PDHonline Course E278 (3 PDH)

Operational Amplifiers at Higher Frequencies

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APPENDIX I

DERIVATION OF EQ. (6-1)

Figure 2-4 of Chapter 2 shows that an Op Amp is equivalent to a signal source $(A_{VOL})V_{id}$ in series with a resistance (R_o), as the load (R_L) "sees" it. An Op Amp also has internal capacitances. Their effect on the Op Amp's output characteristics is the same as the effect of a single *equivalent* capacitance C that is across the output and ground (see Fig. I-1). At low frequencies, the reactance of this capacitance C is so large that it acts like an open and has no influence on the amplitude of the output signal voltage V_o. At higher frequencies, however, the reactance of C decreases, causing the amplitude of the output V_o to decrease. A typical V_o vs. frequency curve is shown in Fig. I-2. Such curves can be plotted by measuring V_o with various frequencies of input signals V_s, while the amplitude of the input signal V_s is kept constant. Note that f_c is the frequency at which V_o decreases to 0.707 of its maximum value. This is a 3-dB decrease. Frequency f_c is called the *critical frequency*, *cutoff frequency*, *half-power frequency*, or *3-dB-down frequency*, to name just a few of the more common terms. As shown in Fig. I-2, f_c is the upper limit of an amplifier's bandwidth.

In the equivalent circuit of Fig. I-1, the reactance of C is equal to the resistance of R at the frequency f_c. Since, generally,

$$X_c = \frac{1}{2\pi f C},$$

then

$$X_c = R = \frac{1}{2\pi f_c C},$$

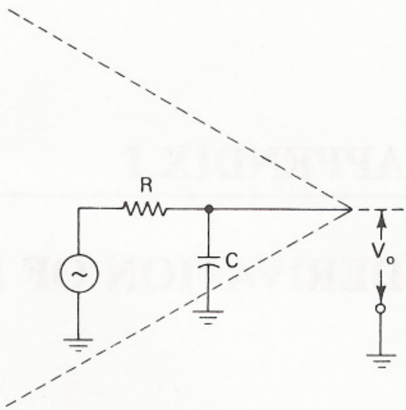

Figure I-1

and therefore,

$$f_c = \frac{1}{2\pi RC}. \qquad (9\text{-}6)$$

Since Op Amps can amplify down to 0 Hz and f_c marks the upper limit of the bandwidth, we can show that the bandwidth BW = f_c. The above equation can thus be modified to

$$\text{BW} = \frac{1}{2\pi RC}. \qquad (\text{I-1})$$

If a relatively high frequency square wave is applied to the input of an amplifier, the equivalent circuit and resulting output are as shown in Fig. I-3a and b. Note that V_o rises to $0.1V_{max}$ at time t_1 and that V_o reaches $0.9V_{max}$ at

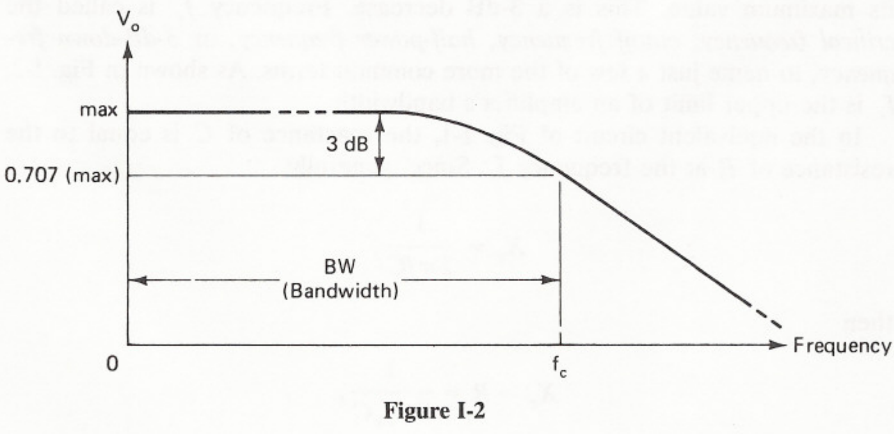

Figure I-2

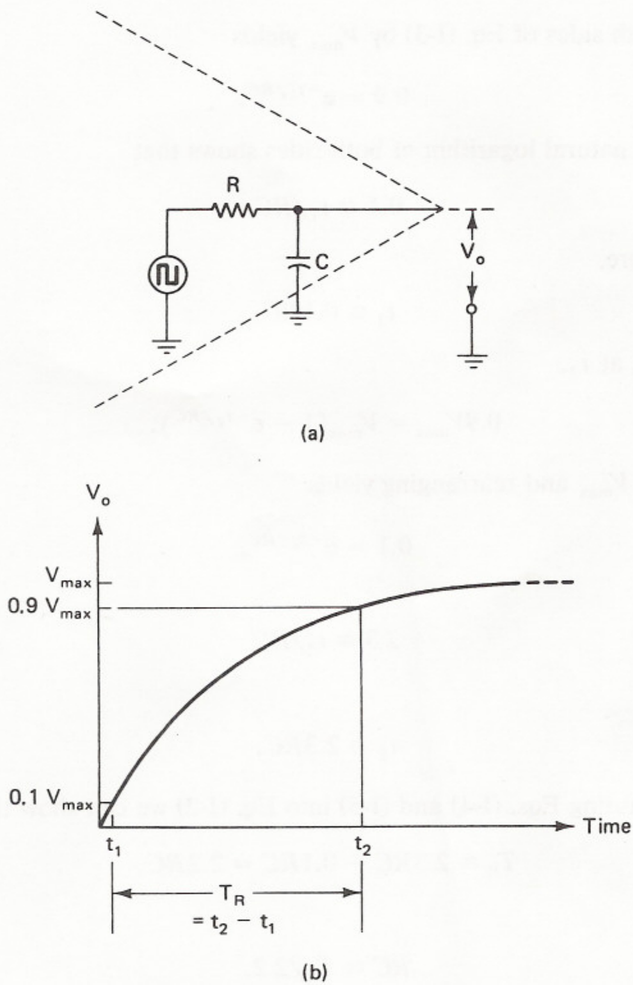

Figure I-3

t_2. Therefore, the rise time

$$T_R = t_2 - t_1. \tag{I-2}$$

Since this output rises exponentially, it can generally be expressed with the equation

$$V_{o(t)} = V_{\max}(1 - e^{-t/RC}).$$

Specifically at time t_1, then,

$$0.1V_{\max} = V_{\max}(1 - e^{-t_1/RC}). \tag{I-3}$$

Dividing both sides of Eq. (I-3) by V_{max} yields

$$0.9 = e^{-t_1/RC}.$$

Finding the natural logarithm of both sides shows that

$$0.1 \cong t_1/RC,$$

and, therefore,

$$t_1 \cong 0.1RC. \tag{I-4}$$

Similarly, at t_2,

$$0.9V_{max} = V_{max}(1 - e^{-t_2/RC}).$$

Dividing by V_{max} and rearranging yields

$$0.1 = e^{-t_2/RC},$$

and, thus

$$2.3 \cong t_2/RC$$

and

$$t_2 \cong 2.3RC. \tag{I-5}$$

By substituting Eqs. (I-4) and (I-5) into Eq. (I-2) we can show that

$$T_R \cong 2.3RC - 0.1RC = 2.2RC,$$

and thus

$$RC \cong T_R/2.2.$$

This last equation substituted into Eq. (I-1) gives us

$$BW \cong \frac{1}{2\pi T_R/2.2}$$

or

$$BW \cong \frac{0.35}{T_R}. \tag{6-1}$$

Similar algebraic steps will show that also $BW \cong 0.35/T_F$.