Simulation Report - Week 3

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1. Introduction

As previously mentioned I wanted to study more about the frequency response of the op-amp and therefore, this week I studied about the stability of op-amps and what it means for an op-amp to be *unity-gain stable*.

Towards the end of the report I also write about *peaking amplifiers* that have high voltage gain only for a specific frequency.

2. Simulation Details

- Environment: LTspiceXVII
- Important component(s): LM741 and OP37[1] op-amp IC
- Reference Book: Gayakwad[2]

2.1 Stability of Op-amps

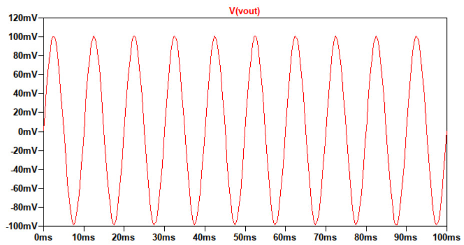
When we prepare op-amp amplifiers we always use negative feedback (i.e., the feedback is always applied at the inverting terminal). Negative feedback is also called *degenerative feedback* because when used it degenerates the output voltage amplitude and in turn reduces voltage gain. It stabilizes the gain, increases the bandwidth at the cost of reduced voltage gain.

Positive feedback is not good for designing op-amps as they make the output unstable and induce oscillations. In positive feedback, the feedback signal aids the input signal, so it is also known as *regenerative feedback*. A system is said to be unstable if its output increases with time instead of achieving a fixed value e.g., the output of a voltage follower created using OP37. See fig. 1 for comparison of stable and unstable voltage follower outputs.

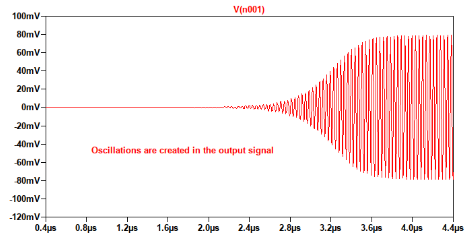
Negative feedback amplifiers can also become unstable if the op-amp in use has not been appropriately compensated. For instance, let us take the example of the open-loop frequency response of OP37. It has a break frequency at around 29 KHz, after this point the voltage gain falls at a rate of 20dB/decade. We should also keep in mind that at every break frequency there is a phase shift of 90° and the minimum gain possible for a closed-loop amplifier is 1 so in order for an op-amp to be unity-gain stable (i.e., stable at 0 dB or at gain of 1), it must not have two break frequencies above the 0 dB line in its open loop frequency response plot. This is because with another break frequency, the gain will fall by yet another 20dB/decade so the adding up, the gain now falls by 40dB/decade, this also means that the phase shift is now (90° + 90° =) 180° so the negative feedback has now turned into positive feedback. Another way to check this is via the phase plot where one must make sure that the phase shift is not equal to or less then -180° before the 0 dB line or before UGB. See fig. 2 for comparing bode plots of LM741 and OP37.

In order to make such an op-amp unity-gain stable we have to add external compensating network, the addition of such network shifts the entire frequency plot down by a certain amount (depends on the composition of the compensating network)[3] and this makes the second break frequency go below the 0 dB, thereby making the op-amp unity-gain stable.

Note: If an op-amp has only one break frequency then it is inherently stable as the total phase shift does not exceed -90° but if we configure the op-amp with non-resistive components, the total phase shift is equal to the phase shift due to feedback network plus phase shift due to the internal circuitry of the op-amp. It maybe possible that after this addition the total phase shift is $\leq$ -180° and hence, the circuit may become unstable.

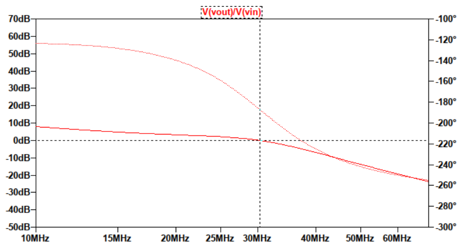


(a) A unity-gain stable op-amp

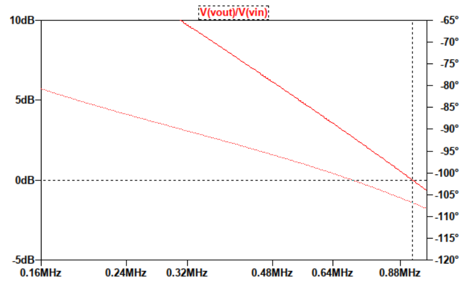


(b) A unity-gain unstable op-amp

Figure 1: Comparing voltage follower output signals



(a) at 0dB, phase shift <-180°, unstable



(b) at 0dB, phase shift >-180°, stable

Figure 2: Comparing bode plots of LM741 and OP37

2.2 Peaking Amplifier

A. Theory

The peaking amplifier provides a *peaking response* which means a frequency response that peaks at a certain frequency. Such a circuit is obtained by using a parallel LC network with the op-amp. See figure 3a for the circuit diagram. The resonant frequency at which peaking occurs can be determined as:

$$f_p = \frac{1}{2\pi\sqrt{LC}} \quad \text{if } Q_{coil} \geq 10 \tag{1}$$

where Q_{coil} = figure of merit of the coil and it can be determined as:

$$Q_{coil} = \frac{X_L}{R} = \frac{2\pi f L}{R} \tag{2}$$

The gain at the resonant frequency is the highest because the impedance of the parallel LC network is very large at that frequency. Hence, the gain of the amplifier at resonance is maximum and given by:

$$A_F = -\frac{R_F||R_P}{R_1} \tag{3}$$

where R_P = equivalent parallel resistance of the LC tank circuit = $Q_{coil}^2 R$
R = internal resistance of the coil

The impedance of the parallel LC network below and above the peak frequency is less then R_P, therefore the gain of the amplifier is less than $\frac{R_F||R_P}{R_1}$ at any other frequency then f_p. Note that we can easily calculate R_P at resonance using the known values of R_1 and R_F.

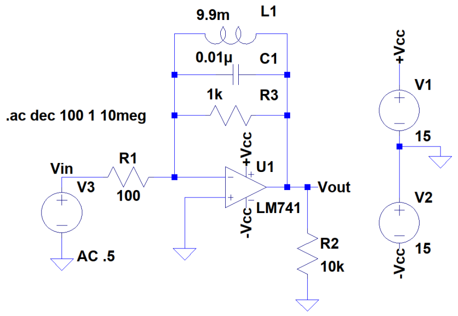
The bandwidth of the peaking amplifier can be determined by using the equation:

$$BW = \frac{f_p}{Q_p} \tag{4}$$

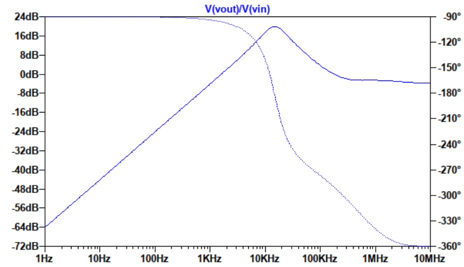
where Q_p = figure of merit of the parallel resonant circuit = $\frac{R_F||R_P}{X_L}$

B. Schematic and Waveform

See Fig. 3.



(a) Circuit schematic



(b) Frequency response with f_p at around 15KHz

Figure 3: The peaking amplifier

References

[1] Analog Devices Inc. OP37 Datasheet. https://www.analog.com/media/en/technical-documentation/data-sheets/OP37.pdf.

[2] Ramakant A. Gayakwad. *Op-Amps and Linear Integrated Circuits*. PHI Learning Pvt. Ltd., New Delhi-110001, fourth edition, 2010.

[3] Analog Devices Inc. Stability 101: Decompensated Operational Amplifiers. https://www.youtube.com/watch?v=Db16d88ZziE.