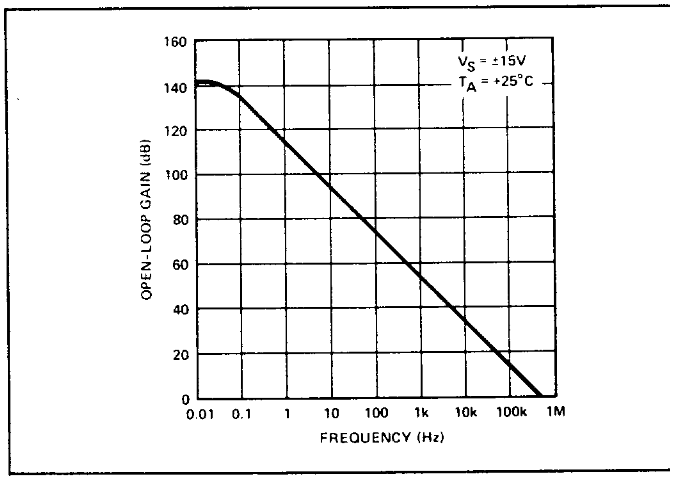


FIGURE 13B: OP-77 Closed-Loop Response for Various Gai Configurations

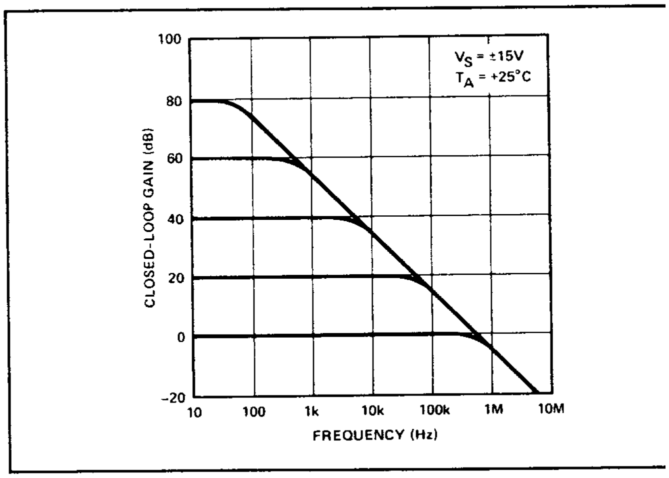
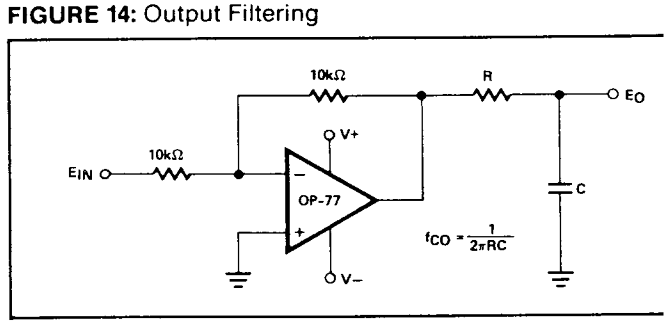


FIGURE 14: Output Filtering



MISCELLANEOUS NOISE MINIMIZATION METHODS

Certain other noise mechanisms merit consideration: use metal film resistors; carbon resistors exhibit "excess noise," with both 1/f and white noise content being related to DC applied voltage. The use of balanced source resistors, while sometimes good for DC error purposes, will increase noise; the balancing resistor is not required for op amps such as the OP-07 and OP-77, since $I_{OS} \cong I_B$. Keep noise in its proper perspective; minimize it without introducing additional DC errors. Use low noise op amps with overall DC specifications that will satisfy the application.

OTHER NOISES

Shot noise (Schottky noise) is a white noise current associated with the fact that current flow is actually a movement of discrete charged particles (electrons) across a potential barrier, such as a PN junction of a transistor or diode. Shot noise is a component of i_n, and indirectly, e_n. In Figure 6, I_{n1} and I_{n2}, above the 1/f frequency, are shot noise currents which are related to the amplifier's DC input bias currents:

$$(20)\quad I_{sh} = \sqrt{2qI_{DC}\,(f_H - f_L)}$$

Where: I_{sh} = rms shot noise value in amps

q = Charge of an electron = 1.602×10^{-19} C

I_{DC} = DC bias current in amps

f_H = Upper frequency limit in hertz

f_L = Lower frequency limit in hertz

At room temperature Equation 20 simplifies to:

$$(21)\quad I_{sh} = 5.66 \times 10^{-10}\sqrt{I_{DC}\,(f_H - f_L)}$$

Shot noise currents also flow in the input-stage emitter dynamic resistances (r_e), producing input noise voltages. These voltages, along with the r_{bb}' thermal noise, make up the white noise portion of E_n; the total equivalent input noise voltage generator.

Shot noise can also be generated from external sources such as PIN photodiodes, zener diodes, and other semiconductor junction devices. Noise current from these sources may be calculated using Equation 20 or 21.

In limited bandwidth, very low frequency applications, *flicker* (1/f) noise is the most critical noise source. An op amp designer minimizes flicker noise by keeping current noise components in the input and second stages from contributing to input voltage noise. Equation 22 illustrates this relationship:

$$(22)\quad \frac{i_{n\ \text{second stage}}}{g_{m\ \text{first stage}}} = e_{n\ \text{input}}$$

Another critical factor is corner frequency. For minimum noise, the current and voltage noise corner frequencies must be low; this is crucial. As shown in Figure 15, low-noise corner frequencies distinguish low-noise op amps from ordinary industry-standard 741 types.

The photograph in Figure 16, taken using the test circuit of Figure 17, illustrates the flicker noise performance of the OP-77. This device demonstrates proper attention to low noise circuit design and wafer processing and achieves a remarkable 0.35μV peak-to-peak input voltage noise in the 0.1Hz to 10Hz bandwidth.

FIGURE 15: Noise Voltage Comparison

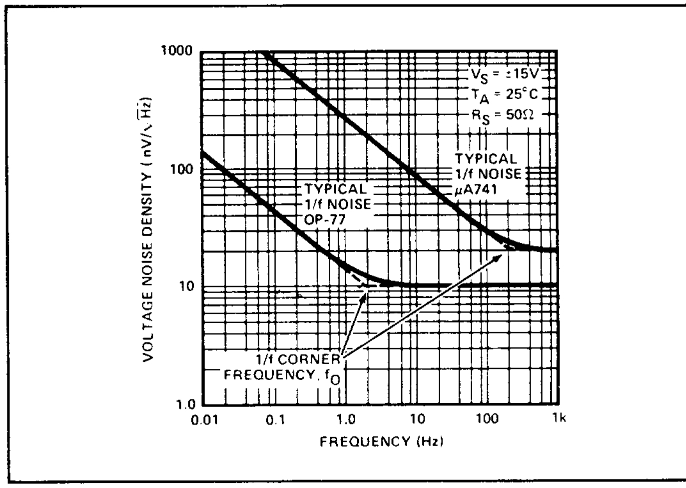


FIGURE 16: OP-77 Low Frequency Noise

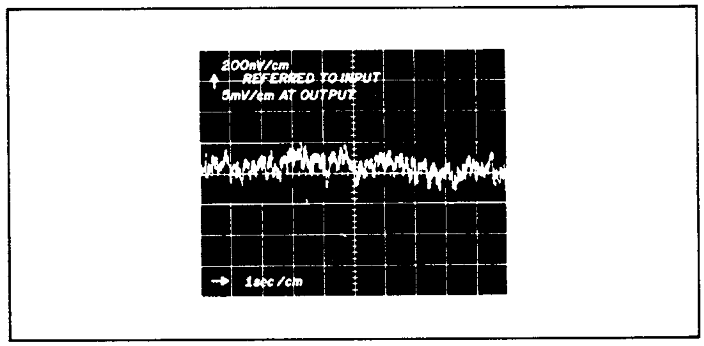
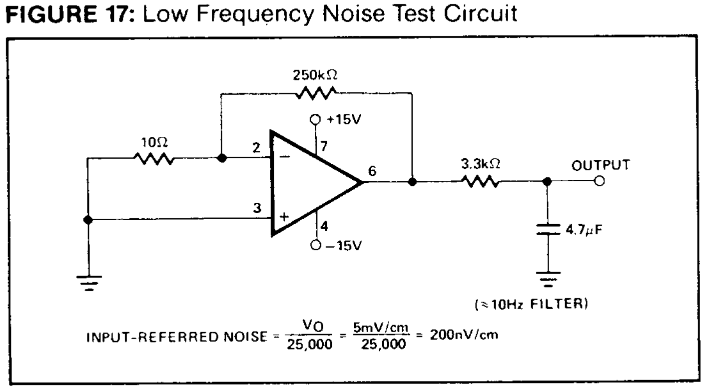


FIGURE 17: Low Frequency Noise Test Circuit

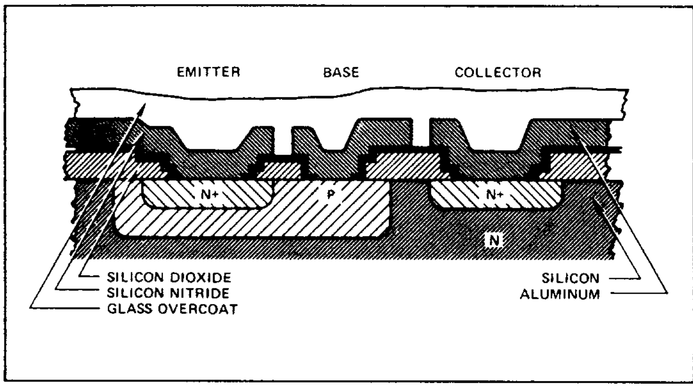


Popcorn noise (burst noise) is a momentary change in input bias current usually occurring below 100Hz, and is caused by imperfect semiconductor surface conditions incurred during wafer processing. Precision Monolithics minimizes this problem through careful surface treatment, general cleanliness, and a special three-step process known as "Triple Passivation."

To begin the process, a specially-treated thermal silicon dioxide layer is grown. This protects the junctions and also attracts any residual ionic impurities to the top surface of the oxide, where they are held fixed. Next, a layer of silicon nitride is applied to prevent the entry of any potential contamination or impurities.

The third step is the thick glass overcoat which leaves only the bonding pads exposed. A cutaway view of a finished device is shown in Figure 18.

FIGURE 18: Triple Passivated Integrated Circuit Process



Op amp manufacturers face a difficult decision in dealing with popcorn noise. Through careful low noise processing, it can be eliminated from almost all devices; alternatively, the processing may be relaxed, and finished devices must be individually tested for this parameter. Special noise testing takes valuable labor time, adds significant amounts to manufacturing cost, and ultimately increases the price a customer has to pay. At Precision Monolithics, the low noise process alternative is used to manufacture high volumes of cost-effective low noise op amps.

SUMMARY

A summary of the major points to consider is as follows:

1. Minimize externally-generated noise.
2. Choose an amplifier with low noise characteristics and low 1/f noise corner frequencies.
3. Limit the circuit bandwidth to signal bandwidth.
4. Eliminate excessive resistance in the input circuit.

CONCLUSION

Recent improvements in IC op amp DC specifications have made noise an important error consideration. From data sheet information and source resistance values, total input-referred noise over a given bandwidth can be easily calculated. Total noise can be minimized by a thorough understanding of the various noise-generation mechanisms.

NOISE BIBLIOGRAPHY

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