# EE105 - Fall 2014 <br> Microelectronic Devices and Circuits 

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## Analog Electronic System Example An FM Stereo Receiver



- Linear functions: Radio and audio frequency amplification, frequency selection (tuning), impedance matching (75- $\Omega$ input, tailoring audio frequency response, local oscillator
- Nonlinear functions: DC power supply (rectification), frequency conversion (mixing), detection/demodulation

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## Amplification Introduction



- A complex periodic signal can be represented as the sum of many individual sine waves. We consider only one component with amplitude $V_{s}=1 \mathrm{mV}$ and frequency $\omega_{s}$ with 0 phase (signal is used as reference):

$$
v_{S}=V_{s} \sin \omega_{s} t
$$

- Amplifier output is sinusoidal with same frequency but different amplitude $V_{o}$ and phase $\theta$ :

$$
v_{O}=V_{o}\left(\sin \omega_{s} t+\theta\right)
$$

## Amplification Introduction (cont.)

- Amplifier output power is:

$$
P_{o}=\left(\frac{V_{o}}{\sqrt{2}}\right)^{2} \frac{1}{R_{L}}
$$

- Example: $\mathrm{P}_{\mathrm{O}}=\mathbf{1 0 0} \mathbf{W}$ with $\mathrm{R}_{\mathrm{L}}=\mathbf{8} \Omega$ and $\mathrm{V}_{\mathrm{s}}=\mathbf{1} \mathrm{mV}$

$$
\therefore V_{o}=\sqrt{2 P_{o} R_{L}}=\sqrt{2 \times 100 \times 8}=40 \mathrm{~V}
$$

- Output power also requires output current which is:

$$
i_{o}=I_{o}\left(\sin \omega_{s} t+\theta\right) \quad I_{o}=\frac{V_{o}}{R_{L}}=\frac{40 \mathrm{~V}}{8 \Omega}=5 \mathrm{~A}
$$

- Input current is given by

$$
I_{s}=\frac{V_{s}}{R_{S}+R_{i n}}=\frac{10^{-3} \mathrm{~V}}{5 \mathrm{k} \Omega+50 \mathrm{k} \Omega}=1.82 \times 10^{-8} \mathrm{~A}
$$

- Output phase is zero because circuit is purely resistive.


## Voltage Gain \& Current Gain

- Voltage Gain:

$$
A_{v}=\frac{v_{o}}{v_{S}}=\frac{V_{o} \angle \theta}{V_{s} \angle 0}=\frac{V_{o}}{V_{s}} \angle \theta
$$

- Magnitude and phase of voltage gain are given by
- For our example,

$$
\left|A_{v}\right|=\frac{V_{o}}{V_{s}} \quad \angle A_{v}=\theta
$$

$$
\left|A_{v}\right|=\frac{V_{o}}{V_{s}}=\frac{40 \mathrm{~V}}{10^{-3} \mathrm{~V}}=4 \times 10^{4}
$$

- Current Gain:

$$
A_{i}=\frac{i_{o}}{i_{S}}=\frac{I_{o} \angle \theta}{I_{s}} \angle 0=\frac{I_{o}}{I_{s}} \angle \theta
$$

- Magnitude of current gain is given by

$$
\left|A_{i}\right|=\frac{I_{o}}{I_{s}}=\frac{5 \mathrm{~A}}{1.82 \times 10^{-8} \mathrm{~A}}=2.75 \times 10^{8}
$$

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## Power Gain

- Power Gain:

$$
\left.A_{P}=\frac{P_{o}}{P_{S}}=\frac{\frac{V_{o}}{\sqrt{2}} \frac{I_{o}}{\sqrt{2}}}{\frac{V_{s}}{\sqrt{2}} \frac{V_{s}}{\sqrt{2}}}=\frac{V_{o} I_{o}}{V_{s}} \frac{I_{s}}{I_{s}}=\left|A_{v}\right| A_{i} \right\rvert\,
$$

- For our example,

$$
A_{P}=\frac{40 \times 5}{10^{-3} \times 1.82 \times 10^{-8}}=1.10 \times 10^{13}
$$

## Expressing Gain in Decibels (dB)

- It is customary to express gain in logarithmic decibel or dB scale due to the large numeric range of gains encountered in real systems.
- dB is defined for power gain, therefore it is the logarithm of the square of voltage gain, or square of current gain.

Voltage Gain: $\quad A_{v d B}=10 \log \left|A_{V}\right|^{2}=20 \log \left|A_{V}\right|$
Current Gain: $\quad A_{i d B}=10 \log \left|A_{I}\right|^{2}=20 \log \left|A_{I}\right|$

Power Gain:

$$
A_{p d B}=10 \log \left|A_{V}\right|\left|A_{l}\right|
$$

Note:

$$
A_{p d B}=\frac{A_{v d B}+A_{i d B}}{2}
$$

## Amplification

 Expressing Gain in dB - Example- For the previous example:

Voltage Gain: $\quad A_{v d B}=20 \log \left|4 \times 10^{4}\right|=92 d B$

Current Gain: $\quad A_{i d B}=20 \log \left|2.75 \times 10^{8}\right|=169 d B$

Power Gain: $\quad A_{p d B}=10 \log \left|1.10 \times 10^{13}\right|=130 d B$

Note: $\quad A_{p d B}=\frac{A_{v d B}+A_{i d B}}{2}$

## Simplified Two-port Model of Amplifier

The two-port model including the Thévenin equivalent of input source and load is shown below


Thevenin Equivalent Circuit of Source

Simplified Two-Port Model of Amplifier

Load Resistance

## Voltage Gain with Finite Source and Load Resistances


$v_{o}=A v_{1} \frac{R_{L}}{R_{\text {out }}+R_{L}}$
$v_{1}=v_{s} \frac{R_{i n}}{R_{S}+R_{i n}}$
$\therefore\left|A_{v}\right|=\frac{V_{o}}{V_{s}}=A \frac{R_{\text {in }}}{R_{S}+R_{\text {in }}} \frac{R_{L}}{R_{\text {out }}+R_{L}}$

If $R_{\text {in }} \gg R_{s}$ and $R_{\text {out }} \ll R_{L}$, then

$$
\left|A_{v}\right|=A
$$

In an ideal voltage amplifier,

$$
R_{\text {in }}=\infty \text { and } R_{\text {out }}=0
$$

$$
\left|A_{i}\right|=\frac{I_{o}}{I_{1}}=\frac{\frac{V_{o}}{R_{L}}}{\frac{V_{s}}{R_{S}+R_{i n}}}=\frac{V_{o}}{V_{s}} \frac{R_{S}+R_{i n}}{R_{L}}
$$

$$
\therefore\left|A_{i}\right|=\left|A_{v}\right| \frac{R_{S}+R_{i n}}{R_{L}}
$$



## Differential Amplifier Model: Impact of Source and Load Resistances



- Op amp circuits are mostly dc-coupled amplifiers.
- Signals $v_{o}$ and $v_{s}$ may have a dc component representing a dc shift of the input away from the Q-point.

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## Differential Amplifier Model Example including Source and Load Resistances

- Example: $A=100, R_{i d}=100 \mathrm{k} \Omega, \mathrm{R}_{\mathrm{o}}=100 \Omega, \mathrm{R}_{\mathrm{S}}=10 \mathrm{k} \Omega, \mathrm{R}_{\mathrm{L}}=$ 1000

$$
\begin{aligned}
& A_{v}=\frac{v_{o}}{v_{s}}=A \frac{R_{i d}}{R_{S}+R_{i d}} \frac{R_{L}}{R_{O}+R_{L}}=100\left(\frac{100 k \Omega}{10 k \Omega+100 k \Omega}\right)\left(\frac{1000 \Omega}{100 \Omega+1000 \Omega}\right) \\
& A_{v}=82.6 \\
& A_{v d B}=20 \log (82.6)=38.3 \mathrm{~dB}
\end{aligned}
$$

- An ideal amplifier's output depends only on the input voltage difference and not on the source and load resistances. This can be achieved by using a fully mismatched resistance condition ( $R_{i d} \gg R_{S}$ or infinite $R_{i d}$, and $R_{o} \ll R_{L}$ or zero $R_{o}$ ). Then:

$$
A_{v}=A
$$

- A = open-loop gain (maximum voltage gain available from the


## Ideal Operational Amplifier (Op Amp)

- The Ideal Op Amp is a special case of ideal differential amplifier with infinite gain, infinite Rid and zero Ro .

$$
v_{i d}=\frac{v_{o}}{A} \quad \text { and } \quad \lim _{A \rightarrow \infty} v_{i d}=0
$$

- If A is infinite, $\mathrm{v}_{\mathrm{id}}$ is zero for any finite output voltage.
- Infinite input resistance $R_{i d}$ forces input currents $i_{+}$and $i_{-}$to be zero.
- Ideal Op Amp analysis utilizes the following assumptions:
- Infinite common-mode rejection, power supply rejection, open -loop bandwidth, output voltage range, output current capability and slew rate
- Zero output resistance, input-bias currents and offset current, input-offset voltage.


## Ideal Operational Amplifier Assumptions for Circuit Analysis



Ideal Op Amp

$$
\begin{aligned}
& A=\infty \\
& R_{i d}=\infty \\
& R_{o}=0
\end{aligned}
$$

- Two assumptions are used to facilitate analysis of circuits containing ideal op amps
- Input voltage difference is zero: $\mathrm{v}_{\mathrm{id}}=0$
- Amplifier input currents are zero: $\mathbf{i}_{+}=0$ and $\mathrm{i}_{-}=0$


## Op Amp Building Blocks: Inverting Amplifier Circuit



- Positive input is grounded.
- The feedback network formed by resistors R1 and R2 is connected between the inverting input and signal source and the inverting input and amplifier output, respectively.


## Inverting Amplifier Voltage Gain and Input Resistance

- Negative voltage gain implies $180^{\circ}$ phase shift between dc /sinusoidal input and output signals.
- Voltage gain depends only on resistance ratio
- Inverting input of op amp is at ground potential (but not connected directly to ground)
$v_{i}-i_{i} R_{1}-i_{2} R_{2}-v_{o}=0$
$i_{i}=i_{2}$ and is said to be a "virtual ground".
$v_{-}=v_{+}=0$
$\therefore i_{i}=\frac{v_{i}}{R_{1}} \quad$ and $\quad A_{v}=\frac{v_{o}}{v_{i}}=-\frac{R_{2}}{R_{1}} \quad R_{i n}=\frac{v_{i}}{i_{i}}=R_{1}$


## Inverting Amplifier Input and Output Resistances



- $\mathrm{R}_{\text {out }}$ is found by applying a test current (or voltage) source to the amplifier output and determining the voltage (or current) with all independent sources turned off. Hence, $\mathbf{v}_{\mathbf{i}}=\mathbf{0}$

$$
v_{x}=i_{2} R_{2}+i_{1} R_{1}=i_{1}\left(R_{1}+R_{2}\right)
$$

Since $\mathrm{i}_{\mathrm{I}}=\mathbf{0}$ giving $\mathrm{i}_{1}=\mathrm{i}_{\mathbf{2}}$

$$
R_{i n}=\frac{\mathrm{v}_{\mathrm{s}}}{\mathrm{i}_{\mathrm{S}}}=R_{1}
$$

- However, since $v_{-}=0, i_{1}=0$, and $\mathrm{v}_{\mathrm{x}}=0$ irrespective of the value of $i_{x}$.

$$
\therefore R_{\text {out }}=0
$$

## Op Amp Building Blocks Non-inverting Amplifier Circuit



- The input signal is applied to the non-inverting input terminal.
- Portion of the output signal is fed back to the negative input terminal.
- Analysis is done by relating the voltage at $v_{1}$ to input voltage $v_{i}$ and output voltage $v_{o}$.



## Non-inverting Amplifier Voltage Gain and Input Resistance

Since $i_{-}=0, \quad v_{1}=v_{o} \frac{R_{1}}{R_{1}+R_{2}} \quad$ and $\quad v_{1}=v_{i}-v_{i d}$
But $v_{i d}=0$ and $v_{1}=v_{i}$

$$
\begin{aligned}
& \therefore v_{o}=v_{i} \frac{R_{1}+R_{2}}{R_{1}} \quad \text { and } \\
& A_{v}=\frac{v_{o}}{v_{i}}=\frac{R_{1}+R_{2}}{R_{1}}=1+\frac{R_{2}}{R_{1}} \\
& R_{i n}=\frac{v_{i}}{i_{+}}=\frac{v_{i}}{0}=\infty
\end{aligned}
$$

## Non-inverting Amplifier Output Resistance


$R_{\text {out }}$ is found by applying a test current source to the amplifier output and setting $v_{i}=0$.

We find the circuit to be identical to that for the output resistance calculation for the inverting amplifier.

Therefore: $\boldsymbol{R}_{\text {out }}=0$


## Op Amp Building Blocks: Unity-gain Buffer



- A special case of the non-inverting amplifier, termed a voltage follower or unity gain buffer, has infinite $R_{1}$ and zero $R_{2}$. Hence $A_{v}$ = +1.
- The unity-gain buffer provides excellent impedance-level transformation while maintaining signal voltage level.
- An ideal voltage buffer does not require any input current and can drive any desired load resistance without loss of signal voltage.
- Unity-gain buffers are used in may sensor and data acquisition systems.


## Op Amp Building Blocks: Summing Amplifier



- Scale factors for the 2 inputs can be independently adjusted by choice of $R_{2}$ and $R_{1}$.
- Any number of inputs can be connected to the summing junction through extra resistors.
- A simple digital-to-analog converter can be formed using this technique.


## Op Amp Building Blocks: Difference Amplifier



- For $R_{1}=R_{2}$ circuit is also called a differential subtractor and amplifies the difference between input signals.
- $R_{\text {in } 2}$ is series combination of $R_{1}$ and $R_{2}$ because $i_{+}$is zero.
- For $v_{2}=0, R_{i n 1}=R_{1}$, as the circuit reduces to an inverting amplifier.
- For the general case, $i_{1}$ is a function of both $v_{1}$ and $v_{2}$.

Cal ${ }^{\text {For } R_{2}=R_{1}: \quad v_{o}=-\left(v_{1}-v_{2}\right)}$
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[^0]:    - Op-amp amplifies both dc and ac components.

