Low power high precision mixed-signal circuits and design

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Introduction

(high) precision is needed in:

• time keeping
every *Swatch* is adjusted to 3 ppm precision ( < 0.3 s/day)
• instrumentation / metering
  measurement of position, angle, weight, ...
  *EM ASIC examples*: caliper (µm), weight scale (100g/130kg)...
• in automotive and industrial applications
to measure pressure, acceleration, angle, ...
  *EM ASIC examples*: sensor interface for airbag/ABS, ...
• ... in summary: everywhere where an analog quantity
  is to be processed

Low power high precision mixed-signal circuits and design
Basic requirements for high precision

• precise voltage references
  --> absolute precision, low drift
• low-noise amplifiers
  --> good measurement reproduceability
• operational amplifiers with high open-loop gain
  --> to minimize influence of Opamp
• linear resistors and capacitors
  --> for continuous and switched-capacitor amplifiers
• precise time bases
  --> for switched-capacitor filters (besides time-keeping)
• linear high-resolution A/D- and D/A converters
  --> to map the analog into the digital world as precise as possible
Requirements for absolute precision

- some elements to allow trimming:
  - *Laser Fuses*: very low-cost in terms on silicon trimming during wafer probing, no reprogrammability small changes possible after packaging
  - *EEPROM*: possibility to calibrate a system at the latest possible stage
    In the *Swatch* the time keeping adjustment is done just before putting the battery ... , if there is one to put.

Δ! the higher the needed absolute precision, the higher the test cost!

- depending on specified temperature range etc., the breakeven abs. tolerance below which we recommend trimming is 5 ... 7 % (corresponds to a bandgap voltage of 1.2 V +- 60 mV...)

  note: CPK requirement > 1.66 --> 5 σ design
Tradeoff precision - low power - cost

is best explained by means of a high-precision resistor string which is often used in D/A and A/D converters

\[ \text{Idd} = \frac{Vdd}{R_{tot}} \quad \text{R} = r \cdot \frac{L}{W} \quad (1 \text{ element}) \]

high precision means: keep the spread of R low \( \rightarrow W \uparrow \)

keeping L the same \( \rightarrow \) lower R\(_{tot} \quad \rightarrow \text{Idd} \uparrow \)

to reduce Idd \( \rightarrow \) increase L \( \rightarrow \) Idd \( \downarrow \) cost \( \uparrow \)

other considerations:
impedance level must be low to minimize noise and influence of the load on the tap points, resp maximize immunity against perturbations \( \rightarrow \) Idd \( \uparrow \)

adding buffers on the tap points solves the problem of loading but has an impact on precision because of the buffer offset \( \rightarrow \) precision \( \downarrow \) cost \( \uparrow \)

To find optimum solutions in this field is EM’s ‘daily bread’!
Typical sensor interface system

EM offers everything on the same silicon, even incl. µC core!

Low power high precision mixed-signal circuits and design
The noise issue (1)

There are basically two types of noise:

- **White (or thermal) noise**: $R_n \sim \frac{2n}{(3gm)} \sim \frac{1}{I}$
  
  Rather important in HF systems

- **Flicker (or 1/f-) noise**: $R_n \sim \frac{\rho}{(fW^2L)}$
  
  Independent of $I$

  Important in slow sensor signal processing systems

\[ \text{1/f noise} \quad \text{thermal noise} \]

$\sim 1\text{kHz}$

EM’s amplifiers can be designed for < 10 nV/rtHz noise at $f=10\text{kHz}$

and < 0.2 $\mu\text{V}/\text{rtHz}$ at $f=1\text{Hz}$ in **standard CMOS**

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The noise issue (II)

the 1/f-noise can be kept low by

• passing to BICMOS  (no 1/f noise)  
  costly solution!  (bigger part of circuit suffers from cost increase)
• larger sized transistors at a given current level  
  (only a small part of chip suffers from cost increase)
• by design techniques such as
  - autozero
  - correlated double sampling
  - chopping

EM has realized very performing circuits in **STD CMOS** using the techniques mentionned above.
Examples of low - noise amplifiers

1. Very low-noise operational amplifier (non-chopped!)

used in weight scales, intrusion detectors, ...
< 0.5 µV integrated noise between 1 ... 10Hz
> 100 dB open-loop gain and CMRR
up to 10 V/µs slewrate and 10 MHz gain bandwidth depending on bias level
current consumption: 10 ... 200 µA depending on above requirement
0.4mm² area for above noise in ALP1 technology

2. Ultra low-noise chopper (instrumentation) amplifier

collaboration with ETHZ; measured results in ALP1 technology:
8.5 nV/rtHz flat response (practically no 1/f-noise)
850 nV residual offset 150dB CMRR
programmable gain (700/1750/2800/7000) and bandwidth (600/1500Hz)
3 mW power consumption 3.6mm² area
ideal for thermopile applications STD CMOS!
Leakage of EM’s input pads vs T

note: any input leakage creates an error voltage on the sensor signal because of its internal resistance being non-zero.

example: \(1 \text{nA} \times 1 \text{k\Omega} = 1 \mu\text{V}\)

Low power high precision mixed-signal circuits and design.
Available A/D converters

1. Low cost 8-bit converter (charge redistribution type)
   - used in our microcontroller family
   - fast (up to 1 MHz sample rate)
   - low voltage operation: Vdd = 2.0 V
   - low current consumption: 10 µA @ 2V  fs = 50 kHz

2. Linear 13-bit converter (incremental type)
   - similar to sigma-delta, proven principle up to > 16-bits
   - ideal for sensor applications (e.g. weight scales, ...)
   - < 1 ms conversion time  precision down to Vdd = 2.4 V
   - Idd = 200 µA (150 µA only for reference voltage divider)

3. 14-bit relative precision converter (RSD principle)
   - designed by IMT Neuchâtel; available as std EM6414 (ADC+DAC)
   - configurable preamplifier with 4 gain values (1; 8; 16; 32)
   - S/(N+D) = 55 dB  78dB dynamic range
   - 25 µA @ 2.5 V and 25 kHz sample rate
   - ideal for processing of audio signals

Low power high precision mixed-signal circuits and design
Functional blocks for sensor applications (I)

“1nA optical receiver” (presented at ESSCIRC’96)

- application: smoke detector / security
- input sensitivity: 960 mV / nA (180 dBΩ transimp.)
- equiv. (DC) input offset: < 1 nA
- equiv. input noise: 34 pA-rms
- total integration time: ~ 300 µs
- output swing: 4 V
- supply voltage: 5 V (works down to < 3 V)
- current consumption: 500 µA (could be reduced)
Functional blocks for sensor applications (II)

Low noise interface for e.g. strain-gauge bridge sensor (Preamplifier + 13-bit A/D converter)

- application: weight scale / white goods
- equiv. input LSB resolution: < 3 µV
- conversion time: < 1 ms
- ADC non-linearity error: linear by design (DNL, INL) production test limit: 2 LSB
- supply voltage range: 2.4 ... 3.6 V (full precision)
- current consumption: 300 µA (could be reduced!)
Functional blocks for sensor applications (III)

Low noise interface for capacitive accelerometer

- application: airbag, ABS (automotive)
- resolution: < 5 fF
- sensitivity: 100 mV/pF
- bandwidth: 4 kHz (adjustable)
- output noise (20 ... 1000Hz): 150 µV-rms
- output noise density: < 14 µV / rtHz
- output swing: 2.4 V
- supply voltage: 5 V

Low power high precision mixed-signal circuits and design
EM’s ultra low-power sleep mode

a lot of analog and digital functions must not be ON all the time

--> most important in terms of long battery life are therefore

the cells which you cannot necessarily switch off

EM offers:

• Static Power-On reset cells with < 30 nA
• 32 kHz quartz oscillator with < 100 nA
• trimmable RC oscillator (32 kHz) with < 250 nA

• if startup time (in case of quartz) is no issue or in quartz-less

applications, we have a ultra low power sleep mode counter,

which generates a periodic 2 s wakeup signal with < 20 nA

Just calculate: 2 µA means ~11 years autonomy on a 200 mAhrs

Lithium (primary) battery

Low power high precision mixed-signal circuits and design
For EM’s ultra low-power run mode we have:

- true 1 cycle / instruction microcontroller cores always less computing cycles for identical tasks
- < 200 nW / (MHz*Gate) for general digital parts (special LP library)
- ultra low-power quartz and RC oscillators a must in watch circuits
- the ultimate example of ultra low-power: EM realized a circuit with an analog part containing 11 operational amplifiers 2 oscillators (1 quartz, 1 RC) consuming < 3 µA @ 2.7V
  The whole circuit including 10k transistors of digital part is specified with < 7 µA!
## EM’s low-power / low-voltage at a glance

<table>
<thead>
<tr>
<th>Function</th>
<th>Vdd-min</th>
<th>Idd @ Vdd</th>
</tr>
</thead>
<tbody>
<tr>
<td>32 kHz quartz oscillator</td>
<td>0.9 V</td>
<td>50 nA @ 1.5V</td>
</tr>
<tr>
<td>32 kHz RC oscillator (trimmed +/– &lt;1 %)</td>
<td>1.0 V</td>
<td>150 nA @ 2.0V</td>
</tr>
<tr>
<td>600 kHz RC oscillator (trimmed +/– 1%)</td>
<td>1.0 V</td>
<td>6 µA @ 1.8V</td>
</tr>
<tr>
<td>1.2 MHz RC oscillator (trimmed +/– 0.25%)</td>
<td>1.0 V</td>
<td>30 µA @ 2.0V</td>
</tr>
<tr>
<td>13-bit/2ms A/D converter linear</td>
<td>2.2 V</td>
<td>50 µA @ 3.0V</td>
</tr>
<tr>
<td>14-bit/40µs A/D converter rel. precision</td>
<td>2.4 V</td>
<td>25 µA @ 2.5V</td>
</tr>
<tr>
<td>8-bit/20µs low-cost A/D converter</td>
<td>2.0 V</td>
<td>10 µA @ 2.0V</td>
</tr>
<tr>
<td>for anything that needs somewhat more supply voltage:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC/DC converters (Vdd x 2, x 3, ...)</td>
<td>&lt; 1 V</td>
<td>dep. on load</td>
</tr>
</tbody>
</table>

Low power high precision mixed-signal circuits and design
Why *must* you choose EM?

because of

- its advanced processes in terms of low power / low voltage
- its tremendous experience in the fights against nA’s in watch circuits against µA’s in mixed-signal circuits which has lead to our low-power oscillators, microcontrollers ...
- its year-long experience of combining high-precision electronics with low-power
- the possibilities of synergies with the various technologies of the Swatch Group
- QS 9000, ISO 9001