Design Considerations for Continuous-Time Bandpass ADCs

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ANALOG
DEVICES

Outline

1 An ADC Figure-of-Merit

2 Overview of Bandpass ADCs

3 A High-Q Active-RC Resonator

4 IDAC Design Considerations
    Thermal noise
    Switching dynamics

An ADC Figure-of-Merit?

- Is an ADC which has SNR = 100 dB over BW = 1 MHz fundamentally better or worse than an ADC which has SNR = 90 dB over the same bandwidth, if ADC1 consumes 1 W while ADC2 consumes 100 mW?

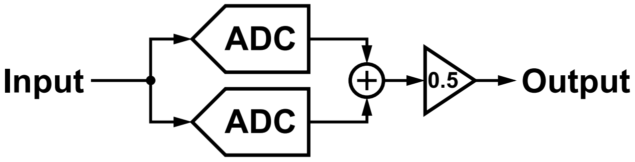
An ADC Figure-of-Merit?

- More generlally, what is the fundamental trade-off between

Bandwidth (BW),
Dynamic Range (DR)
and
Power consumption (P)
?

DR-P Trade-Off: Part 1

- To increase DR at the expense of P, parallel two ADCs and average:



- Averaging reduces noise by a factor of $\sqrt{2}$: DR += 3 dB
  Assuming the ADCs' noises are uncorrelated
- But uses twice the power: P += 3 dB

DR-P Trade-Off: Part 2

- To reduce P at the expense of DR, "cut the ADC in half"
  May not be practical if the ADC is already small, but if it can be done,
  P –= 3 dB & DR –= 3 dB
- ∴ For an ADC of some BW, *x* dB in DR costs *x* dB in P,
  or
  DR (in dB) – $10\log_{10}(P)$ = const

Q: Is This Trade-Off Optimal?

- **A: Yes, because it is bi-directional**

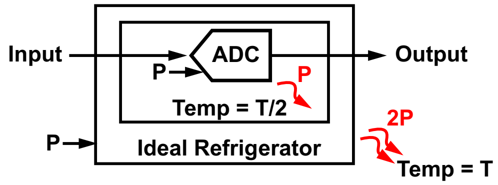
  The fact that you can (in principle) go both ways for any ADC means that no other trade-off can exist for ADCs that are optimal.

- **Consider a (supposedly) optimal ADC that can get more than 3 dB increase in DR for a doubling of P**

  Double P, then cut that ADC in half.
  The resulting ADC has the same P as the original, but more DR.

DR-P Trade-Off: Part 1b

- **Can increase DR by 3 dB by reducing T by a factor of 2:**



- **But this also costs twice the power**

What About BW?

- **Reducing BW by a factor of 2 increases DR by 3 dB but leaves P alone**

  Assuming the noise is white (distortion is not dominant) and that digital filtering takes no power.

- **Time-interleaving two ADCs doubles BW and doubles P, but leaves DR unchanged**

  I/Q processing does the same.
  Assumes that interleaving is perfect (can be calibrated).

Resulting FOM

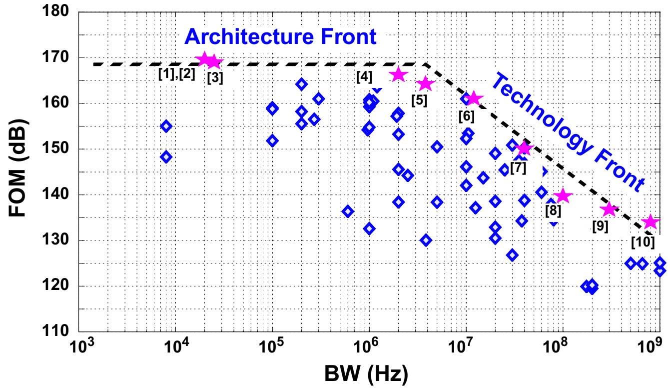
- **Use a dB scale:**

$$FOM = (DR)_{dB} + 10\log\frac{(BW)}{P}$$

- **For a given FOM, factors of 2 in BW or P are equivalent to a 3-dB change in DR**
- **Should really include T, but since T is usually 300K, omit it**

  Steyaert et al. like $FOM = \frac{4kT \times DR \times 2BW}{P}$

State-of-the-Art FOM



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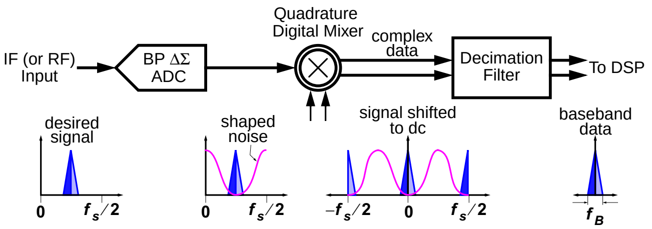
A Bandpass ΔΣ ADC System



- ADC outputs noise-shaped data
- DSP translates signal to baseband and removes out-of-band noise

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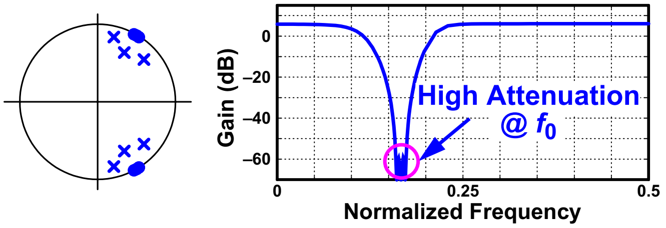
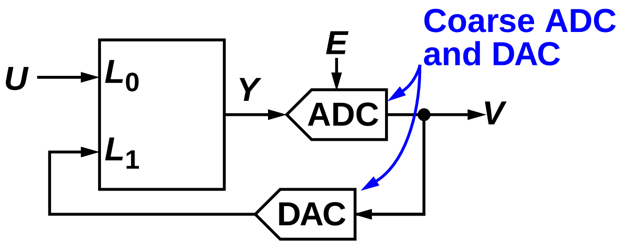
Bandpass NTF



- NTF attenuates quantization noise in the band of interest

Generic ΔΣ ADC

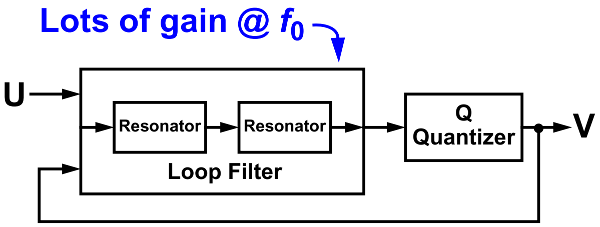


$$\begin{aligned} Y &= L_0U + L_1V \\ V &= Y + E \end{aligned} \Rightarrow \begin{aligned} V &= GU + HE \\ H &= \frac{1}{1-L_1},\ G = L_0H \end{aligned}$$, where

inverse relations: $L_1 = 1 - 1/H$, $L_0 = G/H$

- Poles of L_1 are the zeros of H

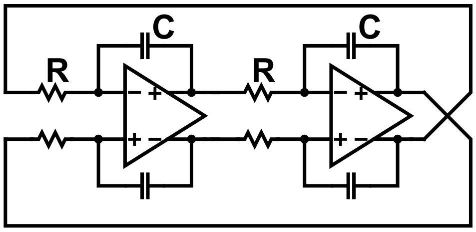
A Bandpass ΔΣ ADC



- Quantization noise is suppressed at frequencies where the loop gain is large

Need high-Q resonances to get deep nulls

Active-RC Resonator

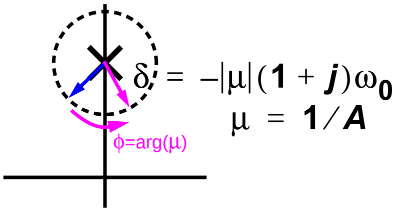


\+ Amenable to integration; Readily tuned over several octaves

– Amplifier drives R and C

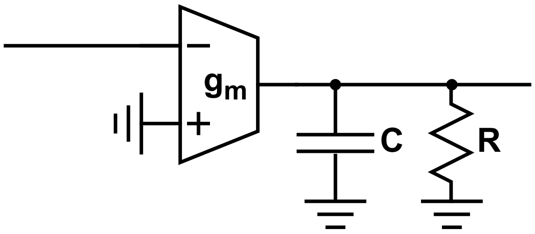
Amplifier Gain and Phase

- Finite gain degrades Q
- Phase lag enhances Q
- Analysis shows ϕ = 45° yields high Q, independent of amplifier gain

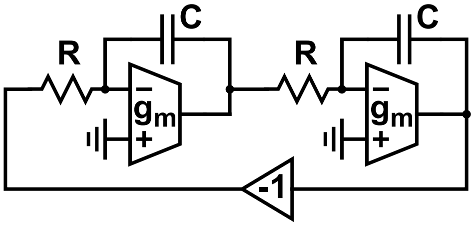


$$\begin{aligned} \delta &= -|\mu|(1 + j)\omega_0 \\ \mu &= 1/A \end{aligned}$$

A Circuit With $\phi = 45^o$ @ f_0



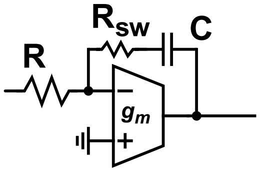
Resulting High-Q Resonator



- Amplifier load yields 45º @ f_0
- Finite gm shifts the pole frequency, but does not degrade Q!

Finite g_m Bandwidth & Non-zero Switch Resistance

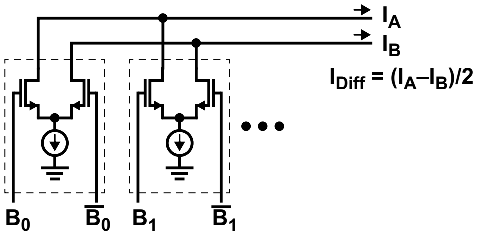
- Switch resistance degrades Q
- Finite gm bandwidth enhances Q



$$g_m = \frac{g_{m0}}{1 + s/\omega_p}$$

- Cancellation occurs if $R_{sw} = \frac{2\omega_0}{g_{m0}\omega_p}$

Current-Mode DAC (IDAC)



- Excellent spectral performance
  “–80 dBc IMD to 300 MHz”
  [Schofield et al., ISSCC 2003]

IDAC SNR/Power Limit

- Assume square-law operation
  i.e. $I_{FS} = K(\Delta V)^2$.
- The power of a –3-dBFS signal is
  $S^2 = (0.5(I_{FS}/2)^2)/2 = K^2(\Delta V)^4/16$
- While the noise in bandwidth B is
  $N^2 = (4kTBK\Delta V)/3$

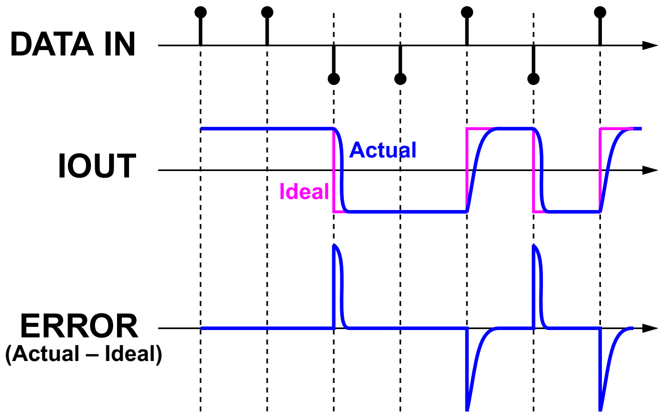
$$\Rightarrow \left(\frac{S}{N}\right)^2 = \frac{3I_{FS}\Delta V}{64kTB}$$

IDAC SNR/Power Limit (cont’d)

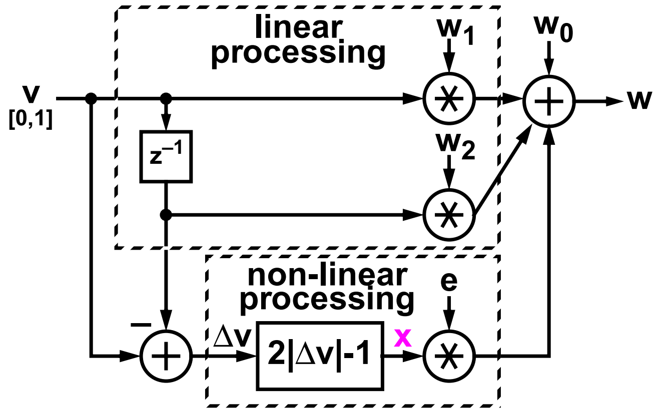
$$\left(\frac{S}{N}\right)^2 = \frac{3I_{FS}\Delta V}{64kTB}$$

- “DAC SNR is proportional to the power allocated to its current sources”
- For example, to get SNR = 100 dB with B = 5 MHz and ΔV = 300 mV requires (at least) I_{FS} = 15 mA

Switching Dynamics



Model of Dynamic Nonlinearity



Model Equations

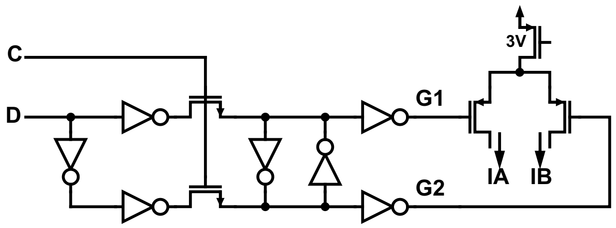
$$\begin{bmatrix} w_0 \\ w_1 \\ w_2 \\ e \end{bmatrix} = \begin{bmatrix} \frac{3}{4} & \frac{1}{4} & \frac{1}{4} & -\frac{1}{4} \\ -\frac{1}{2} & \frac{1}{2} & -\frac{1}{2} & \frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ -\frac{1}{4} & \frac{1}{4} & \frac{1}{4} & -\frac{1}{4} \end{bmatrix} \begin{bmatrix} w_{00} \\ w_{01} \\ w_{10} \\ w_{11} \end{bmatrix}$$

where w_{00}, w_{01}, w_{10} and w_{11} are the output waveforms in response to 00, 01, 10 and 11 data inputs.

- $e = 0.25[(w_{01} + w_{10}) - (w_{00} + w_{11})]$

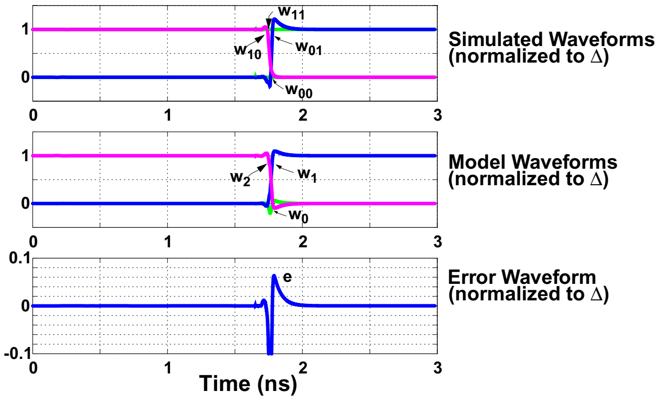
Zero error if the rise and fall waveforms are perfectly complementary

DAC Example

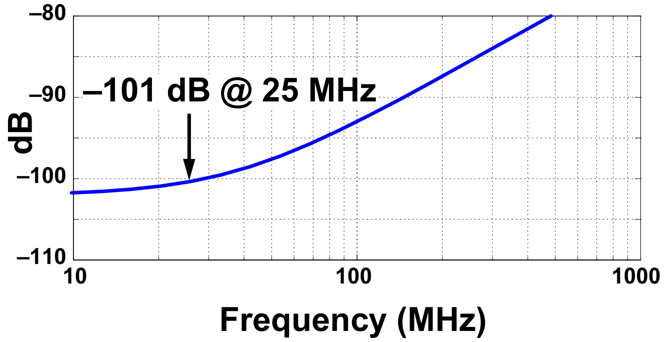


- 3V PMOS for low noise
- Symmetric drive for symmetric switching

Simulated Single-Ended W*

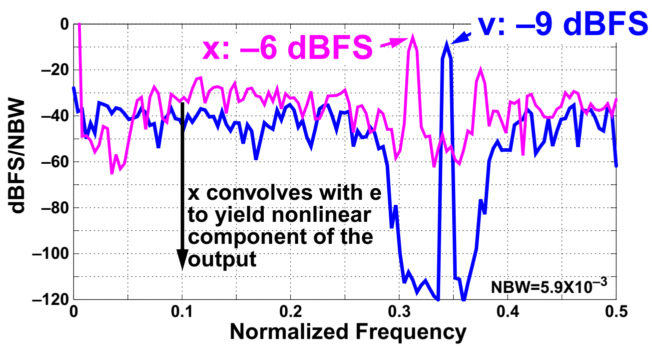


Fourier Transform of E



Example Spectra in Model

33-level v sequence; $f_0 = f_s/3$; no MS



E.g. SFDR Calculation

- The signal level is
  –9 dBFS – 2 dB = –11 dBFS
- The spur level (in the absence of any differential cancellation) will be
  –6 dBFS – 101 dB = –107 dBFS
- Thus, the SFDR will be 96 dB

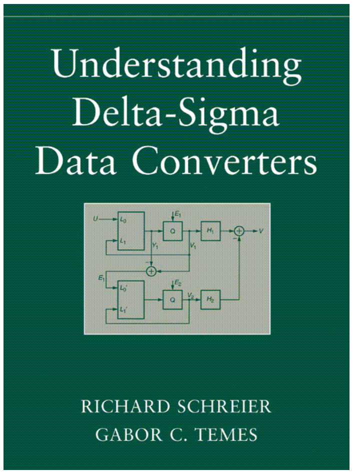
  Need only 4 dB of differential cancellation to reach SFDR = 100 dB
- Calculating the impact of element dynamics on SNR is done similarly

Conclusions

1 3 dB is a factor of 2 (in BW, DR, or P).

2 An active-RC resonator can achieve high Q despite several circuit non-idealities.

3 Current-mode DACs can have near-perfect spectral performance up to several tens of MHz.



Understanding
Delta-Sigma
Data Converters

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