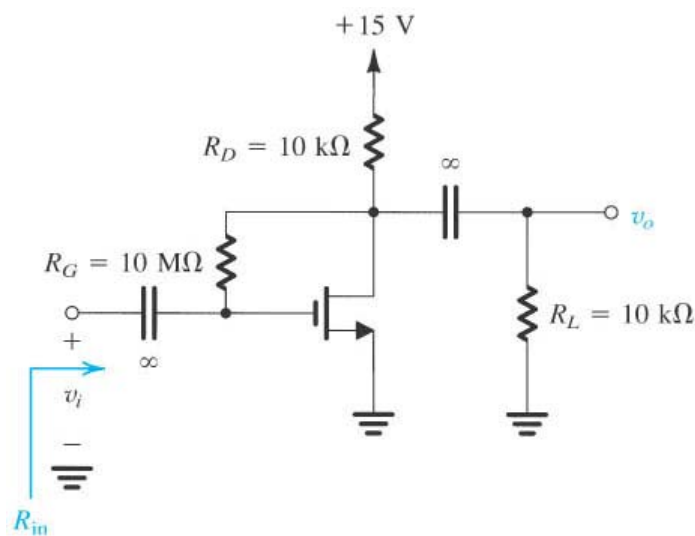


Lecture 29: MOSFET Small-Signal Amplifier Examples.

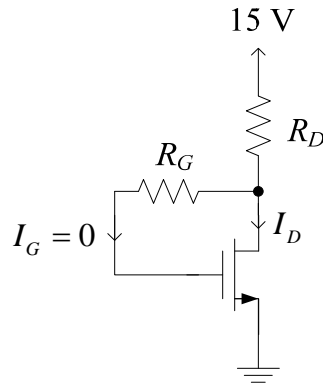
We will illustrate the analysis of small-signal MOSFET amplifiers through two examples in this lecture.

Example N29.1 (text Example 7.3). Determine A_v (neglecting the effects of R_G), R_{in} , and R_{out} for the circuit below given that $V_t = 1.5$ V, $k_n' W/L = 0.25$ mA/V², and $V_A = 50$ V.



(Fig. 7.15)

The first step is to determine the **DC operating point**. The DC equivalent circuit is:



Since $V_{GD} = 0 < V_t$ the MOSFET is operating in the saturation mode if $I_D \neq 0$. Assuming operation in the saturation mode the DC drain current from (5.23) is

$$I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2 (1 + \lambda V_{DS}) \quad (5.23)$$

Notice in the circuit that $V_{GS} = V_{DS}$, so we will eventually create a triatic equation in V_{GS} for I_D .

However, the last factor in (5.23) will be quite small for large V_A (small λ). So, for simplicity we will neglect r_o in (5.23) giving

$$I_D \approx \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2 \quad (7.44)$$

For this DC circuit

$$I_D = \frac{1}{2} \cdot 0.25 \times 10^{-3} (V_{GS} - 1.5)^2 = 1.25 \times 10^{-4} (V_{GS} - 1.5)^2$$

Notice in the circuit that $V_{GS} = V_{DS}$ so that this last equation becomes

$$I_D = 0.125 (V_{DS} - 1.5)^2 \text{ mA} \quad (1)$$

Also, by KVL

$$V_{DS} = 15 - R_D I_D = 15 - 10,000 I_D \quad (7.43), (2)$$

Substituting (2) into (1)

$$I_D = 1.25 \times 10^{-4} (15 - 10,000 I_D - 1.5)^2$$

Solving this equation gives

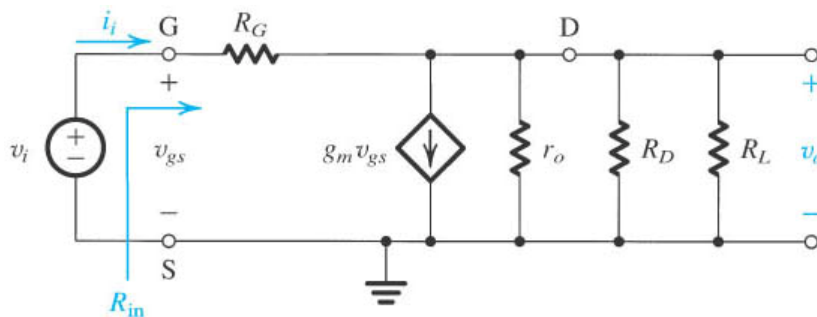
$$I_D = 1.06 \text{ mA} \Rightarrow V_{DS} = 4.4 \text{ V} (= V_{GS})$$

or

$$I_D = 1.72 \text{ mA} \Rightarrow V_{DS} = -2.2 \text{ V} (= V_{GS})$$

This latter result is **not consistent** with the assumption of operation in the saturation mode since $V_{GS} < V_t = 1.5 \text{ V}$. So the **proper solution** for I_D is the first ($I_D = 1.06 \text{ mA}$).

Next, we construct the small-signal equivalent circuit. We'll use the π small-signal model of the MOSFET with r_o included:



(Fig. 7.15c)

$$\checkmark g_m = k_n' \frac{W}{L} (V_{GS} - V_t) = 0.25 \times 10^{-3} (4.4 - 1.5) = 0.725 \text{ mS}$$

$$\checkmark r_o = \frac{V_A}{I_D} = \frac{50}{1.06 \text{ mA}} = 47.2 \text{ k}\Omega$$

Recall from the previous lecture that the proper I_D in the r_o calculation is that with $\lambda = 0$, which is what we ended up calculating earlier.

To compute the **small-signal voltage gain**, we start at the output (assuming R_G is extremely large $R_G \gg r_o \parallel R_D \parallel R_L$)

$$v_o \approx -g_m v_{gs} (r_o \parallel R_D \parallel R_L)$$

At the input notice that $v_{gs} = v_i$. Therefore

$$A_v = \frac{v_o}{v_i} \approx -g_m (r_o \parallel R_D \parallel R_L) = -g_m (4,521) = -3.28 \text{ V/V}$$

Notice that the assumption $R_G \gg r_o \parallel R_D \parallel R_L$ is met and hugely exceeded since $10 \text{ M}\Omega \gg 4,521 \Omega$.

For the input resistance R_{in} calculation, we cannot set $v_{gs} = 0$ – and subsequently open circuit the dependent current source – since this would artificially force $R_{in} = 0$. Rather, we need to **determine i_i as a function of v_i** and use this in the definition:

$$R_{in} \equiv \frac{v_i}{i_i}$$

The dependent current source will remain in these calculations.

Proceeding, at the input of the small-signal equivalent circuit shown above

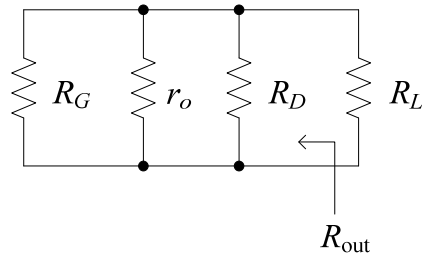
$$i_i = \frac{v_i - v_o}{R_G} = \frac{v_i}{R_G} \left(1 - \frac{v_o}{v_i} \right) = \frac{v_i}{R_G} (1 - A_v)$$

Therefore,
$$i_i = \frac{v_i}{R_G} (1 + 3.28)$$

Consequently, using this expression we find that

$$R_{in} = \frac{v_i}{i_i} = \frac{R_G}{4.28} = 2.34 \text{ M}\Omega$$

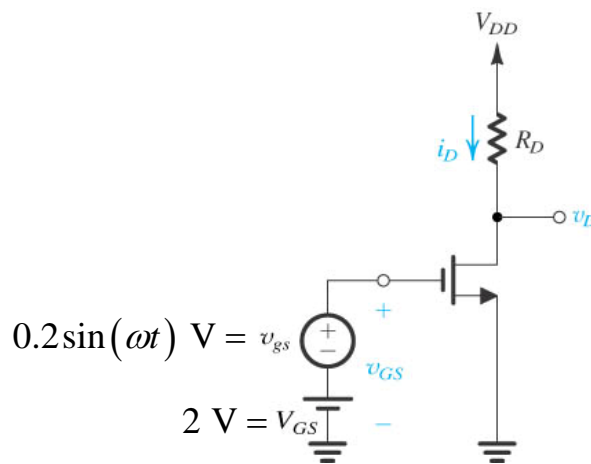
Lastly, to determine the output resistance, we can set $v_{gs} = 0$ in the small-signal equivalent circuit above, which will open circuit the dependent current source leading to the equivalent circuit:



from which we see that

$$R_{out} = R_G \parallel r_o \parallel R_D = 8.24 \text{ k}\Omega$$

Example N29.2 (text Exercise 7.6). Determine the following quantities for the conceptual MOSFET small-signal amplifier of Fig. 7.4 given that $V_{DD} = 5 \text{ V}$, $R_D = 10 \text{ k}\Omega$, and $V_{GS} = 2 \text{ V}$.



(Fig. 7.4)

The MOSFET characteristics are $V_t = 1 \text{ V}$, $k_n' = 20 \mu\text{A}/\text{V}^2$, $W/L = 20$, and $\lambda = 0$.

- (a) Determine I_D and V_D . We see from the circuit that $V_{GS} > V_t$. Therefore, the MOSFET is operating in the saturation or triode mode. We'll **assume saturation**. In that case

$$I_D = \frac{1}{2} k_n' \frac{W}{L} (V_{GS} - V_t)^2 = \frac{1}{2} \cdot 20 \times 10^{-6} \cdot 20 (2 - 1)^2 = \mathbf{0.2 \text{ mA}}$$

$$\text{and} \quad V_D = V_{DD} - I_D R_D = \mathbf{3 \text{ V}}$$

Let's check if the MOSFET is operating in the saturation mode:

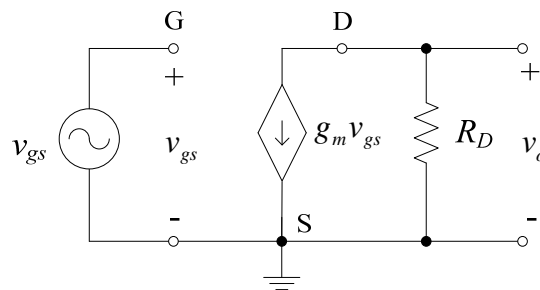
$$V_{GD} = 2 - 3 = -1 < V_t$$

Therefore, the MOSFET is **indeed saturated**, as assumed.

- (b) Determine g_m . Using (7.32)

$$g_m = k_n' \frac{W}{L} (V_{GS} - V_t) = 20 \times 10^{-6} \cdot 20 \cdot (2 - 1) = \mathbf{4.0 \text{ mS}}$$

- (c) Determine the voltage gain A_v . We begin by first constructing the **small-signal equivalent circuit**



Directly from this circuit,

$$v_o = -g_m v_{gs} R_D$$

$$\text{so } A_v = \frac{v_o}{v_{gs}} = -g_m R_D = -0.4 \times 10^{-3} \cdot 10 \times 10^3 = -4 \text{ V/V}$$

(d) If $v_{gs} = 0.2 \sin(\omega t)$ V, find v_d and the max/min v_D .

$$A_v \equiv \frac{v_o}{v_{gs}} \Rightarrow v_d = A_v v_{gs} = -4 \cdot 0.2 \sin(\omega t)$$

Therefore, $v_d = -0.8 \sin(\omega t)$ V

Hence, $v_D|_{\max} = V_D + V_d = 3 + 0.8 = 3.8$ V

while $v_D|_{\min} = V_D - V_d = 3 - 0.8 = 2.2$ V

(e) Determine the **second harmonic distortion**. From (7.28) or (6) in the previous lecture notes, the drain current is given as

$$i_D = I_D + k_n' \frac{W}{L} (V_{GS} - V_t) v_{gs} + \frac{1}{2} k_n' \frac{W}{L} v_{gs}^2$$

$$\begin{aligned} \text{or } i_D &= I_D + 20 \times 10^{-6} \cdot 20(2-1)v_{gs} + \frac{1}{2} \cdot 20 \times 10^{-6} \cdot 20v_{gs}^2 \\ &= I_D + 0.4 \times 10^{-3} v_{gs} + 0.2 \times 10^{-3} v_{gs}^2 \end{aligned}$$

Substituting $v_{gs} = 0.2 \sin(\omega t)$ into this equation gives

$$i_D = I_D + 80 \times 10^{-6} \sin(\omega t) + 8 \times 10^{-6} \sin^2(\omega t)$$

Using the trigonometry identity

$$\sin^2(\omega t) = 1/2 - 1/2 \cos(2\omega t)$$

this last expression becomes

$$i_D = 200 + 80 \sin(\omega t) + 4 - 4 \cos(2\omega t) \mu\text{A}$$

or $i_D = 204 + 80 \sin(\omega t) - 4 \cos(2\omega t) \mu\text{A}$

The first term in i_D is I_D , the DC current. We see that there is a slight shift upward in value by $4 \mu\text{A}$.

The third term in i_D is the second harmonic term because it varies with time at twice the frequency of the input signal.

The second harmonic distortion is

$$\frac{4}{80} \times 100\% = 5\%$$