ESTIMATION OF ENOB OF A/D CONVERTER USING HISTOGRAM TEST TECHNIQUE

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ABSTRACT

This paper reports a new application for one of the widely known Analog to Digital Converter (ADC) dynamic testing methods, namely the histogram method. After estimating code transition levels and applying corrections of the ADC transfer characteristics, the Effective Number of Bits (ENOBs) are computed with standard deviation and overdrive effect. ENOB is determined by taking deviation of corrected rms error from ideal rms error. Simulation results for 5 and 8 bit ADC are presented which show effectiveness of the proposed method. Finally results of this method are compared with earlier reported work and improvements are obtained in present results.

**Keywords:** Effective number of bits; Transfer Characteristics; Code bin width; Error estimation; Transition levels.

1. INTRODUCTION

Testing and characterizing ADC is still a challenging issue for mixed signal device manufacturers and designers, both in terms of speed, resolution and cost. Generally the goal of such procedure is to verify in a short time whether a given ADC meets its performance requirements. As known, many techniques in the time, frequency and amplitude domains have been proposed for ADC testing. ADC is an important device widely used in many electronics applications like: Instrumentation systems, communication system, medical Instrumentation, radar system and military applications for interfacing analog electronics with digital electronics. If the aim is to select a better device for an application then data sheet specifications are sufficient for comparison. But if a selected device is to be used in a design then determination of its functional parameters over application condition is must. Selection of an ADC is done based upon resolution, speed, power consumption, conversion accuracy required and interfacing to the system. In this work method is developed for dynamic testing of an ADC using different inputs like sine wave, triangular wave and application mode signal. ENOB of an
ADC is a function of test frequency. It is necessary to determine the value of ENOB at this test frequency. With increase in input frequency nonlinearity error increases which results in decreases in value of ENOB. Sine wave and triangular wave based histogram methods are popular in determining these errors of an ADC [1]-[3]. First of all code transition levels of ADC transfer characteristics are computed by collecting large number of samples of full scale sine wave by test ADC. Recently work has been reported for computation of DNL, INL, gain error, offset error and ENOB in performance of ADC transfer characteristics [4]. In this proposed work, we have used existing method of error computation in code transition levels and based upon this, error in estimate of nonlinearity and ENOB of an ADC are computed. In addition to existing method of finding error in code transition levels we have also computed error by estimating difference in code transition levels and best fit code transition levels. Dynamic testing using sine wave input based on histogram method is an important activity for characterization of an ADC.

ADC is usually characterized by its figures of merits like Effective Number of Bits (ENOB), Signal to Noise and Distortion ratio (SINAD), DNL and INL [5] [6].

2. COMPUTATION OF ERROR IN CODE TRANSITION LEVELS

Estimate of code transition level \( \hat{T}(i) \) for level \( i \) is given by [1] [7]:

\[
\hat{T}(i) = C - A \cos \left( \frac{\pi Ch[i - 1]}{X} \right), \quad i = 1 \ldots 2^n
\]  

(1)

Where \( A \) is amplitude and \( C \) is offset of sine wave applied to input of an ADC with \( X \) number of samples and \( Ch[i] \) is the cumulative histogram defined by:

\[
Ch[i] = \sum_{j=0}^{i-1} H[j], \quad i = 1, \ldots, 2^n
\]  

(2)

Where, \( H[0] = 0 \) and \( H[j] \) is histogram for code \( j \).

Error in code transition level can also be computed by taking difference of estimated transition level \( \hat{T}(i) \) from best fit transition level \( T_b(i) \).

\[
e\left[ \hat{T}(i) \right] = \hat{T}(i) - T_b(i)
\]  

(3)

Where, best fit code transition levels \( T_b(i) = \frac{i-a_0}{a_1} \)

and best fit parameters

\[
a_0 = \left[ \sum_i i \sum_i T(i) \right] - \left[ \sum_i T(i) \sum_i T(i) \right]
\]

\[
a_1 = \left[ \sum_i T(i) \sum_i i \right] - \left[ \sum_i T(i) \right]^2
\]

Here \( n = 2^{N-1} \), where \( N \) is number of bits of an ideal ADC. Limit for all summation is 0 to \( n \). The real life ADC can be modeled as gain error, offset error, nonlinearity and followed by ideal quantization process is presented in Figure 1 and implementation steps of algorithm for determination of code transition error with estimated code transition levels and best fit code transition levels are given in Figure 2.
3. DETERMINATION OF ENOB WITH SLIGHT OVERDRIVE AND CORRECTION

The values of corrected ENOB considering corrected code transition level can be expressed as \( ENOB_c \).

\[
ENOB_c = N - \log_2 \left( \frac{rmserror(Corrected)}{rmserror(ideal)} \right) \tag{4}
\]
Corrected rms error is computed by considering corrected code transition levels in general formula for computing rms error and is given as [7] [10]:

The rms value of actual and ideal noise can be computed by

\[
\text{rms noise (K)} = \left[ \frac{\int_{x(K)}^{x(K+1)} e^2 dx}{x[ K + 1] - x[ K]} \right]^{1/2}
\]  

(5)

Where \( e \) is the error signal between output and input of transfer characteristic and is expressed as

\[
e = p x + q
\]

(6)

Equation (10) passes through two points \((x(K), e(K))\) and \((x(K+1), e(K+1))\). The parameters \( p \) and \( q \) can be obtained as

\[
p = \frac{e[K] - e[K+1]}{x[K] - x[K+1]}
\]

(7)

\[
q = \frac{1}{2} [ e(K) + e(K+1) - p\{x(K) + x(K+1)\} ]
\]

(8)

For ideal case:

\[
e(K) = V_{cbf}(K) - T_b(K)
\]

(8a)

\[
X(K) = T_b(K)
\]

(8b)

And for actual case:

\[
e(K) = V_{cbf}(K) - T(K)
\]

(9a)

\[
X(K) = T(K)
\]

(9b)

The centre values of best fit transition level \( V_{cbf}(K) \) is given by

\[
V_{cbf}(K) = \frac{Th(K+1)+Th(K)}{2}
\]

(10)

4. SIMULATION RESULTS AND DISCUSSIONS

Ideal ADC transfer characteristics for 5 and 8 bit resolution are simulated and arbitrary nonlinearity error is introduced in their transfer characteristics. Simulated full scale signals with 0.98 MHZ frequency with slight over derive is applied to the ADC and large number of samples at 25 MHZ sampling frequency are collected. In first case using standard histogram technique code transition levels are computed after introducing DNL error in ADC transfer characteristics. Further error in code transition level estimation is done. After that author have determined rms quantization noise error would be equal to total rms error from all sources in the ADC under test. Three types of input are applied to ADC, full scale sine wave in first case and triangular wave in second case and simulated application mode input in third case. ENOB for all the three cases for 5 and 8 bit ADC are estimated by proposed method and plotted in Figure 3 and 4 respectively. It is observed that estimated ENOB for application mode input and sine wave input are close to each other while for triangular wave input estimated value of ENOB is less. The reason for this is due to more than one component in application input and only one component is present in sine wave input. So that the estimated value of ENOB for
these two are very close to exact value. Because triangular wave input is made-up of different sinusoidal component so higher values of error are obtained and due to this estimated value of ENOB are less than sine wave and application mode input. Comparison of the estimated ENOB for 5 and 8 bit ADC with earlier reported works are given in table 1 and 2 respectively.

**Table 1**: Comparison of ENOB estimation for 5 bit ADC with earlier reported work

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Application mode input (Sum of two signals)</td>
</tr>
<tr>
<td>11200</td>
<td>4.379</td>
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<td>4.642014</td>
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<tr>
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<td>-</td>
<td>-</td>
<td>4.746698</td>
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<td>-</td>
<td>4.651987</td>
<td>4.606943</td>
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<td>64K</td>
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<td>4.726531</td>
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<tr>
<td>512K</td>
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<td>-</td>
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<tr>
<td>1024K</td>
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<td>-</td>
<td>4.726574</td>
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</table>

**Figure 3**: Graphical representation of ENOB for 5 bit ADC
### Table 2: Comparison of ENOB estimation for 8 bit ADC with earlier reported work

<table>
<thead>
<tr>
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<tr>
<td>1024</td>
<td>7.3705</td>
<td>6.928920</td>
<td>6.112926</td>
<td>7.7 max. &amp; 7.0 min With 5 – 40 KHz freq.</td>
<td>6.887535</td>
<td>7.657624</td>
<td>7.532015</td>
<td>7.664230</td>
</tr>
<tr>
<td>2048</td>
<td>7.4701</td>
<td>7.347980</td>
<td>6.107440</td>
<td>7.448753</td>
<td>7.667821</td>
<td>7.534660</td>
<td>7.668931</td>
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<tr>
<td>4096</td>
<td>7.5092</td>
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<td>6.129020</td>
<td>7.560021</td>
<td>7.686620</td>
<td>7.548934</td>
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<td>8192</td>
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<td>7.582269</td>
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<td>7.698766</td>
<td>7.557810</td>
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<tr>
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<tr>
<td>64K</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>7.647827</td>
<td>7.558651</td>
<td>7.656341</td>
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<tr>
<td>128K</td>
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<td>7.646182</td>
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<td>7.658302</td>
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<tr>
<td>256K</td>
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<td>7.648210</td>
<td>7.558649</td>
<td>7.658321</td>
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<tr>
<td>512K</td>
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<td>-</td>
<td>7.558652</td>
<td>7.668320</td>
<td></td>
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</tr>
<tr>
<td>1024K</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.557751</td>
<td>7.658328</td>
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</tr>
</tbody>
</table>

**Figure 4 Comparative graphical representation of ENOB for 8 bit ADC**
5. **EFFECTS OF STANDARD DEVIATION OVERDRIVE ON ENOB**

In addition effects of overdrive and standard deviation on ENOB estimation of an ADC are also presented with and without corrections applied in code transition levels. During this process the number of samples was 64k, input frequency was 0.98 MHz and sampling frequency was 25 MHz. Table 3 shows the effects of overdrive and standard deviation. When fixed the values of standard deviation ($\sigma_n$ = 0.25, 0.5, 0.75 and 1.25) with increasing values of overdrive voltage. It is observed that the values of ENOB are better in the range of $\sigma_n$ = 0.25 to 0.75 and overdrive range 0.88 to 1.1 LSB after that values of ENOB is deteriorates.

<table>
<thead>
<tr>
<th>Standard Deviation »</th>
<th>$\sigma_n$ = 0.25</th>
<th>$\sigma_n$ = 0.5</th>
<th>$\sigma_n$ = 0.75</th>
<th>$\sigma_n$ = 1.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. No Over drive Voltage (LSB)</td>
<td>ENOB without correction</td>
<td>ENOB with correction</td>
<td>ENOB with correction</td>
<td>ENOB with correction</td>
</tr>
<tr>
<td>1. 0.11</td>
<td>4.641100</td>
<td>3.591714</td>
<td>3.862237</td>
<td>4.285664</td>
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<tr>
<td>2. 0.22</td>
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<td>3.749800</td>
<td>3.857520</td>
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<tr>
<td>3. 0.33</td>
<td>4.629631</td>
<td>3.954577</td>
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<tr>
<td>4. 0.44</td>
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<td>4.590521</td>
<td>4.102843</td>
<td>4.378797</td>
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<tr>
<td>5. 0.55</td>
<td>3.783103</td>
<td>4.682992</td>
<td>4.246127</td>
<td>4.463543</td>
</tr>
<tr>
<td>6. 0.66</td>
<td>3.580804</td>
<td>4.717010</td>
<td>4.592254</td>
<td>4.585825</td>
</tr>
<tr>
<td>7. 0.77</td>
<td>3.618924</td>
<td>4.674049</td>
<td>4.693146</td>
<td>4.744065</td>
</tr>
<tr>
<td>8. 0.88</td>
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<td>4.858720</td>
<td>4.862046</td>
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<tr>
<td>9.</td>
<td>3.563010</td>
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</tr>
<tr>
<td>10.</td>
<td>3.543120</td>
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</tr>
</tbody>
</table>

6. **CONCLUSION**

In this paper effects of error, overdrive and standard deviation on ENOB have been studied. Mean of transition voltage is calculated and error in transition voltage is computed by taking difference from estimated transition voltages after that correction is applied in the estimated code transition levels. ENOB is determined by taking deviation of actual rms error from best fit (ideal) rms error of ADC transfer characteristics. Simulation results are reported for five bit ADC with different amount of overdrive and additive noise and their effects on ENOB. This work will be useful for error minimization and testing A/D converter from device manufacturer point of view as well as circuit designer. Because this paper mainly concentrated on triangular wave and application mode input based results for higher bits. A test algorithm developed using simulation is equally suitable for testing real life ADC in application conditions.
REFERENCES


