POLYTECH
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Course

«Introduction to Biomedical Engineering»

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Section 1: Basic electronics
Lecture 1.2: Amplifiers

Amplifiers

As the name suggest we are going to be talking about the signal amplification in this lecture.

First of all, why do we need to amplify the signals? Well, first reason is simple: because any signal that you can physically collect from a human body is small. Especially, electrical signals.

On the map of the signal scale VS the frequency content, the smallest would probably be EOG or Electrooculography, which measures eye movement using set of 3 electrodes located on the head. These have range of 10-5 Volts and frequencies of around 1 Hz (you cannot move your eyes faster than 10 cycles a second, can you?).

Figure 1 - Eye movements saccades

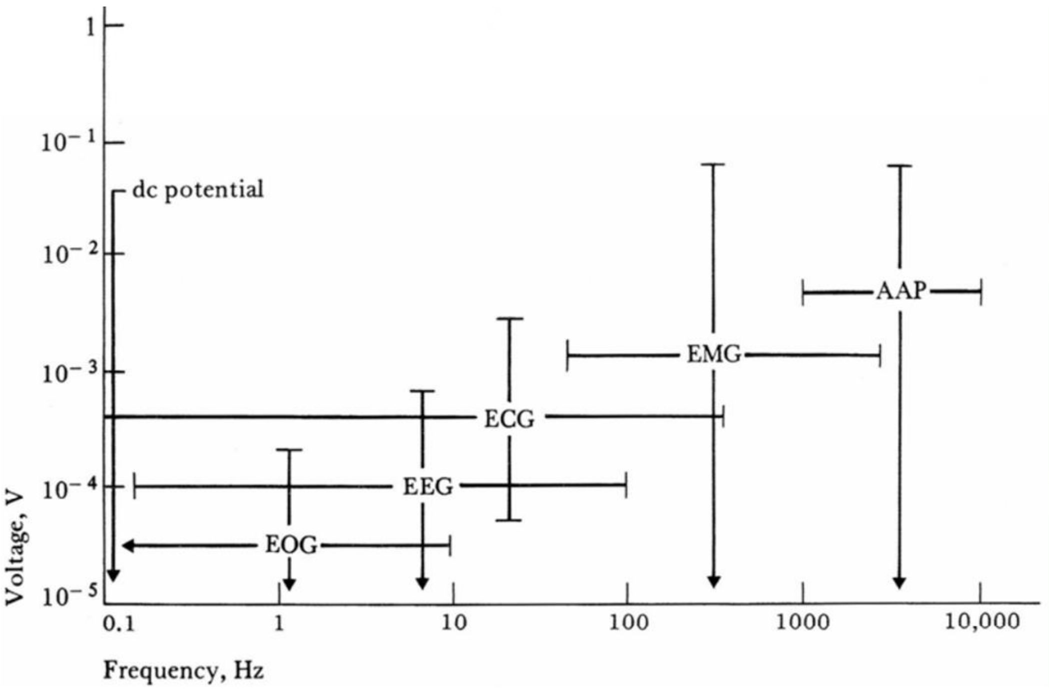


Figure 2 – Voltage over Frequency diagram of electrical signals

Then we have EEG - electroencephalography, which measures electrical potentials from the surface of the head, generated by the neuronal electrical activity within the bran. Typically, it is 10s or 100s of microvolts, and resembles averaged neuronal electrical activity of the cortical regions.

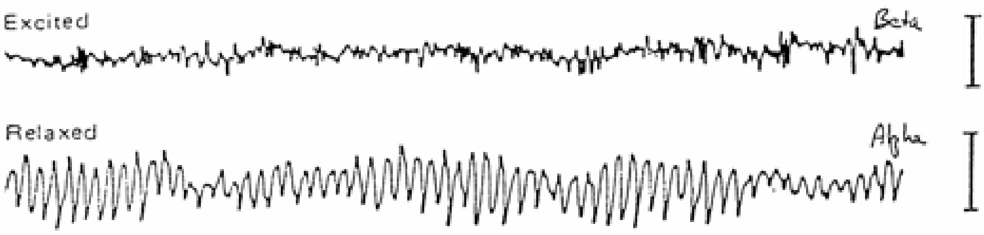


Figure 3 - Electrical activity of the brain

ECG or electrocardiography, measures electrical potentials from the surface of your torso generated by the muscles of your heart when they are contracting. These are typically around a mV, and are a vital component in clinical and hospital care. And yes, now you can even have a business cards measuring ECG using the potentials between your fingers.

Figure 4 - Buisiness card - heart monitor

Figure 5 - Electrical activity of the heart

EMG, or electromyography, measures potentials generated by electrical activity of skeletal muscles. They are similar to ECG, but a bit higher since you can measure them from the surface directly above the muscle of interest. These are 10s of mV, and form a basis for many active bionic prosthetics.

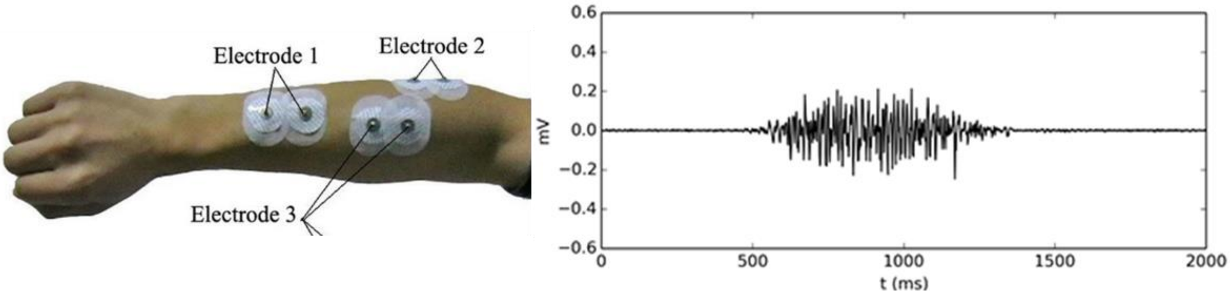


Figure 6 - Electrical activity of skeletal muscles

Right, so we have a signal that is at most mV, which we need to send to the microcontroller and make it digital (digital is better than dealing with analog electronics, remember, at least you can store digital in the computer or something). Normally, we would have limited bit resolution, and supply voltage on a scale of 5V, meaning that our entire signal does not cover even a single bit! We will not see anything basically. So yes, we need to fit the signal to ADC window. But that is not all, we also can improve the 'condition of the signal'. As we all have learned by now, pure components do not exist: wire is a resistor, it has also inductance, and capacitive coupling! These produce all sort of effects especially if located very close to each other on a PCB. Look at all the mess we need to deal with when consider everything properly. That is practically impossible! We cannot ignore that as it is, especially considering the fact that our signals are weak, and amplification is a great way to 'condition' our signals, so they 'learn' to ignore the parasitics.

So we start with the cornerstone of any amplification circuit - the Operational Amplifier. It has 3 signal pins: V+, V-, and V out, and 2 pins for power supply (Vs+ and Vs-). Ideal OpAmp does very simple task: it amplifies the difference between V- and V+ with constant amplification coefficient. Obviously, ideal OpAmp would do this things instantly, produce infinite voltage, and have zero effect on input signals. Right, this is a schematics for a common one, it probably has some limitations, which are many.

For us however, each individual parameter does not matter, and we can summarize OpAmp properties using only 6: Open Loop gain, Input Impedance, Output Impedance, offset, CMRR, and bandwidth.

Open loop gain (the stuff that you need to multiply you input to get the output), ideally we want it to be infinite. We will see why it is important later, but typical OpAmps have it from 2 to 200 k.

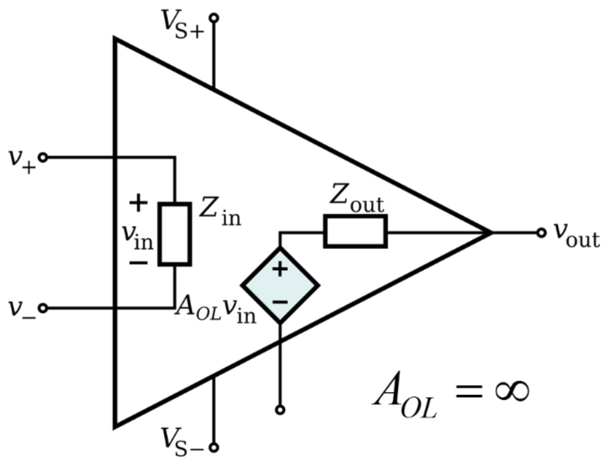


Figure 7 - Infinite Open Loop Gain

Input impedance: The stuff which resist the current flow between - and+, we do not want this otherwise the voltage divider forms (serial to source), essentially we are measuring the voltage across input impedance of the OpAmp, and if it is small, as shown on the diagram, we lose large portion of the total voltage supplied.

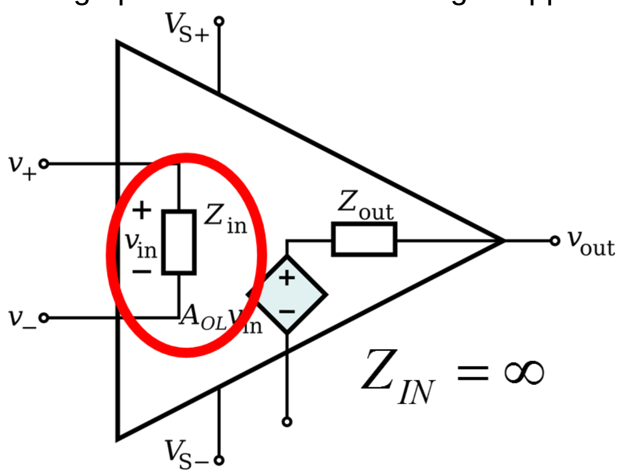


Figure 8 - Infinite Input Impedance

Output impedance: This stuff we want to be zero, otherwise our output current is limited by external components, besides, there is another voltage divider forms and we are losing another portion of our signal.

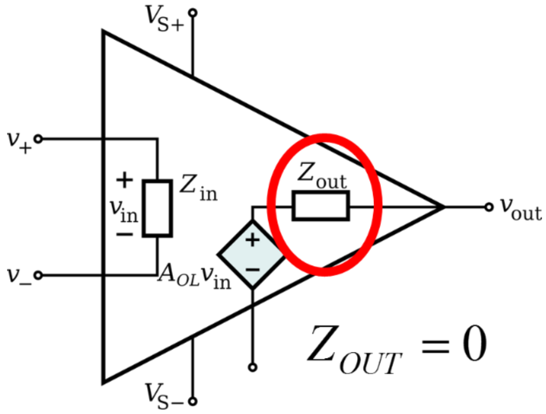


Figure 9 - Zero Output Impedance

Offset is the stuff which shifts our signal, we would expect 0 if V- equals V+, in reality however, very small voltage always persists, and if we want it pure, some specialized circuitry is needed for compensation.

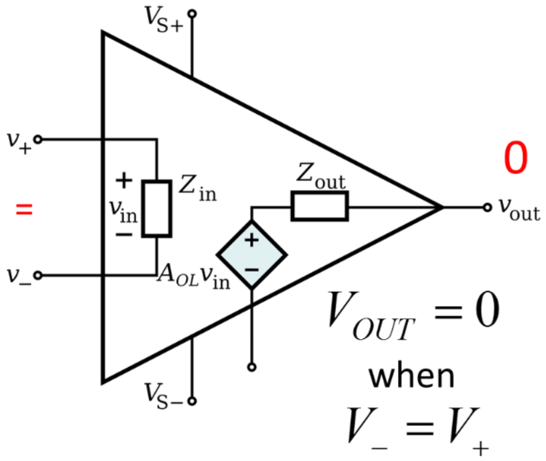


Figure 10 - No offset

CMRR, or common mode rejection ratio, is another vital parameter, This tells us what happens if we have two large but equal (common) signals coming to V+ and V-. Obviously we will expect 0, which makes CMRR to be infinite. In reality it is 80-100dB, which means some fraction of common mode signal comes through to the output (especially important if it is 50 Hz mains!)

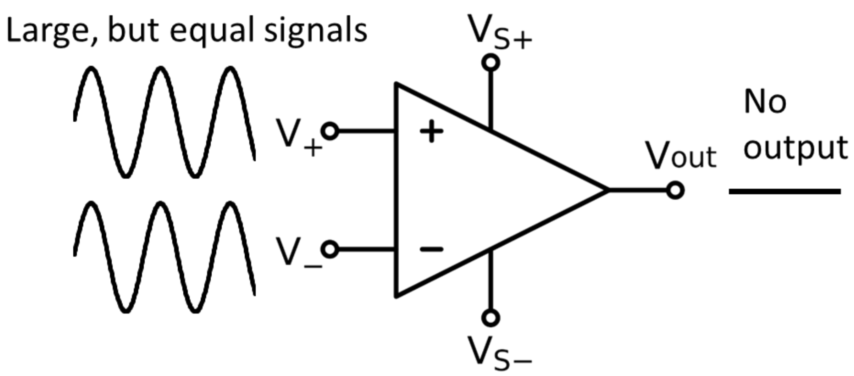


Figure 11 - Infinite CMRR

The real OpAmp can also saturate, this is normally happens when the output voltage need to exceed the supply voltage, so the OpAmp cannot possibly produce this, and outputs all it can do. This not only distorts the signal, but also causes OpAmp to recover which can take more time than expected.

The last but not the least. We would like our amplifier to amplify every frequency equally, and do not distort our signal. In reality, starting at some point, the gain of the OpAmp will decrease with frequency. This often causes signal distortions and delays.

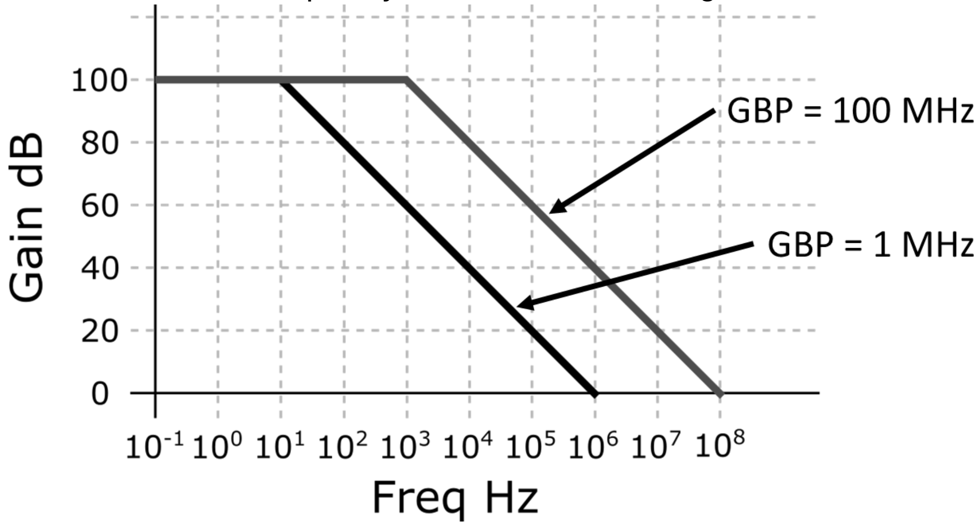


Figure 12 - Gain bandwidth product - GBP

We normally can characterize the open loop gain across frequency as 2 lines in log scale. First line show roughly constant gain up to a certain point (called breakpoint, or -3dB point), after which the gain typically decrease with the rate of -20dB/Decade. When you read the specification for a particular OpAmp, it will have Aol in its datasheet, and also Gain Bandwidth Product, or GBP, which describes the decrease in gain as bandwidth increases. You can build up the frequency characteristics of the OpAmp knowing both.

GBP also shows at which frequency the OpAmp becomes "unity gain", or stops amplifying at all.

GBP is very common characteristic of the OpAmp, and plays key role in constructing actual OpAmp based amplifying circuits, and defines maximum gain of a closed-loop amplifiers as we will see next.

Right, as you probably guessed, nobody uses OpAmp 'as it is' in an amplification circuit. The most common circuits involve feedback. On your screen there is a typical schematics of such circuit. Let's analyze this quickly using the control theory. For those of you who do not know this stuff, do not worry, next section is all about it, for now, just relax and believe me, you can always come back and check my working outs later. So the Voltage-out to voltage-in ratio according to this is Aol over 1+beta Aol, and in ideal case scenario Aol is infinite, so it is just 1/beta, where beta is a constant dependent on the periphery resistors. Well, this is cool, as we have an amplifier, which gain depends ONLY on the external resistors, and to change this we do not have to change the actual IC, YAY, imagine the level of flexibility! This is why OpAmp is so commonly used.

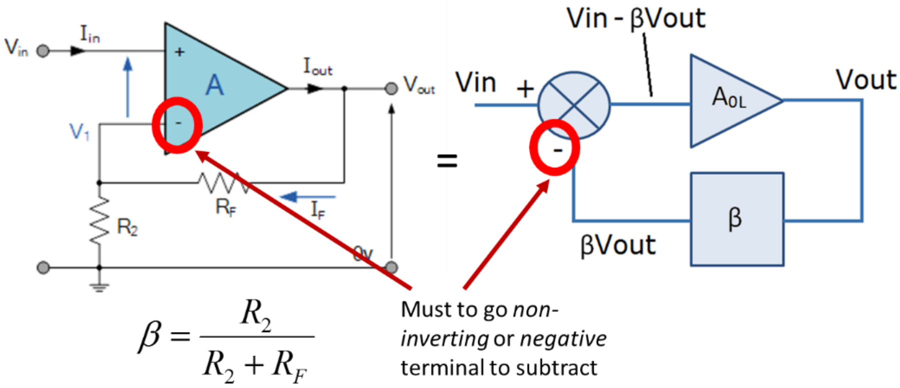
The OpAmp circuits with negative feedback (meaning the output is connected somehow to a negative input of the OpAmp) is very easy to analyze. You do not have to know control theory, and you only need 2 rules: Rule number 1: The OpAmp will do whatever it takes to make V+ to be equal to V-. Rule number 2: inputs draw no current. If you know these 2 rules and Kirchhoff's laws (sum of currents in the node is 0, sum of voltages across closed pass is 0), you can literally crack any OpAmp based circuit like that.

Let’s practice in this one. So V1 = V2, and since V1 is connected to the ground, it is 0. Now, according to rule 2, current through Rin should be equal to a current through Rf. Expressing voltage drops across both, we can relate Vin and Vout as the following: Tada, we have an amplifier with the Amplification factor of - Rf over Rin, note that the voltage is inverted, so we call this an inverting amplifier.

Let’s come back to the non-inverting amplifier. Writing down 2 rules we can instantly get the Vout to Vin relationship and compute the amplification gain.

Right, What if Rf is zero, and/or R2 is infinite. The gain becomes one. Or, we can draw it like this, hence commencing both assumptions. You would probably ask: what? Unity gain? Who needs unity gain? What are you achieving with this? Well, remember the 'conditioning' of the signals that we were talking about? This plays significant role in such conditioning. We can basically break the signal to 'before' and 'after' and consider them separate. So every time we change something on the left hand side, it does not affect the right, and vice versa. Also, we can draw much more current into the system and hence pumping the energy into the circuit preserving our signal at the same time.

Finally, using negative feedback loops and OpAmp, we can also see how the frequency response reacts to the closed-loop gain given fixed GBP. Basically, for higher gains, our bandwidth is small, open loop gain being the maximal we can achieve. Reducing the gain literally gains us the advantage in bandwidth. And in every case the product of two equals GBP. Actual Characteristic of closed-loop performance are typically listed in the datasheet of a particular OpAmp. The rest is literally yours to decide.



$$\beta = \frac{R_2}{R_2 + R_F}$$

$$V_{OUT} = A_{OL}\left(V_{in} - \beta V_{OUT}\right)$$

$$\frac{V_{OUT}}{V_{in}} = \frac{A_{OL}}{\left(1 + \beta A_{OL}\right)} = A_{CL}$$

Ideally $A_{OL} = \infty$

$$A_{CL} = \frac{V_{OUT}}{V_{in}} = \frac{1}{\beta}$$

Figure 13 - Negative Feedback

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