A Detailed Lesson on Operational Amplifiers - Negative Feedback

Dr. Nashwa Nabil Elaraby, Pennsylvania State University, Harrisburg, The Capital College

Dr. Elaraby is a faculty at Penn State Harrisburg since August 2014. She received her PhD degree in Electrical and Computer Engineering from Temple University in 2014. She received her B.Sc and M.Sc. in Electrical Engineering from Alexandria University, Egypt.

Her research interests include digital logic design using Field Programmable Gate Arrays for massively parallel data computations, electronic circuit design, and neuronal data processing for Brain Machine Interface applications.

A Detailed Lesson on Operational Amplifiers - Negative Feedback

Nashwa Elaraby, Ph.D., Penn State Harrisburg

Abstract: Operational Amplifiers present one of the important topics in electronic circuits courses. Although they are widely taught, the model for the operational amplifiers with negative feedback configuration is incomplete in most of the electronics textbooks[1][2][3][4]. The closed loop gain for the non-inverting amplifier is given as $A_{oL}/(1+\beta A_{oL})$[1], while the closed loop model for the inverting amplifier is usually not included. Instead nodal analysis is used to derive the expression for the inverting amplifier gain. Using different derivation paths and models causes confusion for the students, as the comparison is not provided from the same point of view. The constant gain-bandwidth product is mentioned for the closed loop frequency response for the amplifier, but it is not clearly stated that it only applies to the non-inverting amplifier configuration[1]. The missing details usually cause misconception for the students and mismatch between the lab results and their expectations. The main objective of this paper was to provide instructors with a detailed lesson on operational amplifiers using negative feedback, that can be applied in electronic circuit analysis courses for electrical engineering students and electrical engineering technology students.

I. Introduction:

Operational amplifiers with negative feedback have three modes of operation. The non-inverting amplifier, the inverting amplifier and the voltage follower. The voltage follower can be considered a special case of the non-inverting amplifier, but it will be considered separately in this paper, as it is a commonly used buffer circuit that the students need to closely understand. The gain for the different amplifiers can be derived using the negative feedback configuration. The main idea of the negative feedback is to reduce the potential difference between the inverting and the non-inverting amplifier inputs to obtain a voltage at the output that is confined within the boundaries of the dc voltages biasing the internal transistors of the operational amplifier to operate in the forward active mode. The second section of the paper introduces the methodology used to complete the modeling details of the operational amplifier circuit with negative feedback. It covers the three negative feedback models and derives the expressions for the exact calculations of the closed loop gains in terms of the limited open-loop gain of the operational amplifier. The derivation of the ideal closed loop gains is verified using the model. It also discusses the open-loop frequency response of the operational amplifier. The methodology section also provides a transfer function equation for a compensated operational amplifier model, and shows how it is represented by a Bode plot equation. This step shows the students how to algebraically prove the roll off rate on the Bode plot. Lab procedures are included to test and verify the frequency response of a compensated operational amplifier. The closed loop frequency response is then proved algebraically for both the inverting and the non-inverting configurations, and lab procedures are included to test them. The third section provides the overall evaluation results of the applied lesson and the last section provides a discussion on the paper content.

I. Methodology:

(a) Negative Feedback Models:

The negative feedback configuration aims at minimizing the potential difference v_d between the inverting and non-inverting inputs of the operational amplifier, and hence applying it as a linear amplifier with output values limited between the biasing voltages of the internal circuitry. With the negative feedback and an ideal open-loop gain A_{oL} of ∞, we can assume that the differential voltage v_d is zero. For an ideal operational amplifier, the input impedance is infinity, which means that there is no current flowing into the inputs of the operational amplifier. The closed loop gain for the operational amplifier can hence be derived using simple nodal analysis as shown in figure 1.

$$v_d = 0$$
$$v_o = v_{in}$$
$$A_{cL} = 1$$
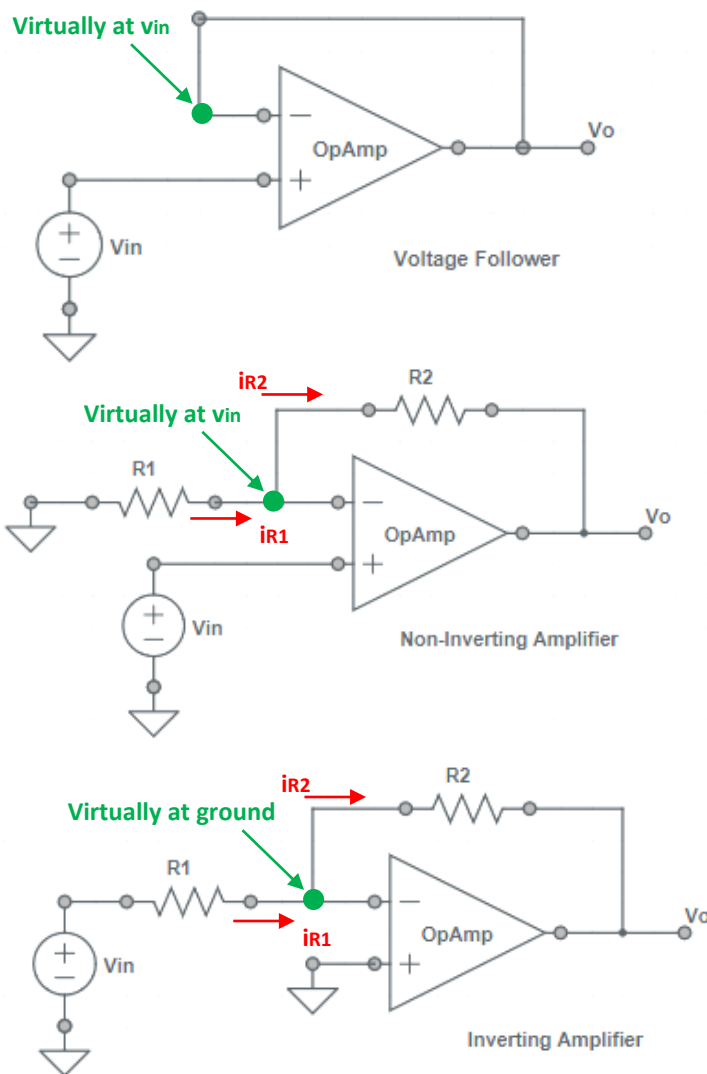
Kirchoff's Current Law:
$$i_{R_1} = i_{R_2}$$
$$\frac{0 - v_{in}}{R_1} = \frac{v_{in} - v_o}{R_2}$$
$$v_o = \left(1 + \frac{R_2}{R_1}\right) \cdot v_{in}$$
$$A_{cL} = \left(1 + \frac{R_2}{R_1}\right)$$

Kirchoff's Current Law:
$$i_{R_1} = i_{R_2}$$
$$\frac{v_{in} - 0}{R_1} = \frac{0 - v_o}{R_2}$$
$$v_o = \left(-\frac{R_2}{R_1}\right) \cdot v_{in}$$
$$A_{cL} = \left(-\frac{R_2}{R_1}\right)$$

Fig. 1 The negative feedback configurations of an ideal operational amplifier: the voltage follower, the non-inverting operational amplifier and the inverting operational amplifier. The derivations of the closed loop gains assume an infinite open-loop gain A_{oL} and an infinite input impedance of the ideal operational amplifier.

For a non-ideal operational amplifier with finite open-loop gain the following models in fig. 2 can be applied to derive the closed loop gain. The addition operator signs are determined based on the connection to the inverting or non-inverting terminals. The negative feedback connection strives to cancel out the input signal contribution to minimize the differential voltage v_d. For the non-inverting amplifier the input is connected to the non-inverting input while the positive feedback signal is fed into the inverting input of the operational amplifier[1]. For the inverting amplifier the feedback signal and a fraction of the input signal are fed into the inverting input, but as the output is negative, the inverting input adds the absolute value of the feedback signal to the negative input signal. The α and β are voltage dividers found by applying the superposition theorem for v_{in} and v_o respectively.

$$A_{cL} = \frac{A_{oL}}{(1 + A_{oL})}$$

(a)

$$A_{cL} = \frac{A_{oL}}{(1 + \beta A_{oL})}$$

where

$$\beta = \left(\frac{R_1}{R_1 + R_2} \right)$$

(b)

$$A_{cL} = \frac{-\alpha A_{oL}}{(1 + \beta A_{oL})}$$

where

$$\alpha = \left(\frac{R_2}{R_1 + R_2} \right)$$

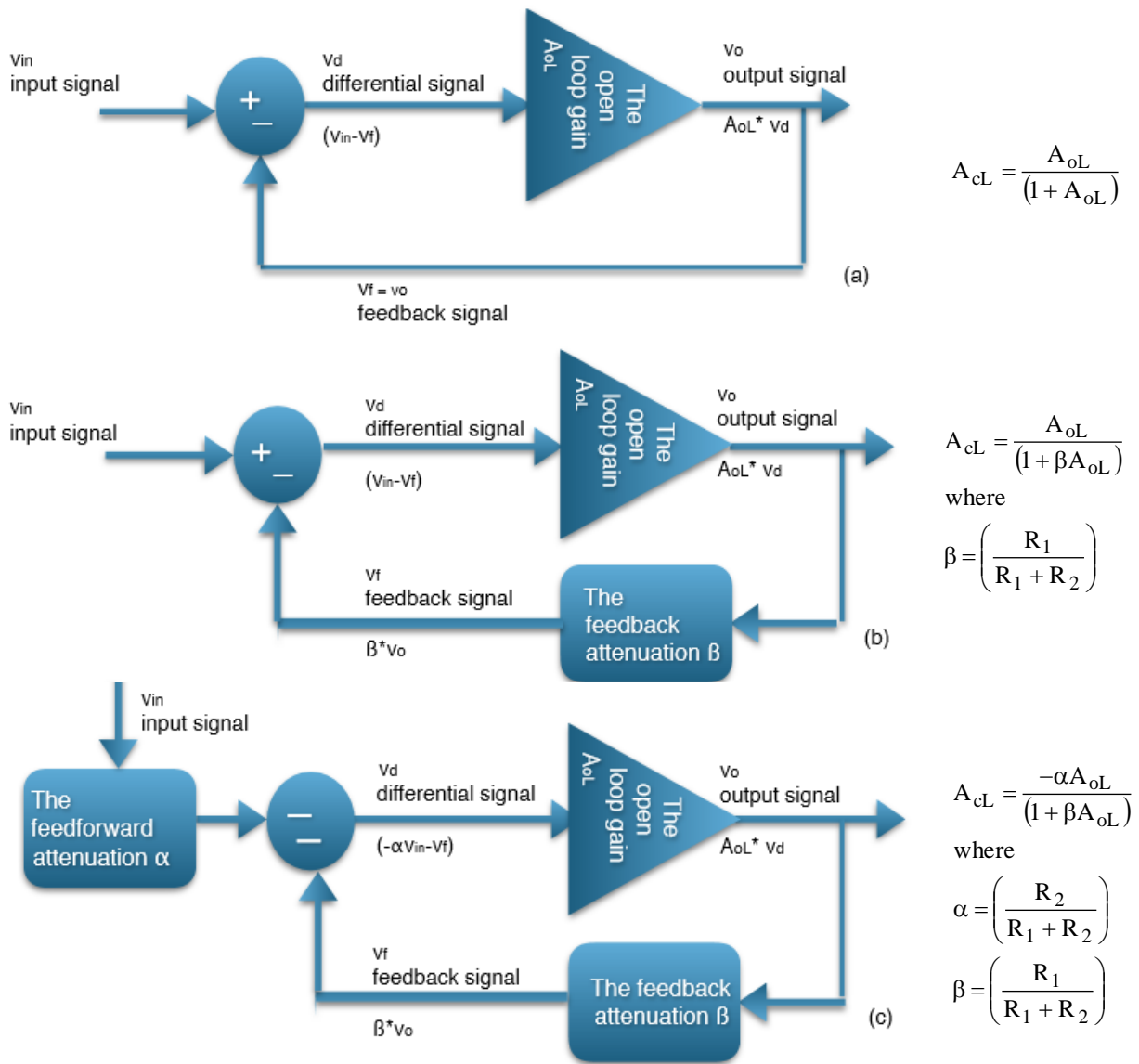$$\beta = \left(\frac{R_1}{R_1 + R_2} \right)$$

(c)

Fig. 2 The negative feedback model of (a) the voltage follower, (b) the non-inverting operational amplifier and (c) the inverting operational amplifier.

In the table 1, a thorough derivation of the closed loop gain expressions is presented.

The voltage follower	The non-inverting amplifier	The inverting amplifier
$v_o = A_{oL} \cdot v_d$ $v_o = A_{oL} \cdot (v_{in} - v_f)$ $v_o = A_{oL} \cdot (v_{in} - v_o)$ $v_o(1 + A_{oL}) = A_{oL} \cdot v_{in}$ $\dfrac{v_o}{v_{in}} = \dfrac{A_{oL}}{(1 + A_{oL})}$	$v_o = A_{oL} \cdot v_d$ $v_o = A_{oL} \cdot (v_{in} - v_f)$ $v_o = A_{oL} \cdot (v_{in} - \beta v_o)$ $v_o(1 + \beta A_{oL}) = A_{oL} \cdot v_{in}$ $\dfrac{v_o}{v_{in}} = \dfrac{A_{oL}}{(1 + \beta A_{oL})}$	$v_o = A_{oL} \cdot v_d$ $v_o = A_{oL} \cdot (-\alpha v_{in} - v_f)$ $v_o = A_{oL} \cdot (-\alpha v_{in} - \beta v_o)$ $v_o(1 + \beta A_{oL}) = -\alpha A_{oL} \cdot v_{in}$ $\dfrac{v_o}{v_{in}} = \dfrac{-\alpha A_{oL}}{(1 + \beta A_{oL})}$

Table 1: The derivation of the closed loop gain of the different negative feedback configurations using their models.

To verify the models used for the negative feedback configurations the open-loop gain can be set to infinity for the ideal operational amplifier, and the derived closed loop expressions will be compared to the ones obtained using nodal analysis. In the derivation steps we neglect the 1 term with respect to βA_{oL} assuming that with the infinite values of A_{oL}, the term $\beta A_{oL} \gg 1$.

|	The voltage follower	The non-inverting amplifier	The inverting amplifier
The ideal A_{cL}	$A_{cL} = 1$	$A_{cL} = \left(1 + \dfrac{R_2}{R_1}\right)$	$A_{cL} = \left(-\dfrac{R_2}{R_1}\right)$
The closed loop gain based on the negative feedback model	$A_{cL} = \dfrac{A_{oL}}{(1 + A_{oL})}$	$A_{cL} = \dfrac{A_{oL}}{(1 + \beta A_{oL})}$ where $\beta = \left(\dfrac{R_1}{R_1 + R_2}\right)$	$A_{cL} = \dfrac{-\alpha A_{oL}}{(1 + \beta A_{oL})}$ where $\alpha = \left(\dfrac{R_2}{R_1 + R_2}\right) \quad \beta = \left(\dfrac{R_1}{R_1 + R_2}\right)$
Verifying the closed loop gain model	$A_{cL} = \dfrac{A_{oL}}{(1 + A_{oL})}$ $A_{cL} \approx \dfrac{A_{oL}}{A_{oL}} = 1$	$A_{cL} = \dfrac{A_{oL}}{(1 + \beta A_{oL})}$ $A_{cL} \approx \dfrac{A_{oL}}{\beta A_{oL}} = \dfrac{1}{\beta}$ $= \dfrac{R_1 + R_2}{R_1}$ $= \left(1 + \dfrac{R_2}{R_1}\right)$	$A_{cL} = \dfrac{-\alpha A_{oL}}{(1 + \beta A_{oL})}$ $A_{cL} \approx \dfrac{-\alpha A_{oL}}{\beta A_{oL}} = \dfrac{-\alpha}{\beta}$ $= \left(\dfrac{-R_2}{R_1 + R_2}\right) \cdot \left(\dfrac{R_1 + R_2}{R_1}\right)$ $= \left(-\dfrac{R_2}{R_1}\right)$

Table 2: Comparison of the negative feedback expressions obtained using the negative feedback model and the nodal analysis assuming ideal operational amplifier open-loop gain and input impedance.

(b) Open-Loop Frequency Response of a Compensated Operational Amplifier:

For this section the lab procedures for measuring the open-loop frequency response and the unity gain bandwidth of the LM741 operational amplifier will be included. The main objective of this lab is to let students realize that the operational amplifier does not have a constant gain for all frequencies, instead it is behaving like a low pass filter with a dominant pole, governed by the following equation:

$$A_{oL}(f) = \frac{A_{oL}(0)}{\left(1 + j\dfrac{f}{f_{pD}}\right)}$$

where $A_{oL}(0)$ = The low frequency open-loop gain

f_{pD} = the dominant pole frequency
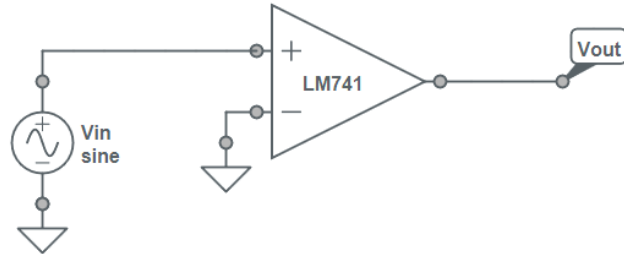
At lower frequencies, it will be very hard to measure the gain, as the operational will reach saturation at the output for very low amplitudes of input voltages due to the high gain. As the frequency increases, the gain decreases, and it will be possible to obtain an undistorted output voltage signal. The students will measure the gain and phase shift at different frequencies between 10KHz and 500KHz. If any non-symmetrical clipping is observed on the output signal, positive or negative DC offset voltage in the range of a few mV can be added to the input signal to cancel out the offset voltage causing the clipping. The range of frequencies examined is much higher than the dominant pole frequency (~10Hz), hence the magnitude and the phase equations can be approximated to the following formulas. It is important to measure the gain based on undistorted signals.

$$|A_{oL}(f)| = \frac{A_{oL}(0)}{\sqrt{1 + \left(\dfrac{f}{f_{pD}}\right)^2}} \approx \frac{A_{oL}(0)}{\sqrt{\left(\dfrac{f}{f_{pD}}\right)^2}} = \frac{A_{oL}(0)}{\left(\dfrac{f}{f_{pD}}\right)}$$

$$\phi(f) = \text{Phase angle}$$

$$\phi(f) = \tan^{-1}\left(\frac{f}{f_{pD}}\right) \approx 90°$$

$$|A_{oL}(f)|_{dB} = 20 \log(A_{oL}(0)) - 20 \log\left(\frac{f}{f_{pD}}\right) \longleftarrow$$ **This term sets the roll-off rate at -20dB/decade on the Bode plot applying logarithmic scale for the frequency**

The students then plot | A$_{oL}$(f) |$_{dB}$ versus the frequency using a logarithmic scale for the frequency. On the graph, the data points are extrapolated to find the frequency f$_T$ at which the gain is unity or 0$_{dB}$. To get the dominant pole frequency, the graph is extrapolated to the frequency at which the gain reaches the maximum value of the LM741 gain of 107$_{dB}$.

The following MATLAB code can be used to plot the data points on the Bode plot and extrapolate it to obtain f_T and f_{pD}.

```matlab
% Data Points Obtained:
f      = [ ];              % enter your frequency values as a vector
GaindB = [ ];              % enter the gain values as a vector
semilogx(f,GaindB,'o','MarkerFace','b')     % Original points
hold on

% Curve Fitting:
f_extended = 1:1:10^7;
GaindB_extended = polyval(polyfit(log10(f),GaindB,1),log10(f_extended));
% The maximum gain for the LM741 is 107dB
for i = 1:length(f_extended)
    if GaindB_extended(i) > 107
        GaindB_extended(i) = 107;
    end
end
semilogx(f_extended,GaindB_extended,'r','LineWidth',2)
grid on

legend ('Measured points','Curve Fitting Result')
xlabel('frequency in Hz')
ylabel('Gain in dB')
```


Spring 2017 Mid-Atlantic ASEE Conference, April 7-8, 2017 MSU
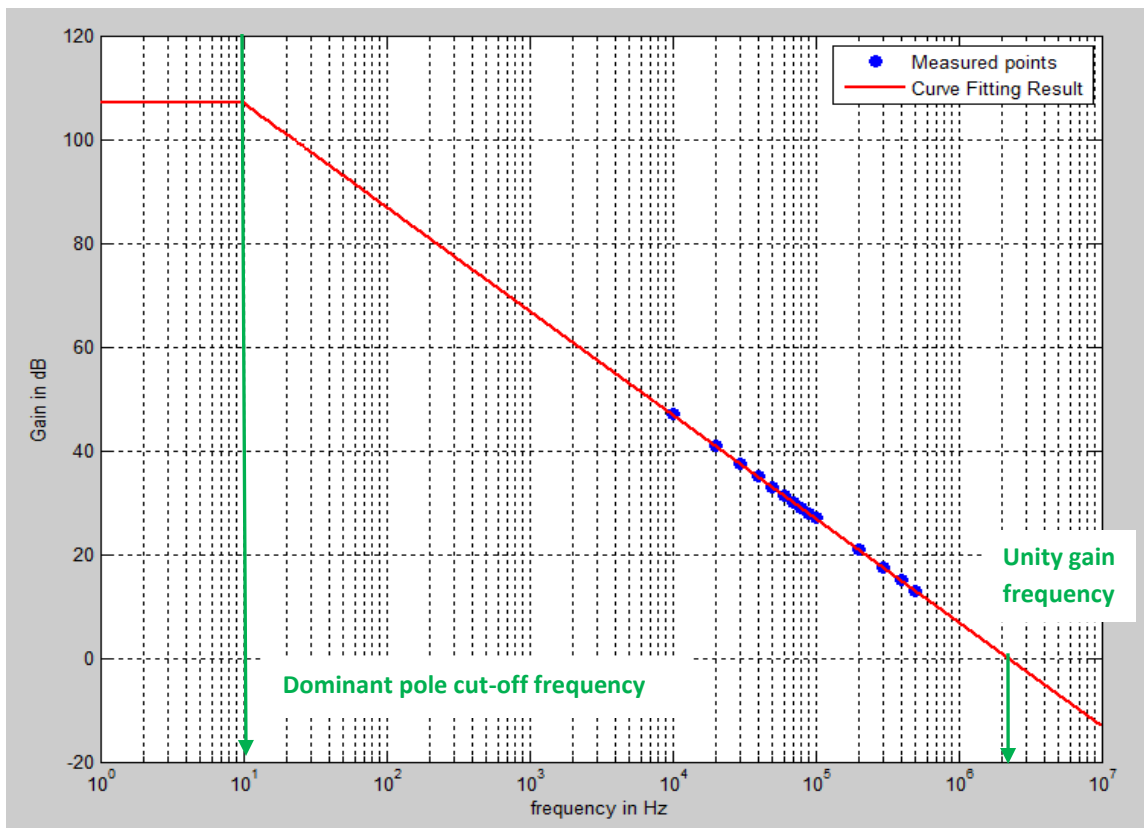
(c) Closed-Loop Frequency Response:

The operational amplifier with negative feedback also behaves as a low-pass filter. To find its bandwidth, the feedback models presented in section II will be applied. The closed-loop gain equations derived will be implemented by substituting for the open-loop gain A_{oL} by the function $A_{oL}(f)$, and the comparing the equation to the general low-pass filter transfer function.
The voltage follower:

$$A_{cL}(f) = \frac{A_{oL}(f)}{1 + A_{oL}(f)} = \frac{\left(\dfrac{A_{oL}(0)}{1 + j\dfrac{f}{f_{pD}}}\right)}{1 + \left(\dfrac{A_{oL}(f)}{1 + j\dfrac{f}{f_{pD}}}\right)} = \frac{A_{oL}(0)}{1 + j\dfrac{f}{f_{pD}} + A_{oL}(0)} = \frac{A_{oL}(0)}{\left(1 + A_{oL}(0)\right)\cdot\left(1 + j\dfrac{f}{f_{pD}\left(1 + A_{oL}(0)\right)}\right)}$$

$$A_{cL}(f) = \frac{A_{cL}(0)}{1 + j\dfrac{f}{f_{pD}\left(1 + A_{oL}(0)\right)}} \qquad \text{where} \quad A_{cL}(0) = \frac{A_{oL}(0)}{1 + A_{oL}(0)} \qquad \text{B.W.}_{\text{voltage follower}} = f_{pD}\left(1 + A_{oL}(0)\right)$$

The non-inverting Amplifier:

$$A_{cL}(f) = \frac{A_{oL}(f)}{1 + \beta A_{oL}(f)} = \frac{\left(\dfrac{A_{oL}(0)}{1 + j\dfrac{f}{f_{pD}}}\right)}{1 + \beta\cdot\left(\dfrac{A_{oL}(f)}{1 + j\dfrac{f}{f_{pD}}}\right)} = \frac{A_{oL}(0)}{1 + j\dfrac{f}{f_{pD}} + \beta A_{oL}(0)} = \frac{A_{oL}(0)}{\left(1 + \beta A_{oL}(0)\right)\cdot\left(1 + j\dfrac{f}{f_{pD}\left(1 + A_{oL}(0)\right)}\right)}$$

$$A_{cL}(f) = \frac{A_{cL}(0)}{1 + j\dfrac{f}{f_{pD}\left(1 + \beta A_{oL}(0)\right)}} \qquad \text{where} \quad A_{cL}(0) = \frac{A_{oL}(0)}{1 + \beta A_{oL}(0)} \qquad \text{B.W.}_{\text{non-inverting}} = f_{pD}\left(1 + \beta A_{oL}(0)\right)$$

For the voltage follower and the non-inverting amplifier the Gain-Bandwidth product is a constant value:

$$A_{cL}(0)\cdot\text{B.W.} = A_{oL}(0)\cdot f_{pD}$$

$$A_{cL}(0) = A_{oL}(0)\cdot\left(\frac{f_{pD}}{\text{B.W.}}\right) \qquad\qquad \left|A_{cL}(0)\right|_{dB} = \left|A_{oL}(0)\right|_{dB} - 20\cdot\log\left(\frac{\text{B.W.}}{f_{pD}}\right)$$

The inverting Amplifier:

$$A_{cL}(f) = \frac{-\alpha A_{oL}(f)}{1 + \beta A_{oL}(f)} = \frac{\left(\dfrac{-\alpha \cdot A_{oL}(0)}{1 + j\dfrac{f}{f_{pD}}}\right)}{1 + \beta \cdot \left(\dfrac{A_{oL}(f)}{1 + j\dfrac{f}{f_{pD}}}\right)} = \frac{-\alpha \cdot A_{oL}(0)}{1 + j\dfrac{f}{f_{pD}} + \beta A_{oL}(0)} = \frac{-\alpha \cdot A_{oL}(0)}{(1 + \beta A_{oL}(0)) \cdot \left(1 + j\dfrac{f}{f_{pD}(1 + A_{oL}(0))}\right)}$$

$$A_{cL}(f) = \frac{-\alpha \cdot A_{cL}(0)}{1 + j\dfrac{f}{f_{pD}(1 + \beta A_{oL}(0))}} \qquad \text{where} \quad A_{cL}(0) = \frac{-\alpha \cdot A_{oL}(0)}{1 + \beta A_{oL}(0)} \qquad \text{B.W.}_{\text{non-inverting}} = f_{pD}(1 + \beta A_{oL}(0))$$

For the voltage follower and the non-inverting amplifier the Gain-Bandwidth product is a constant value:

$$A_{cL}(0) \cdot \text{B.W.} = -\alpha \cdot A_{oL}(0) \cdot f_{pD}$$

The gain-bandwidth product is not a constant value. It depends on the forward attenuation α, which varies for every closed loop gain.

Lab procedures:

The lab procedures for the closed loop frequency gain are divided into two main sections: the closed loop gain for the non-inverting amplifier and the closed loop gain for the inverting amplifier. Each section is subdivided into two parts, one showing that the operational amplifier with the negative feedback is behaving as a low-pass filter, and then calculating the GBW product for different gain values.

In the discussion section of the lab report, students compare the frequency responses of the two configuration of negative feedback. They compare the GBW products. They also compare their frequency responses to that of the open-loop configuration.

They plot the closed-loop low frequency gain versus the frequency on a logarithmic scale and explain the roll-off rate using the constant GBW product relation for the non-inverting amplifier. They show that this relation does not hold for the inverting amplifier.

The set of labs explaining the different negative feedback models and the frequency response, help students build a concrete foundation for the understanding of the operational amplifier application as a linear amplifier in the different modes.

Part 1: Closed-loop Frequency Response of a Non-Inverting Amplifier:
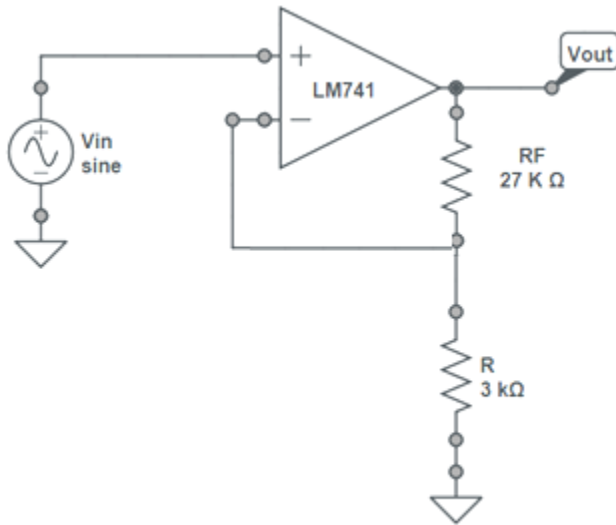
(1) Connect the circuit shown in figure. Verify the gain as the ratio of V_{out}/V_{in} using a low frequency sinusoidal signal of an appropriate amplitude. (avoid clipping, but remember that the larger the signal the more accurate your recordings will be)

(2) What is the feedback attenuation β?

(3) Measure the gain at different frequencies between 100Hz and 1MHz, and plot the closed-loop frequency response. Plot the graph (Take at least 20 readings). Measure the bandwidth by gradually raising the frequency until the gain drops to 0.707 times its nominal value (The nominal value $A_{cL}(0)$ is the value of the gain at very low frequencies). The cut-off frequency needs to be one of you recordings.

(4) For any non-inverting amplifier circuit, the gain of the amplifier is

$$A_{CL} = \frac{A_{oL}}{(1 + \beta A_{oL})}.$$

Sketch the model for the non-inverting amplifier, and prove the equation for the closed-loop gain. At high values of βA_{oL} the closed loop gain can be approximated to be $1/\beta$. Prove that, and show how it applies to your circuit results.

(5) Using the transfer function of the operational amplifier

$$A_{oL}(f) = \frac{A_{oL}(0)}{\left(1 + j\dfrac{f}{f_{pD}}\right)}$$

prove that the bandwidth for the non-inverting amplifier is $f_c = f_{PD}(1 + \beta AoL(0))$.

(6) Prove that the Gain-Bandwidth Product (GBW) for the non-inverting amplifier is a constant value equal to $GBW = f_{pD} \cdot A_{oL}(0)$. The GBW value also represents the Unity gain Band Width f_T, which is the bandwidth at a closed loop gain of 1 (Voltage follower).

(7) Use different values of Rf to obtain closed-loop gains from 20dB to 50dB with a step size of 5dB. For each value of the low-frequency closed-loop gain, chose an appropriate feedback resistor value, and verify gain by calculating the ratio of Vout/Vin., using a low frequency sinusoidal signal of an appropriate amplitude (avoid clipping at the output) For each gain value, measure the bandwidth by gradually raising the frequency until the gain drops to 0.707 times its nominal value.

(8) Use your measurements to create a graph of the gain (in dB) on the y-axis versus the bandwidth (logarithmically scaled) in Hz on the x-axis.

$$f_c \cdot A_{cL} = f_{pD} \cdot A_{oL(0)}$$

$$A_{cL:} = A_{oL(0)} \cdot \left(\frac{f_{pD}}{f_c}\right)$$

$$20 \log(A_{cL:}) = 20 \log(A_{oL(0)}) + 20 \log\left(\frac{f_{pD}}{f_c}\right)$$

$$|A_{cL}|_{dB} = |A_{oL(0)}|_{dB} - 20 \log\left(\frac{f_c}{f_{pD}}\right)$$

(9) On your graph, extrapolate your data points to the location where gain would be unity (zero dB). At this point, the unity gain bandwidth will be equal to the value of the GBW. Then extrapolate your graph to the point where the gain would be 220,000 (107dB). At that point, the bandwidth should be that of the 741 in an open-loop configuration.

(10) Connect a voltage follower and increase the frequency until the gain becomes 0.707 to find the unity gain BW fᴛ. What might be your limitation for the gain measurement at the high frequency?

Part 2: Closed-loop Frequency Response of an Inverting Amplifier:
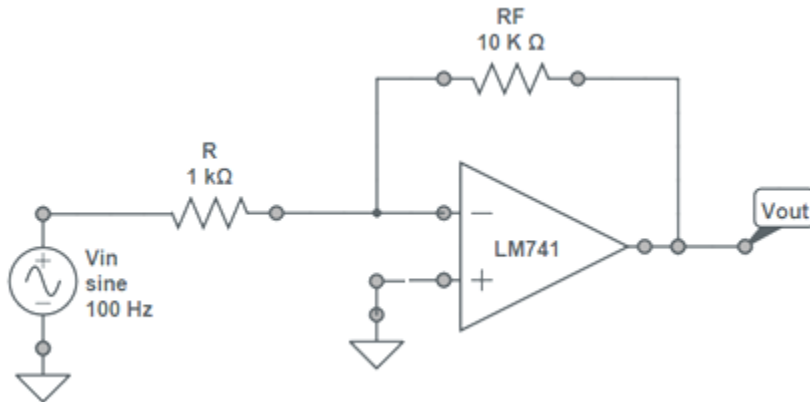
(1) Connect the circuit shown in figure. Verify the gain as the ratio of V_{out}/V_{in} using a low frequency sinusoidal signal of an appropriate amplitude. (avoid clipping, while the larger the signal the more accurate will be your recordings)

(2) What is the feedback attenuation β and the multiplier α?

(3) Measure the gain at different frequencies between 100Hz and 1MHz, and plot the closed-loop frequency response. Plot the graph (Take at least 20 readings). Measure the bandwidth by gradually raising the frequency until the gain drops to 0.707 times its nominal value (The nominal value is the value of the gain at very low frequency). The cut-off frequency needs to be one of your recordings.

(4) For an inverting amplifier circuit, the gain of the amplifier is

$$A_{CL} = \frac{-\alpha A_{oL}}{(1 + \beta A_{oL})}.$$

Sketch the model for the non-inverting amplifier, and prove the equation for the closed-loop gain. At high values of βA_{oL} the closed loop gain can be approximated to be -α/β. Prove that, and show how it applies to your circuit results.

(5) Using the transfer function of the operational amplifier

$$A_{oL}(f) = \frac{A_{oL}(0)}{\left(1 + j\dfrac{f}{f_{pD}}\right)}$$

prove that the bandwidth for the non-inverting amplifier is $f_c = f_{PD}(1 + \beta AoL(0))$.

(6) Prove that the Gain-Bandwidth Product (GBW) for the inverting amplifier is equal to
$GBW = -\alpha \cdot f_{pD} \cdot A_{oL}(0)$.

(7) Use different values of R_f to obtain closed-loop gains from 20dB to 50dB with a step size of 5dB. For each value of the low-frequency closed-loop gain, chose an appropriate feedback resistor value, and verify gain by calculating the ratio of $V_{out}/V_{in.}$, using a low frequency sinusoidal signal of an appropriate amplitude (avoid clipping at the output) For each gain value, measure the bandwidth by gradually raising the frequency until the gain drops to 0.707 times its nominal value.

(8) Use your measurements to create a graph of the gain (in dB) on the y-axis versus the bandwidth (logarithmically scaled) in Hz on the x-axis.

$$f_c \cdot A_{cL} = -\alpha \cdot f_{pD} \cdot A_{oL(0)}$$

$$\frac{A_{cL:}}{-\alpha} = A_{oL(0)} \cdot \left(\frac{f_{pD}}{f_c} \right)$$

$$20 \log \left(\frac{A_{cL:}}{-\alpha} \right) = 20 \log \left(A_{oL(0)} \right) + 20 \log \left(\frac{f_{pD}}{f_c} \right)$$

$$20 \log \left(\frac{A_{cL:}}{-\alpha} \right) = 20 \log \left(A_{oL(0)} \right) - 20 \log \left(\frac{f_c}{f_{PD}} \right)$$

(9) The GBW for the non-inverting amplifier is a constant value. What about the inverting amplifier? Explain.

III. Results:

I have taught circuits courses covering the operational amplifier application as linear amplifier for both Electrical Engineering and Electrical Engineering Technology student for at least three years both in the spring and fall semesters. With the detailed modeling of the operational amplifier circuits and emphasizing the difference between the inverting and non-inverting configurations, I had much better results for the exams and quizzes. The lab experiments go faster and are successfully completed with more than 95% of success rate compared to 60% in the past when we relied on the incomplete theoretical explanation and models of the textbooks. I have asked students whether it was easier to study from the textbook or from the class notes, and they answered that the detailed comparison of the different negative feedback configurations provided in the class notes, made it easier for them to remember their differences and similarities. Before adding the detailed lesson to my class notes, many students were applying the constant GBW product for both the inverting and the non-inverting amplifier configurations,

and they were frustrated when the lab results were not aligned with their calculations. With the detailed explanation the rate of these instances has significantly decreased.

IV. Conclusion:

Modeling the negative feedback configurations of operational amplifiers and the frequency response of the amplifier circuits is a topic that needs clarification in most of the textbooks. A detailed comparison of the three configurations: Non-inverting amplifier, inverting amplifier and voltage followers are needed to give the students a concrete theoretical basis to understand the circuit behavior. The main objective of this paper was to provide instructors with a detailed lesson on operational amplifiers, that can be applied in electronic circuit analysis courses for electrical engineering students and electrical engineering technology students. It presents a thorough lesson with lab procedures on the negative feedback models as well as their frequency responses, which has improved student's understanding of the operational amplifier behavior and modeling.

References:

1. Donald A. Neaman, Microelectronics: Circuit Analysis and Design, 4th Edition McGraw-Hill 2010, ISBN 978-0-07-338064-3

2. Basic Operational Amplifiers and Linear Integrated Circuits, 2nd edition, Floyd and Buchla, Prentice Hall, 1999

3. Adel S. Sedra and Kenneth C. Smith Microelectronic Circuits, Oxford Series in Electrical & Computer Engineering, 6th Edition

4. Richard C. Jaeger, Travis N Blalock, Microelectronic Circuit Design, 4th edition, McGraw-Hill 2011, ISBN 978-0-07-338045-2