EE 508
Lecture 25

Integrator Design
Parasitic capacitances ideally have no affect on filter when on a non-floating node but directly affect transfer function when they appear on a floating node.

Parasitic capacitances are invariably large, nonlinear, and highly process dependent in integrated filters. Thus, it is difficult to build accurate integrated filters if floating nodes are present.

Generally avoid floating nodes, if possible, in integrated filters.
Review from last time

Which type of Biquad is really used?

- Not Floating Node
- Floating Node

Integrator-based structures with no floating nodes dominantly used in integrated filters with floating nodes are used.

Some high-frequency or programmable filters are used.

Integrator Based Structures
Filter Design/Synthesis Considerations

Cascaded Biquads

\[ T(s) = T_1 T_2 \cdots T_m \]

Leapfrog

Multiple-loop Feedback – One type shown

Observation: All filters are comprised of summers, biquads and integrators

And biquads usually made with summers and integrators

Integrated filter design generally focused on design of integrators, summers, and amplifiers (Op Amps)

Will now focus on the design of integrators, summers, and op amps
Basic Filter Building Blocks
(particularly for integrated filters)

- Integrators
- Summers
- Operational Amplifiers
Integrator Characteristics of Interest

Properties of an ideal integrator:

\[ |I(j\omega)| = \frac{I_0}{\omega} \]

Gain decreases with \(1/\omega\)

\[ \angle I(j\omega) = -90^\circ \]

Phase is a constant \(-90^\circ\)

\[ |I(jI_0)| = 1 \]

Unity Gain Frequency = \(I_0\)

How important is it that an integrator have all 3 of these properties?
Integrator Characteristics of Interest

\[ I(s) = \frac{I_0}{s} \]

\[ |I(j\omega)| = \frac{I_0}{\omega} \]
\[ \angle I(j\omega) = -90^\circ \]
\[ |I(jI_0)| = 1 \]

How important is it that an integrator have all 3 of these properties?

Consider a filter example:

\[ T(s) = \frac{-I_0^2}{s^2 + \alpha I_0 s + I_0^2} \]
\[ Q = \frac{1}{\alpha} \]
\[ \omega_0 = I_0 \]

In many (most) applications it is critical that an integrator be very nearly ideal (in the frequency range of interest)
Fig. 10-17  Plot of upper half-plane root of

\[ s^3 + s^2 \left( \frac{1}{2} + \frac{1}{Q} + \frac{GB_w}{4} \right) + s \frac{1}{4Q} \left( 1 + GB_w \right) + \frac{GB_w}{4} = 0 \]
Some integrator structures

Inverting Active RC Integrator

Are there other integrator structures?

Termed an OTA-C or a gm-C integrator
Some integrator structures

Are there other integrator structures?

Termed a TA-C integrator

Termed MOSFET-C integrator
Some integrator structures

Are there other integrator structures?

\[ V_2 = V_1 - I_{IN} \frac{1}{sC} \]
\[ I_{OUT} = \frac{V_2 - V_1}{R} \]

- Output current is independent of \( Z_L \)
- Thus output impedance is \( \infty \) so provides current output

Termed active RC current-mode integrator
Some integrator structures

There are many different ways to build an inverting integrator

There are other useful integrator structures (some will be introduced later)
Integrator Functionality

Basic Active RC Inverting Integrator

\[ V_{OUT} = -\sum_{k=1}^{n} \frac{1}{CR_k}s \ V_{IN_k} \]

Noninverting Integrator

\[ I(s) = \frac{1}{sRC} \]

Summing Integrator

\[ V_{OUT} = -\sum_{k=1}^{n} \frac{1}{CR_k}s \ V_{IN_k} \]

Fully Differential Integrator

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

Lossy Integrator

\[ V_{OUT} = -\frac{R_F}{1+CR_Fs} V_{IN} \]

Many different types of functionality from basic inverting integrator
Same modifications exist for other integrator architectures
Integrator-Based Filter Design

Any of these different types of integrators can be used to build integrator-based filters.
Are new integrators still being invented?

Searching US Patent Collection...

Results of Search in US Patent Collection db for:
TTL/integrator: 419 patents.
Hits 1 through 50 out of 419
<table>
<thead>
<tr>
<th>PAT. NO.</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>8,290,897</td>
<td>System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems</td>
</tr>
<tr>
<td>8,283,966</td>
<td>Integrator circuit</td>
</tr>
<tr>
<td>8,275,307</td>
<td>Vehicle audio integrator</td>
</tr>
<tr>
<td>8,264,388</td>
<td>Frequency integrator with digital phase error message for phase-locked loop applications</td>
</tr>
<tr>
<td>8,258,990</td>
<td>Integrator, resonator, and oversampling A/D converter</td>
</tr>
<tr>
<td>8,253,473</td>
<td>Integrated circuit of an integrator with enhanced stability and related stabilization method</td>
</tr>
<tr>
<td>8,199,038</td>
<td>Active resistance-capacitor integrator and continuous-time sigma-delta modulator with gain control function</td>
</tr>
<tr>
<td>8,164,873</td>
<td>Integrator and circuit-breaker having an integrator</td>
</tr>
<tr>
<td>8,145,597</td>
<td>System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems</td>
</tr>
<tr>
<td>8,129,972</td>
<td>Single integrator sensorless current mode control for a switching power converter</td>
</tr>
<tr>
<td>8,125,262</td>
<td>Low power and low noise switched capacitor integrator with flexible input common mode range</td>
</tr>
<tr>
<td>8,098,377</td>
<td>Electric gated integrator detection method and device thereof</td>
</tr>
<tr>
<td>8,081,098</td>
<td>Integrator, delta-sigma modulator, analog-to-digital converter and applications thereof</td>
</tr>
<tr>
<td>8,065,439</td>
<td>Multi-channel integrator</td>
</tr>
<tr>
<td>8,031,404</td>
<td>Fly's eye integrator, illuminator, lithographic apparatus and method</td>
</tr>
<tr>
<td>8,029,144</td>
<td>Color mixing rod integrator in a laser-based projector</td>
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<td>8,028,304</td>
<td>Component integrator</td>
</tr>
<tr>
<td>8,013,657</td>
<td>Temperature compensated integrator</td>
</tr>
<tr>
<td>8,011,180</td>
<td>Light integrator for more than one lamp</td>
</tr>
<tr>
<td>7,997,740</td>
<td>Integrator unit</td>
</tr>
<tr>
<td>7,965,795</td>
<td>Prevention of integrator wind-up in PI type controllers</td>
</tr>
<tr>
<td>7,965,151</td>
<td>Pulse width modulator with two-way integrator</td>
</tr>
<tr>
<td>7,954,962</td>
<td>Laser image display, and optical integrator and laser light source package used in such laser image display</td>
</tr>
<tr>
<td>7,943,893</td>
<td>Illumination optical system and image projection device having a rod integrator uniformizing spatial energy distribution of diffused illumination beam</td>
</tr>
<tr>
<td>7,933,812</td>
<td>System integrator and commodity roll-up</td>
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<tr>
<td>Patent Number</td>
<td>Title</td>
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<tr>
<td>7,932,960</td>
<td>Integrator array for HUD backlighting</td>
</tr>
<tr>
<td>7,911,256</td>
<td>Dual integrator circuit for analog front end (AFE)</td>
</tr>
<tr>
<td>7,907,115</td>
<td>Digitally-synchronized integrator for noise rejection in system using PWM dimming signals to control brightness of cold cathode fluorescent lamp for backlighting liquid crystal display</td>
</tr>
<tr>
<td>7,905,631</td>
<td>Illumination system having coherent light source and integrator rotatable transverse the illumination axis</td>
</tr>
<tr>
<td>7,884,662</td>
<td>Multi-channel integrator</td>
</tr>
<tr>
<td>7,880,962</td>
<td>Optical integrator for an illumination system of a microlithographic projection exposure apparatus</td>
</tr>
<tr>
<td>7,873,223</td>
<td>Cognition integrator and language</td>
</tr>
<tr>
<td>7,834,963</td>
<td>Optical integrator</td>
</tr>
<tr>
<td>7,830,197</td>
<td>Adjustable integrator using a single capacitance</td>
</tr>
<tr>
<td>7,811,792</td>
<td>Controllable integrator</td>
</tr>
<tr>
<td>7,788,309</td>
<td>Interleaved comb and integrator filter structures</td>
</tr>
<tr>
<td>7,778,730</td>
<td>Voice record integrator</td>
</tr>
<tr>
<td>7,729,577</td>
<td>Waveguide-optical Kohler integrator utilizing geodesic lenses</td>
</tr>
<tr>
<td>7,726,819</td>
<td>Structure for protecting a rod integrator having a light shield plate with an opening</td>
</tr>
<tr>
<td>7,724,063</td>
<td>Integrator-based common-mode stabilization technique for pseudo-differential switched-capacitor circuits</td>
</tr>
<tr>
<td>7,714,684</td>
<td>Pseudo-differential active RC integrator</td>
</tr>
<tr>
<td>7,706,072</td>
<td>Optical integrator, illumination optical device, photolithograph, photolithography, and method for fabricating device</td>
</tr>
<tr>
<td>7,696,913</td>
<td>Signal processing system using delta-sigma modulation having an internal stabilizer path with direct output-to-integrator connection</td>
</tr>
<tr>
<td>7,693,430</td>
<td>Burst optical receiver with AC coupling and integrator feedback network</td>
</tr>
<tr>
<td>7,679,540</td>
<td>Double sampling DAC and integrator</td>
</tr>
<tr>
<td>7,671,771</td>
<td>Analog-to-digital converter with integrator circuit for overload recovery</td>
</tr>
<tr>
<td>7,658,497</td>
<td>Rod integrator holder and projection type video display</td>
</tr>
<tr>
<td>7,629,917</td>
<td>Integrator and cyclic AD converter using the same</td>
</tr>
<tr>
<td>7,619,550</td>
<td>Delta-sigma AD converter apparatus using delta-sigma modulator circuit provided with reset circuit resetting integrator</td>
</tr>
<tr>
<td>7,611,246</td>
<td>Projection display and optical integrator</td>
</tr>
</tbody>
</table>
PAT. NO. | Title
--- | ---
7,605,645 | Transconductor, integrator, and filter circuit
7,599,631 | Burst optical receiver with AC coupling and integrator feedback network
7,575,159 | Point of sale integrator
7,570,032 | Regulator with integrator in feedback signal
7,565,326 | Dialect independent multi-dimensional integrator using a normalized language platform and secure controlled access
7,554,400 | Integrator and error amplifier
7,543,945 | Integrator module with a collimator and a compact light source and projection display having the same
7,532,145 | High resolution and wide dynamic range integrator
7,528,818 | Digitally synchronized integrator for noise rejection in system using PWM dimming signals to control brightness of light source
7,511,648 | Integrating/SAR ADC and method with low integrator swing and low complexity
7,474,241 | Delta-sigma modulator provided with a charge sharing integrator
7,471,456 | Optical integrator, illumination optical device, exposure device, and exposure method
7,454,750 | Integrator adaptor and proxy based composite application provisioning method and apparatus
7,447,049 | Single ended flyback power supply controllers with integrator to integrate the difference between feedback signal a reference signal
7,423,729 | Method of monitoring the light integrator of a photolithography system
7,417,485 | Differential energy difference integrator
7,415,716 | Component integrator
7,411,534 | Analog-to-digital converter (ADC) having integrator dither injection and quantizer output compensation
7,411,198 | Integrator circuitry for single channel radiation detector
7,395,090 | Personal portable integrator for music player and mobile phone
7,385,426 | Low current offset integrator with signal independent low input capacitance buffer circuit
7,379,160 | Optical integrator, illumination optical device, exposure apparatus, and exposure method
7,352,510 | Light-pipe integrator for uniform irradiance and intensity
7,345,285 | Spectra acquisition system with threshold adaptation integrator
7,333,626 | Arbitrary coverage angle sound integrator
7,324,654  Arbitary coverage angle sound integrator
7,324,025  Non-integer interpolation using cascaded integrator-comb filter
7,315,268  Integrator current matching
7,304,592  Method of adding a dither signal in output to the last integrator of a sigma-delta converter and relative sigma-delta converter
7,280,405  Integrator-based current sensing circuit for reading memory cells
7,262,056  Enhancing intermolecular integration of nucleic acids using integrator complexes
7,243,844  Point of sale integrator
7,242,333  Alternate sampling integrator
7,205,849  Phase locked loop including an integrator-free loop filter
7,187,948  Personal portable integrator for music player and mobile phone
7,182,468  Dual lamp illumination system using multiple integrator rods
7,180,357  Operational amplifier integrator
7,170,959  Tailored response cascaded integrator comb digital filter and methodology for parallel integrator processing
7,155,470  Variable gain integrator
7,152,981  Projection illumination system with tunnel integrator and field lens
7,152,084  Paralleized infinite impulse response (IIR) and integrator filters
7,150,968  Bridging INtegrator-2 (Bin2) nucleic acid molecules and proteins and uses therefor
7,138,848  Switched capacitor integrator system
7,130,764  Robust DSP integrator for accelerometer signals
7,102,844  Dual direction integrator for constant velocity control for an actuator using sampled back EMF control
7,102,548  Cascaded integrator comb filter with arbitrary integer decimation value and scaling for unity gain
7,098,845  Apparatus for generating an integrator timing reference from a local oscillator signal
7,098,827  Integrator circuit
7,098,718  Tunable current-mode integrator for low-frequency filters
7,087,881  Solid state image pickup device including an integrator with a variable reference potential
Example – OTA-C Tow Thomas Biquad

\[
\frac{V_{OUT}}{V_{IN}} = \frac{g_{m3}g_{m2}}{\left(s^2C_1C_2 + s g_{m4}C_2 + g_{m1}g_{m2}\right)}
\]

Assume \( g_{m1} = g_{m2} = g_m \), \( C_1 = C_2 = C \)

\[
\frac{V_{OUT}}{V_{IN}} = \frac{\left(\frac{g_{m3}}{g_m}\right)\frac{g_m^2}{C^2}}{\left(s^2 + s \left(\frac{g_m}{g_m} + \frac{g_m^2}{C} + \frac{g_m^2}{C^2}\right)\right)}
\]

Express as

\[
\frac{V_{OUT}}{V_{IN}} = \frac{\left(\frac{g_{m3}}{g_m}\right)\omega_0^2}{\left(s^2 + s \frac{\omega_0}{Q} + \omega_0^2\right)}
\]

where

\[
\omega_0 = \frac{g_m}{C} \quad Q = \frac{g_m}{g_{m4}}
\]
Basic Integrator Functionality

Noninverting

\[ X_{IN} \rightarrow \frac{l_0}{s} X_{OUT} \]

Inverting

\[ X_{IN} \rightarrow -\frac{l_0}{s} X_{OUT} \]

Lossy Noninverting

\[ X_{IN} \rightarrow \frac{l_0}{s + \alpha} X_{OUT} \]

Lossy Inverting

\[ X_{IN} \rightarrow -\frac{l_0}{s + \alpha} X_{OUT} \]

Summing (Multiple-Input) Inverting/Noninverting

\[ X_{OUT} = \sum_{k=1}^{n} \frac{\pm l_{Ok}}{s} \]

Summing (Multiple-Input) Lossy Inverting/Noninverting

\[ X_{OUT} = \sum_{k=1}^{n} \frac{\pm l_{Ok}}{s + \alpha_k} \]

Balanced Differential

\[ X_{OUT}^+ - X_{OUT}^- = \frac{l_0}{s} (X_{IN}^+ - X_{IN}^-) \]

Fully Differential

\[ X_{OUTdiff} = \frac{l_0}{s} X_{INdiff} \]
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.
Example – Basic Op-Amp Feedback Integrator

Inverting Integrator of Family

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

Noninverting Integrator

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

Summing Inverting Integrator

\[ V_{OUT} = -\sum_{k=1}^{n} \frac{1}{CR_{k}s} V_{IN_k} \]
Example – Basic Op-Amp Feedback Integrator

Inverting Integrator of Family

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

Summing Inverting Integrator

\[ V_{\text{OUT}} = -\sum_{k=1}^{n} \frac{1}{CR_k s} V_{\text{INk}} \]

Lossy Summing Inverting Integrator

\[ V_{\text{OUT}} = -\sum_{k=1}^{n-1} \frac{R_n V_{\text{INk}}}{R_k (1+CR_n s)} \]
Example – Basic Op-Amp Feedback Integrator

Inverting Integrator of Family

Lossy Summing Inverting Integrator

Lossy Inverting Integrator

Mathematical Expressions:

1. Inverting Integrator: \[ V_{OUT} = -\frac{1}{CR_s} V_{IN} \]
2. Lossy Summing Inverting Integrator: \[ V_{OUT} = -\frac{\sum_{k=1}^{n} R_{FK} V_{INK}}{1+CR_{FS}} \]
3. Lossy Inverting Integrator: \[ V_{OUT} = -\frac{R_{F}}{1+CR_{FS}} V_{IN} \]
Example – Basic Op-Amp Feedback Integrator

Inverting Integrator of Family

Balanced Differential Inverting Integrator

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

\[
V_{IN}^+ \quad R \quad V_{OUT}^+
\]

\[
V_{IN}^- \quad R \quad V_{OUT}^-
\]

\[
V_{IN}^{diff} \quad V_{OUT}^{diff}
\]

Axis of Symmetry
Example – Basic Op-Amp Feedback Integrator

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

Inverting Integrator of Family

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

Fully Differential Inverting Integrator
End of Lecture 25