EE 508
Lecture 28

Integrator Design
Review from Last Time

- What are the basic integrator architectures?
- How can integrator performance be improved?
Review from Last Time

**Basic Integrator Functionality**

- **Noninverting**
  \[ X_{IN} \xrightarrow{\frac{l_0}{s}} X_{OUT} \]

- **Inverting**
  \[ X_{IN} \xrightarrow{-\frac{l_0}{s}} X_{OUT} \]

- **Lossy Noninverting**
  \[ X_{IN} \xrightarrow{\frac{l_0}{s+\alpha}} X_{OUT} \]

- **Lossy Inverting**
  \[ X_{IN} \xrightarrow{-\frac{l_0}{s+\alpha}} X_{OUT} \]

- **Summing (Multiple-Input) Inverting/Noninverting**
  \[ X_{IN1} \quad \ldots \quad X_{INn} \xrightarrow{\frac{l_0k}{s}} X_{OUT} \]
  \[ X_{OUT} = \sum_{k=1}^{n} \frac{\pm l_0k}{s} \]

- **Summing (Multiple-Input) Lossy Inverting/Noninverting**
  \[ X_{IN1} \quad \ldots \quad X_{INn} \xrightarrow{\frac{l_0k}{s+\alpha_k}} X_{OUT} \]
  \[ X_{OUT} = \sum_{k=1}^{n} \frac{\pm l_0k}{s+\alpha_k} \]

- **Balanced Differential**
  \[ X_{IN}^+ \xrightarrow{+\frac{l_0}{s}+} X_{OUT}^+ \]
  \[ X_{IN}^- \xrightarrow{-\frac{l_0}{s}-} X_{OUT}^- \]
  \[ X_{OUT}^+ - X_{OUT}^- = \frac{l_0}{s} \left( X_{IN}^+ - X_{IN}^- \right) \]

- **Fully Differential**
  \[ X_{IN_{\text{diff}}}^+ \xrightarrow{+\frac{l_0}{s}+} X_{OUT_{\text{diff}}} \]
  \[ X_{IN_{\text{diff}}}^- \xrightarrow{-\frac{l_0}{s}-} X_{OUT_{\text{diff}}} \]
  \[ X_{OUT_{\text{diff}}} = \frac{l_0}{s} X_{IN_{\text{diff}}} \]
Basic Integrator Functionality

- An inverting/noninverting integrator pair define a family of integrators.
- All integrator functional types can usually be obtained from the inverting/noninverting integrator pair.
- Suffices to focus primarily on the design of the inverting/noninverting integrator pair since properties of class primarily determined by properties of integrator pair.
Integrator Types

Will consider first the Voltage Mode type of integrators
Voltage Mode Integrators

- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C
- Switched Capacitor
- Switched Resistor

Sometimes termed “current mode”
Active RC Voltage Mode Integrator

\[ V_{\text{OUT}} = -\frac{1}{CR_s} V_{\text{IN}} \]

- Limited to low frequencies because of Op Amp limitations
- No good resistors for monolithic implementations
  - Area for passive resistors is too large
  - Some recent work by Haibo Fei shows promise for some audio frequency applications
- Active devices are highly temperature dependent, proc. Dependent, and nonlinear
- No practical tuning or trimming scheme for integrated applications with passive resistors

Review from Last Time
MOSFET-C Voltage Mode Integrator

- Limited to low frequencies because of Op Amp limitations
- Area for RMOS is manageable!
- Active devices are highly temperature dependent, process dependent
- Potential for tuning with $V_C$
- Highly Nonlinear (can be partially compensated with cross-coupled input)

A Solution without a Problem
OTA-C Voltage Mode Integrator

- Requires only two components
- Inverting and Noninverting structures of same complexity
- Good high-frequency performance
- Small area
- Linearity is limited (no feedback in integrator)
- Susceptible to process and temperature variations
- Tuning control can be readily added

Widely used in high frequency applications

\[
\begin{align*}
V_{\text{OUT}} &= -\frac{g_m}{sC} V_{\text{IN}} \\
V_{\text{OUT}} &= \frac{g_m}{sC} V_{\text{IN}}
\end{align*}
\]
TA-C Voltage Mode Integrator

- Can operate at very high frequencies
- Low device count circuit
- Simplicity is important for operating at very high frequencies
- $I_0$ is process and temperature dependent
- Linearity is limited

$$V_{OUT} = \left( \frac{-g_m}{sC} \right) V_{IN}$$

Typically $M=1$

Review from Last Time
Review from Last Time

**TA-C Voltage Mode Integrator**

Some other perspectives

\[ V_{\text{OUT}} = \left( \frac{-g_m}{sC} \right) V_{\text{IN}} \]

Inverting Integrators

n-channel input

\[ V_{\text{IN}} \rightarrow g_m \rightarrow C \rightarrow V_{\text{OUT}} \]

p-channel input

\[ V_{\text{IN}} \rightarrow g_m \rightarrow C \rightarrow V_{\text{OUT}} \]
TA-C Voltage Mode Integrator

\[ V_{OUT} = \left( \frac{-g_m}{sC} \right) V_{IN} \]

n-channel input

Inverting Integrators

p-channel input
Another Voltage Mode Integrator

\[ V_{OUT} = \left( \frac{-1}{sRC} \right) V_{IN} \]

- Infinite input impedance (in contrast to basic Active RC Integrator)
- Both R and C have one terminal grounded
- Requires integrated process
- Accuracy limited by process and temperature
- Size limitations same as basic Active RC Integrator
- Limited to lower frequencies because of Op Amp
- Good linearity
Another Voltage Mode Integrator

Inverting Integrator

\[ V_{OUT} = \left( \frac{-1}{sR_{FET}C} \right) V_{IN} \]

- \( M_1 \) in triode region
- Reduces Area Concerns but Loss of Linearity
- \( I_0 \) is programmable with \( V_{RR} \)
- Accurate control of \( I_B \) critical

Noninverting Integrator

\[ V_{OUT} = \left( \frac{1}{sR_{FET}C} \right) V_{IN} \]
Regulated Cascode Voltage Mode Integrator

**Inverting Integrator**

\[ V_{OUT} = \left( -\frac{g_{MT}}{sC} \right) V_{IN} \]

\( g_{MT} \) is triode region transconductance of \( M_1 \)

- \( M_1 \) operating in triode region
- \( R_{FET} \) programmable with \( V_{RR} \)
- Very good linearity properties
- Input impedance still infinite

**Noninverting Integrator**

\[ V_{OUT} = \left( \frac{g_{MT}}{sC} \right) V_{IN} \]
Regulated Cascode Voltage Mode Integrator

\[ V_{OUT} = \left( -\frac{g_{mT}}{sC} \right) V_{IN} \]

\[ I_D = \mu \frac{C_{OX} W}{L} \left( V_{GS} - V_T - \frac{V_{RR}}{2} \right) V_{RR} \]

\[ V_{OUT} = \left( -\frac{g_{mT}}{sC} \right) V_{IN} \]

Linearity Properties:

Assuming square-law triode model

\[ I_D = \mu \frac{C_{OX} W}{L} V_{RR} V_{IN} + \mu \frac{C_{OX} W}{L} \left( V_T + \frac{V_{RR}}{2} \right) V_{RR} \]

Note linear dependence on \( V_{IN} \)

\[ g_{mT} = \left[ \frac{L}{\mu C_{OX} W V_{RR}} \right] \]
Regulated Cascode Voltage Mode Integrator

Inverting Integrator

\[ V_{OUT} = \left( \frac{-1}{sR_{FET}C} \right) V_{IN} \]

- Multiple inputs require single additional transistor
- Accurate ratioing of gains practical
- Can also sum currents on C
Regulated Cascode Voltage Mode Integrator

Inverting Integrator

\[ V_{OUT} = \left( \frac{-1}{sR_{FET}C} \right) V_{IN} \]

Inverting Lossy Integrator
Another Voltage Mode Integrator

Inverting Integrator

\[ V_{OUT} = \left( \frac{-1}{sRC} \right) V_{IN} \]

Noninverting Integrator

\[ V_{OUT} = \left( \frac{1}{sRC} \right) V_{IN} \]
Switched-Capacitor Integrators

\[ V_{OUT}(nT+T) = V_{OUT}(nT) - \frac{C_1}{C} V_{IN}(nT) \]

\[ H(z) = -\frac{\frac{C_1}{C}}{z-1} \]

Sensitive to parasitic capacitances
Switched-Capacitor Integrators

Summing Inputs
Switched-Capacitor Integrators

Summing Inputs and Lossy
Switched-Capacitor Integrators

- Stray-Insensitive Noninverting

- Stray-Insensitive Inverting
Switched-Capacitor Integrators

Stray-Insensitive Properties

$C_{GD}$ does not affect gain of integrator
Switched-Resistor Voltage Mode Integrators

Observe that if a triode-region MOS device is switched between a precharge circuit and a filter circuit (or integrator) and $V_{GS}$ is held constant, it will behave as a resistor while in the filter circuit.

Observing that if two such circuits are switched between a precharge circuit and a filter circuit (or integrator) and $V_{GS}$ is held constant, it will behave as a resistor in the filter circuit at all times.

$$R_{FET} \approx \frac{L}{\mu C_{OX} W (V_{GS} - V_T)}$$
Switched-Resistor Voltage Mode Integrators

Switched-resistor integrator

- Clock frequency need only be fast enough to prevent droop on $C_X$
- Minor overlap or non-overlap of clock plays minimal role in integrator performance
- Switched-resistors can be used for integrator resistor or to replace all resistors in any filter
- Pretune circuit can accurately establish $R_{FET}C_{REF}$ product proportional to $f_{REF}$
- $R_{FET}C$ product is given by $R_{FET}C=R_{FET}C_{REF}=R_{FET}C_{REF}\cdot\frac{C}{C_{REF}}$ and is thus accurately controlled
Switched-Resistor Voltage Mode Integrators

- Aberations are very small, occur very infrequently, and are further filtered
- Play almost no role on performance of integrator or filter
Switched-Resistor Voltage Mode Integrators

- Accurate \( CR_{\text{FET}} \) products is possible
- Area reduced compared to Active RC structure because \( R_{\text{FET}} \) small
- Single pretune circuit can be used to “calibrate” large number of resistors
- Clock frequency not fast and not critical
- Since resistors are memoryless elements, no transients associated with switching
- Since filter is a feedback structure, speed limited by BW of op amp