Operational Amplifier Noise Prediction

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Introduction

When working with op amp circuits an engineer is frequently required to predict the total RMS output noise in a given bandwidth for a certain feedback configuration. While op amp noise can be expressed in a number of ways, "spot noise" (RMS input voltage noise or current noise which would pass through 1Hz wide bandpass filters centered at various discrete frequencies), affords a universal method of predicting output noise in any op amp configuration.

The Noise Model

Figure 1 is a typical noise model depicting the noise voltage and noise current sources that are added together in the form of root mean square to give the total equivalent input voltage noise (RMS), therefore:

$$E_{ni} = \sqrt{e_{ni}^2 + I_{ni}^2 R_G^2 + 4KTR_G} \text{ where,}$$

E_{ni} is the total equivalent input voltage noise of the circuit,

e_{ni} is the equivalent input voltage noise of the amplifier, and

$I_{ni}^2 R_G^2$ is the voltage noise generated by the current noise.

$4KTR_G$ expresses the thermal noise generated by the external resistors in the circuit where K = 1.38 x 10^{-23} joules/^{o}K; T = 300^{o}K (27^{o}C) and:

$$R_G = \left(\frac{R_1 R_3}{R_1 + R_3}\right) + R_2$$

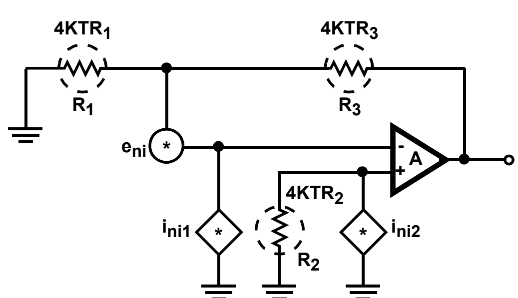

FIGURE 1.

The total RMS output noise (E_{no}) of an amplifier stage with gain = G in the bandwidth between f_1 and f_2 is:

$$E_{no} = G\left(\int_{f_1}^{f_2} (E_{ni})^2 df^{1/2}\right)$$

Note that in the amplifier stage shown, G is the non-inverting gain:

$$\left(G = 1 + \frac{R_3}{R_1}\right),$$

regardless of which input is normally driven.

Procedure for Computing Total Output Noise

1. Refer to the voltage noise curves for the amplifier to be used.
2. Enter values of e_{ni}^2 line (a) of the table below from the curve labeled "Noise spectral density" (the values must be squared).
3. From the current noise curves for the amplifier, obtain the values of i_{ni}^2 for each of the frequencies in the table, and multiply each by R_G^2, entering the products in line (b) of the table.
4. Obtain the value of $4KTR_G$ from Figure 8, and enter it on line (c) of the table. This is constant for all frequencies. The $4KTR_G$ value must be adjusted for temperatures other than normal room temperature.
5. Total each column in the table on line (d). This total is E_{ni}^2.

	10Hz	100Hz	1kHz	10kHz	100kHz
(a) e_{ni}^2					
(b) $I_{ni}^2 R_G^2$					
(c) $4KTR_G$					
(d) E_{ni}^2					

6. On linear scale graph paper enter each of the values for E_{ni}^2 versus frequency. In most cases, sufficient accuracy can be obtained simply by joining the points on the graph with straight line segments.

For the bandwidth of interest, calculate the area under the curve by adding the areas of trapezoidal segments. This procedure assumes a perfectly square bandpass condition; to allow for the more normal -6dB/octave bandpass skirts, multiply the upper (-3dB) frequency by 1.57 to obtain the effective bandwidth of the circuit, before computing the area. The total area obtained is equivalent to the square of the total input noise over the given bandwidth.

7. Take the square root of the area found above and multiply by the gain (G) of the circuit to find the total Output RMS noise.

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A Typical Example

It is necessary to find the output noise of the circuit shown below between 1kHz and 24kHz.

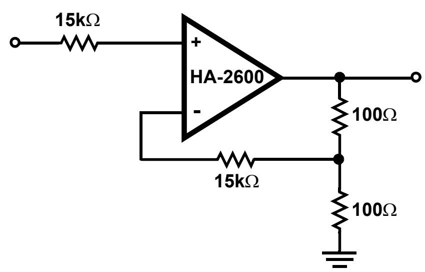

FIGURE 2. THE HA-2600 IN A TYPICAL G = 1000 CIRCUIT

Values are selected from the data sheet and Figure 8 to fill in the table as shown below. An R_G of 30kΩ was selected.

	10Hz	100Hz	1kHz	10kHz	100kHz
(a) e_{ni}^2	$3.6x10^{-15}$	$1.156x10^{-15}$	$7.84x10^{-16}$	$7.29x10^{-16}$	$7.29x10^{-16}$
(b) $I_{ni}^2R_G^2$	$9.9x10^{-16}$	$1.89x10^{-16}$	$3.15x10^{-17}$	$7.2x10^{-18}$	$72x10^{-18}$
(c) $4KTR_G$	$4.968x10^{-16}$	$4.968x10^{-16}$	$4.968x10^{-16}$	$4.968x10^{-16}$	$4.968x10^{-16}$
(d) E_{ni}^2	$5.09\ x10^{-15}$	$1.86x10^{-15}$	$1.31x10^{-15}$	$1.23x10^{-15}$	$1.23x10^{-15}$

The totals of the selected values for each frequency is in the form of E_{ni}^2. This should be plotted on linear graph paper as shown below:

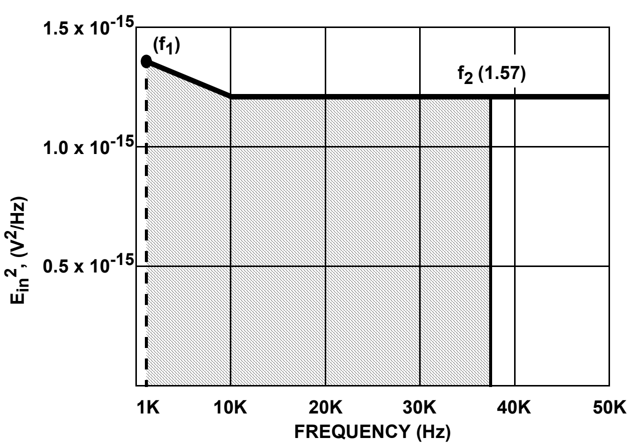

FIGURE 3. HA-2600 TOTAL EQUIVALENT INPUT NOISE

Since a noise figure is needed for the frequency of 1kHz to 24kHz, it is necessary to calculate the effective bandwidth of the circuit. With A_V = 60dB the upper 3dB point is approximately 24kHz. The product of 1.57 (24kHz) is 37.7kHz and is the effective bandwidth of the circuit.

The shaded area under the curve is approximately 45 x $10^{-12}V^2$; the total equivalent input noise is $\sqrt{E_{in}^2}$ or 6.7μV, and the total output noise for the selected bandwidth is $\sqrt{E_{in}^2}$ x (closed loop gain) or $6.7mV_{RMS}$.

Actual Measurements for Comparison

The circuit shown below was used to actually measure the broadband noise of the HA-2600 for the selected bandwidth:

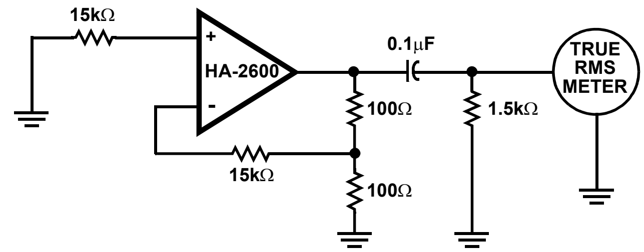

FIGURE 4. A TYPICAL TEST CIRCUIT FOR BROADBAND NOISE MEASUREMENTS

The frequencies below the f1 point of the bandwidth selected are filtered out by the RC network on the output of HA-2600. The measurement of the broadband noise is observed on the true RMS voltmeter. The measured output noise of the circuit is $4.7mV_{RMS}$ as compared to the calculated value of $6.7mV_{RMS}$.

Acquiring the Data for Calculations

Spot noise values must be generated in order to make the output noise prediction. The effects of "Popcorn" noise have been excluded due to the type of measurement system.

The Quan-Tech Control Unit, Model No. 2283 and Filter Unit, Model No. 2181 were used to acquire spot noise voltage values expressed in (V/√Hz). The test system performs measurements from 10Hz by orders of magnitude to 100kHz with an effective bandwidth of 1Hz at each tested frequency.

Several source resistance (R_G) values were used in the measuring system to reveal the effects of R_G on each type of Intersil's op amps and to obtain proper voltage noise values essential for current noise calculations.

A Discussion On "Popcorn" Noise

"Popcorn" noise was first discovered in early 709 type op amps. Essentially it is an abrupt step-like shift in offset voltage (or current) lasting for several milliseconds and having amplitude from less than one microvolt to several hundred microvolts. Occurrence of the "pops" is quite random - an amplifier may exhibit several pops per second during one observation period and then remain "popless" for several minutes. Worst case conditions are usually at low temperatures with high values of R_G. Some amplifier designs and some manufacturer's products are notoriously bad in this respect. Although theories of the popcorn mechanism differ, it is known that devices with surface contamination of the semiconductor chip will be particularly bad "poppers". Advertising claims not withstanding, the author has never seen any manufacturer's op amp that was completely free of "popcorn." Some peak detector circuits have been developed to screen devices for low amplitude "pops", but 100% assurance is impossible because an infinite test time would be required. Some studies have shown that spot noise measurements at 10Hz and 100Hz, discarding units that are much higher than typical, is an effective screen for potentially high "popcorn" units.

The vast majority of Intersil op amps will exhibit less than

$3\mu V_{P-P}$ “popcorn”. Screening can be performed, but it should be noted that the confidence level of the screen could be as low as 60%.

References

[1] Fitchen, F.C. and Motchenbacker, C.D. Low Noise Electronic Design. New York: John Wiley and Sons, 1973.

Instruction Manual, Model 2173C Transistor Noise Analyzer Control Unit. Quan-Tech, Division of KMS Industries. Whippany, New Jersey.

Typical Spot Noise Curves Unless Otherwise Noted: $V_S = \pm15V$, $T_A = 25^oC$

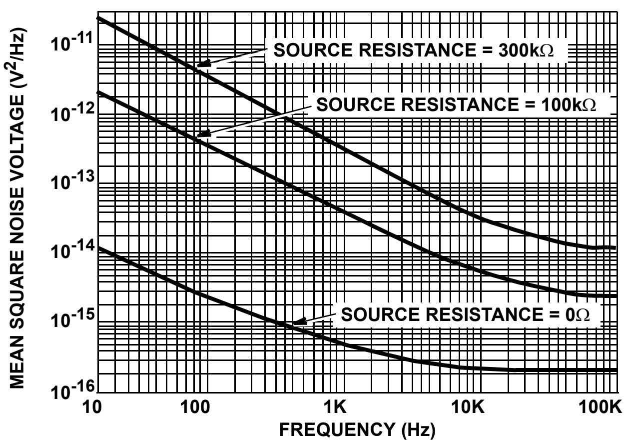

FIGURE 5. HA-2500/2510/2520 INPUT NOISE VOLTAGE

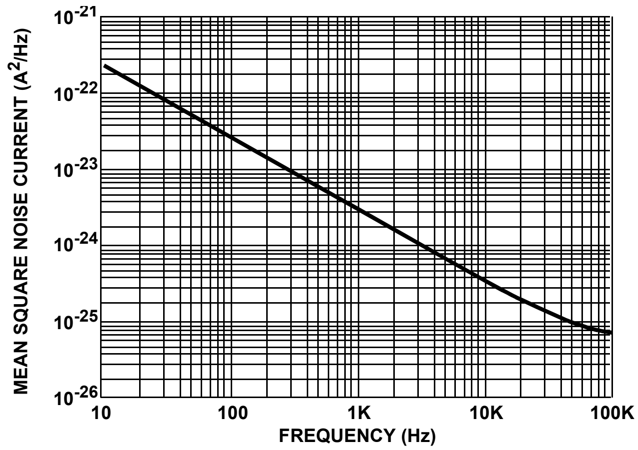

FIGURE 6. HA-2500/2510/2520 INPUT NOISE CURRENT

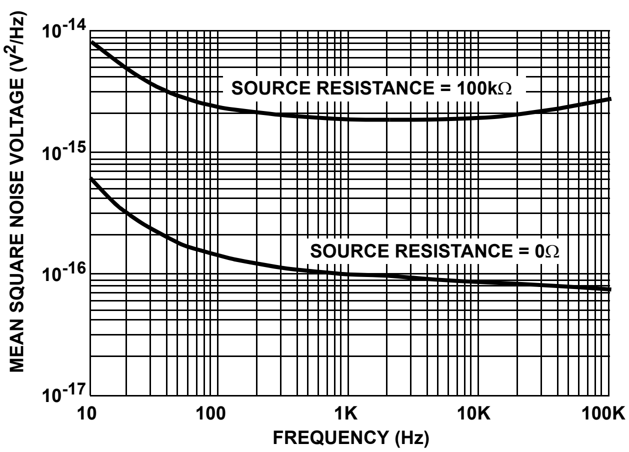

FIGURE 7. HA-4741 INPUT NOISE VOLTAGE

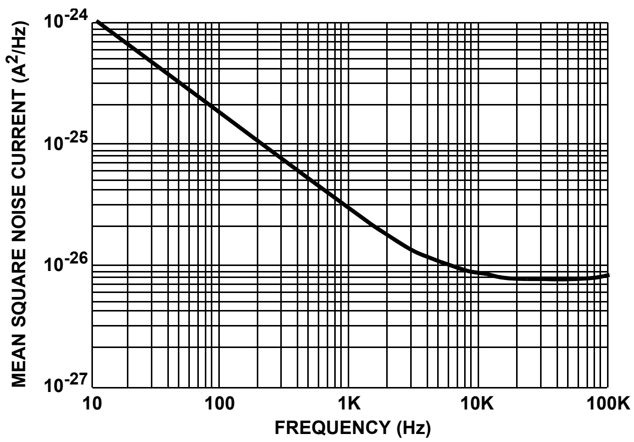

FIGURE 8. HA-4741 INPUT NOISE CURRENT

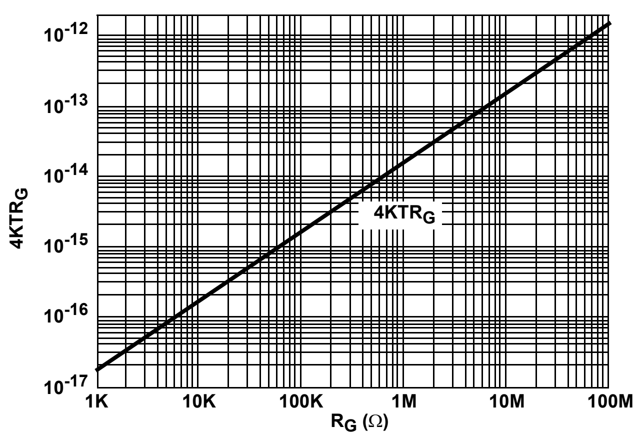

FIGURE 9. NOISE vs RESISTOR VALUE

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