EE 320L Final Project

High-Speed Instrumentation Amplifier in an Active Probe Application

By

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Introduction:

We are all familiar with the passive probes that are used with oscilloscopes. These probes are passive because they simply consist of an attenuator, a length of coaxial cable, and the probe tips. There is no active circuitry involved. Through careful design, passive probes can be created to operate at frequencies up to 1 GHz. To go beyond this frequency, or to look at very low level, sensitive signals an active probe is required. An active probe is called such because there is an amplifier at the head of the probe which amplifies the signal before sending it through a coaxial cable to the oscilloscope. Active probes are very expensive and can cost thousands to tens of thousands of dollars. In this project we will investigate whether we can approach the performance of active probes at a fraction of the cost using modern high-speed op-amps.

Topology:

We will be our active probe in the instrumentation amplifier topology. The instrumentation amplifier is commonly used in applications requiring high gain and high precision. The topology is fully differential which allows it to interface with a wide variety of transducers and sensors. Datasheets for instrumentation amplifiers show that they generally have high DC precision but poor bandwidth [1] [2] [3]. This is because most transducers interfaced to them don't have high bandwidths either so other parameters are optimized. Using modern op-amps there is no reason that the instrumentation amplifier topology can't be used in a high speed design. The basic instrumentation amplifier is shown below in Fig. 1.

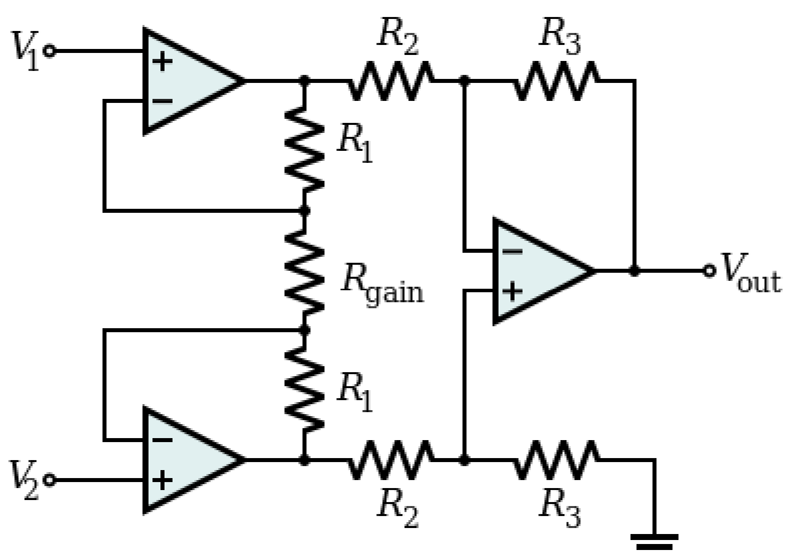

Figure 1 Instrumentation Amplifier (From Wikimedia Commons)

The first two op-amps in this circuit are used for input buffering. The gain of each op-amp is the same as the non-inverting amplifier. Since this is a differential amplifier, the input is in terms of the difference between the voltages V1 and V2. The third op-amp is configured as a difference amplifier. This amplifier is used to convert a differential signal to a single-ended signal. The input impedances are inherently unbalanced which is why the first two op-amps are needed to present equal input impedances to the signal source. The total differential gain of the circuit is given by

$$\frac{V_{out}}{V_1 - V_2} = \left(1 + \frac{2 * R_1}{R_{gain}}\right) * (\frac{R_3}{R_2})$$

Note that if the gain resistor is removed then the two op-amps operate as unity gain buffers and the total gain is simple R3/R2. Resistor pairs R1, R2 and R3 need to be well matched. Any mismatch degrades the common-mode rejection ratio (CMRR). The resistor pairs R2 and R3 need to be especially well matched. This matching is taken care of by using an LT5400 matched resistor set [4]. For this project either the quad 10k or 1k set is best. The resistor tolerance of 0.025%-0.01% is possible due to the fact that the resistors are all fabricated on the same die.

An example circuit design is shown in Fig. 2. The corresponding populated PCB is shown in Fig. 3. The names of all the parts in the schematic and the PCB match for easy reference. To make the circuit easy to follow we will example one section of the circuit at a time and explain what is involved in the design of that section and relevant trade-offs. There are five main sections in this circuit, the input buffers, the difference amplifier, the attenuator, the output buffer, and the output matching circuit.

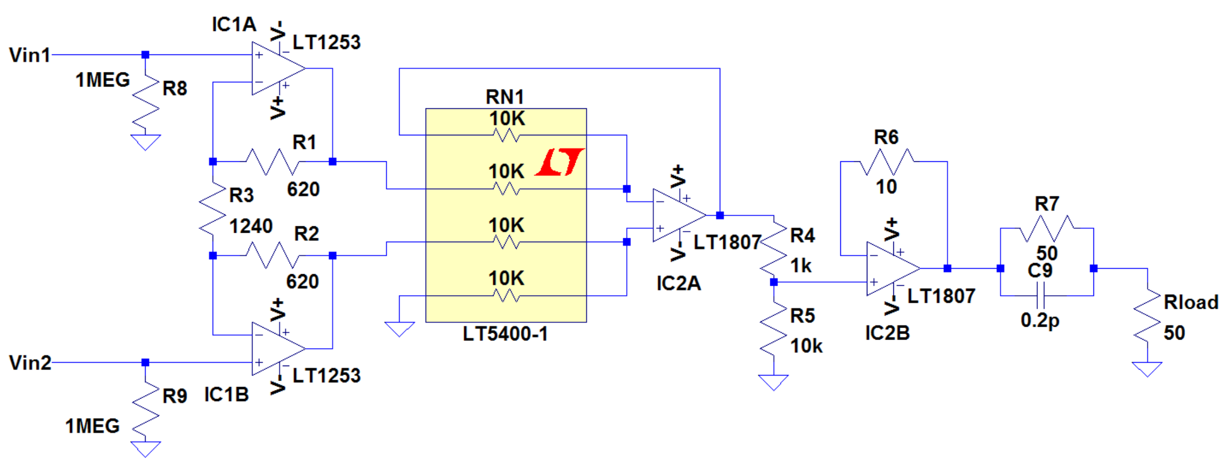

Figure 2 Practical Implementation of Instrumentation Amplifier

The main sections in the circuit are highlighted in the schematic below in Fig. 3. The section in blue is the input buffer section. The two 1 MEG resistors, R8 and R9, are used to provide a ground reference to the input. This is important so that the input nodes don't float. Otherwise, with no input, the output will move about wildly. R1 and R2 are the feedback resistors for each op-amp. The gain is controlled by R3 which is shared between the two op-amps. This topology is basically taking two op-amps in a non-inverting configuration and combining them.

The difference amplifier is highlighted in orange. This circuit amplifies the difference between the op-amps inputs. The most important factor in the performance of this circuit is the matching between the resistors. For this reason, four monolithic (made on the same integrated circuit) resistors are used. The matching is within 0.01%. This results in a common-mode rejection ratio (CMRR) approaching the theoretical values. CMRR is a measure of how well the circuit rejects signals that are identical at both inputs. This translates into how well the circuit rejects noise caused by sources such as AC hum or radio frequency interference. The calculation and discussion of CMRR is outside the scope of this project but the interested reader is referred to [5]. One big problem with the difference amplifier is that the input impedance presented is different for each input. The input impedance of the positive input is twice that of the negative input. To reduce the impact of this, the buffer stage preceding it has very low output impedance.

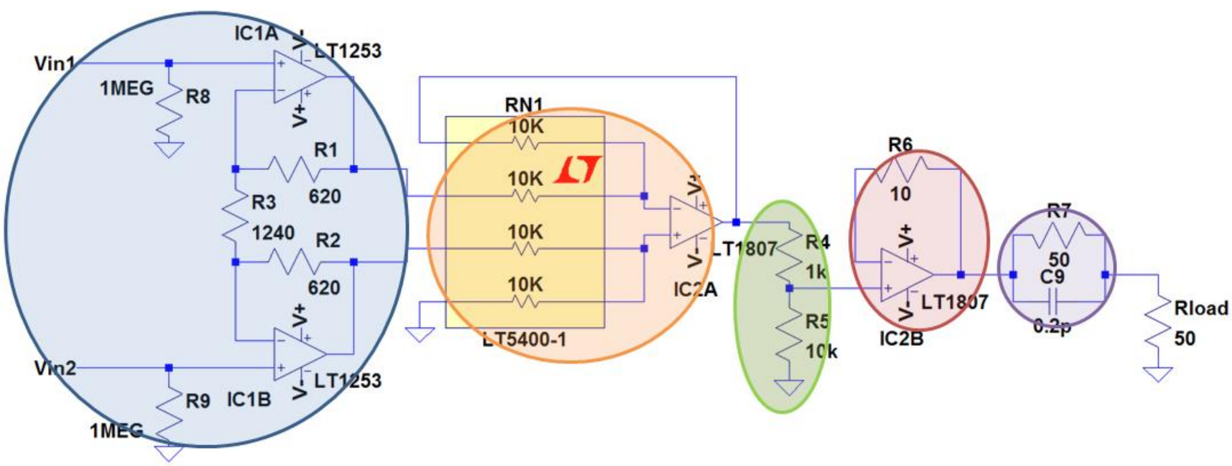

Figure 3 Breakdown of Instrumentation Amplifier

The next stage is very simple as it is just the familiar voltage divider. Why would we attenuate the input signal at this stage? The reason for this attenuator is that most op-amps do not exhibit their small-signal bandwidth at large output swings. If we desire the maximum possible bandwidth from the op-amps then the signal swing needs to be reduced. Unfortunately this has the effect of increasing noise and limiting the types of signals that can be viewed with the probe. If the highest possible bandwidth is desired then the buffer stage will need to be designed with a gain of 1 and the attenuator will likely need to be set to divide the signal by 10 or more. However, a probe that amplifies weak signals is often more useful for many applications. In order to do this, R4 should be either shorted or be a very small value, while R5 should be a sufficiently high value so as not to cause any voltage division.

The next stage is a unity gain voltage follower, highlighted in Fig. 3 in red. Generally this circuit is seen with the inverting input directly shorted to the output. However, high speed op-amps can oscillate in this condition and placing a small value resistor between the inverting input and the output can prevent this. For some high-speed op-amps, the datasheet suggests an optimal value for this resistor.

The final stage is the output matching network. This is comprised of a resistor and capacitor in parallel. The capacitor is optional but will serve an important purpose. The resistor however is not optional. Any op-amp that is to be connected to transmission line needs to be series terminated in the characteristic impedance of that line, in most cases, 50 ohms. The discussion of transmission line theory is outside the scope of this document but the interested reader is referred to [6] and [7].

Current Feedback Vs. Voltage Feedback Amplifiers

Many of the high-speed op-amps on the market are current feedback type. These operate differently than voltage feedback op-amp and can't be used in many of the same configurations. In a traditional voltage feedback op-amp, both inputs are symmetrical and present the same input impedance. A current feedback op-amp has a high impedance noninverting input and a very low impedance inverting input. For this reason, any of the op-amp topologies that use the noninverting input as the signal input can be not be used with current feedback op-amps. Furthermore, any topology that relies on the symmetry of the inputs can't be used either. For this project, current feedback op-amps can be used in the buffer stage, but they can't be used in the difference amplifier stage at all. Using them in the difference amplifier stage will eliminate the advantages gained by the matched resistors or simply not work at all. For more information on current feedback op-amps refer to [8] and [9].

Output Matching Network

The purpose of the output matching network is to provide proper impedance matching to coaxial cables and 50 ohm test equipment. The series resistor at the output of the unity gain buffer accomplishes this, and results in a 50 ohm output impedance. However, most op-amps actually don't have constant impedance throughout their bandwidth. This is seen below in Fig. 4 in a plot of output impedance vs. frequency for a THS3202 op-amp. The rising impedance with frequency indicates that this is due to inductance from the chip's package.

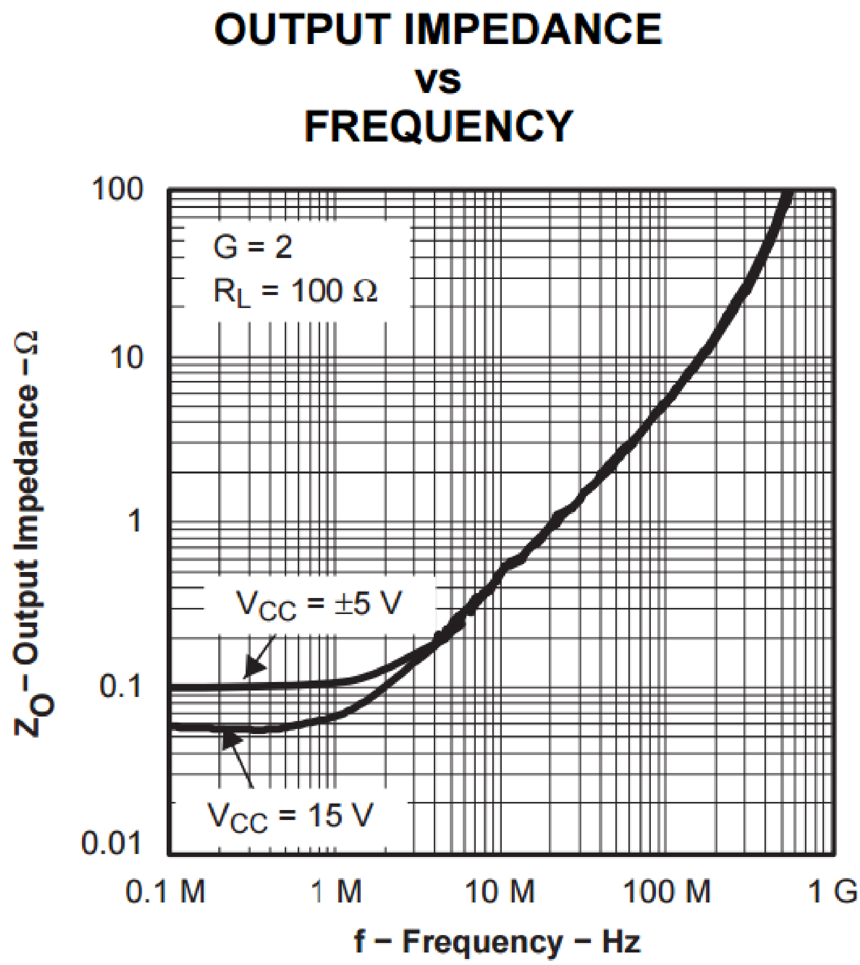

Figure 4 Output Impedance Vs. Frequency for THS3202 op-amp.

To further explore this, let's use a simple model of the output pin of the op-amp. In Fig. 5 below there is a voltage source, an inductor, and two 50 ohm resistors. The voltage source with an internal 0.1 ohm resistance represents the op-amp chip itself. This value was taken from the graph in Fig. 4. The portion of the curve where the impedance is flat is resistive. The value of 40 nH for the inductor was determined by looking at the 200 MHz point in the curve where the impedance rise is significant at roughly 10 ohms. This combined with the 50 ohm series termination resistor results in a voltage divider with the load resistor. For the combined output impedance of 60 ohms and the 50 ohm load resistor, this results in a voltage divider that attenuates the signal by 7 dB. The 40 nH inductor was selected somewhat empirically and different frequencies were tested to ensure that the value was accurate. Otherwise, a hand calculation could be done to find what combined impedance of L1 and Rout results in 7 dB loss. The frequency response is shown in Fig. 6 and it is apparent that there is 7dB loss at 200 MHz and 9 dB loss (corresponding to the bandwidth in this case) at 400 MHz.

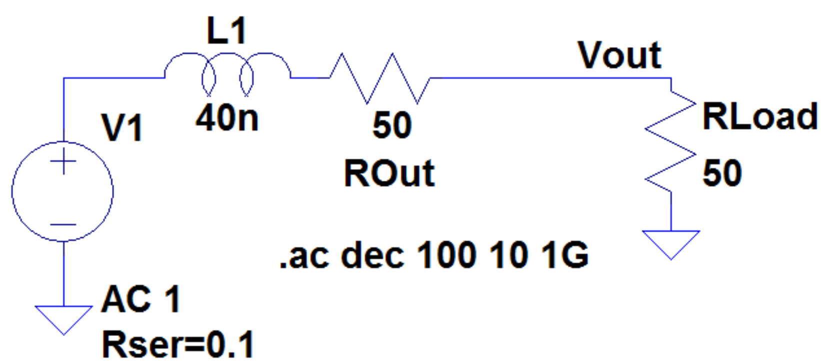

Figure 5 Output pin, series termination resistor, and load resistor.

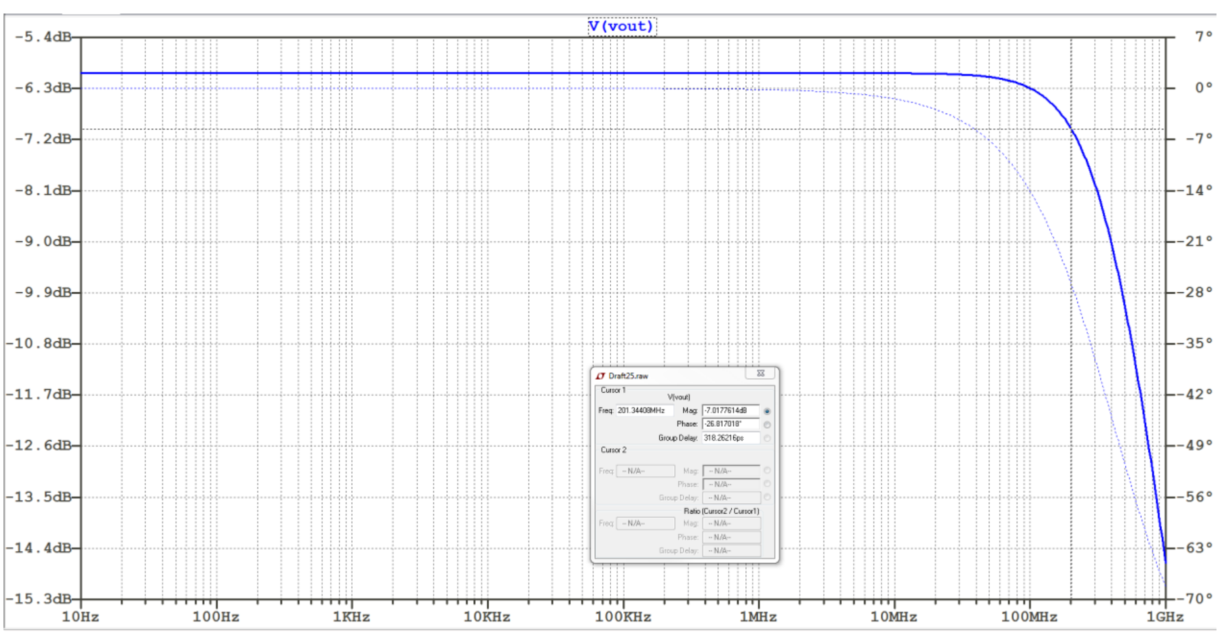

Figure 6 Frequency Response

Adding a capacitor in parallel with Rout helps to cancel out the effect of the inductance and extends the bandwidth. The schematic of this is shown below in Fig. 7. The 5pF capacitor reduces the loss at 200 MHz to 0.2 dB and the bandwidth is extended to 570 MHz. This is a very important result showing that adding a simple capacitor can extend the bandwidth significantly as shown in Fig. 8. This technique will allow the bandwidth potential of these high speed op-amps to be realized.

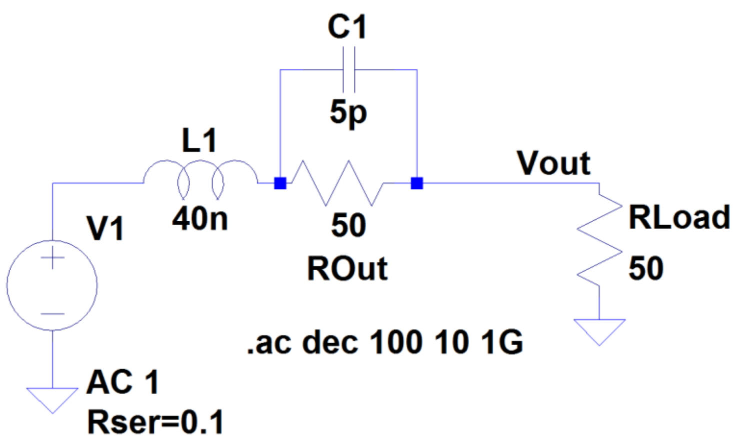

Figure 7 Adding a Capacitor in Parallel

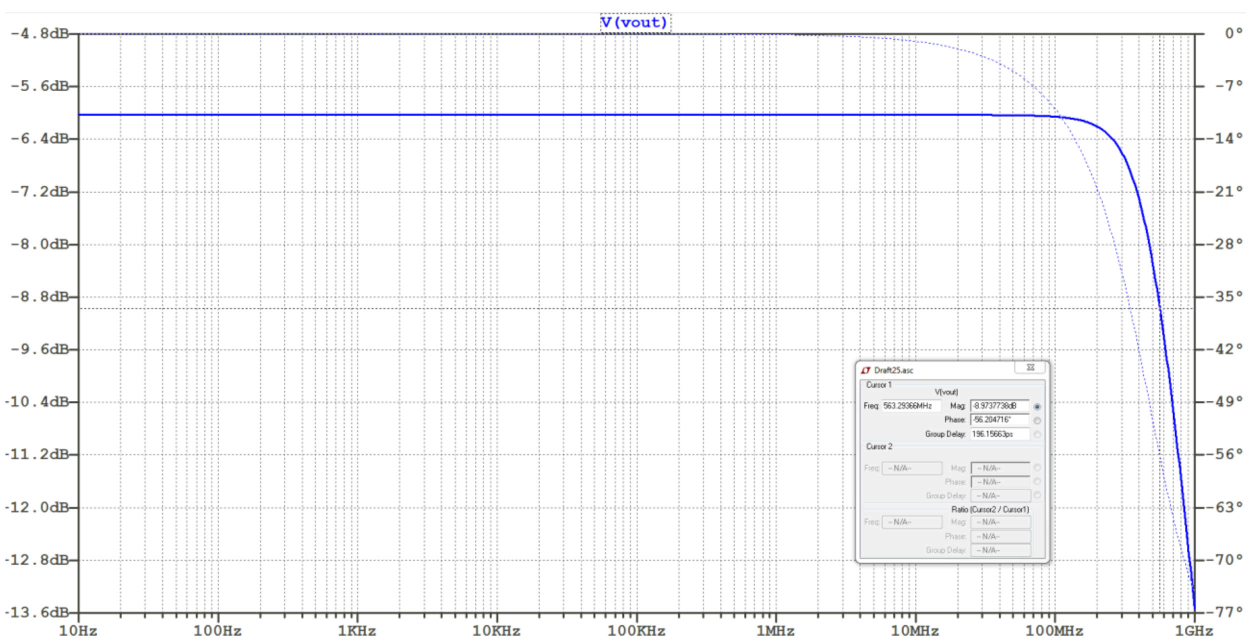

Figure 8 Frequency Response is Extended

References:

[1] http://www.analog.com/en/products/amplifiers/instrumentation-amplifiers/ad8221.html

[2] http://www.linear.com/product/LT1167

[3] http://www.ti.com/product/ina128

[4] http://www.linear.com/product/LT5400

[5] http://www.analog.com/en/education/education-library/dh-designers-guide-to-instrumentation-amps.html

[6] http://www.analog.com/media/en/training-seminars/design-handbooks/36888492358237Section2.pdf

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