Advanced Analog Integrated Circuits

Switched Capacitor Gain Stages

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OpAmp versus OTA

OpAmp

- Low output resistance (voltage source)
- Buffer benefits from high $g_m$
- Gain independent of $R_L$
- Often preferable with BJT

OTA

- High output resistance (current source)
- No buffer
- Can’t “drive” low $R_L$
- Preferable with MOS
Gain Stages

Resistive Feedback

\[ v_i \rightarrow R_1 \rightarrow \text{O} \rightarrow R_2 \rightarrow v_o \]
Gain Stages

Resistive Feedback

Capacitive Feedback
Transconductor Choices

BJT    MOS
Aside: MOS Voltage Buffers
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Switched Capacitor Gain Stage

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SC Gain Stage

Switches controlled from non-overlapping 2-phase clock:

Note: **important** details of clocks and switches will be discussed later.
Multiphase Clock Generators

Cross-coupled RS flip-flop

Delay sets nonoverlap period.
(time period in which both $\phi_1$ and $\phi_2$ are 0).

Spectre:

```spectre
phi1 (vphi1 0) vsource type=pulse val0=0 val1=1.8 + period=1/fs width=0.45/fs delay=0.01/fs
```

http://ece-research.unm.edu/jimp/vlsi/slides/chap5_2-34.gif
Phase 1

\[ Q_1 = -v_i \cdot C_1 \]

\[ Q_2 = 0 \]

\[ Q_{X1} = -v_i \cdot C_1 + \Delta \cdot C_2 \]
Phase 2

\[ Q \times 2 = 0 \cdot C_1 = v_0 \cdot C_2 \]

\[ = Q \times c \]
Charge Conservation

Since no charge escapes when switching from phase 1 to phase 2:

\[ Q_{x_1} = Q_{x_2} \]

\[ \frac{V_0}{V_{x_2}} = + \frac{C_0}{C_2} \]
Transient Analysis

\[ v_i(t) = \frac{C_i}{C_2} \]

- \( v_{in} [V] \)
- \( av \cdot vin \)
- \( v_o [V] \)
- \( \phi_{in} \)
- \( e_{in} \)

Time [s]

\( 0 \) to \( 3u \)

200m
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Time Invariant Circuits

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Switched Capacitor Circuits

- Signals valid at discrete times (clock) $f_s$
- Spectrum: $0$ to $f_s/2$

- SC: OTAs, switches, caps
- SC circuit apps
  - amp, (non) inverting
  - integrators, filters
  - $1/f$ offset

B. E. Boser
EE240B – SC Gain Stages
**Time Invariant and Linear**

- SC gain → linear
  \[ v_o \propto v_i \]

- Time variant

- AC ?

  periodic:
  - op → pss
  - ac → pae
Periodic ac Simulation (Spectre)

- Perform first a “periodic operating point analysis”:
  
  ```
  pss1 pss fund=fs maxacfreq=20*fs
  +errpreset=conservative harmonicbalance=no
  
  - fund is the sampling frequency
  - maxacfreq is the highest frequency from which folding noise is relevant. Run several circuit simulations, doubling the value each time until the result no longer changes.
  ```

- Now perform the ac analysis:
  
  ```
  pac1 pac start=1k stop=10G log=100
  ```
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Sampling Noise

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Sampling Noise

Noise in phase 1 (sampling phase):

Voltage across $C_1$:

Noise Folding

Noise densities:

Continuous time
\[ \overline{v^2_{ct}} = 4kTR \]

Discrete time
\[ \frac{\overline{v^2_{dt}}}{C} = \frac{kT}{C} \cdot \frac{2}{f_s} \]

Ratio:
\[ \frac{\overline{v^2_{ct}}}{\overline{v^2_{dt}}} = \pi \frac{f_{-3dB}}{fs} \gg 1 \]

\[ = \frac{kT}{C} \cdot \frac{2}{fs} \cdot \frac{1}{4\pi e^2 2f_s R C} \]
\[ = \frac{N_1}{2} \]

Sampled RC Noise Spectrum

\[ S_y(f) = \frac{k_B T_r}{C} \frac{2}{f_s} \frac{1-e^{-2a}}{1+e^{-2a}(1-\cos 2\pi fT)} \]

\[ a = \frac{T}{R_{sw}C} = \frac{T}{\tau} \quad \text{and} \quad T = \frac{1}{f_s} \]

\[ \int_0^{f_s/2} S_y(f)df = \frac{k_B T_r}{C} \]
Effective Noise Bandwidth
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SC Noise Analysis

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Circuit for Noise Analysis

Assumptions:
- \( R_{on} \ll \frac{1}{g_m} \), \( R_o \approx \infty \)
- OTA, low-noise
Noise in Phase 1
Equipartition Principle

\[ \frac{1}{2} Q_x^2 C = \frac{1}{2} C V^2 = \frac{f}{2} k_B T \left( C_1 + C_2 + C_x \right) \]
Noise in Phase 2

\[ V_{aq} = 4 f \mu \frac{\alpha k T}{g_m} \cdot \alpha P \]

- \[ N_{sw} = 4 f \mu C_1 - C_2 \left( \frac{C_1}{C_2} \right)^2 \left| H(j\omega) \right|^2 \]
- \[ N_a = 4 f \mu \frac{\alpha k T}{g_m} \cdot (1 + \frac{C_1}{C_2})^2 \left| H(j\omega) \right|^2 \]
- \[ \frac{N_a}{N_{sw}} = \frac{\alpha k T}{g_m \cdot R_{on}} \cdot \frac{(1 + \frac{C_1}{C_2})^2}{\left( \frac{C_1}{C_2} \right)^2} \]
Total Integrated Amplifier Noise

\[ R_o \approx \frac{1}{\beta g_m} \]

\[ \beta = \frac{C_2}{C_1 + C_2 + C_X} \]

\[ C_{L+0} = C_L + (1-\beta) \cdot C_2 \]

\[ BW = \frac{1}{R_o \cdot C_{Cpe} \cdot \frac{1}{C_{Cpe} + \frac{1}{\beta}} \cdot \frac{1}{\beta} \cdot \frac{1}{\beta}} \]

\[ \bar{N}_{o,a}^2 = 4 \frac{f_0}{g_m} \frac{\alpha f}{g_m} \cdot \frac{1}{\beta} \cdot \frac{BW}{4} = \frac{\alpha f}{\beta} \cdot \frac{b_2}{C_{Cpe}} \]
Total Noise from Phases 1 & 2

\[ \overline{N^2_{\phi_1}} = \frac{9kT}{C_z^2} = \frac{h^2}{\beta} \cdot \frac{C_1 + C_z + C_x}{C_z} = \frac{h^2}{\beta \cdot C_z} \]

\[ \overline{N^2_{\phi_2}} = \frac{8kT}{\beta \cdot C_{4.501}} \]

\[ \overline{S_{0.5}} = \frac{1}{\beta} \left( \frac{1}{C_z} + \frac{8kT}{C_{4.501}} \right) \]
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Noise Simulation

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Methods to Simulate Noise for Verification

1. .noise analysis
   - Linear time-invariant circuits only
   - For time variant circuits, simulate each phase separately and combine results manually (as in hand analysis)

2. Periodic noise analysis
   - Analog to pac
   - Perform pss analysis first

3. Transient noise analysis
   - Closest to “reality”, very general
   - Average results from many simulations
   - Good alternative when pss has convergence problems
   - Can be slow …


Periodic Noise Simulation (Spectre)

- Perform first a “periodic operating point analysis”
- Then perform the pnoise analysis:
  
  \[
  \text{pnoise1} \ pnoise \ (\text{vo} \ 0) \ \text{fund}=\text{fs} \ \text{start}=0 \ \text{stop}=\text{fs}/2
  \]

  +\text{noisetype}=\text{timedomain} \ \text{maxsideband}=150
  +\text{noisetimepoints}=[1 \mu\text{s}]

  - \text{noisetype}=\text{timedomain} \ instructs \ the \ simulator \ to \ compute \ the \ spectrum \ of
  discrete \ time \ noise \ samples \ at \ specified \ sampling \ instances
  - \text{maxsideband}=150 \ sets \ the \ maximum \ frequency \ relative \ to \ \text{fs} \ for \ which
  noise \ folding \ is \ significant. \ Try \ doubling \ this \ value \ and \ increase \ until \ simulator
  output \ converges.
  - \text{noisetimepoints}=[1 \mu\text{s}] \ is \ the \ sampling \ instance. \ For \ the \ SC \ gain
  stage, \ this \ is \ near \ the \ end \ of \ phase \ 2
  - See \ simulator \ docs \ and \ http://www.designers-guide.org/analysis/sc-filters.pdf