Novel Test Solutions for Dynamic Performance Parameter Testing of High-resolution Converters

K. Georgopoulos

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Outline

1. Background of work and related issues
2. Familiarisation with the sigma-delta A/D converter
3. Dynamic specification analysis and conventional test set-up
4. Alternative transformation approaches
5. Experimental results
6. Distortion meter test solution
7. Conclusions
Introduction

- Sigma-Delta A/D Converter – A device with numerous electronic applications (digital video cameras, mobile communications and others)
- Radix-2 Fast Fourier Transform is a common method for testing its dynamic specification parameters (SNR, THD, SINAD)
- This amounts to long test times and prohibits any possible on-chip realisation
- A new test set up is needed to overcome the FFT drawbacks
The Sigma-Delta A/D Converter (I)

- Employs the oversampling principle
- Relaxes the analogue design requirements
- Anti-aliasing ensured in two stages
- Offers high resolution digital output
- Very powerful at low-frequency applications
The Sigma-Delta A/D Converter (II)

Three main stages

- Anti-aliasing filter
- Sigma-delta modulator block (high-frequency single bit output)
- Decimation stage (averaging of modulator bit stream leading to multi-bit converter output)

Modulated input signal – high frequency bit stream
The Sigma-Delta A/D Converter (III)

- Order $L$ of the sigma-delta modulator is dependant upon the number of integration stages, $H(z)$.
- Signal transfer function, $z^L$, low-pass filters the signal of interest $X(z)$.
- Noise transfer function, $(1 - z^{-1})^L$, high-pass filters the quantisation noise $E_q(z)$.
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Conventional Approach

- The conventional approach: Radix-2 FFT
- Developed to effectively implement the Discrete Fourier Transform
- Requires data for processing, $N$, to be a power of two
- Number of arithmetic operations is proportional to $N$, i.e. $O(N\log N)$
- Involves real and complex calculations
- Large data sets are usually needed in order to provide sufficient results for SNR, THD, SI NAD
- Needs windowing
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Proposed Techniques (1)

- Fourier-based methods
  - *Arithmetic Fourier Transform*. Less arithmetic operations, only real calculations
  - *Discrete Sine Transform*. Same number of arithmetic operations but only with real data

- Non Fourier-based methods
  - *Wavelets*. Less arithmetic operations, non-complex calculations, no windowing requirements, flexibility in basis-functions
  - *Walsh Transform*. Square wave basis-functions, the same number of arithmetic operations but only real data and elimination of multiplications

- Distortion meter method
Proposed Techniques (II)

- Wavelets and AFT need less arithmetic operations
- Walsh needs the same numbers but requires NO multiplications
- DST has no complex multiplications

\( O(x) \) shows proportionality, \( N \) size of input data

<table>
<thead>
<tr>
<th>Method</th>
<th>Additions</th>
<th>Multiplications</th>
<th>Arithmetic operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walsh</td>
<td>Yes</td>
<td>None</td>
<td>( O(N\log N) )</td>
</tr>
<tr>
<td>Haar</td>
<td>Yes</td>
<td>Non-complex</td>
<td>( O(N) )</td>
</tr>
<tr>
<td>Line</td>
<td>Yes</td>
<td>Non-complex</td>
<td>( O(N) )</td>
</tr>
<tr>
<td>Daubechies</td>
<td>Yes</td>
<td>Non-complex</td>
<td>( O(N) )</td>
</tr>
<tr>
<td>DST</td>
<td>Yes</td>
<td>Non-complex</td>
<td>( O(N\log N) )</td>
</tr>
<tr>
<td>AFT</td>
<td>Yes</td>
<td>Non-complex, fewer</td>
<td>( O(2N) )</td>
</tr>
<tr>
<td>FFT</td>
<td>Yes</td>
<td>Complex</td>
<td>( O(N\log N) )</td>
</tr>
</tbody>
</table>
**Input Stimulus Requirements**

- Fourier based, i.e. AFT and DST, employ sine wave input test stimulus as FFT analysis.

- Daubechies and Line wavelet converge with a sinusoidal test stimulus.

- Walsh transform and Haar wavelet do not converge with a sinusoidal signal and require a square wave test input.
  - The advantage of a square wave signal is that it can be easily generated on-chip.
  - Only two amplitude levels – a small portion of the sigma-delta modulator transfer function is tested.
Modelling and Simulation

- High-level behavioural C model
- Mathematical representation of key modulator blocks, integrators, quantiser, summation point etc.
- Modulator model accounts for a differential implementation

\[
\begin{align*}
\text{AAF} \quad &\quad a_1(z) \quad s_1 \quad a_2(z) \quad s_2 \quad a_3(z) \quad s_3 \quad a_4(z) \\
\text{vr1} \quad &\quad +V_{\text{ref}} \quad \text{sum} \quad -V_{\text{ref}}
\end{align*}
\]
Failure Modes

- Considered for individual internal blocks at a time
- “Global” failure modes have been modelled within the simulated input test stimulus

<table>
<thead>
<tr>
<th>Failure</th>
<th>Affected Internal blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset effects</td>
<td>Each integrator, D/A converter, Reference voltages $\pm V_{ref}$</td>
</tr>
<tr>
<td>Gain deviations</td>
<td>Each integrator, $SUM$ node input</td>
</tr>
<tr>
<td>Feedback failures</td>
<td>From 4th to 3rd integrator, Feedback loop of the modulator</td>
</tr>
<tr>
<td>Noise effects</td>
<td>Global, i.e. noisy test input signal</td>
</tr>
<tr>
<td>Harmonic distortion</td>
<td>Global</td>
</tr>
</tbody>
</table>
Test Set-up

- All methods were applied on 16384 samples of the modulator bit stream
- Walsh transformation and Haar wavelet
  - Square wave test stimulus @ 1.5 kHz
  - 2.1 V amplitude for Walsh
  - 2.2 V amplitude for Haar
- DST and Daubechies wavelet
  - Sine wave test stimulus @ 1.5 kHz
  - 2.5 V amplitude
- Line wavelet
  - Sine wave test stimulus @ 1kHz
  - 2.5 V amplitude
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Ideal Parameter Values

- These values are only inherently restricted by each method, i.e. ideal modulator conditions
- DST achieves closest match to FFT
- Daubechies wavelet is second best followed by Line wavelet
- Square wave based methods offer the lowest dynamic specifications

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>FFT (dB)</th>
<th>Walsh (dB)</th>
<th>Haar (dB)</th>
<th>Line (dB)</th>
<th>Daub. (dB)</th>
<th>DST (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNR</td>
<td>119.5</td>
<td>92.4</td>
<td>102</td>
<td>106.1</td>
<td>108</td>
<td>123.3</td>
</tr>
<tr>
<td>THD</td>
<td>125.6</td>
<td>98.3</td>
<td>98.1</td>
<td>91.9</td>
<td>123.9</td>
<td>119.4</td>
</tr>
<tr>
<td>S/(N+THD)</td>
<td>118.5</td>
<td>91.4</td>
<td>96.6</td>
<td>91.8</td>
<td>107.9</td>
<td>117.9</td>
</tr>
</tbody>
</table>
SNR vs Input Amplitude (1)

- Stimuli of different amplitudes (dBV) have been applied
- Corresponding SNR has been evaluated
- Analysis has been normalised to maximum allowable FFT input amplitude of 3 V
- DST computes the best dynamic range, 0 – 110 dB
- DST maximum SNR is slightly higher than that of FFT, i.e. 124.6 dB to 121.1 dB
- Daubechies offers the next best match followed by the two square wave based methods, i.e. Walsh transform and Haar wavelet
- Line wavelet shows disappointing response
SNR vs Input Amplitude (II)
Noise Content – SNR (I)

- Suitable candidate technique must match FFT results in terms of pass/fail decisions.
- SNR values are computed for increasing noise content in input stimulus.
- Only DST follows closely FFT response.
- Walsh transform, Line and Daubechies wavelets record sharp transition from close-to-ideal to catastrophic failure – pass/fail test and can be performed but max. noise threshold cannot be set freely.
- Haar wavelet does not yield any useful information.
Failure mode 1 - roughly 1mV
Failure mode 12 - roughly 10 mV
Harmonic Content – THD (I)

- Assumption – Harmonics are signal components located at integer multiple frequencies of the fundamental.
- Harmonics have been modelled within the input test stimulus.
- DST in full agreement with FFT.
- Rest of the techniques are non-suitable and common observations have been:
  - More than a single tone at the output while just a single harmonic applied to the modulator model.
  - Modulator noise shaping function completely corrupted.
## Harmonic Content – THD (II)

<table>
<thead>
<tr>
<th>Method</th>
<th>Ability</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT</td>
<td>Ref.</td>
<td>-</td>
</tr>
<tr>
<td>Walsh</td>
<td>Poor</td>
<td>Clear 1st harmonic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extra harmonics stimulated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Noise floor unaffected</td>
</tr>
<tr>
<td>Haar</td>
<td>Poor</td>
<td>Clear 1st Harmonic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extra harmonics stimulated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Noise transfer function altered</td>
</tr>
<tr>
<td>Line</td>
<td>Poor</td>
<td>Noise transfer function severely altered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Some harmonics are non-detectable</td>
</tr>
<tr>
<td>Daubechies</td>
<td>Poor</td>
<td>Noise transfer function severely altered</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Some harmonics are non-detectable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Extra harmonics stimulated</td>
</tr>
<tr>
<td>DST</td>
<td>Ideal</td>
<td>Identical to FFT</td>
</tr>
</tbody>
</table>
Integrator Gain Deviations

- Several low-level errors can be the cause for failure, i.e. capacitor mismatch and others
- Corrupted response is the result from the related integrator block
- FFT has shown the modulator structure to be robust to such source of errors
- Fourier-based methods such as AFT and DST offer acceptable results
- Daubechies and Line wavelet do not match FFT results
- Walsh and Haar techniques reveal good proximity to reference FFT response
Offset Effects

- Offsets modelled at key modulator blocks, i.e. integrators, D/A converter, summation point etc.
- Modulator architecture is extremely robust to such errors
- DST in full agreement with reference FFT
- Line and Daubechies wavelets are also in good agreement with FFT results
- Walsh and Haar techniques respond differently to offset effects due to different test input stimulus
Experimental Results (I)

Bit steam data have been extracted from CODEC demonstrator

Candidate techniques have been tested on the real data
Experimental Results (II)

- 2.5 V @ 1kHz and 1.5 kHz sine wave input
- 1.4 V @ 1.5 kHz square wave input

<table>
<thead>
<tr>
<th>Demonstrator</th>
<th>SNR (dB)</th>
<th>THD (dB)</th>
<th>SINAD (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT software model</td>
<td>119.5</td>
<td>125.6</td>
<td>118.5</td>
</tr>
<tr>
<td>FFT demonstrator</td>
<td>99.1</td>
<td>90.4</td>
<td>89.8</td>
</tr>
<tr>
<td>DST demonstrator</td>
<td>98.9</td>
<td>90.5</td>
<td>90.4</td>
</tr>
<tr>
<td>Line demonstrator</td>
<td></td>
<td></td>
<td>Catastrophic Response</td>
</tr>
<tr>
<td>Daubechies demonstrator</td>
<td>63.7</td>
<td>76</td>
<td>63.5</td>
</tr>
<tr>
<td>Walsh demonstrator</td>
<td>83</td>
<td>88.5</td>
<td>81.9</td>
</tr>
<tr>
<td>Haar demonstrator</td>
<td>88.9</td>
<td>96.6</td>
<td>88.2</td>
</tr>
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Distortion Meter Method (I)

- High-quality sine wave input
- Filter to remove fundamental
- Calculate power of filtered and unfiltered response
- Determine ratio (S/N+THD)
- Aimed at on-chip implementation and core test time reduction
- Smaller number of samples required for processing

ADC_output

Notch filter

800

DC suppression

RMS computation

S/(N+THD)[dB]
Distortion Meter (II)

- #samples: 1024 to 16384
- Performance constant over the number of samples
- Fluctuations in the order 0.1 dB
- SINAD ~2dB above FFT
- Notch settling time imposes an extra delay
- Computation of signal RMS is initiated
Conclusions

- Several transform techniques that can challenge conventional radix-2 FFT bottlenecks have been investigated.
- Fourier-based methods are the most suitable potential replacements.
- Can reduce computational complexity for on-chip implementation.
- Test time savings for off-chip application are small.
- Walsh has potential for dedicated SNR solution.
- Distortion meter is a strong replacement candidate.
- Possible on-chip realisation due to less number of samples.