Instrumentation Amplifier

Chris Curro

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As per the project specification, I designed and implemented an instrumentation amplifier with a gain of at least 100 over a minimal frequency range of 5 Hz to 1 kHz.

Design

As can be seen in Figure 1, I designed the two-stage amplifier with three LF356 operational amplifiers. I selected this amplifier because of its wide-band open-loop gain [1] to ensure that I met the bandwidth specification. I decided to design the amplifier with a gain of about 200 so that even if there were some unexpected issues, I would still be likely to meet the specification of 100. As per Equation 1, I selected an R_2 value of 100 kΩ and an R_1 value of 1 kΩ to result in a gain of about 200.

$$K = 1 + 2\frac{R_2}{R_1} \tag{1}$$

For the sake of simplicity, the remaining resistors, including the load, were chosen to be 1 kΩ. As a final design consideration, the supply voltages were selected to be 12 V so that I would have the greatest tolerance to amplifier saturation with respect to the differential input voltage.

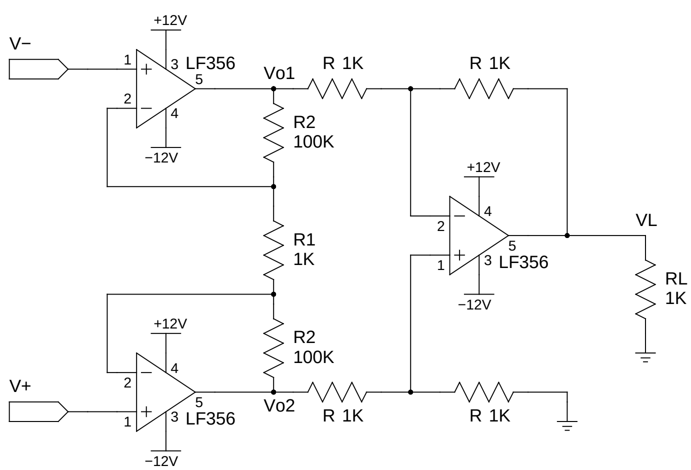

Figure 1: Test schematic for the instrumentation amplifier. A 1 KΩ load is included at the output of the final operational amplifier.

Derivation of Equation 1

As practical considerations for the derivation, I will take the ideal operational amplifier assumption as true, most specifically that the amplifiers have infinite input impedance and that the two differential inputs are at the same potential [2].

First I will consider the gain at the node V_{O1}. By the principle of superposition I will first assume that V_+ is 0 V, and then I will assume that V_- is 0 V, and then sum each result to reach the final solution.

Case 1 If V_+ is at 0 V, then the inverting input to the same amplifier will also be at 0 V, therefore the bottom half of the circuit effectively disappears. In this case the top amplifier will act as a non-inverting amplifier with a gain of:

$$1+\frac{R_2}{R_1} \tag{2}$$

Case 2 If V_- is at 0 V, then the inverting input to the same amplifier will be also be 0 V, while the inverting input to the bottom amplifier will be at V_+. In this case the the top amplifier will act as an inverting amplifier with a gain of:

$$-\frac{R_2}{R_1} \tag{3}$$

Combining the two gains by superposition I get:

$$V_{O1} = V_-\left(1+\frac{R_2}{R_1}\right) - V_+\frac{R_2}{R_1} \tag{4}$$

Similarly, it can be shown that

$$V_{O2} = V_+\left(1+\frac{R_2}{R_1}\right) - V_-\frac{R_2}{R_1} \tag{5}$$

These two voltages, V_{O1} and V_{O2} serve as the two inputs for the final operational amplifier, which acts as a differential amplifier with unity gain. Therefore the output voltage of the differential amplifier is:

$$V_L = V_{O2} - V_{O1} \tag{6}$$

Which, with some algebra, becomes:

$$V_L = (V_+ - V_-)\left(1+2\frac{R_2}{R_1}\right) \tag{7}$$

Test Procedure and Results

Frequency Response To measure the frequency response of the instrumentation amplifier, I set V_- to be one of the output terminals of an Agilent 33210A function generator. The other function generator terminal was tied to the circuit ground. V_+ was also tied to the circuit ground. I set the output voltage of the function generator to be 10 mV. I then set the output waveform to be a sine wave at 5 Hz, and then increased the frequency according to the scheme set in the specification. All of the following measurements were made with an Agilient MSO-X 2012A oscilloscope. At each frequency I measured the peak-to-peak output voltage of the function generator, and the peak-to-peak output voltage of the instrumentation amplifier. I divided these quantities to calculate the gain at each frequency. These results are summarized in Figure 2.

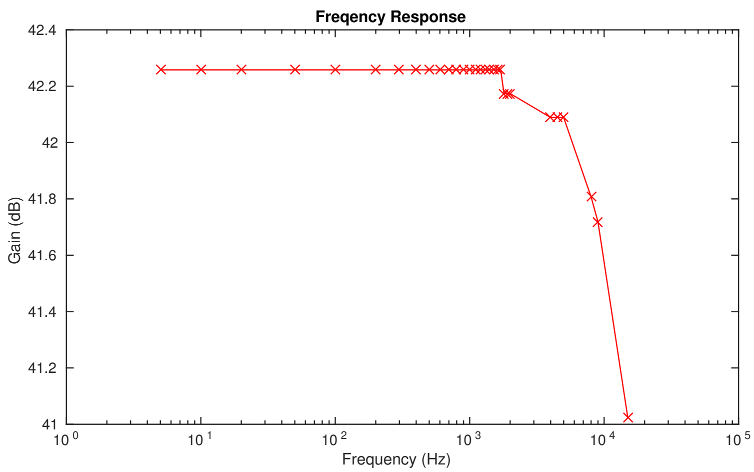

Figure 2: Frequency response of the instrumentation amplifier

Power Consumption In order to measure the power consumption for a 100 Hz input signal, I took note of the voltage and current readouts on the power supply unit. From these (I'm sure ridiculously inaccurate) measurements, I estimate the power consumption to be 48 mW.

Common Mode Rejection Ratio In order to measure the CMRR I connected one terminal of the function generator to both inputs of the instrumentation amplifier; the other function generator terminal was connected to ground. I set the output of the function generator to be 1 V, so that even if the CMRR were very high I could still expect to (maybe) see something at the output of the instrumentation amplifier. Despite this, I discovered that the the CMRR is too high to be measured with my current experimental setup. Looking back this is to be expected because the CMRR of a single LF356 is 100 dB.

References

[1] National Semiconductor, "LF155/LF156/LF256/LF257/LF355/LF356/LF357 JFET Input Operational Amplifiers," December 2001.

[2] P. Horowitz and W. Hill, *The Art of Electronics*, 2nd ed. Cambridge University Press, 1989.