Electronic Circuits Laboratory
EE462G
Lab #6

Small Signal Models: The MOSFET Common Source Amplifier

AC and DC Analysis

Amplifier circuits have DC and AC components that can be analyzed separately.

- The purpose of the DC component is to bias currents and voltages to a static operating point in a region where the input and output relationship is reasonably linear for small deviations about the operating point.

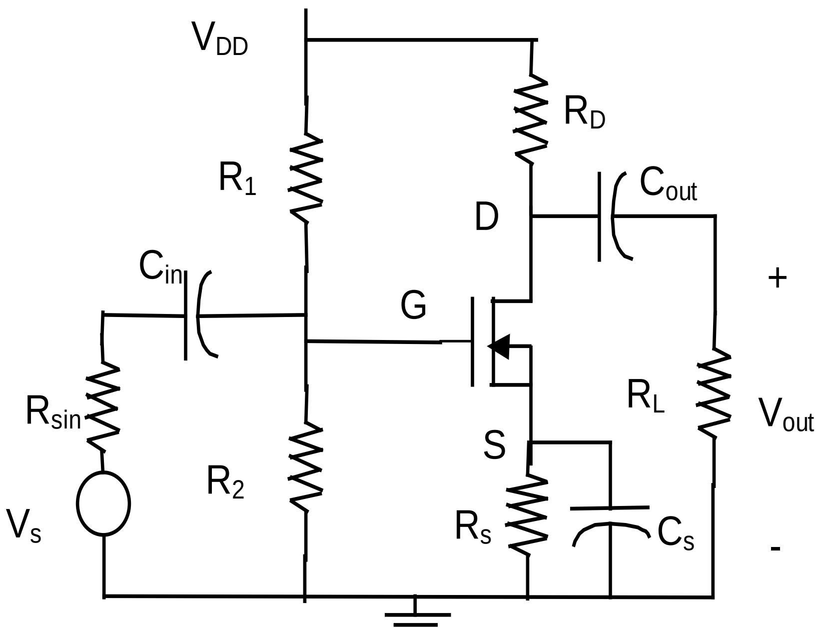
- The purpose of the AC component is to provide gain and/or impedance coupling for the information component of a signal, so it can be measured, processed, or used to drive an output device.

- The AC and DC components can be analyzed separately if the AC components are small relative to the DC components, and blocking capacitors are inserted to block DC biasing voltages and currents from the points at which the AC signal couples to the input and output.

Common Source Amplifier

What would happen if there were no capacitors?

The input and output share a common node at ground through the source of the NMOS transistor. Determine how “good” capacitor values should be chosen to isolate the DC from the AC without significantly affecting the AC operation or DC settings.



For DC blocking, any capacitor value will do:

$$\left|\frac{1}{j\omega C}\right| \to \infty \quad \text{as} \quad \omega \to 0$$

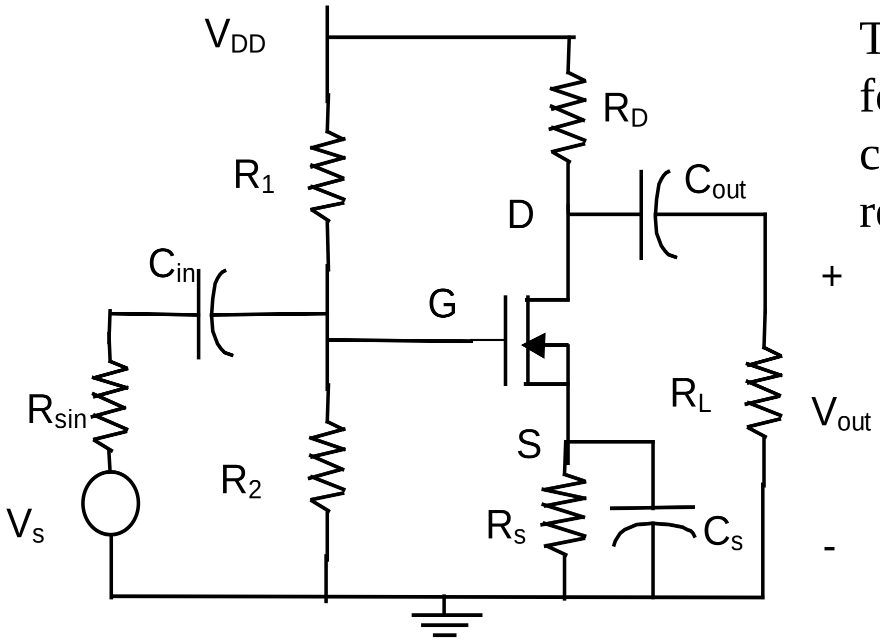
To pass AC components, capacitor impedance should behave as an effective short:

$$\left|\frac{1}{j\omega C_{in}}\right| <<< R_{sin}\ , \quad \left|\frac{1}{j\omega C_s}\right| <<< R_s\ ,$$

$$\left|\frac{1}{j\omega C_{out}}\right| <<< R_L$$

Blocking Capacitors

If the expected frequency of operation was between 300 and 4kHz, determine good capacitor values to isolate the DC from the AC without significantly affecting the AC operation.



The capacitive impedance will be largest for the smallest frequencies, choose worse case, *f*=300 Hz and assume smallest resistor value in circuit to be 500Ω:

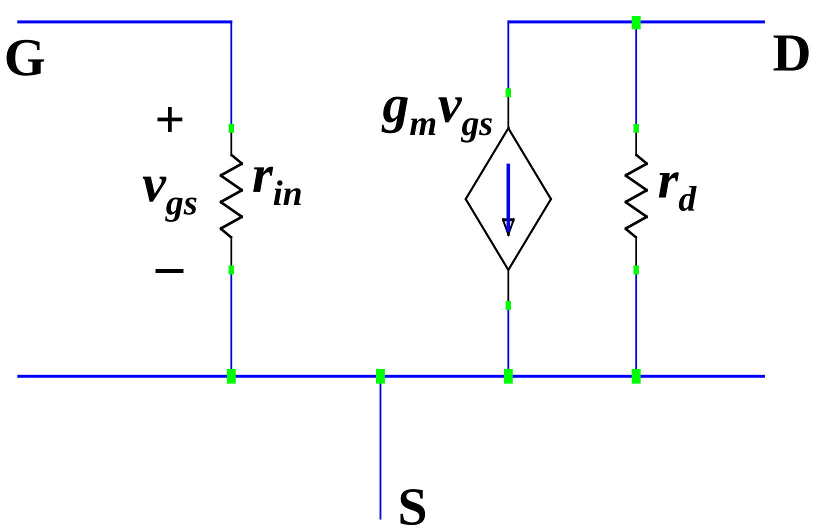
$$\left|\frac{1}{\omega R_{sin}}\right| <<< C$$

$$\left|\frac{1}{2\pi(500)(300)}\right| = 1.1\mu\text{F} <<< C$$

Between 10 to 100 times bigger than this value is good rule of thumb

Small Signal Model

For a common source connection and small-signal AC analysis in the linear range, the MOSFET can be modeled with the following circuit:



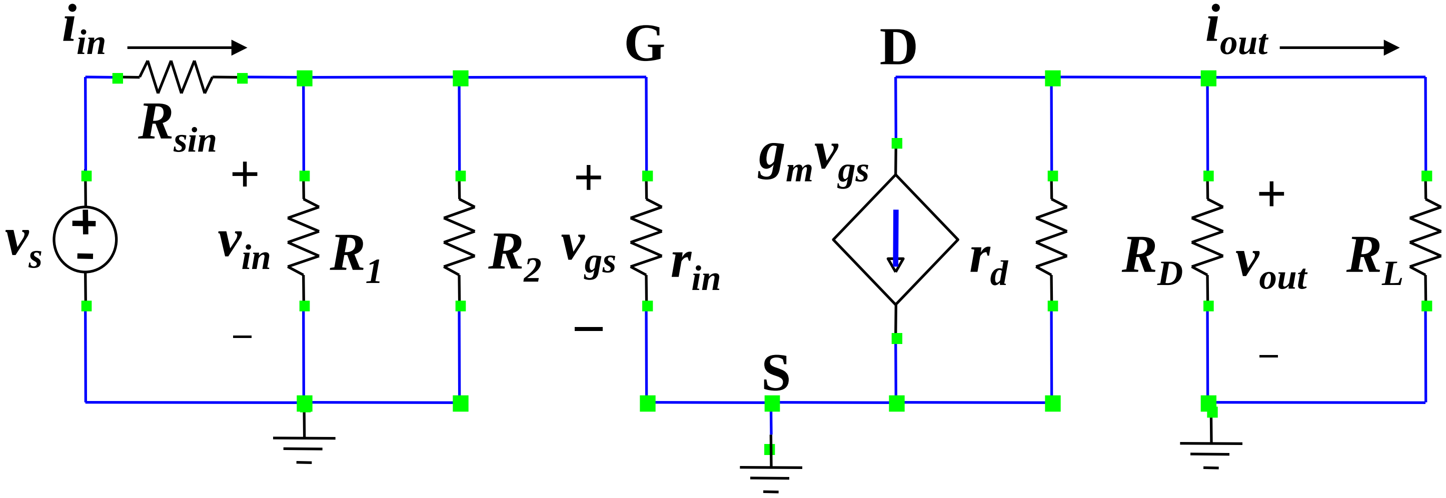
r_{in} – Input resistance (typically very large compared with biasing resistors)

r_d – Output resistance (typically very large compared with biasing resistors)

g_m - MOSFET transconductance

Small Signal Model

The small-signal equivalent of the common source amplifier results from deactivating all DC sources and treating the blocking capacitors as short circuits:



How to calculate the small-signal voltage gain $A_v = v_{out}/v_{in}$ if $r_{in} \to \infty$, $r_d \to \infty$?

Small-Signal System Parameters

In general, the internal resistor of the source, R_{sin}, and load, R_L, are not considered part of the system; however they will affect critical system parameters listed below:

Small-signal voltage gain: $A_v = \dfrac{\hat{v}_{out}}{\hat{v}_{in}}$

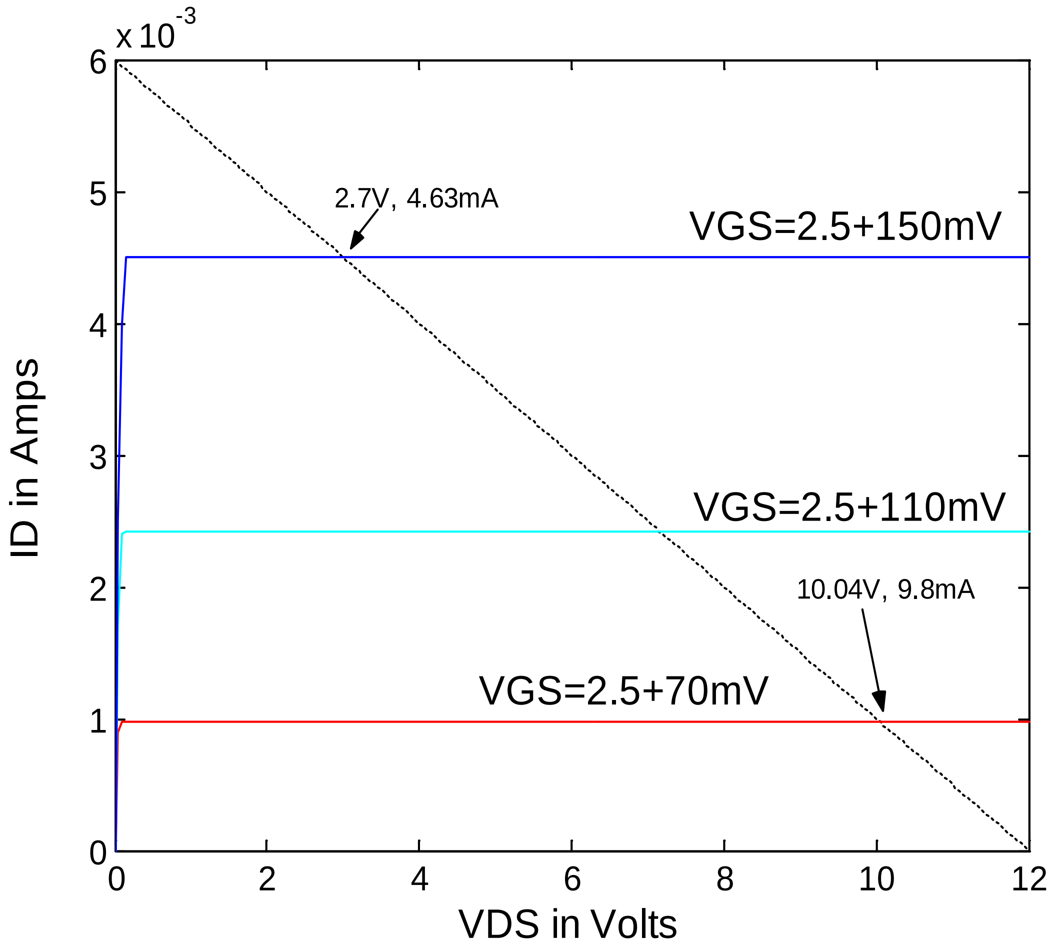
Small-signal current gain: $A_i = \dfrac{\hat{i}_{out}}{\hat{i}_{in}}$

Input resistance: $R_{in} = \dfrac{\hat{v}_{in}}{\hat{i}_{in}}$

Output resistance: $R_{out} = \dfrac{\hat{v}_{out}}{\hat{i}_{out}}$

Explain how to measure these quantities.

Gain About a Quiescent Point



If changes about V_{GSQ} are consider the input, and changes in V_{DSQ} are considered the output, then the gain of this system is:

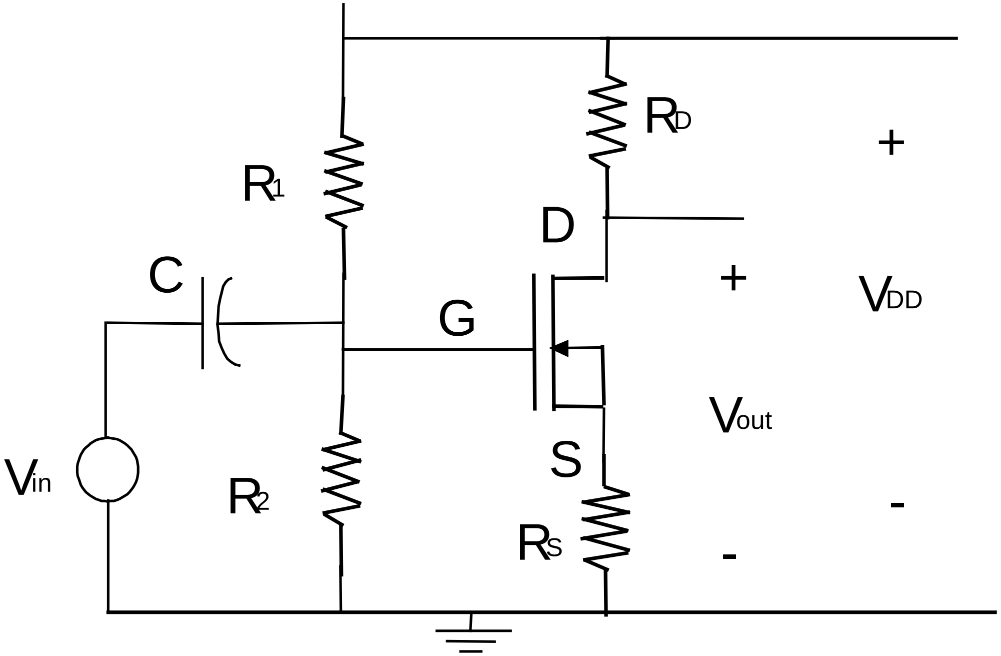
$$G_V = \frac{\Delta V_{DS}}{\Delta V_{GS}} = \frac{(2.7 - 10.04)\text{V}}{(150 - 70)\text{mV}}$$

$$G_V = -91.75$$

Note gain is dependent on the transconductance of the MOSFET (related to K_p and the bias point) and the slope of the load line.

AC Circuit for Gain Measurement

V_{in} will perturb the voltage at the gate causing a perturbation in V_{out}



What is the purpose of the capacitor in this circuit?

AC Gain of Amplifier

Once the quiescent point is set, small perturbations around V_{GS}, driven by variations V_{in} will perturb I_{DS} , which cause larger perturbations in V_{out}. The ratio of the change in V_{out} to the change in V_{in} is the gain of the amplifier. To measure the gain, the quiescent or DC component resulting from the bias must be subtracted out, so the ratios of the AC components are computed.

$$\text{Gain} = \frac{\left|\hat{v}_{out}\right|}{\left|\hat{v}_{in}\right|} = \frac{\max\left(\left|V_{out}(t) - V_{outQ}\right|\right)}{\max\left(\left|V_{in}(t) - V_{inQ}\right|\right)}$$

The removal of the DC component happens naturally with **a peak to peak measurement** (under either AC or DC coupling) and for rms measurement under AC coupling.

What kind of coupling on the oscilloscope channels would be best to use for the measurements to compute the gain?

Does it make a difference in the gain computations if the AC voltages are measured in peak, peak-to-peak, or RMS?

Amp Distortion

A MATLAB script was written (**lab6_AmpDistortion.m**, see webpage) to compute the transfer characteristics of an NMOS amplifier and map signals from input to output. It finds the operating point and computes the intersection of the load line with the FET transfer characteristic for a series of inputs (see mfile **qpoint_iter.m**).

A function was then written to map a signal through the tabulated input-output relationship (see mfile **ampdist.m**).

The script will be used to show examples of distortion from the non-linearity introduced by the amplifier.

Script for Distortion Analysis

```
% This script runs an example of a load line analysis for a MOSFET amp
% to:
%  1. find the operating point for Vgs through iteration
%  2. then compute a table of input (Vgs) and output (Vds)amplitude values
%     to get the transfer characteristic (TC) curve for the amp.
%  3. then apply the resulting TC curve to an input sinusoid with
%     increasing amplitude to illustrate distortion.  The sine wave
%     will be plotted and played in the demonstration.
% The functions nmos.m and ampdist.m are needed to run this script
%
% Set Parameters:  Operating point will be set to half VDD
K=.5; vto = 1.8;                % Nmos parameters
W=1; L=1; KP=2*K;               % Nmos parameters
VDD=15;  RS=400; RD=1e3;        % Load line parameters
idsmax = VDD/(RD+RS);           % Maximum Load line value on Drain current axis
                                % Operation point will be the max drain current divided by 2.
vds = [0:.05:VDD];              % Create X-Axis

idsll = -vds/(RD+RS) + VDD/(RD+RS);  % Generate Load Line

err = .2e-3;       % Set initial error for quiescent point to get while loop started
toler = .05e-3;    % Set tolerance value for stopping rule on while loop
incgs = .01;       % Set increment for vgs to find intersection with load line.
vgs = vto;         % Initialize vgs to threshold voltage so initial guess will below desired operating point
```

Script for Distortion Analysis

```
% Set flag to denote when guess goes above the operating point in
% order to reduce iteration interval.
passflag = 0;  % If zero implies the last step is below the desired value, 1 implies last step was above

% Set while loop to run until error is below tolerance
while err >= toler
   ids = nmos(vds,vgs,KP,W,L,vto);              % Compute characteristic curve
    [edum, inderr] = min(abs(idsll - ids));     % Find intersection with loadline
   err =abs(idsmax/2 - idsll(inderr(1)));       % Find error between desired current and actual

   % Check to see if we are above or below the target and make adjustments to move closer to desired operating point
   if idsmax/2>ids(inderr)     % If below target value ....
      vgs = vgs + incgs        % Still below threshold so increase
      if passflag == 1
         incgs = incgs/2;      % If we just came from above the threshold cut increment in half for more resolution
         passflag = 0;         % reset flag
      end
   else                        % If above target value
      vgs = vgs - incgs        % Still above threshold so decrease
      if passflag == 0
         incgs = incgs/2;      % If we just came from below the threshold cut increment in half for more resolution
         passflag = 1;         % reset flag
      end
   end
   % Comment out the next 4 lines to stop the while loop from being interrupted by plots and pauses
   figure(1);   plot(vds, idsmax*ones(size(vds))/2, 'c--', vds,idsll,'k:',vds,ids,'r')  % Check plot along the way
   disp(['Iteration in progress'])
   pause(.1)
 end
```

Script for Distortion Analysis

```
vgsq = vgs;  %  Set quiescent Vgs to last result of iteration

disp([' The operating point for Vgs is ' num2str(vgsq)])

%  Compute corresponding output quiescent voltage amplitude at output
ids = nmos(vds,vgsq,KP,W,L,vto);  % Compute transfer characteristic (TC) curve at quiescent
[err, inderr] = min(abs(ids - idsll));   %  Find intersection with load line and TC
vdsq = vds(inderr(1)); disp([' The operating point for Vds is ' num2str(vdsq)])   %  Output voltage quiescent
idsq = ids(inderr(1)); disp([' The operating point for Ids is ' num2str(idsq)])      %  Output current quiescent

%  Display text on screen.
disp([' Now compute transfer characteristic between amp input and output '])
```

Script for Distortion Analysis

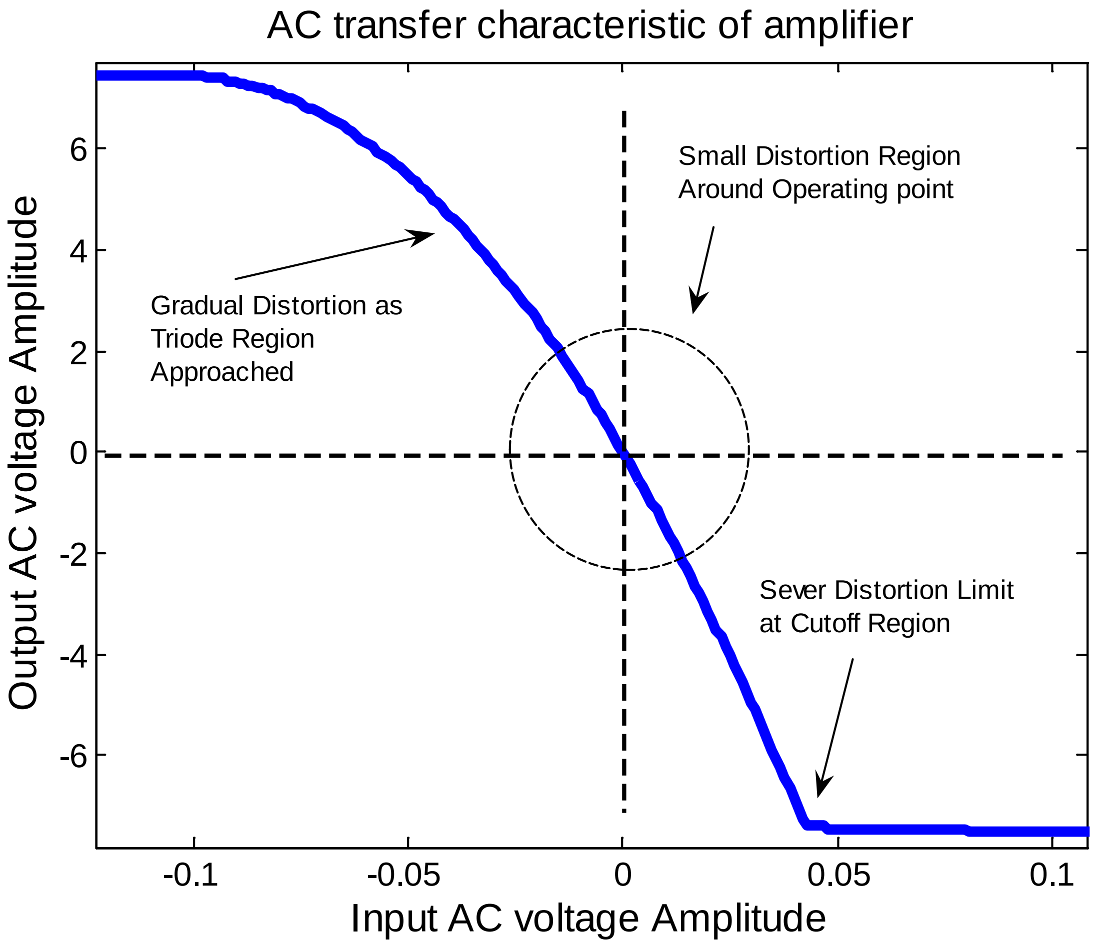
```
%   Now compute array for mapping the input to the output of the amplifier
inarray = [0:.001:2*vgsq];        %   AC input array amplitude sweep
                                  %   range should include quiescent Vgs

%  Loop to compute each point on intersection of load line for input
%  vortage amplitude sweep for output VDS
for karry = 1:length(inarray)
        vgsdcac= inarray(karry);                     %  Vgs level with AC and DC energy
        ids = nmos(vds,vgsdcac,KP,W,L,vto);  % Compute characteristic curve for that vgs
        [err, inderr] = min(abs(ids - idsll));       %  Find closest point between load line and TC
        outarray(karry) = vds(inderr(1));            %  Assign VDS as output array correspond to that Vgs value
end

%  Subtract quiesent Vgs offset from input array to result in AC input only component
insigac = inarray - vgsq;

%  Subtract quiesent Vds offset from input array to result in AC output only component
outsigac = outarray - vdsq;

%  Plot transfer characteristics for AC voltage gain
figure(2)
plot(insigac,outsigac)
xlabel('Input AC voltage Amplitude')
ylabel('Output AC voltage Amplitude')
title('AC transfer characteristic of amplifier')
disp(['Hit any key to continue to hear examples of sounds played through amplifier'])
pause
```

Script for Distortion Analysis

```
% Create a unit 300 Hz sine wave sampled at 8000 Hz and pass it through the amp
 fs = 8000;                     % Sampling frequency
t= [0:3*fs-1]/fs;               % Create a time axis for signal for 3 seconds
sigin = sin(2*pi*t*300);        % Create unit sine wave
a = [.01, .05, .15];            %Set up amplitude scales for input voltage

% Loop to distort and play sound
for k=1:3
   sigout = ampdist(sigin*a(k),insigac,outsigac);  % Distort sound by mapping amplitudes through TC

   % Plot original and amplified signal on same scale to observe distortion
   figure(2+k); plot(t(1:100),sigin(1:100)/max(abs(sigin)),'r',t(1:100),-sigout(1:100)/max(abs(sigout)),'b')
   title([' Compare Scaled Input (red) at amplitude ' num2str(a(k)), ' output (blue) for Distortion'])

   % Play both sounds consecutively
   soundsc([sigin/(max(abs(sigin))+eps), sigout/(max(abs(sigout))+eps)],fs);

   % Pause for user key press to go on to next sound if not at the end
   if k~=3
      disp(['Hit any key to continue to next sound'])
      pause
   end
end
```

Amp Distortion

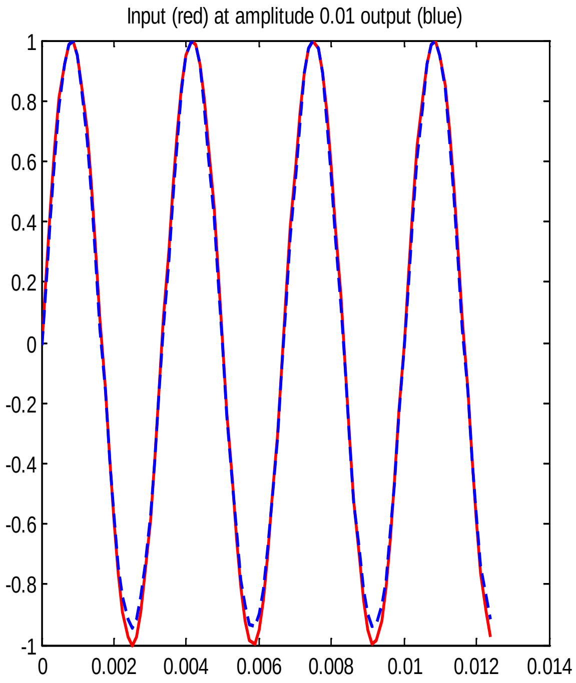
For nominal settings, a transfer characteristic is generated by an amp similar to the one studied in this lab, plotted below over a critical range.

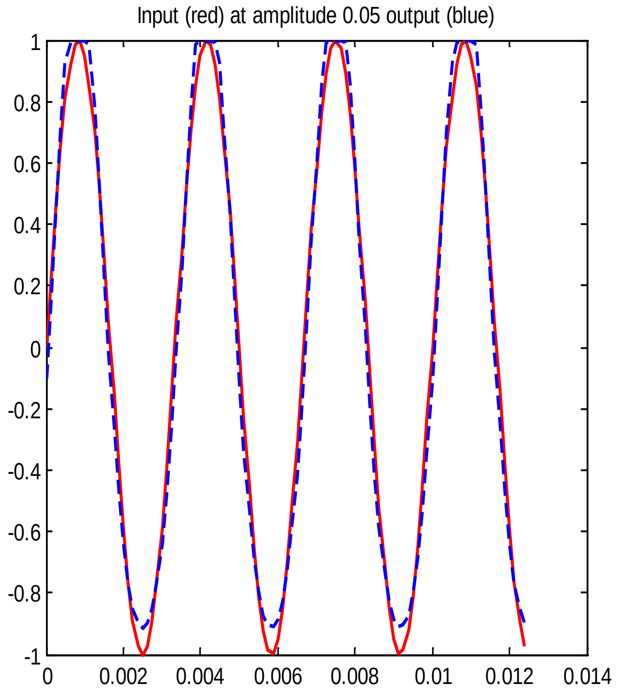


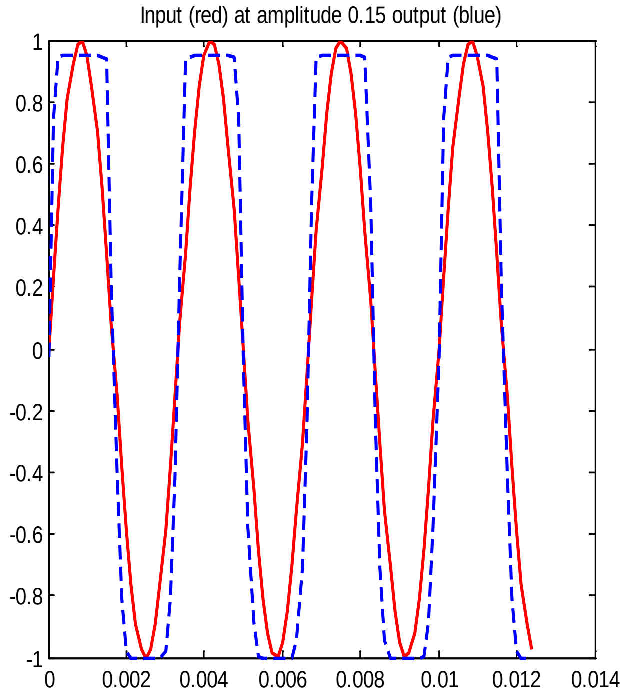
Amp Distortion

Run simple sinusoids through the amp with increased amplitudes to observe the distortion pattern.

Let input be of the form: $x(t) = A\sin(2\pi 300t)$





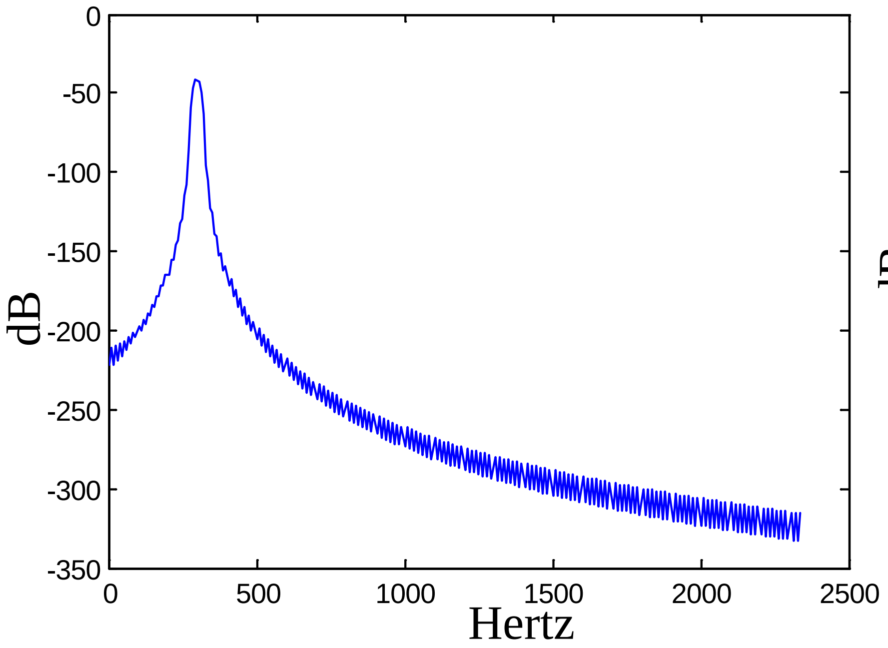


Amp Distortion

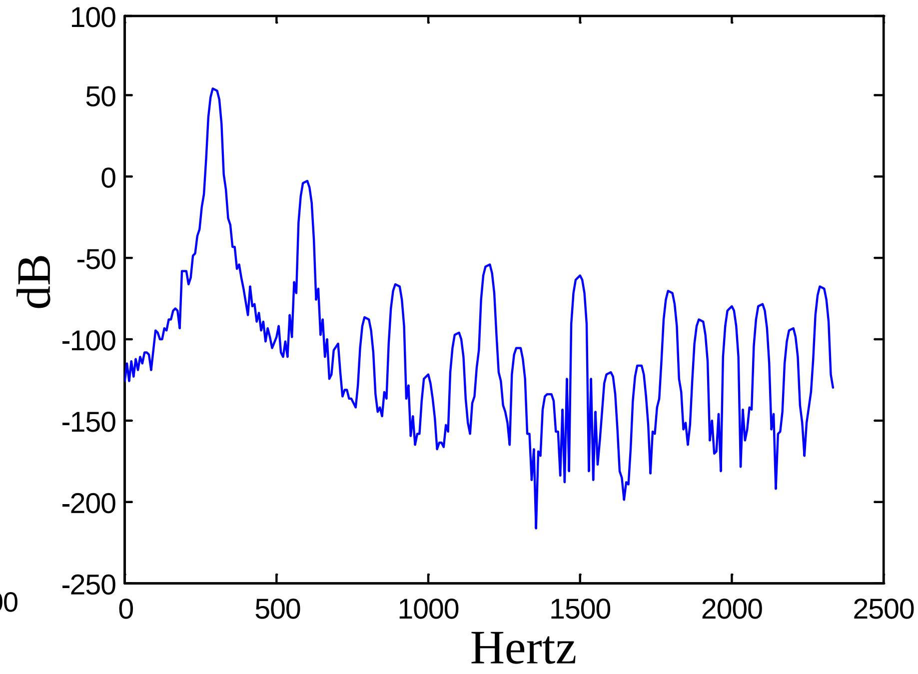
Spectrum of input and output comparisons A = .01

Input played first, then output

Input Spectrum



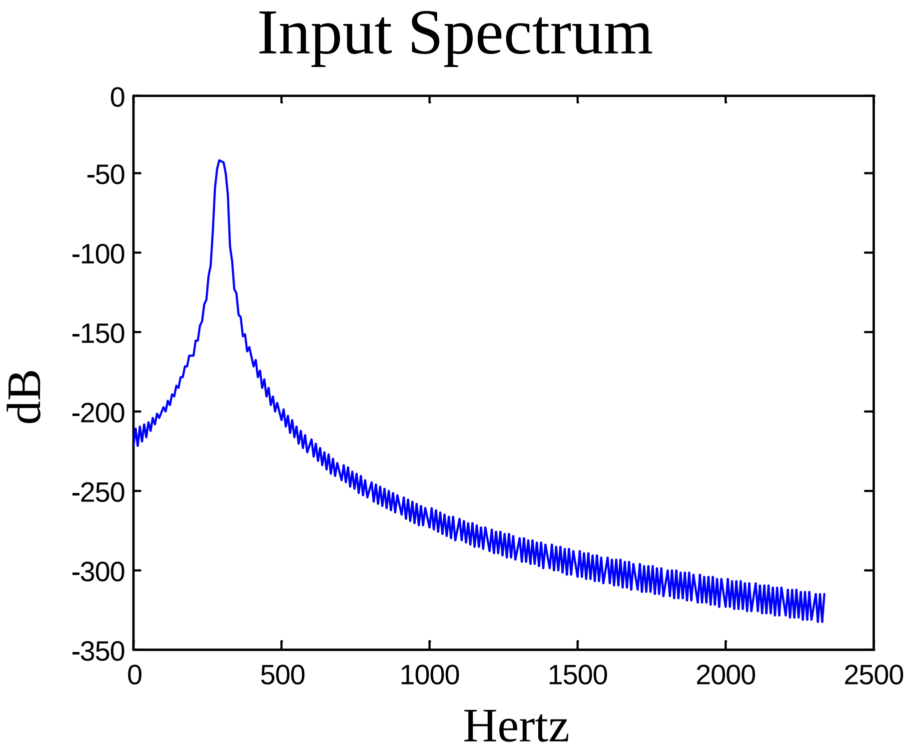
Output Spectrum

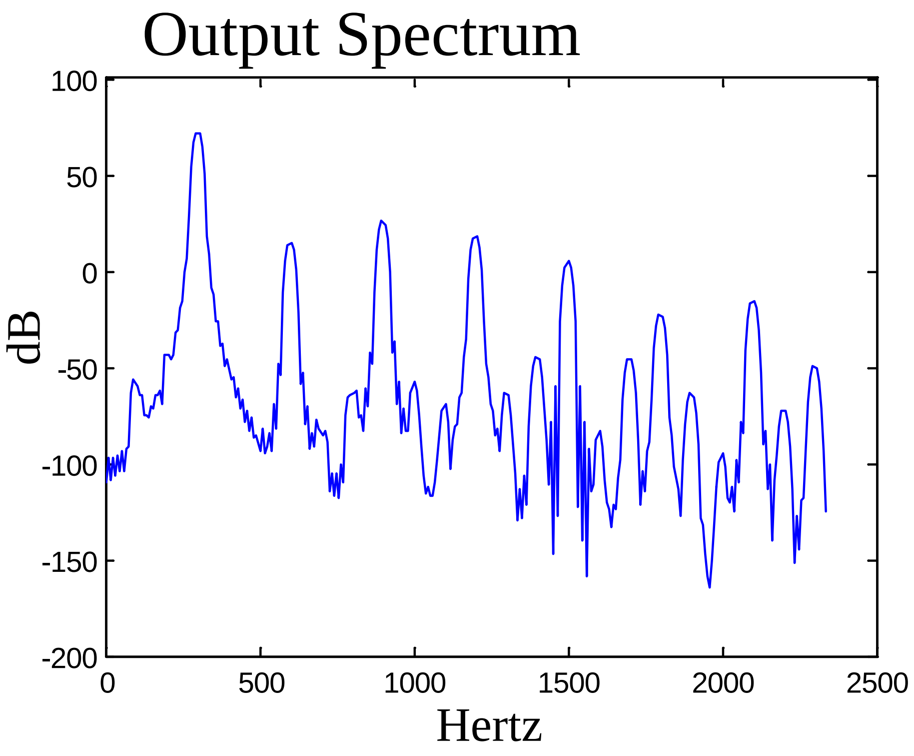


Amp Distortion

Spectrum of input and output comparisons A = .03

Input played first, then output 





Amp Distortion

Spectrum of input and output comparisons A = .15

Input played first, then output