3. OP-AMP NOISE MEASUREMENTS

3.1   Object

The object of this experiment is to measure the equivalent input noise voltage and noise current of a number of commonly used integrated circuit op-amps. These are the 741, OP-27, TL071, and LF351.

3.2   Laboratory Procedure

3.2.1   Gain Stage Design

Because the noise output voltage of the op-amps is very low, it will be necessary to amplify it before it can be analyzed on the Dynamic Signal Analyzer. The object of this step is to assemble a 40 dB gain stage for this purpose using one of the TL071 op-amps. The stage is to be operated in the non-inverting configuration with a series feedback resistor of 10 $k\Omega$ and a shunt feedback resistor of 100 Ω. A 330 μF capacitor should be used in series with the shunt resistor to provide 100% feedback at DC so that the DC offset of the op-amp being measured will not be amplified by the full 40 dB gain of this stage.

Assemble the 40 dB gain stage near one end of the solderless breadboard. The reason for putting this stage at one end of the board is to minimize the possibility of oscillations due to coupling from input to output of the final circuit. A power supply decoupling network is to be used on the op-amp rails on the breadboard; this consists of a 100 μF capacitor from the rail to ground and a 100 Ω resistor in series with the output of the power supply and the power supply rail. After the gain stage is assembled, measure its midband gain and its lower and upper half-power cutoff frequencies. The test signal amplitude should be low enough so that slew-rate limiting does not occur during the measurements.

After making the preceding measurements, ground the input to the op-amp and use the dynamic signal analyzer to measure the spectrum of its output noise from 0 Hz to 1 kHz and from 0 Hz to 100 kHz. Obtain plots of these. There will probably be some 60 Hz and integer multiplies on the 0 to 1 kHz plot; this will not show up in the other plot because the resolution on the 0 to 100 kHz is not sufficient to show it.

In all further measurements, the 40 dB gain stage will be used to amplify the output noise of another op-amp. It should be observed during these measurements that the noise of the cascade combination of the two op-amps will be much greater than that generated by the 40 dB gain stage by itself. For this reason, it can be assumed that the 40 dB gain stage

has negligible noise during these measurements.

3.2.2 Device Under Test

On the other end of the breadboard, configure the test op-amp as a 40 dB non-inverting amplifier stage using a 1 $k\Omega$ series feedback resistor and a 10 Ω shunt feedback resistor. Because these values are so small, the noise generated in the feedback resistors can be neglected in the calculation. Connect the output of this op-amp to the input of the 40 dB gain stage assembled in the preceding step. With the non-inverting input of the test op-amp grounded ($R_S = 0$), use the Dynamic Signal Analyzer to measure the spectrum of the output noise from 0 to 1 kHz and from 0 to 100 kHz. Place the cursor or marker at a spot on the spectrum which appears to be reasonably flat. Obtain plots of these. Use the same marker frequency for all of the measurements.

   Repeat the measurements of the preceding paragraph for source resistor values of $R_S = 1$ $k\Omega$, 10 $k\Omega$, and 100 $k\Omega$. Record the marker value at a portion of the spectrum which is reasonably flat. Oscillations may occur due to capacitive coupling from the output of the second 40 dB gain stage to the non-inverting input of the first stage with the higher resistor values. This can be minimized by carefully routing all wires and leads to keep the capacitive coupling between output and input at a minimum. Even through oscillation problems may not be experienced, some high frequency gain peaking in the 0 to 100 kHz spectrum may be observed. This is an indicator of positive feedback.

   Attempt to repeat the preceding measurements for a source resistance of $R_S = 1$ $M\Omega$. If the circuit oscillates, reduce R_S to the largest value between 100 $k\Omega$ and 1 $M\Omega$ for which oscillations do not occur and perform the measurements.

   Repeat the previous step for the two remaining test op-amps.

   Repeat all measurements using the shielded boxes and batteries as the DC power supplies.

3.3 Laboratory Report

1. From the measured data, calculate e_{ni} for each value of R_S at the marker frequency. On separate graphs, plot e_{ni} versus R_S for each of the op-amps that were tested.

   2. From the data obtained with $R_S = 0$, calculate e_n at the marker frequency for each op-amp. From the data obtained with the highest value of R_S, calculate i_n at the marker frequency for each op-amp. In the latter calculation, the value obtained previously for e_n with $R_S = 0$ to obtain i_n. Assume that $R_i = \infty$ for all the op-amps in this calculation. Compare the experimental results for e_n and i_n with textbook and manufacturers' published data.

   3. Address the question as to whether or not the largest value of R_S was sufficient to place e_{ni} on the asymptote of the e_{ni} versus R_S curve. Explain and justify the answer with

numerical calculations.

    4. What would be an advantage and a disadvantage of operating the 40 dB gain stage in the inverting configuration rather than the non-inverting configuration?

    5. Derive a least squares curve fitting routine to obtain least squares estimated of e_n and i_n from the experimental data of e_{ni} versus R_S. Use the theoretical equation for e_{ni} as a function of R_S and e_n and i_n and determine the appropriate LSQ algorithm. See Appendix A following this experiment.

    6. Discuss any unusual and interesting results obtained.

Chapter 1   Appendix A—LSQ Curve Fitting

1.1   Introduction

The major goal of the third experiment is to obtain e_n and i_n for each of the op-amps tested at some particular frequency. For each op-amp K data points were taken of (R, E_o) where R is the input resistance and E_o is the output noise voltage measured at a frequency f where the measurement bandwidth is B.

The theoretical expression is given by

$$E_o^2 = G^2 B[i_n^2 R^2 + 4kTR + e_n^2] \tag{A3.1}$$

where G is the gain of the measurement circuit ($\cong 80\ dB = 10,000$ linear). As this equation states, e_n can be obtained if R is set to zero and i_n can be obtained if R is made sufficiently large. There are two practical problems with this approach: (1) R cannot be made exactly zero and (2) for large values of R many of the circuits will either oscillate or saturate which makes the data useless. (The resistor $R = R_s + R_1 \| R_2$ where R_s is the resistor connected to the noninverting input and R_1 and R_2 are the two resistors in the feedback network for the input op-amp.)

Values can be obtained for e_n and i_n by performing a least squares curve fit of the experimental data (R, E_o) to the theoretical equation (Eq. A3.1). This is done by selecting e_n and i_n so that the curve passes between the data points so that the squared error is minimized. The equation to be fit is a quadratic polynomial in R.

1.2   Least Squares Curve Fitting for Quadratic Equations

The mathematical problem is to fit K data points (x_i, y_i) to a quadratic equation

$$\hat{y} = ax^2 + bx + c \tag{A3.2}$$

This can be done by forming the squared error

$$\epsilon = \sum_{i=1}^{K} [\hat{y} - y_i]^2 \tag{A3.3}$$

and then setting

$$\frac{\partial \epsilon}{\partial a} = \frac{\partial \epsilon}{\partial b} = \frac{\partial \epsilon}{\partial c} = 0 \tag{A3.4}$$

and then solving the three equations that result for the least squared estimates for a, b, and c. Fortunately, the linear term is known in Eq. A3.1 so that least squared estimates are needed for only a and c.

The solution is then given by

$$\begin{bmatrix} a \\ c \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}^{-1} \begin{bmatrix} \beta_1 \\ \beta_2 \end{bmatrix} \tag{A3.5}$$

where

$$a_{11} = \sum_{i=1}^{K} x_i^4 \tag{A3.6}$$

$$a_{12} = a_{21} = \sum_{i=1}^{K} x_i^2 \tag{A3.7}$$

$$a_{22} = K \tag{A3.8}$$

$$\beta_1 = \sum_{i=1}^{K} [y_i x_i^2 - b x_i^3] \tag{A3.9}$$

$$b = 4kTBG^2 \tag{A3.10}$$

$$\beta_2 = \sum_{i=1}^{K} [y_i - b x_i] \tag{A3.11}$$

and, of course, x_i are the K values for R and y_i are the K values for E_o^2.

Once a and c are known, the least squares estimates for e_n and i_n are given by

$$\hat{i}_n = \sqrt{\frac{a}{B}} \frac{1}{G} Amps/\sqrt{Hz} \tag{A3.12}$$

$$\hat{e}_n = \sqrt{\frac{c}{B}} \frac{1}{G} Volts/\sqrt{Hz} \tag{A3.13}$$

The goodness of fit may be determined by plotting the data and then plotting Eq. A3.1 using the least squares estimates for e_n and i_n.