ECE 304: Feedback (Read S&S p. 668-674)

Bandwidth

Feedback can improve bandwidth, but the gain-bandwidth product tends to remain constant. This assertion is rigorously true for a single time-constant voltage gain in a simple voltage amplifier:

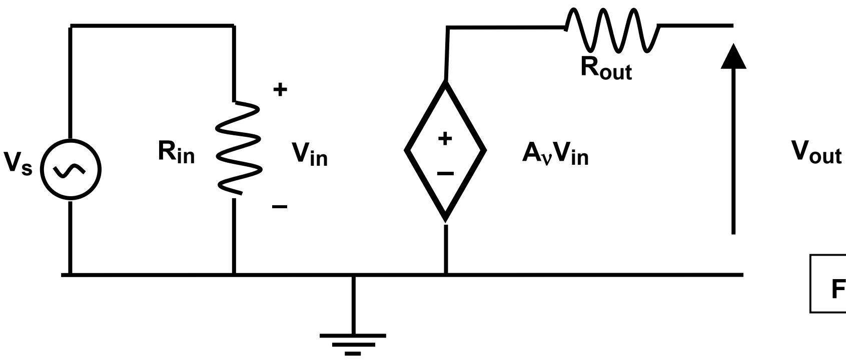


FIGURE 1

The so-called *open-loop gain* of this simple amplifier is assumed to have a *single time-constant* frequency behavior. That is,

$$A_\upsilon = A_O/(1 + j\ \omega\ \tau_1) \qquad (1)$$

Its Bode plot looks like:

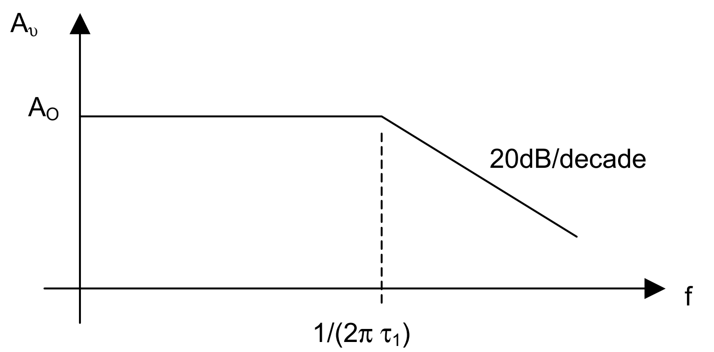


FIGURE 2

The *gain bandwidth* product of this amplifier is $A_O/(2\pi\ \tau_1)$ *i.e.* the mid-band gain times the corner frequency $1/(2\pi\ \tau_1)$. We now show that the bandwidth of this amplifier can be increased by feedback. We hook the amp up in a non-inverting amplifier configuration using two feedback resistors R_{F1} and R_{F2}:

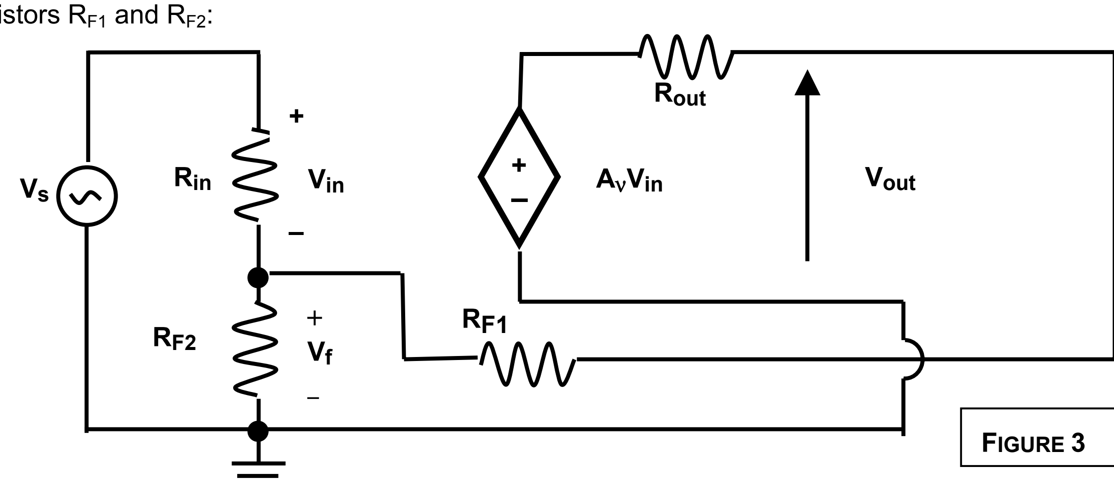


FIGURE 3

We now find the new gain with feedback, called the *closed-loop gain*. We will assume that R_{IN} is very large, so the current through R_{IN} is negligible. Negligible current does *not* mean there is no voltage V_{in}. We also will assume that R_{OUT} is very small, so that there is negligible drop across it and $V_{out} \approx A_\upsilon V_{in}$. Then we can use KCL at the node common to R_{F1} and R_{F2} to obtain

$$(V_{out} - V_f)/R_{F1} = V_f/R_{F2}\ , \text{ or } \ V_f = V_{out}\, R_{F2}/(R_{F1} + R_{F2})$$

From KVL, $V_f = V_s - V_{in} = V_s - V_{out}/A_\upsilon$. Combining these two equations we find

$$V_s - V_{out}/A_\upsilon = V_{out}\, R_{F2}/(R_{F1} + R_{F2}), \text{ or}$$

$$V_{out}/V_s = 1/[1/A_\upsilon + R_{F2}/(R_{F1} + R_{F2})] = 1/[(1/A_O)(1 + j\omega\tau_1) + R_{F2}/(R_{F1} + R_{F2})]$$

We can rearrange this by introducing the *feedback ratio* $\beta_{FB} = R_{F2}/(R_{F1} + R_{F2})$

$$V_{out}/V_s = A_O/[\,1 + \beta_{FB} A_O + j\omega\tau_1]\ , \text{ or}$$

$$\frac{V_{out}}{V_s} = \left(\frac{A_O}{1+\beta_{FB}A_O}\right)\frac{1}{\left(1+\frac{j\omega\tau_1}{1+\beta_{FB}A_O}\right)} \qquad (2)$$

From Eq. (2) we see that due to the feedback the mid-band gain has dropped from

$$\frac{V_{out}}{V_s} = A_O \qquad \text{to} \qquad \frac{V_{out}}{V_s}(FB) = \left(\frac{A_O}{1+\beta_{FB}A_O}\right)$$

while the bandwidth has increased from

$$f_C = 1/(2\pi\tau_1) \qquad \text{to} \quad f_C(FB) = [1 + \beta_{FB}A_O)/(2\pi\tau_1)$$

while the *gain-bandwidth product* changed from

$$A_O/(2\pi\tau_1) \quad \text{to} \quad \left(\frac{A_O}{1+\beta_{FB}A_O}\right)\left(\frac{1+\beta_{FB}A_O}{j\omega\tau_1}\right) = A_O/(2\pi\tau_1)\ .$$

That is, there is ***no change*** in the gain-bandwidth product.

The factor $(1+\beta_{FB}A_O)$ is referred to as the *performance factor,* or (S&S p. 669) the *amount of feedback*, or (S&S p. 671) the *desensitivity factor.*

The gain curves with and without feedback are shown below.

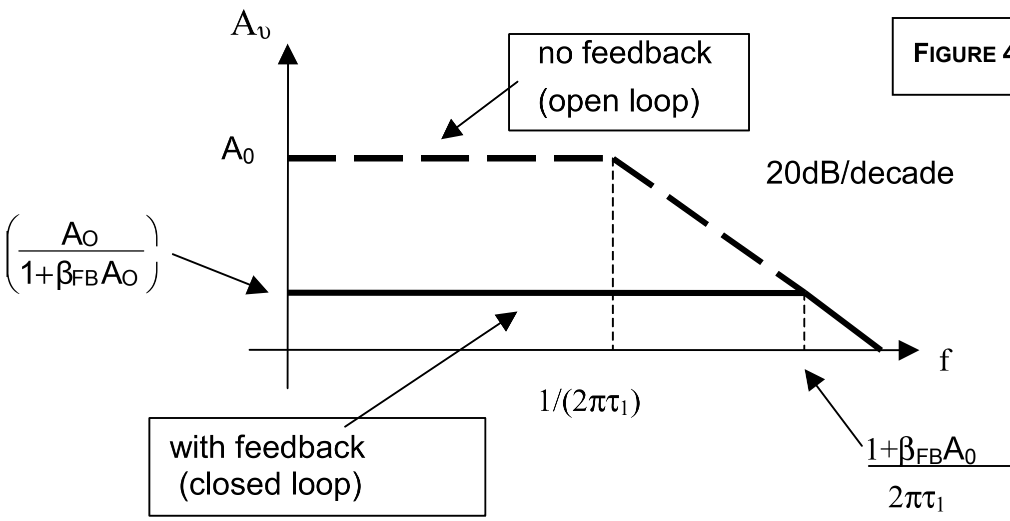


FIGURE 4

Transient Response (Gain-Time Response Trade-off)

Consider the single time constant amplifier shown in Figure 5.

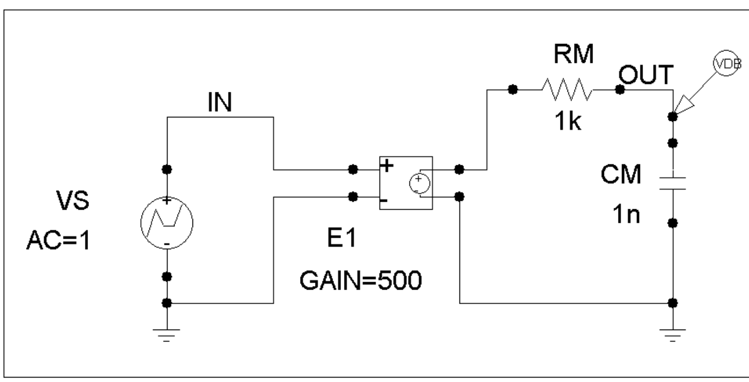


FIGURE 5: PSpice model of single time constant amplifier

The Bode magnitude plot for this amplifier is shown in Fig. 6.

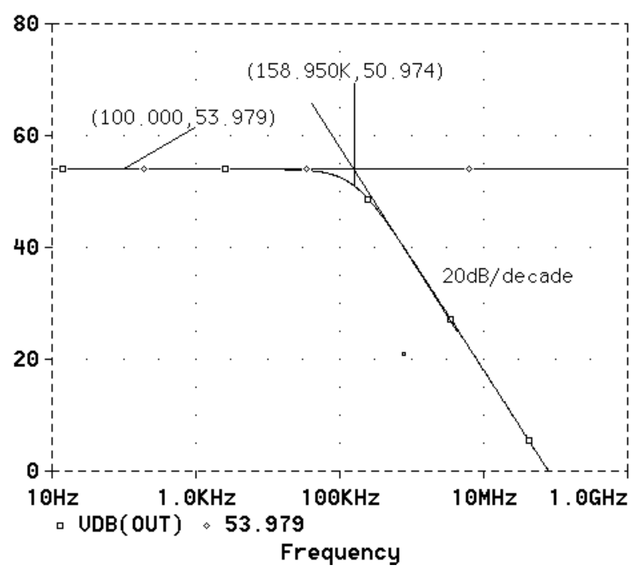


FIGURE 6: Bode magnitude plot for circuit of Fig. 5. The time constant is $\tau_M = R_M C_M = 1\mu s$ and the corner frequency is $f_C = 1/[2\pi\ \tau_M] = 159kHz$.

The response of this amplifier to a step input is shown in Fig. 7. The output rises to $(1-1/e) = 0.6321$ of final value at the time constant $\tau_M = 1\mu s$.

FIGURE 7:
Output voltage vs. time of single time constant amplifier with a step input.

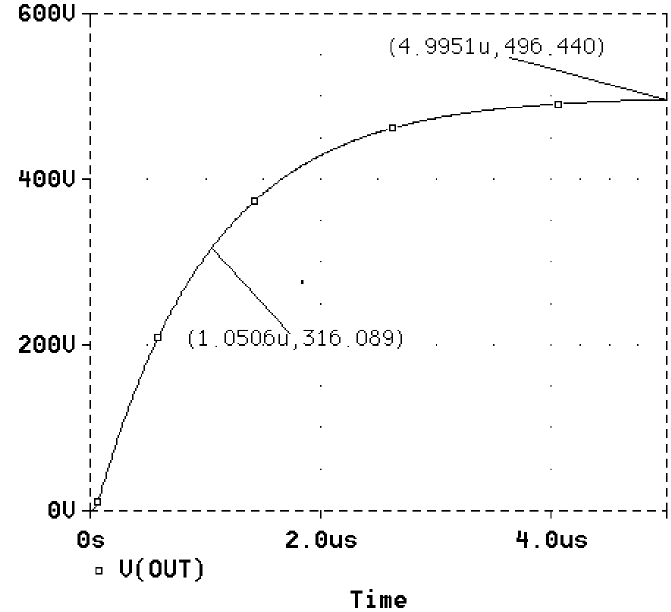
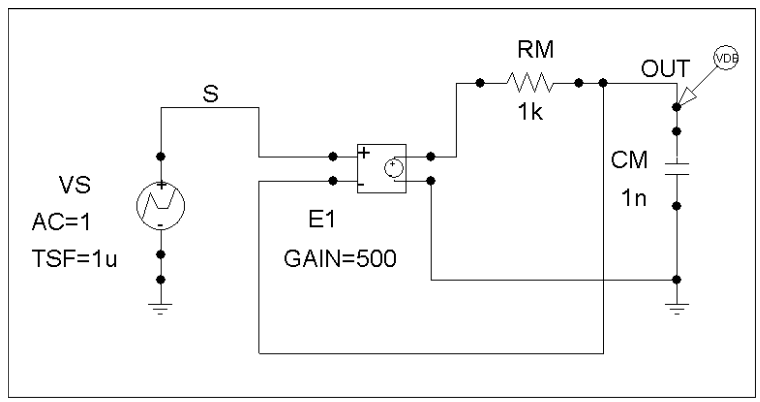
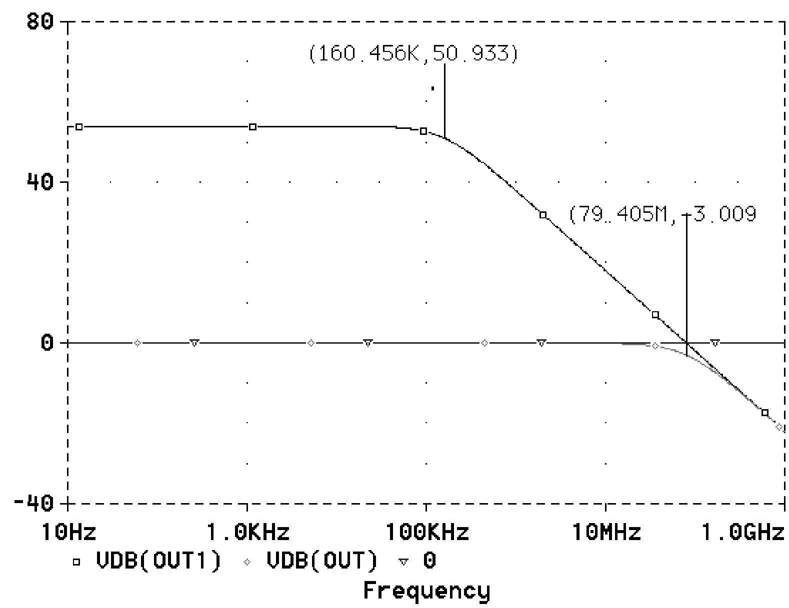


FIGURE 8 :
The single time constant amplifier hooked up with feedback to make a *unity gain voltage buffer.*



Let the amplifier gain be $A(j\omega) = A_0 /(1+j\omega\tau_M)$. Then the output is $V_{OUT}=A(j\omega)V_{IN} = A(j\omega)(V_S–V_{OUT}) \rightarrow V_{OUT} = V_S\ A(j\omega)/[1+A(j\omega)] = V_SA_0 /(1+A_0\ ) x1/\ [1+j\omega\tau_M/(A_0\ +1)]$. That is, the time constant has been shortened by feedback to $\tau_M/(A_0+1) = 1\mu s/(501) \approx 2ns$, and the corner frequency has been increased to $f_c = 1/[2\pi\ \tau_M/(A_0+1)] = (A_0+1)\ /[2\pi\ \tau_M]$ or 501 x 159kHz = 79.7MHz.

FIGURE 9:
The frequency response of the unity gain buffer compared with the original (*open-loop)* amplifier.



Both the open loop and the closed loop systems are single time constant. Feedback has not changed this aspect of the system because the feedback is provided with resistors and so the feedback loop has no frequency dependence of its own.

The wider bandwidth of the feedback system means that it is faster to respond to an input. For example, a step input response is shown in Figure 10. Clearly the closed loop system follows the input better. *We have sacrificed gain for faster response*.

The fast response of the unity gain buffer means that it follows the input step so closely in Fig. 10 that it is the rise time of the step (≈0.1μs) that determines the time to (1-1/e) of final value, and not the time constant τ = 2ns of the buffer.

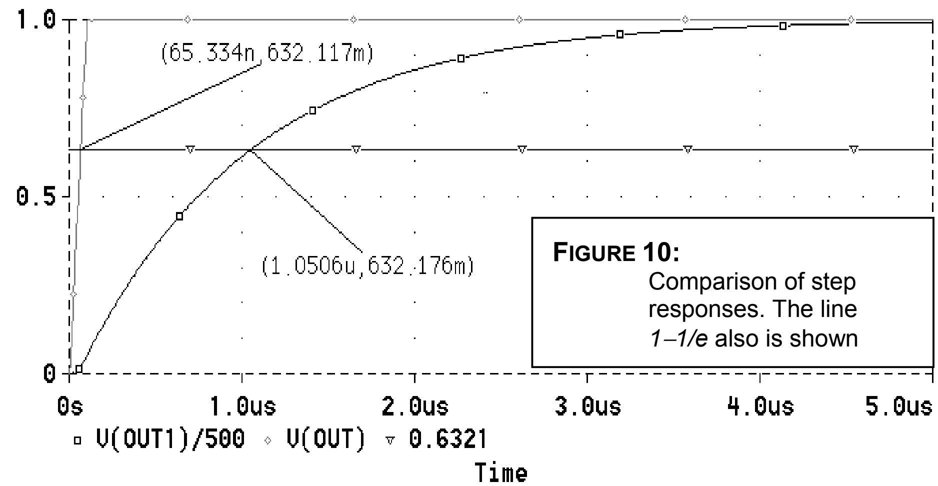


FIGURE 10: Comparison of step responses. The line *1–1/e* also is shown

Feedback and Amplifier Linearity

The use of feedback can make the output of an amplifier more linear. An example is the power amplifier shown below. This is a Class B amplifier, and it exhibits a large dead zone, as we know.

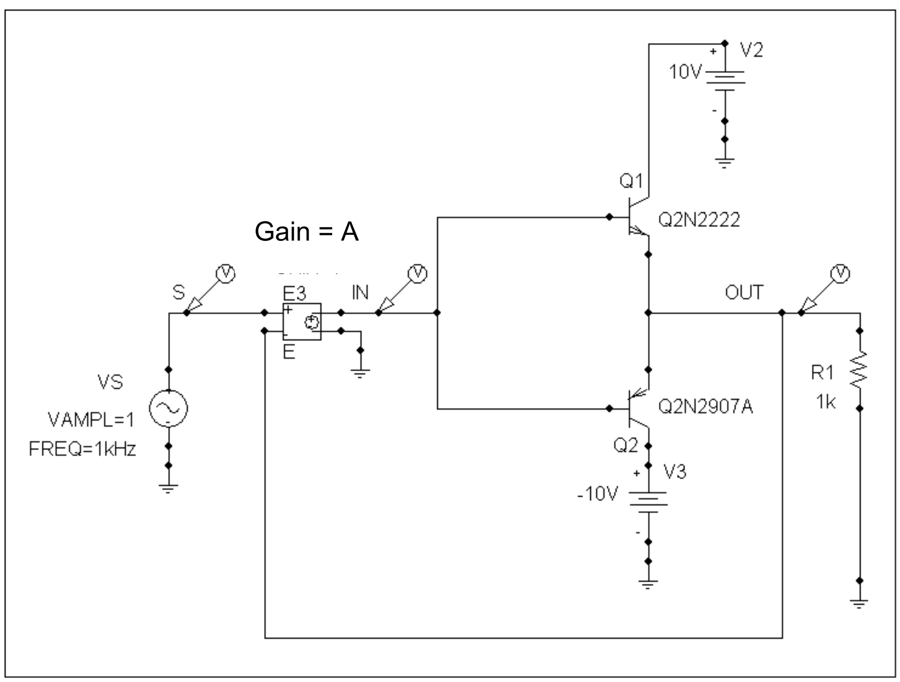
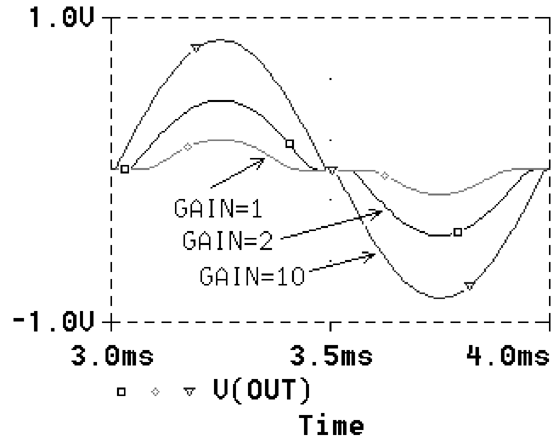


FIGURE 11: Class B power amplifier with a feedback loop.

By introducing extra gain and a feedback loop that senses the output voltage V_{OUT} and subtracts it from the signal voltage V_S (VCVS with Gain=A), the dead zone can be reduced, as shown in Fig. 12 below.

FIGURE 12:
Output of power amplifier with feedback for three values of the gain A of the VCVS



In the dead zone, the gain of the power amplifier is less than 1, say α, and $V_{OUT} = \alpha V_{IN}$. When the gain (let's call it A) of the input VCVS is 1, the input to the power amplifier is $V_{IN} = V_S - V_{OUT} = V_S - \alpha V_{IN} \approx V_S$. The feedback doesn't affect the input much, and no improvement is seen. However, as the gain A increases, the input is $V_{IN} = A(V_S - V_{OUT})$, and the output is $V_{OUT}=\alpha V_{IN} = \alpha A(V_S - V_{OUT}) \rightarrow V_{OUT} = \alpha A V_S/(1+\alpha A)$. For $\alpha A \gg 1$, $V_{OUT} \rightarrow V_S$, that is, the output *follows the input linearly*, with no dead zone.

Some Feedback Information

Amplifier Type	Delivers	R_i (ideal)	R_i (FB)	R_O(ideal)	R_O(FB)	Gain Open Loop	Gain (FB)	FB Hook-up (input)	FB Hook-up (output)
Current	I	0	R_i/PF	∞	R_O x PF	A_i	A_i/PF	shunt (//'ℓ)	series
Trans R	V	0	R_i/PF	0	R_O/PF	A_r	A_r/PF	shunt (//'ℓ)	shunt
Trans G	I	∞	R_i x PF	∞	R_O x PF	A_g	A_g/PF	series	series
Voltage	V	∞	R_i x PF	0	R_O/PF	A_υ	A_υ/PF	series	shunt

Here PF $\equiv$ performance factor = $1+\beta_{FB} A$, where A=gain, and β_{FB} is the feedback factor.

To remember shunt or series hook-up at the input, think that parallel resistors lower resistance, so shunt connection reduces R_i, while series connection increases resistance, so series connection makes R_i larger.

At the output, think of the feedback as tending to maintain the output variable at a constant level. So, for voltage output, voltage will tend to be constant ($R_{THEVENIN} = R_O$ reduced, use shunt connection). For current output, current will tend to be constant ($R_{NORTON} = R_O$ increased, use series connection).

Amplifier type	Gain dimensions (O/I)	β_{FB} dimensions (I/O)	Feedback two-port
Current	A/A = dimensionless	A/A $\rightarrow$ CCCS	g-equivalent
Trans R	V/A = Ω	A/V $\rightarrow$ VCCS S	y-equivalent
Trans G	A/V = S	V/A $\rightarrow$ CCVS	z-equivalent
Voltage	V/V = dimensionless	V/V $\rightarrow$ VCVS	h-equivalent

Important Note

Remember that the performance factor is a *number*, that is, has no dimensions. Therefore, $\beta_{FB}A$ must be a number, and so the dimensions of β_{FB} must be the *inverse* of the dimensions of A.