Small-Signal Analysis of the 741

We can analyze the small-signal voltage gain of the 741 op-amp by dividing it into its basic circuits and using results previously obtained in the DC analysis.
The Input Stage

\[ i_e = \frac{v_i}{4r_e} \]

\[ r_e = \frac{V_T}{I} = \frac{25 \text{ mV}}{9.5 \mu\text{A}} = 2.63 \text{ k}\Omega \]

\[ R_{id} = 4(\beta_N + 1)r_e \]

For \( \beta_N = 200 \), \( R_{id} = 2.1 \text{ M}\Omega \)
The load circuit of the input stage

\[ i_o = 2\alpha i_e \]

\[ G_{m1} = \frac{i_o}{v_i} = \frac{\alpha}{2r_e} \]
Finding $R_{o5}$ and $R_{o6}$

\[
R_o = r_o [1 + g_m (R_E // r_\pi)]
\]

$R_E = r_e = 2.63 \text{ k}\Omega$

$r_o = V_A / I; V_A = 50 \text{ V}; I = 9.5 \mu\text{A}$

$R_{o4} = 10.5 \text{ M}\Omega; R_{o6} = 18.2 \text{ M}\Omega$

$R_{o4} // R_{o6} = R_{o1} = 6.7 \text{ M}\Omega$
Example: Determine the small-signal differential voltage gain of the 741 op-amp input stage. Assume transistor gain of $\beta = 200$ and Early voltages of $V_A = 50$ V.
\[ A_d = -g_m \left( r_{o4} \parallel R_{ac1} \parallel R_{i2} \right) = \frac{I_{CQ}}{V_T} \left( r_{o4} \parallel R_{ac1} \parallel R_{i2} \right) \]

\[ R_{ac1} = r_{o6} \left[ 1 + g_m \left( R_2 \parallel r_\pi 6 \right) \right] \]

\[ R_{i2} = r_\pi 16 + (\beta + 1) R_E \]

\[ R_E = R_9 \parallel \left[ r_\pi 17 + (\beta + 1) R_8 \right] \]

\[ r_\pi 17 = \frac{\beta V_T}{I_{C17}} = \frac{200 \times 0.026}{0.54} = 9.63 \text{ k} \Omega \]

\[ R_E = 50 \parallel \left[ 9.63 + (201)(0.1) \right] = 18.6 \text{ k} \Omega \]

\[ r_\pi 16 = \frac{\beta V_T}{I_{C16}} = \frac{200 \times 0.026}{0.0158} = 329 \text{ k} \Omega \]

\[ R_{i2} = 329 + (201)(18.6) = 4.07 \text{ M} \Omega \]

\[ r_\pi 6 = \frac{\beta V_T}{I_{C6}} = \frac{200 \times 0.026}{0.0095} = 547 \text{ k} \Omega \]

\[ g_m 6 = \frac{I_{C6}}{V_T} = \frac{0.0095}{0.026} = 0.365 \text{ mA/V} \]
\[ r_{o6} = \frac{V_A}{I_{C6}} = \frac{50}{0.0095} = 5.26 \text{ MΩ} \]

\[ R_{act1} = 5.26[1 + 0.365(1/547)] = 7.18 \text{ MΩ} \]

\[ r_{o4} = \frac{V_A}{I_{C4}} = \frac{50}{0.0095} = 5.26 \text{ MΩ} \]

\[ A_d = -\left(\frac{9.5}{0.026}\right)(5.26//7.18//4.07) = -636 \]
The Gain (Second) Stage

\[ R_{i2} = (\beta_{16} + 1)[r_{e16} + R_9 // (\beta_{17} + 1)(r_{e17} + R_8)] \]

\[ R_{o2} = (R_{o13B} // R_{o17}) = 81 \, k\Omega \]

\[ R_{o13B} = r_{o13B} \]
The Output Stage

\[ v_{o\text{max}} = \bar{V}_C C - V_{CE\text{sat}} - V_{BE14} \]

\[ v_{o\text{min}} = -V_{EE} + V_{CE\text{sat}} + V_{EB23} + V_{EB20} \]
Circuit for Finding the Output Resistance $R_{out}$
Gain, Frequency Response, and Slew Rate of the 741

\[ \frac{v_o}{v_i} = \frac{v_{i2}}{v_i} \frac{v_{o2}}{v_{o2}} \]

\[ -G_{m1} \left( R_{o1} \parallel R_{12} \right) \left( -G_{m2} R_{o2} \right) G_{vo3} \frac{R_L}{R_L + R_{out}} \]

\[ A_o = 243147 \text{ V/V} \]
Frequency Response

\[ C_{in} = C_C (1 + |A_2|) \]

\[ R_t = (R_{o1} \parallel R_{i2}) = (6.7 \, \text{M}\Omega \parallel 4 \, \text{M}\Omega) = 2.5 \, \text{M}\Omega \]

\[ f_p = \frac{1}{2\pi C_{in} R_t} = 4.1 \, \text{Hz} \]

\[ A_0 = 107.7 \, \text{dB} \]

\[ f_{3\,\text{dB}} \approx 4.1 \, \text{Hz} \]

\[ f_i = A_0 f_{3\,\text{dB}} = 1 \, \text{MHz} \]
A Simple Model of the 741

\[ A(s) = \frac{V_o(s)}{V_i(s)} = \frac{G_{m1}}{sC_C} \]

\[ A(j\omega) = \frac{G_{m1}}{j\omega C_C}; \quad \omega t = \frac{G_{m1}}{C_C} \]
Slew Rate

\[ v_o(t) = \frac{2I}{C_C} t \]

\[ SR = \frac{2I}{C_C} \]

\[ v_i(t) \pm 10 \text{ V} \]

\[ v_o(t) \]

\[ i_{c6} = 2I \]