Operational Amplifiers

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Operational Amplifiers

Robert J. Scoff, PE

1. Introduction

Operational Amplifiers have been a part of the electrical and electronics world for a long time. They are defined as high gain (ideally infinite), high input impedance (again, ideally infinite), DC coupled, amplifiers with a differential input and a single ended output. Before we get into the design, construction, and operation of operational amplifiers, let's have a review of how gain is determined for operational amplifiers. We need to have a little review of how gain is looked at from both the voltage and power gains and decibel gain. The Bel, a unit of power measurement is named after Alexander Graham Bell, the inventor of the telephone. Its definition is:

Bel = $\log_{10}$ (Power Gain), where Power Gain = $P_G = P_{out} / P_{in}$

In the electronics world, we use the term decibel (dB) which is a tenth of a Bel. Also, by definition, a dB is:

dB = 10 * $\log_{10}$ (Power Gain)

The only way that I have ever made sense of this is shown below:

1 Bel = $\log_{10} P_G$ by definition.

Therefore 0.1 Bel = 1 decibel (dB) = 10 $\log_{10} P_G$

This has always been mathematically confusing to me.

Here's a way to look at it by a specific example:

If we let Power Gain (P_G) =100

Bel = $\log_{10} P_G = \log_{10} 100$ = 2 Bel

Then: dB = 10 $\log_{10}$ 100 = 10 *2 = 20 dB

And 20 dB = 2 Bel, and 20 dB is indeed 2 Bel

So, there are 10 times the number of decibels as there are Bels for any given power gain.

For most of the examples in this paper we are going to use Voltage and Power Gains and decibels. One more equation that is necessary is:

dB = 20 $\log_{10}$ (V_G) where V_G is Voltage Gain and $V_G = V_{out} / V_{in}$.

This is much easier to see because Power is the square of voltage. Therefore:

$$dB = 10 \log_{10} (\{V_{out}^2 / R_{out}\} / \{V_{in}^2 / R_{in}\})$$

If we assume that $R_{out} = R_{in}$ (This is not always a good assumption, but for simplicity we are doing it), the R's cancel and we get:

$$dB = 10 \log_{10} (V_{out}^2 / V_{in}^2) = 10 \log_{10} (V_{out} / V_{in})^2 = 20 \log_{10} V_G$$

With this little review of Voltage, Power, and Decibel gains, let's look at some of the history of operational amplifiers.

2. A Brief History of Operational Amplifiers

Before the advent of the vacuum tube amplifier, it was not possible to make an electronic amplifier, and thus operational amplifiers. In 1906, Lee De Forest added a third element to the Fleming Vacuum Tube Diode which was patented in 1904. Figure 2.1 shows how amplification was possible with the addition of the third lead.

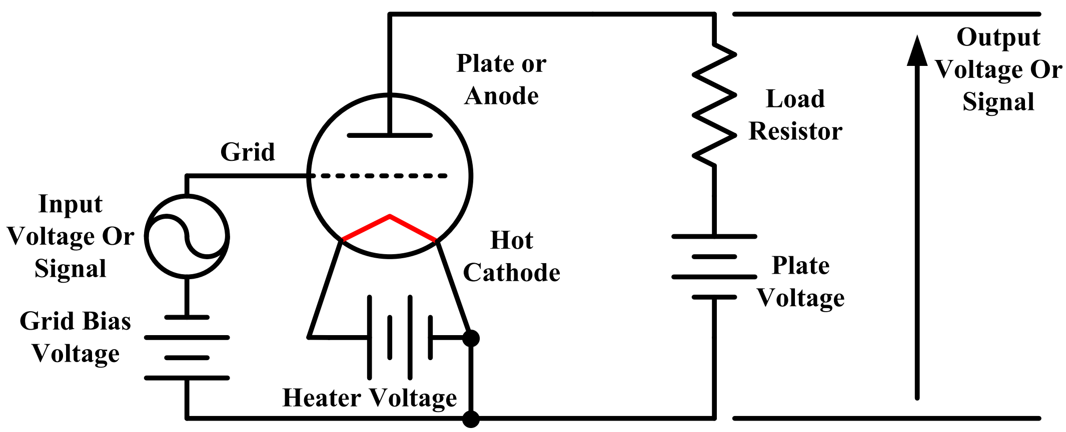

Figure 2.1 Schematic of a Simple Triode Amplifier Circuit

With this circuit, it was possible to get an output voltage swing that was larger than the input voltage swing. As a matter of interest, in the above Figure 2.1, the AC output voltage was inverted and riding on a DC voltage. The voltage gain of a triode is usually very low, and a voltage gain of more than 50 was very unusual. As a matter of interest, the dB gain for a voltage gain of 50 is about 34 dB.

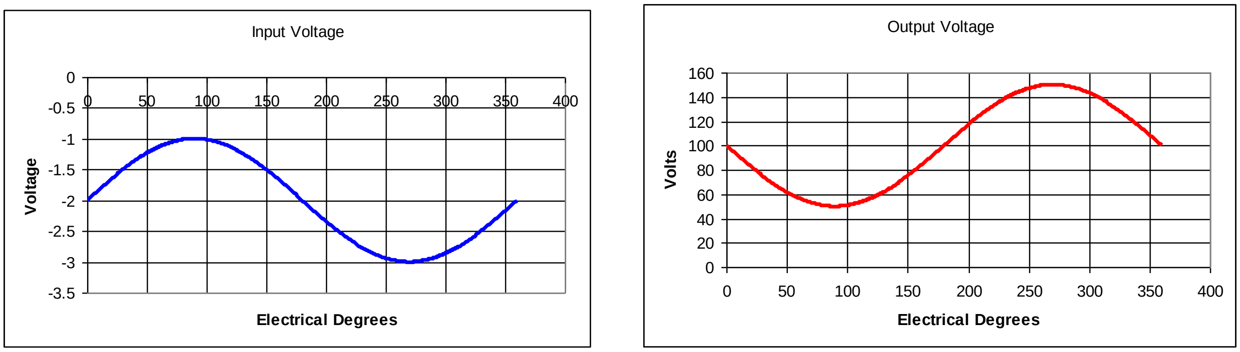

Figure 2.2 Graph of Input and Output Voltages for Triode Amplifier of Figure 2.1

Figure 2.2 shows what the input and output voltages of the triode amplifier of Figure 2.1 would look like. A voltage gain of 50 is assumed for these waveforms. Also, the input grid bias voltage would be minus 2 volts and the plate voltage would be plus 200 volts. I show this to illustrate some of the difficulties of making a DC vacuum tube amplifier.

From 1906 to 1940 there were advances made in the design and building of vacuum tubes. In 1941, Karl D. Swartzel, Jr. of Bell Labs filed US Patent Number 2,401,779 on "Summing Amplifiers". This design used three vacuum tubes and had a dB gain of 90dB (This would be a Voltage Gain of about 31,600). During World War II it was used in an artillery aiming device to achieve hit rates of near 90%. Technically this was not a true Operational Amplifier (OP Amp) as it had only an inverting input. Modern Op Amps have both inverting and non-inverting inputs. Figure 2.3 is a schematic of this amplifier from the US patent. One of its best uses was to direct the guns that were used to shoot down the German unmanned bombs in WW II.

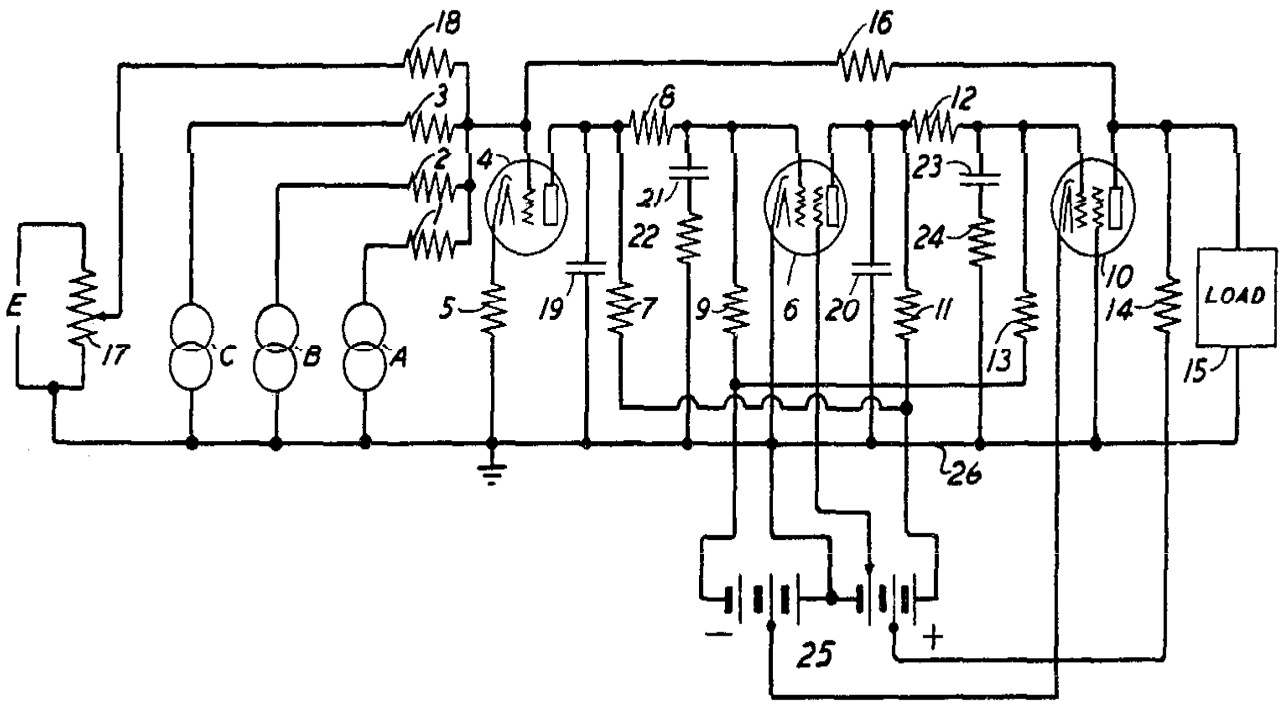

Figure 2.3 Schematic of the M2 Summing Amplifier from US Patent Number 2,401,779

The Op Amp was not formally defined and named until 1947. This was done by Professor John R. Ragazzini of Columbia University. A student, Loebe Julie, designed a vacuum tube circuit that had two inputs, an inverting input and a non-inverting input. Figure 2.4 is a schematic of the first commercial vacuum tube Operational Amplifier. Due to drift problems with vacuum tubes this idea was not to be used very much until the advent of transistorized and integrated circuits.

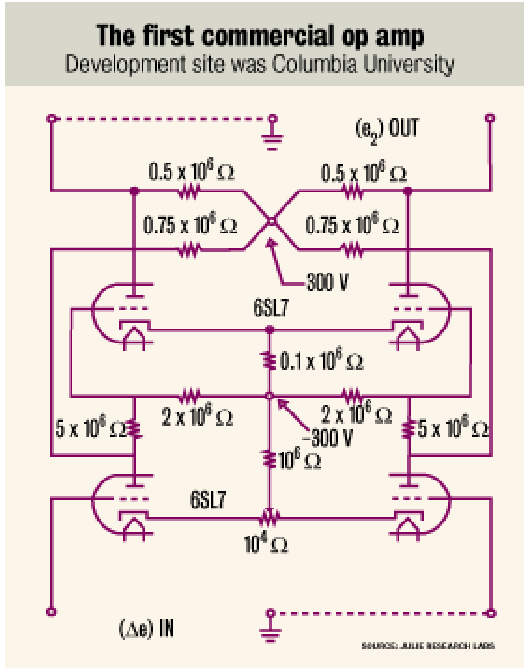

Figure 2.4 Schematic of the First Commercial Op Amp

One thing to notice here is that the positive and negative inputs are connected to the grids of two triode vacuum tubes are the two inputs. Figure 2.5 shows a schematic with only the differential amplifier input circuit. This is a design characteristic of most of the Operational Amplifiers ever built. The constant current source is also a common design feature of Operational Amplifiers.

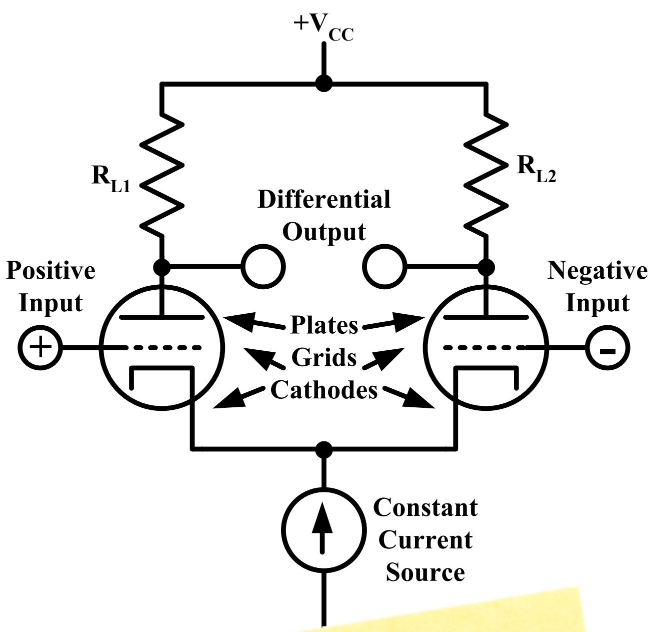

Figure 2.5 S… fier Circuit

The constant current s… uum tube biased to supply a constant curre… ie resistor with a balancing potentiomete… sides of the differential amplifier. The plate vo… ified output could be taken from between the … ced because the vacuum tube characteris… ors. It was a significant advance and … e are used in most Operational Amplifier de…

Chopper stabilized circui… ociated with vacuum tube amplifiers. … bilized amplifier. Chopper stabilized amplif… …nal, which can then be amplified by a convention… …elps minimize drift problems which occur with vacuum tube a… …gure 2.6 shows how a chopper stabilized amplifier would work. A mechanical switch operated at either 60 or 400 cycles per second would turn the DC signal into an AC square wave which would then be amplified by a more stable AC amplifier and converted back to a DC level. Most car radios manufactured until the early 1960's used a similar device, called a vibrator, to turn the 6 or 12-volt DC battery voltage into a square wave which was then transformed to a high voltage to run the vacuum tubes that were used in these designs. Fortunately, solid state devices enabled designers to build both car radios and stable Operational Amplifiers without these noisy failure prone devices.