"Split-ADC"

Digital Background Correction of Open-Loop Residue Amplifier Nonlinearity Errors in a 14b Pipeline ADC

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Outline

• Background
  – Goals
  – Pipeline ADC Review
  – Previous Self-Calibration Techniques

• "Split ADC" Architecture
  – Area / Noise / Speed / Power Implications
  – Design Details
  – Results

• Conclusion
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Goals

General: Take advantage of CMOS scaling
• Digital
  – Relax requirements on analog precision
  – All calibration / complexity in digital domain
• Background
  – Calibration continuous in background
• Deterministic
  – Short time constant for adaptation
  – No requirements on input signal behavior

Specific Implementation:
  14b Pipeline ADC
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Pipeline ADC Review
Residue Expression

- Linear gain: \( v_R = G_i (v_{IN} - D_i \cdot V_{REF}) \)
Residue Expression

• Linear gain:
  \[ v_R = G_i(v_{IN} - D_i \cdot V_{REF}) \]

• Nonlinearity error:
  \[ v_R = G_i(v_{IN} - D_i \cdot V_{REF}) - e \]
Nonlinearity Error

• Function of input:

\[ e(v_{IN}) \]
Nonlinearity Error

• Function of output:

$$e(v_R)$$
Open-Loop Differential Pair

- Nonlinearity error:
Pipeline ADC Review

\[ v_{R1} = G_1(v_{IN} - D_1 \cdot V_{REF}) \]

(assumes linear gain)
Pipeline ADC Review

Residue 2

\[ v_{R2} = G_2 \left( v_{R1} - D_2 \cdot V_{REF} \right) \]

\[ v_{R2} = G_2 \left( \left[ G_1 (v_{IN} - D_1 \cdot V_{REF}) \right] - D_2 \cdot V_{REF} \right) \]
Pipeline ADC Review

\[ \frac{v_{IN}}{V_{REF}} = D_1 + \left( \frac{1}{G_2 \cdot G_1} \right) D_2 + \left( \frac{1}{G_2 \cdot G_1} \right) v_{R2} \]

**Output Code**

**Quantization Error**
Pipeline ADC Review

- All stage results:

\[ x = D_1 + \frac{1}{G_1} D_2 + \frac{1}{G_1 G_2} D_3 + \frac{1}{G_1 G_2 G_3} D_4 + \frac{1}{G_1 G_2 G_3 G_4} D_5 \]
Pipeline ADC Review

- $D_b$: Result of "back end" digitizing $v_{R1}$

$$x = D_1 + \frac{1}{G_1} \left( D_2 + \frac{1}{G_2} D_3 + \frac{1}{G_2 G_3} D_4 + \frac{1}{G_2 G_3 G_4} D_5 \right) D_b$$
Digital Correction: Gain

- $D_b$: Result of "back end" digitizing $v_{R1}$

\[ x = D_1 + \frac{1}{\hat{G}_1} D_b \]

- $\hat{G}_1$: Digital estimate of analog gain $G_1$
Digital Correction: Nonlinearity

- $D_b$: Result of "back end" digitizing $v_{R1}$

$$x = D_1 + \frac{1}{\hat{G}_1} D_b + e(\hat{p}_1, D_b)$$

- $\hat{p}_1$: Estimate of nonlinearity parameter $p_1$

Murmann ..., "A 12b 75MS/s Pipelined ADC using open-loop residue amplification," ISSCC2003
Functional Calibration

• $D_b$: Result of "back end" digitizing $v_{R1}

\[ x = D_1 + \frac{1}{\hat{G}_1} D_b + e(\hat{p}_1, D_b) \]

How to estimate $G_1, \ p_1 \ ...$

• Digitally
• In the background
• Without a known input?
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Previous Work

• Multiple-mode residue amplifier

Murmann ..., "A 12b 75MS/s Pipelined ADC using open-loop residue amplification," ISSCC2003
Previous Work

• PR choice between residue amplifier modes
• Compare statistics of results from each mode

Murmann..., "A 12b 75MS/s Pipelined ADC using open-loop residue amplification," ISSCC2003
Difficulty

- About $2^{2N}$ samples needed to decorrelate calibration signal from unknown ADC input

Murmann ..., "A 12b 75MS/s Pipelined ADC using open-loop residue amplification," ISSCC2003
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Split ADC Architecture

- Split ADC into identical halves
- Use different residue mode on each side

\[ x = \frac{x_A + x_B}{2} \]

\[ \Delta x = x_B - x_A \]
Split ADC Architecture

- Average of A, B results is ADC output code
- Calibration signal developed from difference

\[
x = \frac{x_A + x_B}{2}
\]

\[
\Delta x = x_B - x_A
\]
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Same Area, Noise, Speed, Power

\[
f_T = b \left( \frac{g_m}{C} \right)
\]

\[
f_T = b \left( \frac{g_m/2}{C/2} \right) = b \left( \frac{g_m}{C} \right)
\]

<table>
<thead>
<tr>
<th>Speed</th>
<th>( P = p \cdot g_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>( P = p \cdot \frac{g_m}{2} + p \cdot \frac{g_m}{2} = p \cdot g_m )</td>
</tr>
<tr>
<td>Noise</td>
<td>( \sigma_x = n \sqrt{\frac{kT}{C}} )</td>
</tr>
<tr>
<td></td>
<td>( \sigma_x = \sqrt{\left( \frac{1}{2} n \sqrt{\frac{kT}{C/2}} \right)^2 + \left( \frac{1}{2} n \sqrt{\frac{kT}{C/2}} \right)^2} = n \sqrt{\frac{kT}{C}} )</td>
</tr>
</tbody>
</table>

- Negligible impact on analog complexity
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Digital Correction

CALIBRATION
(SET OF 32 CONVERSIONS)

ADC MODE SELECTION

NONLIN L.U.T.

DIGITAL CORRECTION

CONVERSION

\( \hat{G}, \hat{p} \)

UPDATE \( \hat{G}, \hat{p} \)

\( \hat{\varepsilon}_G, \hat{\varepsilon}_p \)

UPDATE \( \hat{\varepsilon}_G, \hat{\varepsilon}_p \)

ESTIMATES

\( \mu \)

\( \Delta x \)

DIFF

\( x \)

AVG

\( x_{A^*, B^*} \) CODES

(UNCORRECTED)

\( x_{A^*, B^*} \) CODES

\( x_{OUT} \)
Calibration: Intuitive View

- **A, B residue modes**

- **Larger** $v_{RA} \Rightarrow$
  Corrected code $x_A$
  more sensitive to nonlinearity

- **Nonzero** $\Delta x = x_B - x_A \Rightarrow$
  More likely due to error in A parameters $\Rightarrow$

- **Adjust** $G_{1A}, p_{1A}$
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# MATLAB Simulation Parameters

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
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<tbody>
<tr>
<td>Input full scale range</td>
<td>$V_{FS}$</td>
</tr>
<tr>
<td>Residue Amplifier Gain</td>
<td>$G$</td>
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<tr>
<td>Initial Gain Estimate</td>
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</tr>
<tr>
<td>Amplifier Nonlinearity Parameter</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>Initial Nonlinearity Estimate</td>
<td></td>
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<tr>
<td>Differential Pair Overdrive Bias</td>
<td>$V_{OV}$</td>
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<tr>
<td>LMS Parameter</td>
<td>$\mu$</td>
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<tr>
<td>Conversions per Matrix Iteration Group</td>
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<tr>
<td>Sub-ADC Transition Level Error Range</td>
<td></td>
</tr>
<tr>
<td>Input Referred Noise</td>
<td></td>
</tr>
</tbody>
</table>
Simulated INL

Integral nonlinearity, uncalibrated.

Integral nonlinearity, calibrated.
Calibration Convergence

- Long decorrelation times not necessary
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• "Split ADC" architecture
  – Average: Output code
  – Difference: Drive to zero to correct errors
  – Deterministic: Converges rapidly
    • Suitable for high resolution ADCs
  – Negligible effect on analog
    Area, power, noise, speed
  – Complexity moved into digital domain

• 14b Pipeline ADC
  – Correct gain, nonlinearity errors
  – Self-calibration in ~ 50,000 conversions
Acknowledgments

• Analog Devices
  – Precision Nyquist Converters group
  – Michael Coln
  – Brian Larivee
  – Bob Adams
  – Bob Brewer
  – Larry DeVito
  – Paul Ferguson
  – Colin Lyden
  – Katsu Nakamura
  – Richard Schreier
  – Larry Singer
• Stanford University
  – Boris Murmann