EE5390: Analog Integrated Circuit Design

Introduction

Nagendra Krishnapura

Department of Electrical Engineering
Indian Institute of Technology, Madras
Chennai, 600036, India

6 Jan. 2010
Course info

- http://www.ee.iitm.ac.in/~nagendra/EE539/201001/courseinfo.html
- TAs: P. Rakesh, Kunal Karanjkar
- E Slot (Tue. 1100-1150, Wed. 1000-1050, Thu. 0800-0850, Fri. 1400-1450)

Check it regularly for recorded lectures, assignments, and references
Modern signal processing systems

Sensor(s) → Digital Processing → Actuator(s)

Interface Electronics (Signal Conditioning) (A-D and D-A Conversion)

Continuous-time Continuous-amplitude

Discrete-time Discrete-amplitude
Analog circuits in modern systems on VLSI chips

- Analog to digital conversion
- Digital to analog conversion
- Amplification
- Signal processing circuits at high frequencies
- Power management-voltage references, voltage regulators
- Oscillators, Phase locked loops

The last two are found even on many “digital” ICs
Chip Micrograph

- Voltage Regulator
- Column CDS circuits
- 703 x 499 pixels (VGA format)
- Timing Generator
- I/O circuit
- 10b pipelined ADC

Chip size: 4.74mm x 6.34mm
Die Micrograph
Many companies starting analog centers
Multinationals-TI, National, ST, ADI etc.
Indian start ups-Cosmic, Manthan, Karmic, Sankalp etc.
Big demand for skilled designers
Interesting and profitable activity 😊
Course goals

Learn to design negative feedback circuits on CMOS ICs
- Negative feedback for controlling the output
- Amplifiers, voltage references, voltage regulators, biasing
- Phase locked loops
Course prerequisites

- Circuit analysis-small and large signal
- Laplace transforms, frequency response, Bode plots, Differential equations
- Opamp circuits
- Single transistor amplifiers, differential pairs

EE542 (Analog Electronic Circuits)/EC201 (Analog Circuits)
Amplifiers using negative feedback
Stability, Frequency compensation
Negative feedback circuits using opamps
Opamp macromodel
Course contents-Opamps on CMOS ICs

- Components available on a CMOS integrated circuit
- Device models-dc small signal, dc large signal, ac small signal, mismatch, noise
- Single stage opamp
- Cascode opamps
- Two stage opamp with miller compensation
Course contents - Fully differential circuits

- Differential and common mode half circuits, common mode feedback
- Fully differential miller compensated opamp
- Fully differential feedforward compensated opamp
Course contents-Phase locked loop

- Frequency multiplication using negative feedback
- Type I, type II loops
- Oscillators
- Phase noise basics
- PLL noise transfer functions
Course contents-Design of opamps

- Single stage opamp
- Folded, telescopic cascode opamps
- Two stage opamp
- Fully differential opamps and common mode feedback
- Applications: Bandgap reference, constant $g_m$ bias generation
Course contents - Applications

- Bandgap reference
- Constant current and constant gm bias generators
- Continuous-time filters
- Switched capacitor filters
Design versus Analysis

- Design: Create something that doesn’t yet exist
- Analysis: Analyze something that exists
To be able to design

- Knowing analysis is necessary, not sufficient
- Multiple ways of looking at building blocks
- Trial and error approaches
- Intuitive thinking/understanding
- Curiosity
- Open mind
- Thoroughness
Intuitive thinking is not sloppy thinking!
Relate problems to other problems already solved
Use boundary conditions, dimension checks etc.
Build your intuition
  - Solve many problems
  - Think about why the answer is what it is
  - Come up with the form of the solution before applying full blown analysis
Circuit analysis

- Nodal analysis-Kirchoff’s Current Law (KCL) at each node
- Solve \( N \) simultaneous equations for an \( N \) node circuit
- Mesh analysis-Kirchoff’s Voltage Law (KVL) around each loop
- Solve \( M \) simultaneous equations for a circuit with \( M \) independent loops
Nodal analysis

\[
i_{11}(\mathbf{v}) + i_{12}(\mathbf{v}) + \ldots + i_{1N}(\mathbf{v}) = i_1
\]
\[
i_{21}(\mathbf{v}) + i_{22}(\mathbf{v}) + \ldots + i_{2N}(\mathbf{v}) = i_2
\]
\[\vdots\]
\[
i_{N1}(\mathbf{v}) + i_{N2}(\mathbf{v}) + \ldots + i_{NN}(\mathbf{v}) = i_N
\]

- \(i_{kl}\): Current in the branch between nodes \(k\) and \(l\)
- \(i_{kk}\): Current in the branch between node \(k\) and ground
- \(v_k\): Voltage at node \(k\); \(\mathbf{v} = [v_1, v_2, \ldots, v_N]^T\)
- \(i_k\): Current source into node \(k\)

\(i_{kl}\) can be a nonlinear function of \(\mathbf{v}\)
Nodal analysis—Linear circuits

\[ g_{11}v_1 + g_{12}v_2 + \cdots + g_{1N}v_N = i_1 \]
\[ g_{21}v_1 + g_{22}v_2 + \cdots + g_{2N}v_N = i_2 \]
\[ \vdots \]
\[ g_{N1}v_1 + g_{N2}v_2 + \cdots + g_{NN}v_N = i_N \]

- \( g_{kl} \): Conductance between nodes \( k \) and \( l \)
- \( g_{kk} \): Conductance between node \( k \) and ground
- \( v_k \): Voltage at node \( k \)
- \( i_k \): Current source into node \( k \)
Nodal analysis—Independent voltage source

\[ g_{k1}v_1 + g_{k2}v_2 + \ldots + g_{kN}v_N = i_k \quad \text{node } k \]

\[ v_k = V_o \quad \text{node } k \]

- Ideal voltage source $V_o$ connected to node $k$
Nodal analysis—Controlled voltage source

\[ \begin{align*}
  g_{k1}v_1 + g_{k2}v_2 + \cdots + g_{kN}v_N &= i_k \quad \text{node } k \\
  \vdots \\
  v_k - kv_i &= 0 \quad \text{node } k
\end{align*} \]

Voltage controlled voltage source \( v_k = kv_i \) driving node \( k \)
Nodal analysis—Controlled voltage source

\[ g_k v_1 + g_{k2} v_2 + \ldots + g_{kl} v_l + \ldots + g_{kN} v_N = i_k \quad \text{node } k \]

\[ g_k v_1 + g_{k2} v_2 + \ldots + \frac{v_k}{R_m} + \ldots + g_{kN} v_N = i_k \quad \text{node } k \]

\[ g_l v_1 + g_{l2} v_2 + \ldots + g_{lk} v_k + \ldots + g_{lN} v_N = i_l \quad \text{node } l \]

\[ g_l v_1 + g_{l2} v_2 + \ldots - \frac{v_k}{R_m} + \ldots + g_{lN} v_N = i_l \quad \text{node } l \]

Current controlled voltage source \( v_k = R_m i_{kl} \) driving node \( k \)
\[ g_{k1} v_1 + g_{k2} v_2 + \ldots + g_{kl} v_l + \ldots + g_{kN} v_N = i_k + g_m v_l \]

\[ g_{k1} v_1 + g_{k2} v_2 + \ldots + g_{kl} v_l - g_m v_l + \ldots + g_{kN} v_N = i_k \]

- Current controlled voltage source \( i_0 = g_m v_l \) driving node \( k \)
Nodal analysis—Ideal opamp

\[ g_{m1}v_1 + g_{m2}v_2 + \ldots + g_{mN}v_N = i_m \quad \text{node } m \]

\[ v_k - v_l = 0 \quad \text{node } m \]

- Ideal opamp with input terminals at nodes \( k, l \) and output at node \( m \)
Nodal analysis—solution

\[
\begin{bmatrix}
g_{11} & g_{12} & \cdots & g_{1N} \\
g_{21} & g_{22} & \cdots & g_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
g_{N1} & g_{N2} & \cdots & g_{NN}
\end{bmatrix}
\begin{bmatrix}
v_1 \\
v_2 \\
\vdots \\
v_N
\end{bmatrix}
= 
\begin{bmatrix}
i_1 \\
i_2 \\
\vdots \\
i_N
\end{bmatrix}
\]

\[
Gv = \bar{i}
\]

\[
v = G^{-1}\bar{i}
\]

- \(g_{kl}\): Conductance between nodes \(k\) and \(l\)
- \(g_{kk}\): Conductance between node \(k\) and ground
- \(v_k\): Voltage at node \(k\)
- \(i_k\): Current source into node \(k\)
- Modified terms for voltage sources or controlled sources
- Matrix inversion yields the solution
### Nodal analysis—solution

Cramer’s rule can be used for matrix inversion

\[
v_k = \frac{\begin{vmatrix}
    g_{11}g_{12} \cdots i_1 \cdots g_{1N} \\
    g_{21}g_{22} \cdots i_2 \cdots g_{2N} \\
    \vdots \\
    g_{N1}g_{N2} \cdots i_N \cdots g_{NN} \\
    g_{11}g_{12} \cdots g_{1k} \cdots g_{1N} \\
    g_{21}g_{22} \cdots g_{2k} \cdots g_{2N} \\
    \vdots \\
    g_{N1}g_{N2} \cdots g_{Nk} \cdots g_{NN}
\end{vmatrix}}{\begin{vmatrix}
    g_{11}g_{12} \cdots i_1 \cdots g_{1N} \\
    g_{21}g_{22} \cdots i_2 \cdots g_{2N} \\
    \vdots \\
    g_{N1}g_{N2} \cdots i_N \cdots g_{NN}
\end{vmatrix}}
\]
Circuits with capacitors and inductors

\[
\begin{bmatrix}
Y_{11}(s) & Y_{12}(s) & \ldots & Y_{1N}(s) \\
Y_{21}(s) & Y_{22}(s) & \ldots & Y_{2N}(s) \\
\vdots & \vdots & \ddots & \vdots \\
Y_{N1}(s) & Y_{N2}(s) & \ldots & Y_{NN}(s)
\end{bmatrix}
\begin{bmatrix}
V_1(s) \\
V_2(s) \\
\vdots \\
V_N(s)
\end{bmatrix}
=
\begin{bmatrix}
I_1(s) \\
I_2(s) \\
\vdots \\
I_N(s)
\end{bmatrix}
\]

\[\mathbb{Y}(s)\mathbb{V}(s) = \mathbb{l}(s)\]
\[\mathbb{V}(s) = \mathbb{Y}^{-1}\mathbb{l}(s)\]

- Conductances $g_{kl}$ replaced by admittances $Y_{kl}(s)$
- Roots of the determinant of $\mathbb{Y}(s)$ are system poles
Laplace transform analysis for linear systems

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(s)$</td>
<td>$H(s)X(s)$</td>
</tr>
<tr>
<td>$e^{st}$</td>
<td>$H(s)e^{st}$</td>
</tr>
<tr>
<td>$X(j\omega)$</td>
<td>$H(j\omega)X(j\omega)$</td>
</tr>
<tr>
<td>$e^{j\omega t}$</td>
<td>$H(j\omega)e^{j\omega t}$</td>
</tr>
<tr>
<td>$\cos(\omega t)$</td>
<td>$</td>
</tr>
</tbody>
</table>

- Linear time invariant system described by its transfer function $H(s)$
- $H(s)$ is the laplace transform of the impulse response
- $s = j\omega$ represents a sinusoidal frequency $\omega$
Transfer function $H(s)$ (no poles at the origin)

$$H(s) = A_{dc} \frac{1 + b_1 s + b_2 s^2 + \ldots + b_M s^M}{1 + b_1 s + b_2 s^2 + \ldots + b_N s^N}$$

$$= A_{dc} \prod_{k=1}^M \frac{1 + s/z_k}{\prod_{k=1}^N 1 + s/p_k}$$

Single pole at the origin

$$H(s) = \frac{\omega_u}{s} \prod_{k=1}^M \frac{1 + s/z_k}{\prod_{k=2}^N 1 + s/p_k}$$

- All poles $p_k$ must be in the left half plane for stability
Frequency and time domain analyses

Frequency domain
- Algebraic equations-easier solutions
- Only for linear systems

Time domain
- Differential equations-more difficult to solve
- Can be used for nonlinear systems as well
- Piecewise linear systems occur quite frequently (e.g. saturation)
Bode plots

- Sinusoidal steady state response characterized by $|H(j\omega)|$, $\angle H(j\omega)$
- Bode plot: Plot of $20 \log |H(j\omega)|$, $\angle H(j\omega)$ versus $\log \omega$ approximated by straight line segments
- Good approximation for real poles and zeros
Simulators

Very powerful tools, indispensable for complex calculations, but GIGO!

- Matlab: System level analysis (Frequency response, pole-zero, transfer functions)
- Spice: Circuit analysis
- Maxima: Symbolic analysis
EC201: Analog Circuits
EE539: Past years’ lectures

URL: http://www.ee.iitm.ac.in/~nagendra/videolectures/
References

- Sergio Franco, *Design with operational amplifiers and analog ICs*, Tata McGraw Hill.