High Frequency response of FET amplifier

At high frequency interelectrode and wiring capacitances are also provided to the FET amplifier.

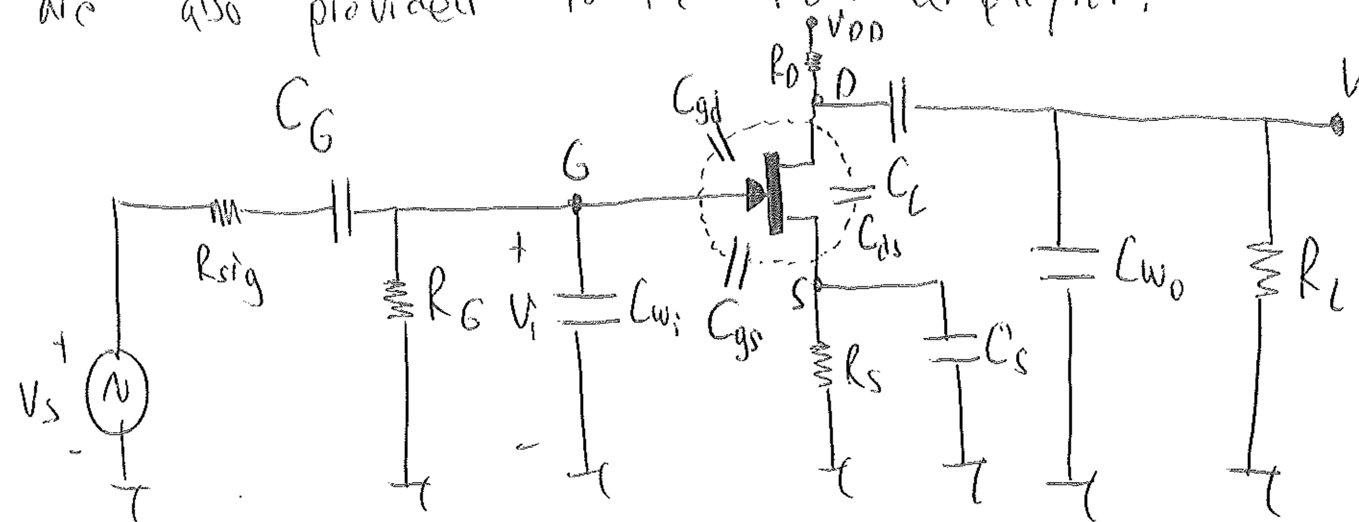


Figure: Capacitive elements that effect high-frequency response of FET amplifier

C_{gs}, C_{gd}, C_{ds} → parasitic capacitance between terminals of FET at high frequencies

C_{gs} and C_{gd} typically vary from 1pf to 10pf.

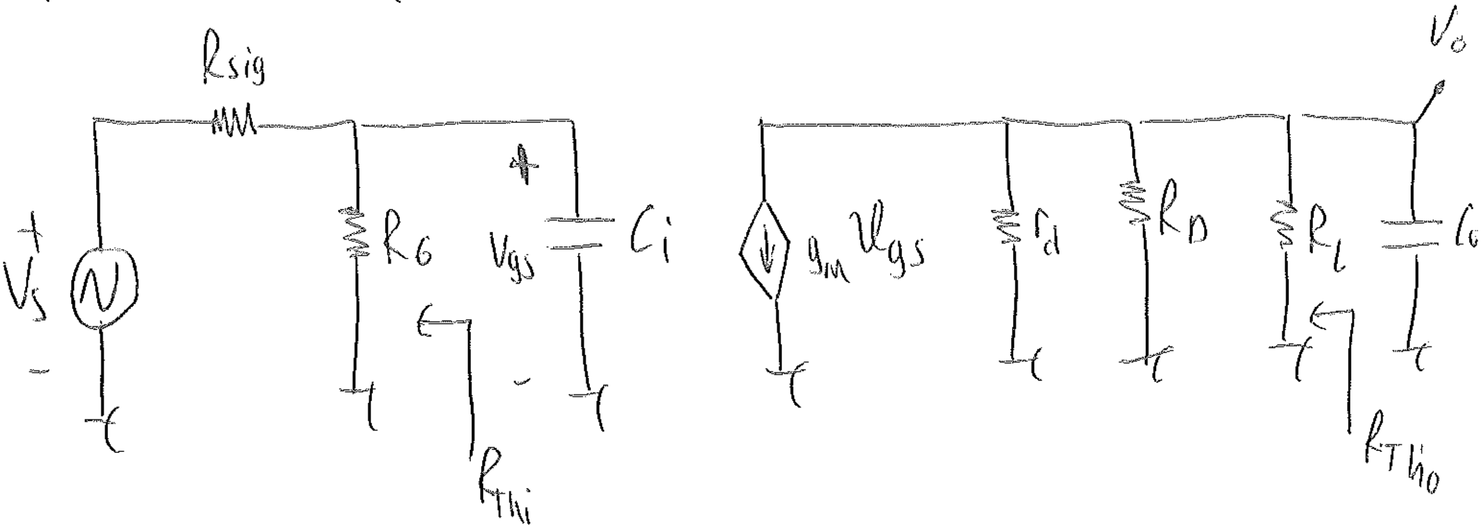
C_{ds} is generally smaller ranging between 0.1pf to 1pf.

C_{wi} → input wiring capacitance

C_{wo} → output wiring capacitance

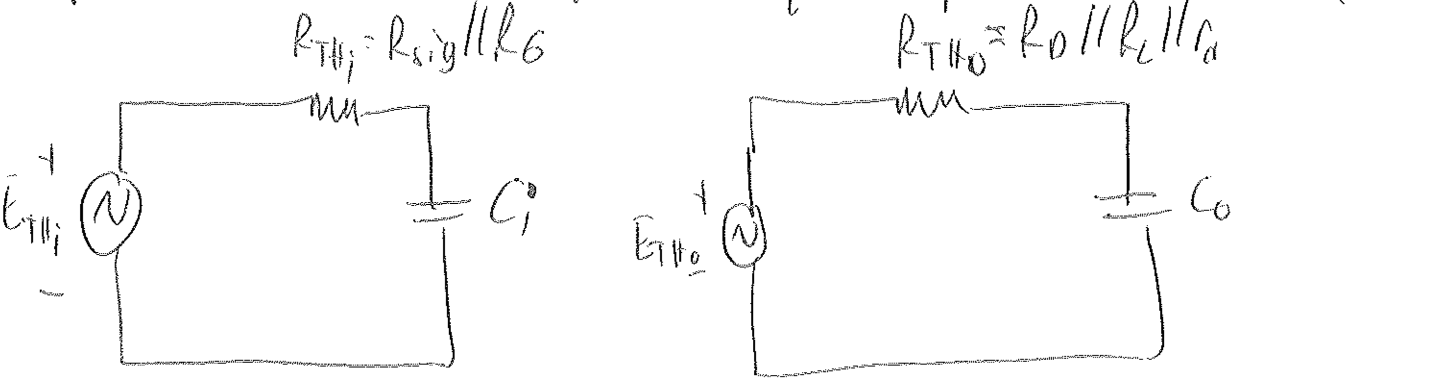
The FET amplifier in the figure above is an inverting amplifier. It has also a miller effect capacitance due to C_{gd}.

The ac equivalent circuit will have the circuit representation below:



In the circuit above C_i is the equivalent input capacitance and C_o is the equivalent output capacitance

find the thevenin equivalent parts of the circuit above



The equations for C_i and C_o in FET amplifier similar to the equations of C_i and C_o computed for BJT amplifier.

$R_{THi} = R_{sig} \| R_G$ → Thevenin input resistance

$C_i = C_{w_i} + C_{gs} + C_{M_i}$ where $C_{M_i} = (1 - A_v) C_{gd}$

miller effect capacitance at input side

$$f_{H_i} = \frac{1}{2\pi R_{TH_i} C_i}$$ → High frequency range cut-off frequency due to input-side circuit of FET amplifier.

$R_{TH_o} = R_D \| R_L \| r_d$ → Thevenin output resistance

$C_o = C_{w_o} + C_{ds} + C_{M_o}$ where $C_{M_o} = \left(1 - \frac{1}{A_v}\right) C_{gd}$

↳ miller effect capacitance at output side

$$f_{H_o} = \frac{1}{2\pi R_{TH_o} C_o}$$ → High frequency range cut-off frequency due to output-side circuit of FET amplifier.

Choose the smallest of f_{H_o} and f_{H_i} to determine approximately the ~~cut-off~~ high frequency range cut-off frequency of the ~~fet~~ FET amplifier.

Multistage Frequency Effects

- There will be significant changes when a second stage amplifier is connected to a first stage amplifier.
- C_o should include (C_{w_1}) ⇒ the wiring capacitance
  C_{be} → the parasitic capacitance
  C_{M_i} → the miller capacitance
  of the second stage at this case
- There will be additional low-frequency cut-off levels due to second stage, that will diminish the overall gain in this region.
- for each additional stage, the upper cut-off frequency will be determined primarily by the stage having lowest cut-off frequency,
- The low-frequency cut-off frequency is primarily determined by that stage having the highest low-frequency cut-off frequency.

Assume identical stages, lets determine an equation for each band frequency as a number of stages (n)

For the low frequency region

$$A_{V_{low}(overall)} = A_{V_{1low}} A_{V_{2low}} \ldots A_{V_{n_{low}}}$$

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Since all stages are identical

$Av_{1_{low}} = Av_{2_{low}} = \dots = Av_{n_{low}}$ and $Av_{low,\,overall} = \left(Av_{1_{low}}\right)^n$

$$\frac{Av_{low}}{Av_{mid}}\,(\text{overall } n \text{ stages}) = \left(\frac{Av_{low}}{Av_{mid}}\right)^n = \frac{1}{\left(1 - j\frac{f_1}{f}\right)^n}$$

$$\left|\frac{Av_{low}}{Av_{mid}}\right| = \frac{1}{\sqrt{\left[1 + \left(\frac{f_1}{f}\right)^2\right]^n}}$$

where f_1 is the low ~~cut~~-off frequency for a single stage amplifier

Let f_1' be the low cut-off frequency of n stage amplifier

Then

$$\frac{1}{\sqrt{\left[1 + \left(\frac{f_1}{f_1'}\right)^2\right]^n}} = \frac{1}{\sqrt{2}}$$

$$\Downarrow$$

$$\left[1 + \left(\frac{f_1}{f_1'}\right)^2\right]^n = 2 \longrightarrow 1 + \left(\frac{f_1}{f_1'}\right)^2 = 2^{\frac{1}{n}}$$

$$\boxed{f_1' = \frac{f_1}{\sqrt{2^{\frac{1}{n}} - 1}}} \longrightarrow$$ low cut-off frequency on n stage identical amplifier where f_1 is the low-cut off frequency of a single stage

In the similar manner

$$f_2' = \left[\sqrt{2^{\frac{1}{n}} - 1}\right] f_2$$

where $f_2' \rightarrow$ high frequency cut-off frequency of n stage identical amplifier

$f_2 \longrightarrow$ high frequency cut-off frequency of a single stage amplifier

Square-wave testing

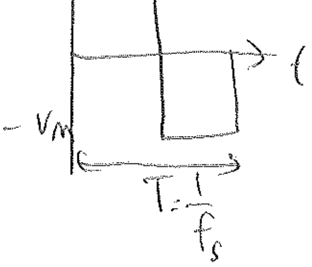
— Apply square wave to estimate the frequency response of an amplifier

— Shape of output waveform will reveal whether the high or low frequencies are being properly amplified

— less time consuming than applying different sinusoidals to find the frequency response

— square wave $\xrightarrow[\text{Fourier series}]{}$ $\sum$ series of sinusoidals with different magnitudes and frequencies

Fourier series expansion of a square wave



$$V(t) = \frac{4}{\pi} V_M \left(\overbrace{\sin(2\pi f_s t)}^{\text{fundamental}} + \overbrace{\frac{1}{3}\sin(2\pi(3f_s)t)}^{\text{third harmonic}} + \overbrace{\frac{1}{5}\sin(2\pi(5f_s)t)}^{\text{fifth harmonic}} + \dots + \underbrace{\frac{1}{n}\sin(2\pi(nf_s)t)}_{n^{th}\text{ harmonic}} \right)$$

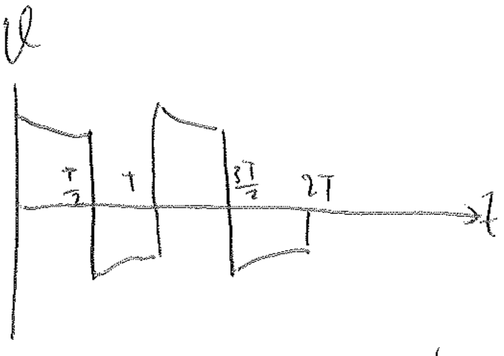
- Ninth harmonic has a magnitude greater than 10% of fundamental form. The fundamental harmonic to ninth harmonic are main contributers of square wave.

- If the application of a square wave of a particular frequency results in a nice clean square wave at the output, then the terms from the fundamental through the ninth harmonic are being amplified without visual distortion by the amplifier

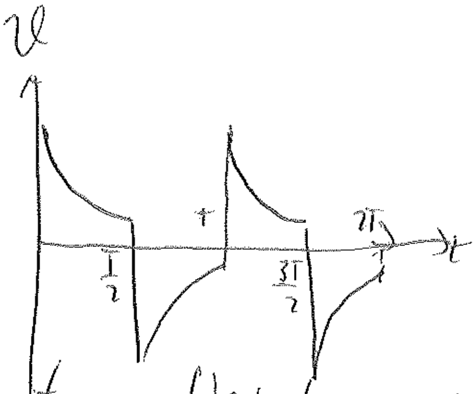
- If an audio amplifier with a bandwidth of 20kHz (audio range is from 20Hz to 20kHz) is to be tested, the frequency of the applied signal should at least be $20kHz/9 = 2.22\ kHz$.

- If the response of an amplifier to an applied square wave is an undistorted replica of the input, the frequency response (or Bandwidth) of the amplifier is obviously sufficient for the applied frequency.

- If the response is as the figures below

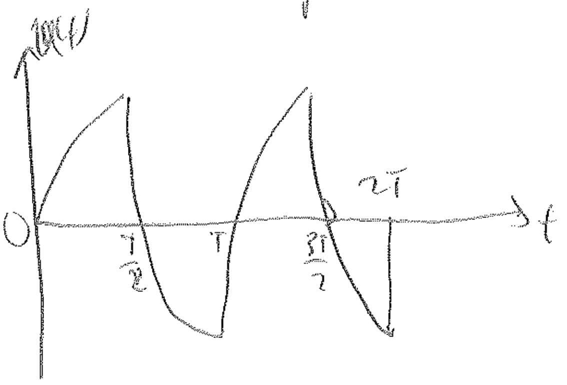


or



the low frequencies are not amplified properly and the low cut-off frequency has to be investigated

- If the waveforms are as below



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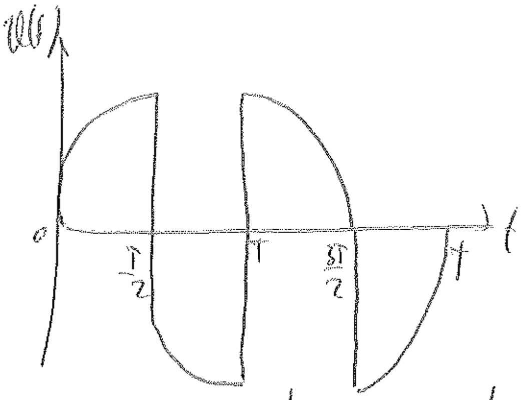
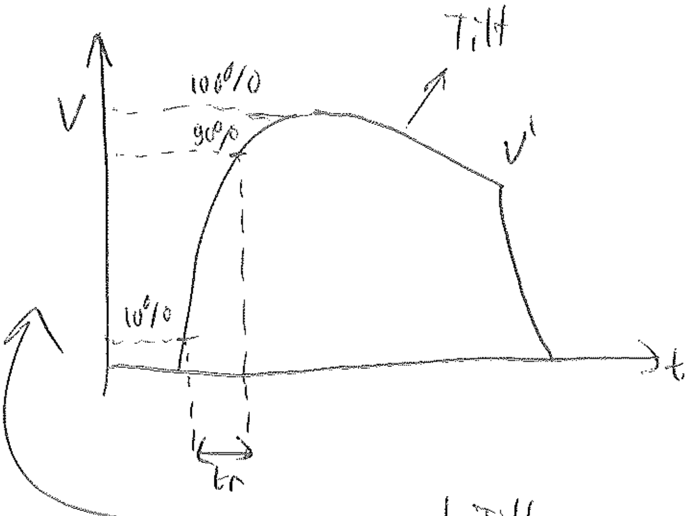


that means high-frequency components are not receiving sufficient amplification and for this reason high cutoff frequency (or bandwidth) has to be reviewed

- The actual high cut-off frequency (or bandwidth) can be determined from the output waveform by measuring rise time (defined %10 and %90 of peak value)



t_r - time passed between the observed outputs such that %10 and %90 of the max output is observed

Rise time and Tilt of square wave response

$$\text{Bandwidth} \cong f_{hi} = \frac{0.35}{t_r}$$

f_{hi} → high cut-off frequency

The low cut-off frequency can be calculated from tilt.

$$\%Tilt = P\% \doteq \frac{V - V'}{V} \times 100\%$$

$$tilt = P = \frac{V - V'}{V} \quad \text{(decimal form)}$$

$$f_{Lo} = \frac{P}{\pi} f_s$$

f_s → frequency of square wave

f_{Lo} → low cut-off frequency