Investigation of the noise characteristics of a 741 operational amplifier

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Abstract

The article focuses on the identification and calculation of noise components inherent in operational amplifiers. The investigation focuses on the noise characteristics of a UA741CN.

Introduction

Noise is omnipresent. It is created by background electric activity and inherent in circuitry due to the quantum level fluctuations in the components themselves. Background interference can be greatly reduced by effective shielding and careful circuit design, but the inherent noise, although reducible by extreme cooling, is impossible to completely exclude. By formally identifying and gauging the noise characteristics of an amplifier, its boosted noise components can be predicted and appropriate adjustment can be made to the output to reflect the true signal.

Theory

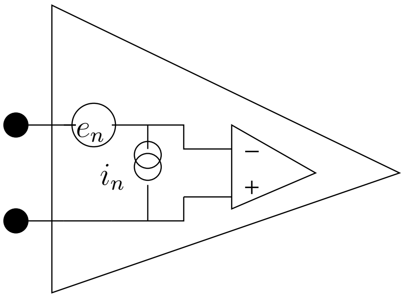

Figure 1: Operational amplifier model [1, p. 78]

Operational amplifiers can be modeled by assuming the existance of a perfect noiseless amplifier, which takes a noise voltage and noise current generator as inputs.

The noise current source acts across the resistance at the input, and therefore dominates the noise when this resistance is large. Similarly, when the resistance at the input is low, the noise voltage source dominates.

The total noise is described by:

$$e_A^2 = (e_n^2 + (R_s i_n)^2)^{\frac{1}{2}}$$

Adding these quantities in quadrature leads to the dominance of large terms, to the extent where if one noise source is three times larger then another, neglecting the smaller noise source results in an error of about 5% [1, P. 74].

In amplifying circuits, the noise added earliest is boosted and dominates the noise added later in the circuit. Thus it becomes possible to investigate the individual noise characteristics of an amplifier with the following circuit.

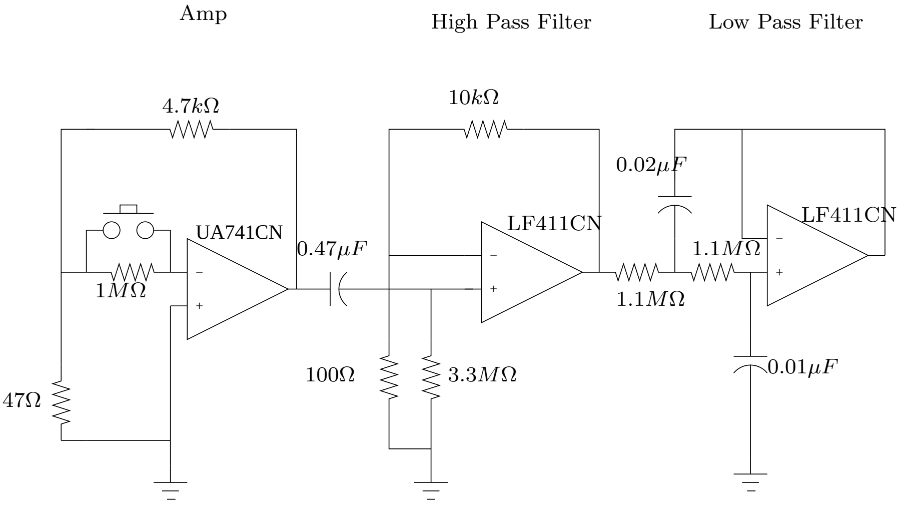

Figure 2: Band filtered amplifier under investigation

Circuit description

The circuit is comprised of three distinct units. The amp has a gain of a 100, leading on to a first order high pass filter with a further gain of 100, leading on to the second order low pass filter.

Since we are addressing white noise sources they need to be specified over a known bandwidth in order to be quantified.

When S is closed, the $1M\Omega$ resistor is short circuited and the 741 therefore has an input resistance of 47Ω, which leads to dominance by the voltage noise source. When S was opened, the $1M\Omega$ falls into series with the 47Ω, giving a resistance of approximates $1M\Omega$ at the input.

The high pass filter has a -3dB frequency of 0.1 Hz
The low pass filter has a -3dB frequency of 10 Hz
The frequency response of the output is described by :

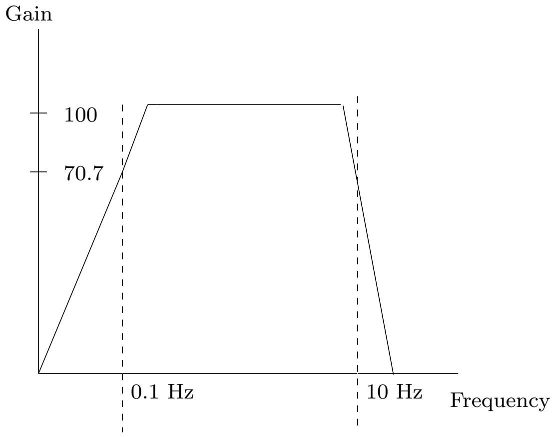

Figure 3: Band filtered amplifier

background

$$
\begin{aligned}
V_{rms} &= \sqrt{B} \times e_n \times Gain[1, p.11] && (1) \\
V_{rms} &= \sqrt{B} \times R_s i_n \times Gain[1, p.11] && (2) \\
BrickWallfrequency &= 1.22 \times f_{3dB}(\text{pair of buffered RCS}) && (3)
\end{aligned}
$$

where B is the bandwidth of the amplifier

Active filters have a "Brick Wall" cutoff frequency where they start to rapidly roll off. We have to calculate the brick wall frequency for passive filters using equation 3.

Rms values can be approximated by dividing the peak to peak values by a factor between 6 and 8. [1, p. 15] I will use 6 in my calculations

Procedure

The circuit described by figure 2 was constructed. The component values were rigidly maintained in order to retain the bandwidth stipulated in the original design of the high and low pass filters. The op amps were supplied with rail voltages of ± 12V. The output was observed with the aid of a digital oscilloscope. V_{p2p} values were obtained from traces aquired with the switch closed and then with it open.

Results

Measurements

	Observation	Oscilloscope
	S closed	
V_{p2p}	30 mV	40 mV
V_{rms}	5 mV	6.56 mV
	S open	
V_{p2p}	60 mV	60.8 mV
V_{rms}	10 mV	25.5 mV

Calculations

High Pass Filter
$f_B = 0.1$ Hz
Low Pass Filter
$f_B = 12.2$ Hz
Bandwidth = 12.1 Hz
$e_n = 143 \times 10^{-9} \frac{V_{rms}}{\sqrt{Hz}}$
$i_n = 2.87 \times 10^{-13} \frac{A_{rms}}{\sqrt{Hz}}$

Discussion

Discovering the rms value of the signal by dividing the peak to peak voltage by a factor between 6 and 8 strikes me as being a non-empirical step. We are intentionally identifying the outliers, and then using them in order to gauge an averaged value for the signal. Even for a rule of thumb, the variations I witnessed between peak to peak values in frozen frames of input noise made me very wary of this. Since the digital oscilloscope we were utilising was capable of doing graphical measurements of the signal it was displaying, it was far more reassuring to read a fairly stable rms value off the oscilloscope than to utilise the aforementioned rule of thumb.

Upon opening the switch the output signal bounced and then came to rest looking like the previous signal. After about 2 seconds the signal on display plunged out of sight, and gradually rose up to the 0 axis, swelling into a perfect sine wave as it rose. It then maintained a perfect sine wave until the power to the operational amplifiers was removed. The sine wave had a frequency of 50 Hz, which argued for the presence of mains interference. I attempted to discover the source of interference, relocating electrical wires previously in close proximity to my circuit and basically trying to isolate my circuit as much as conveniently possible. The magnitude of the external interference dropped considerably, though could not be completely removed and dominated my signal output with a value of about half a volt. I reviewed my circuit, even enlisting the aid of two colleagues, in an attempt to find the source of error, but found nothing. I would have expected signals at mains frequencies to have been heavily attenuated by the second order low pass filter, and can offer no explanation for the output. I managed to attain initial measurements by focusing on the noise apparent on the sine wave itself and by viewing the sine signal over a short enough period of time, to consider it flat. I then rebuilt the circuit from scratch in a final attempt to remedy the situation. This time the circuit produced a noise signal that was free of any obvious sinusoidal interference yet still offered results very similar to those obtained under the wayward circuit.

The signal strength did not drastically change when the switch was opened or closed. This a point of worry as one of the fundemental assumptions made in calculating the seperate components, was that either e_n or i_n could be made to dominate the other signal by changing the value of R_s. In calculating e_n, i_n was succesfully made very small by minimising R_s. In calculating i_n however, e_n cannot be diminished, i_n can only be boosted. Even with a 1 MΩ resistor my i_n did not achieve an order of magnitude higher response then e_n, which leads me to believe that i_n was remarkably small and also disqualifies my assumptions that I could cleanly seperate my noise sources into distinct components.

I downloaded the datasheet for the ST Microelectronics UA741CN (Appendix 1) since this is the exact model of operational amplifier I was using. Alas, this data sheet contained no graphs of circuit behavior and offered only one noise related point :

Equivalent Input Noise Voltage f = 1kHz, Rs = 100W : 23 $\frac{nV}{\sqrt{Hz}}$

This wasn't much use, so I downloaded the Philips Semiconductors UA741CN datasheet (Appendix 2)
In the DC range :
$e_n = 80 \times 10^{-9} \frac{V}{\sqrt{Hz}}$
$i_n = 8 \times 10^{-12} \frac{A}{\sqrt{Hz}}$

The value of e_n is of a similar order of magnitude to my measured figures, however there is a fairly large discrepancy between my measured noise current and that described by the datasheet. There may have been something intrinsically faulty with my circuit construction, and a rough way of testing this would be by greatly increasing the input resistance, thereby attempting to see whether the output signal can be significantly increased.

Conclusion

Using fairly simple approximations and rudimentary experimentation, it is possible to get a fairly accurate indication of the noise characteristics of a specific operational amplifier.

References

[1] R. Grant. *Electronics Design : Noise.* Rhodes University Physics Department, 2005.