Decreasing the Sensitivity of ADC Test Parameters by means of Wobbling

R. de Vries

Philips Semiconductors, 811 E. Arques Ave, Sunnyvale, CA 94088-3409, US
Ronald.deVries@sv.sc.philips.com

A.J.E.M. Janssen

Philips Research Lab., Prof. Holstlaan 4, 5656 AA Eindhoven, The Netherlands
janssena@natlab.research.philips.com

Abstract. *In this paper we propose a new technique, wobbling, for the stabilization of spectral ADC-test parameters with respect to offset and amplitude deviations of the sinusoidal stimulus. Wobbling aims at removing the effect of the rounding operation that takes place in an ADC, so that the measured harmonic distortion and noise amplitude can be truly ascribed to the intrinsic non-linearity and noise of the ADC. We compare the wobbling technique with subtractive and non-subtractive noise dithering, both from a performance and an implementation point-of-view. We present results of simulations and measurements validating the wobbling technique for use in a production environment.*

Keywords: ADC, Spectral Test, Wobble, Dither.

1 Introduction

The repeatability of tests performed on ADCs in a production environment is of increasing importance since the quality demands imposed upon ICs become more stringent. This issue occurs in particular in spectral ADC test parameters which are very sensitive to offset and amplitude deviations of the applied sinusoidal signals. A deviation of less than 0.1 quantization step can already result in a variation of 10 dB or more in the measured harmonic distortion. Deviations of this size are quite common in a production environment, where amplitude deviations of around 1% may occur, yielding a deviation of more than one half quantization step in a 6-bit converter.

The sensitivity of the spectral ADC test parameters to offset and amplitude variations of the applied sinusoids is due to the rounding operation that takes place in the converter. Especially the low-frequency components of the ADC's output suffer from this circumstance. The precise relative position of the extrema of the applied sinusoid with respect to the quantization levels, see Figure 2 in Section 2, is of great importance here. In this paper we propose to eliminate this key factor by gently shifting the applied sinusoid over one quantization level: wobbling[1]. This is effectuated by adding a ramp signal (with span one quantization level and extending over several periods of the sinusoid) to the sinusoid and subtracting it again from the output.

The proposed method for stabilizing spectral ADC test parameters is related to the commonly used method of noise dithering in audio. In the latter method one adds, to the input signals to be quantized, noise of span one or more

1. The term wobbling is also used in other applications, for example the addressing and timing control in recordable CDs. In that case sinusoidal wobble signals are used.

quantization levels and subtracts or does not subtract this noise again from the output, depending on whether one uses subtractive or non-subtractive noise dithering, [1]-[5]. Noise dithering is pre-eminently appropriate when the input signals are random in nature themselves, such as audio-signals. For the test problem at hand the input signal (a sinusoid of known frequency with amplitude, phase and offset that vary only in a small range) is much more deterministic. It is, therefore, more obvious to try to stabilize the spectral ADC test parameters by using a technique which is more deterministic in nature itself. Indeed, the wobbling method provides such a technique and does outperform noise dithering for the present problem.

In Section 2 we present a simple model for the operation of an ADC, and we describe the spectral test parameters *THD* and *SINAD* we want to stabilize for deviations in offset and amplitude of the applied sinusoid. In Section 3 we introduce and elaborate the wobbling method, we compare it with the noise dithering method, and we point at certain advantages of it over the latter method for the problem at hand. In Section 4 we verify the wobbling methodology by showing results from simulations and measurements. These were done on a 6-bit ADC, and the results were encouraging enough to implement the wobbling technique in a production test environment for testing 8-bit video ADCs. In Section 5 we present the conclusions.

2 ADC testing

ADCs convert a continuous-valued signal *f(t)* into a discrete-valued signal *Q(t)* through quantization according to

$$Q(t) = [h(f(t)) + n(t)] \quad \textbf{(EQ 1)}$$

where the square brackets denote the operation of rounding to the nearest integer, *h* is the non-linearity of the converter and *n* is the noise internal to the converter. In Figure 1 transfer functions of an ideal ADC and a converter with a non-linearity *h* and noise *n* are shown.

When testing an ADC we are interested in the non-linearity *h* and the noise *n* of the converter rather than in the non-linearity and noise which are the result of the rounding operation. Two types of tests are commonly used to determine the non-linearity and noise of a converter:

1. Linearity test
2. Spectral test.

The linearity test of the converter is usually performed by applying a ramp to the ADC and determining the Differential Non Linearity (*DNL*) and Integral Non Linearity (*INL*) parameters. The *DNL* and *INL* are hardly influenced by amplitude and offset deviations.

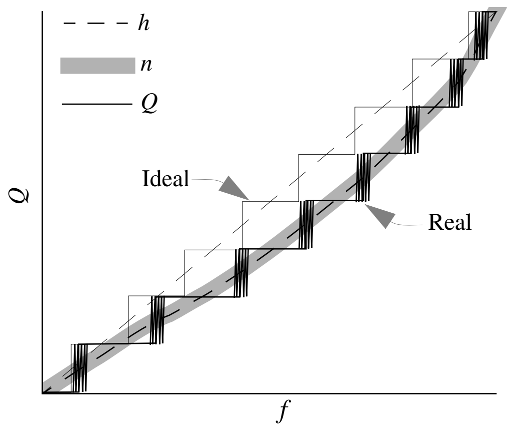


Figure 1: ADC Transfer function

In this paper we focus on spectral tests. Spectral tests are often used because of test time reduction (using FFT) and specification related reasons. In the spectral test, sinusoidal test stimuli are applied to the ADC. These stimuli are of the form

$$f(t) = A\sin(2\pi\upsilon t) - c\,;\; A = \tilde{A}\cdot 2^{q-1}, \quad \textbf{(EQ 2)}$$

with $\tilde{A}$ being the relative amplitude which is unity at the full-scale of the ADC, υ the frequency which is set to unity in this paper, *c* the offset of the test signal and *q* the number of bits of the converter. In spectral tests the signal power of the harmonics of the output signal is used to determine the different test parameters like the Total Harmonic Distortion (*THD)* and Signal to Noise Ratio *(SNR)*. Often another test parameter, which we will call the SIgnal to Noise And Distortion (*SINAD*), is determined instead of the *SNR*. The described spectral test parameters are defined by:

$$THD^2 = \frac{P_{\mathrm{hd}}}{P_s + P_{\mathrm{hd}}} \approx \frac{P_{\mathrm{hd}}}{P_s}, \quad \textbf{(EQ 3)}$$

$$SNR^2 = \frac{P_{\mathrm{s}}}{P_{noise}}, \quad \textbf{(EQ 4)}$$

$$SINAD^2 = \frac{P_{\mathrm{s}}}{P_{\mathrm{hd}} + P_{\mathrm{n}oise}} = \frac{1}{THD^2 + SNR^{-2}}. \quad \textbf{(EQ 5)}$$

In (EQ 3)-(EQ 5), P_s is the signal power determined by the first harmonic in the frequency spectrum of *Q(t),* P_{hd}

is the harmonic distortion power determined by the higher harmonics of $Q(t)$,

$$P_{\mathrm{hd}} = \sum_{m=2}^{N} P_m , \qquad \text{(EQ 6)}$$

and P_{noise} is the total noise power in the output signal $Q(t)$ of the converter which is determined by

$$P_{noise} = \text{total power of } Q(t) - \sum_{m=0}^{N} P_m . \qquad \text{(EQ 7)}$$

In (EQ 6) and (EQ 7) P_m and N are the power of the m^{th} harmonic of the output $Q(t)$ and the number of harmonics to be treated as harmonic distortion, respectively. Generally, only the first few harmonics of the output signal are actually treated as harmonic distortion, while the remaining distortion is treated as noise. In this paper the number of harmonics N is set to 10.

Figure 2 gives an example of what the influence of a small deviation in amplitude of the input signal may be on the result of the rounding operation, the spectrum of the quantized sinusoid and therefore the test parameters. It shows that the main source of the sensitivity problem is the variation of the extreme values of the test stimulus relative to the rounding levels. In the next section a technique will be described which reduces the impact of rounding, enabling us to assess the influence of the non-linearity h and noise n in (EQ 1) without being bothered by the non-linearity and noise introduced by the rounding operation.

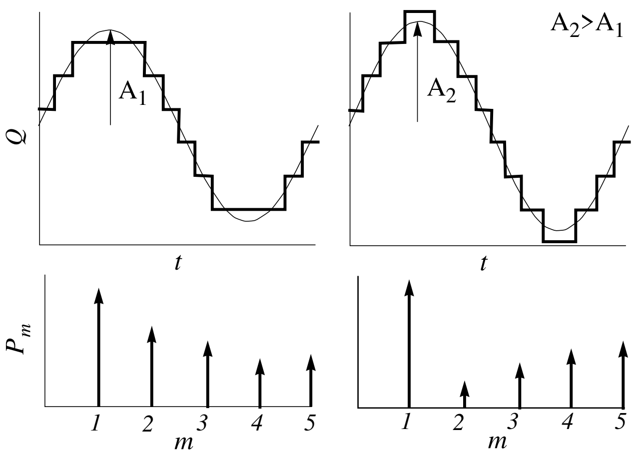


Figure 2: Result of small change in amplitude.

3 Dithering vs. Wobbling

The present-day solution to the sensitivity problem of ADC test parameters is dithering. With dithering a low-amplitude signal of a high frequency or broad frequency spectrum is added to the stimulus signal. The most commonly used dither technique is noise dithering. With this technique noise is added to the test stimulus, yielding an output

$$Q_{dithered}(t) = [h(f(t) + D_{noise}(t))] , \qquad \text{(EQ 8)}$$

where $D_{noise}(t)$ is the noise dither signal ($|D_{noise}|$~1/2 quantization step).

Noise dithering has some drawbacks. First of all, a relatively large number of samples is needed to achieve a significant reduction in the sensitivity of especially the *THD*. Furthermore, although noise dithering improves the stability of the *THD,* it influences the *SNR* and the *SINAD* (as for example a small noise dither amplitude near a transition voltage may have a substantial effect on the output noise). The influence of the noise dither on the test parameters can be approximated if a relative large number of samples is taken. The *SNR* and *SINAD* can also be determined accurately by doing an extra measurement. Such an extra measurement results in extra costs for production testing.

Alternatively, it is also possible to make use of subtractive noise dithering. With this technique perfect synchronization between the added and subtracted noise is needed, as there is no relation between subsequent samples of the noise dither (a missynchchronization of one sample between added and subtracted noise already increases the measured noise significantly) [5]. Another drawback of noise dithering is that, for noise dither amplitudes larger than that of the noise n of the converter, it will be very difficult to accurately determine the noise level n. Video ADCs for example have a relatively low noise level n which may be below 0.1 quantization step.

We propose using wobbling to assess the test parameters accurately without the disadvantages of noise dithering. As a sine signal has only two extreme values, small deviations in the amplitude may result in significant differences, as already shown in Figure 2. When the sine is wobbled slightly, the resulting signal has a more uniform distribution of its extreme values. Figure 3 shows the effect of the proposed ramp wobble technique on the rounding operation. We have shown mathematically in [8] that ramps are among the optimal signals with respect to reducing rounding *THD*. Furthermore, among these optimal signals, ramps are in a sense least disturbing and they are least sensitive for misadjustments etc.

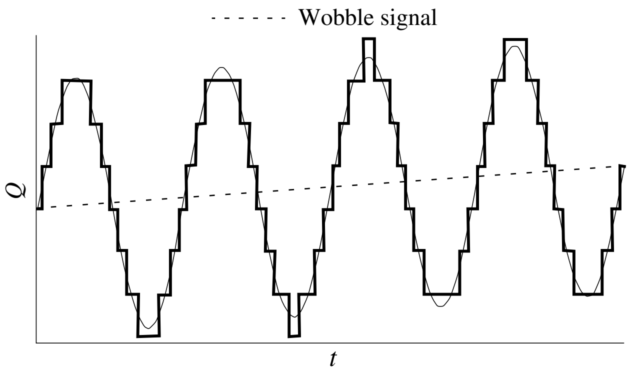


Figure 3: Ramp wobbling.

The wobble signal itself contributes to the spectrum of *Q(t)*. This can be removed effectively by using subtractive wobbling which can be described by

$$Q_{wobbled}(t) = [h(f(t) + g_P(t))] - g_P(t) \qquad \textbf{(EQ 9)}$$

with $g_P(t)$ being the *P* periodic ramp wobble signal. Although synchronization between the added and subtracted ramp is needed, as was also the case with noise dithering, it does not need to be perfect as it introduces only a small error. Note that since $g_P(t)$ has jumps of one quantization step, one could also think of (EQ 9) as being obtained by adding and subtracting a linear signal with the same slope as $g_P(t)$ but without any discontinuity at all.

In the following analysis of wobbling we will assume that we may write (EQ 9) approximately as

$$\begin{aligned} Q_{wobbled}(t) &= [h(f(t)) + g_P(t)h'(\xi(t))] - g_P(t) \\ &\approx [h(f(t)) + g_P(t)] - g_P(t) \,. \end{aligned} \qquad \textbf{(EQ 10)}$$

with $\xi(t)$ being near *f(t)*. This approximation is valid in practice as the amplitude of the wobble signal is less than 1 quantization step, which is small compared with the amplitude of a converter with more than 4 bits, and $h'(\xi(t))$ will be close to one as the Differential Non Linearity (*DNL*), h', of a converter is usually close to unity (see for example Figure 1). It can be shown that when the number of sinusoids in a single ramp becomes large, or $P \to \infty$, the m^{th} harmonic (for $m>1$) of (EQ 10) is closely related to the m^{th} harmonic of

$$\frac{[P \cdot h(f(t))]}{P}, \qquad \textbf{(EQ 11)}$$

i.e. the situation where no wobbling is used, but with a quantization step that is *P* times smaller than the original one. This can intuitively be explained by changing the amplitude *A* of the sinewaves in Figure 2 and Figure 3 gradually over one quantization step. Then we see from Figure 2 that the levels to which the maxima of the unwobbled sine are rounded all have a unit jump at the same time, viz. when *A* crosses a half-integer level. For the wobbled sine, see Figure 3, the levels to which any 4 consecutive maxima are rounded have unit jumps as well, but they occur one after another separated by a variation in *A* of 1/4 quantization step. Hence the influence of quantization is effectively reduced by a factor *P*=4 when wobbling is applied. It has been shown by the authors that the correspondence between the harmonics of (EQ 10) and (EQ 11) can be given a precise mathematical formulation, but this is outside the scope of the present paper.

When we make use of wobbling, we have to be aware that the test parameters are influenced, in the sense that the effect of the rounding operation on the harmonics is greatly reduced. This means that the *THD* due to the nonlinearity *h* of (EQ 1) is actually assessed. The following approximation can be used to determine the THD which does include the average THD due to rounding. When *P* is chosen sufficiently large (*P>5*) there holds

$$\overline{THD^2} = THD^2_{wobbled} + \overline{THD^2_{round}}, \qquad \textbf{(EQ 12)}$$

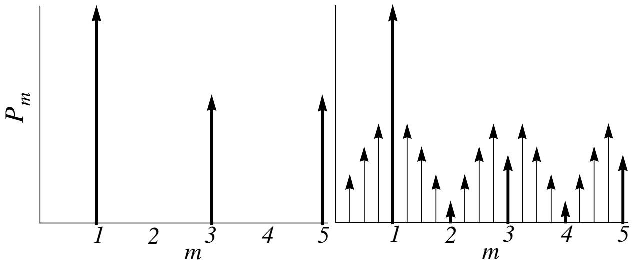
where $THD^2_{wobbled}$ is the measured THD^2 when wobbling is used and $\overline{THD^2_{round}}$ is the average THD^2 introduced by the rounding operation which can be shown to be given by [8]

$$\overline{THD^2_{round}} = -9.54q - 0.06 - 30\log\tilde{A} \;\; [\mathrm{dB}]. \qquad \textbf{(EQ 13)}$$

The *SNR* is increased by the term $\overline{THD^2{}_{round}}$, which is added to the noise of the converter. We can simply account for this increase through

$$\overline{SNR^2} = SNR^2_{wobbled} - \overline{THD^2_{round}}. \qquad \textbf{(EQ 14)}$$

No correction is needed for the *SINAD* since it turns out (and this can be made mathematically precise) that the wobble technique transfers the error power due to rounding at the harmonics to frequency components between the harmonics. An example of this effect is shown in Figure 4 for an ideal converter with *P=4*.



a. Non-wobbled b. Wobbled

Figure 4: Spectrum of an ideal ADC (P=4).

In this example the higher harmonics at *m=3* and *m=5* are reduced, which will result in a reduction of the *THD* caused by the rounding operation, while frequency components arise between the harmonics due to wobbling. As the power of the higher harmonics and the power of the frequency components between the harmonics are included in the *SINAD,* wobbling does not change the average value of the *SINAD.*

4 Simulations and Measurements

To verify the wobble methodology, we performed simulations and measurements on a 6 bit Flash ADC used in video application ICs. The sample frequency of this particular ADC was 10 MHz and the test signal frequency was specified at 1 MHz. Only the test parameters *THD* and *SINAD* as a function of the input amplitude were determined, since the *SNR* is directly related to these parameters. Furthermore, we made use of (EQ 12) and (EQ 13).

Initially, we performed simulations with an ideal quantizer. Figure 5 shows the *THD* and *SINAD* as a function of the relative input amplitude $\tilde{A}$ with and without wobbling. At each amplitude 10000 samples were used to determine the *THD* and *SINAD*. A deviation in amplitude of less than one percent can cause a deviation of more than 20 dB in the *THD* (i.e. a factor 10). Figure 5 shows us furthermore that the ramp wobbling results in a significant reduction in the sensitivities of the *THD*, *SINAD*. Particularly noteworthy is the *THD*'s sensitivity reduction. The error between the average or expected (wobbled) *THD* and the unwobbled *THD* may be 100%. When the number of periods *P* of the sinusoid within a single ramp wobble was chosen to be larger than 5, no real further reduction in the sensitivities was observed. When $\tilde{A}$ became larger than 1, the converter started to clip, which had an adverse effect on the *THD* and *SINAD*.

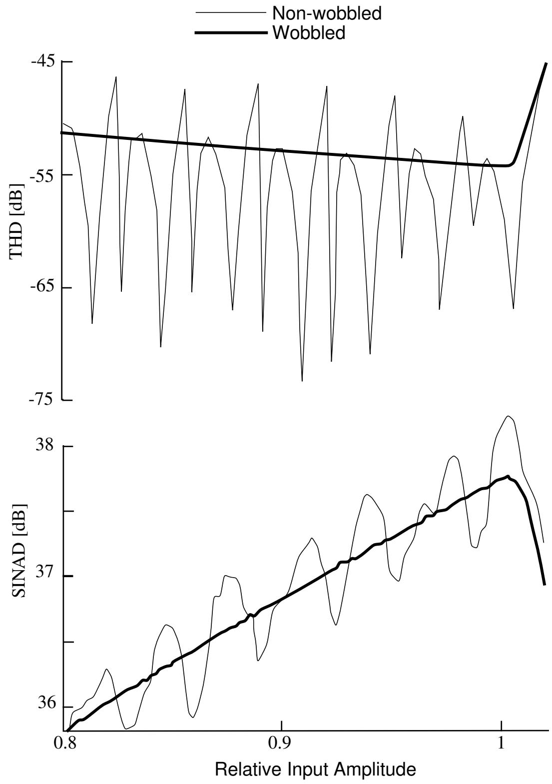


Figure 5: Simulation results ideal ADC

In the simulations and the measurements using non-ideal devices, we took 5000 samples of the output signal per amplitude. The measurements were performed in a DSP-based environment, using an Arbitrary Waveform Generator (AWG) to generate the sine wave with the ramp wobble and DSP facilities to determine the test parameters [6][7]. In the simulations we incorporated a choice of the noise term *n* and the non-linearity *h,* as one finds them in a real ADC. Figure 6 shows the simulation results obtained with the *THD* and the *SINAD* as a function of the relative amplitude of the input signal with and without wobbling. The measurement results are shown in Figure 7.

The simulations and measurements show that the sensitivities of the *THD* and *SINAD* were greatly reduced. Differences of up to 100% were observed between the wobbled (expected) value and the non-wobbled value. There is still some sensitivity in the *THD* measurements over a broader range of amplitudes. This is due to the fact that the simulation model (EQ 1) does not take into account all the effects, that may occur in a real-life ADC.

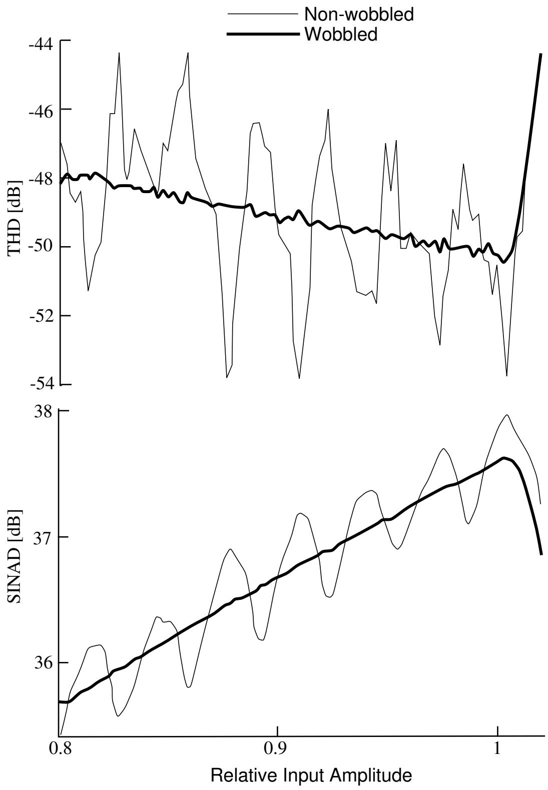


Figure 6: Simulation results non-ideal ADC.

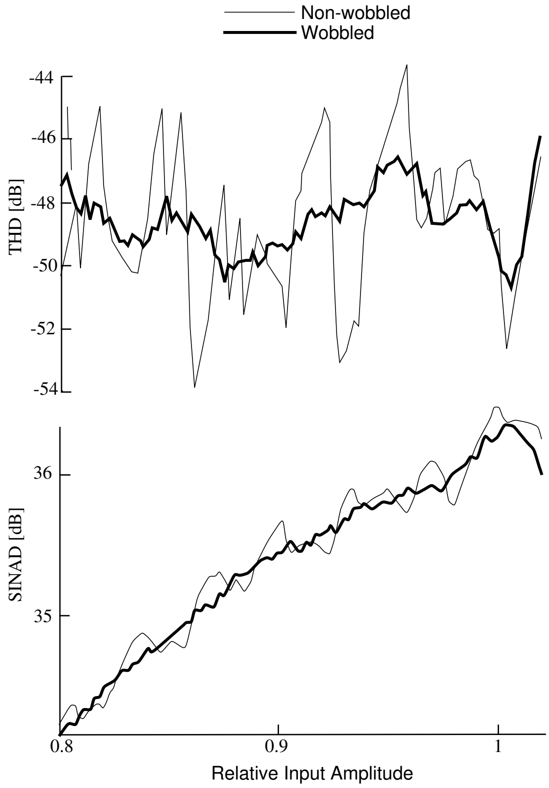


Figure 7: Measurement results.

We have only shown the sensitivities to amplitude deviations. We also performed analysis, simulations and experiments for offset deviations. A deviation in the offset c yielded similar results as a deviation in the amplitude, and wobbling is equally effective for reducing sensitivity due to offset deviations.

Our experiments with noise dithering showed that approximately 40 times more samples were needed in order to obtain the same results as with the ramp wobble method. The substantial influence of the dither noise on the *SNR* and *SINAD* also proved to be a major drawback.

5 Conclusion and Outlook

We have presented an alternative technique to dithering, viz. wobbling. Owing to the rounding operation of the ADC the spectral test parameters *THD*, *SINAD* and *SNR* are sensitive to amplitude and offset deviations in the input signal. This sensitivity may result in errors of as much as 100% between the non-dithered or non-wobbled value and the expected average value. With the wobbling technique, the sensitivity of the spectral ADC test parameters, and also the error, is greatly reduced.

Analytical results have shown that the influence of the rounding operation on the harmonics of an output signal of an ADC can be reduced by a factor of P, where P is the ratio of the period of the wobble signal and that of the unwobbled signal. This reduction also means that the *THD* due to rounding is reduced by the same factor.

The simulations and measurements have shown that in particular the *THD* is sensitive to amplitude and offset variations. The wobbling technique greatly reduces the sensitivity and error of the test parameters. The reduction of the sensitivity and error leads to a better repeatability of the tests. We have done preliminary experiments in a setting as occurs in a production environment, and further experiments of this type are under way. These show that the method has indeed a substantial stabilizing effect on the ADC test parameters for the rounding operation. The extra costs implied by adding and subtracting the ramp signal are practically nil.

The proposed wobble technique has some major advantages over the more commonly used dither techniques. The wobble and dither techniques both influence the test parameters. In the case of the wobble technique it is possible to make corrections for this influence, whereas in the case of the dither techniques corrections for this influence, which is most apparent in the *SNR* and the *SINAD* test parameters, can be impracticable in a testing environment. Another advantage is that fewer samples are needed in order to achieve a significant reduction in the sensitivity of the test parameters than with noise dither techniques.

We have not tried to asses the influence of missynchronization in the wobbling method. Neither did we try to find out how severe the accuracy demands on the wobbling signal are for the method to work well. As a matter of fact, this is presently under investigation. We noticed from the simulations and measurements that the method is robust for moderate timing errors and ramp span errors. The results of the measurements as performed with the 6-bit Flash ADC, as well as the experiences with the 8-bit video ADCs in a production environment, are encouraging in this respect. A topic for further investigation could be to work out this point, especially for higher resolution ADCs.

In [8] we have also considered the effect of sampling on the performance of the method. It turns out that, at least in simulations, the wobbling method is robust on this point and outperforms noise-dithering methods by far.

Acknowledgment

Special thanks go to Mark Looijer, who conducted experiments in the sensitivity analysis of ADCs with A.J.E.M. Janssen in an earlier stage of this research, and Geert Seuren, for discussions and his assistance with the measurements. We also want to thank the referees for their constructive comments.

References

[1] R.M. Gray and T.G. Stockham, “Dithered Quantizers”, *IEEE Trans. Inform. Theory*, Vol. 39, No. 3, pp. 805-812, May 1993.

[2] P. Carbone, D. Petri, "Effect of Additive Dither on the Resolution of Ideal Quantizers”, *IEEE Trans. Instrum. Meas.*, Vol. 43, No. 3, pp. 389-396, June 1994.

[3] I. De Lotto, G. E. Paglia, “Dithering Improves A/D Converter Linearity”, *IEEE Trans. Instrum. Meas.*, Vol. IM-35, No. 2, pp. 170-177, June 1986.

[4] J. Vanderkooy, S.P. Lipshitz, “Dither in Digital Audio”, *J. Audio Eng. Soc.*, Vol. 35, No. 12, pp. 966-975, December 1987.

[5] B. Brannon, “Overcoming Converter Nonlinearities with Dither”, *Analog Devices Application Note AN-410*, Norwood, Massachusetts.

[6] M. Mahoney, “DSP-Based Testing of Analog and Mixed-Signal Circuits”, Washington, D.C., USA, *Computer Society of the IEEE*, 1987.

[7] R. Mehtani et-al, “*MixTest* : A Mixed-Signal Extension to a Digital Test System”, *International Test Conference*, Washington, U.S.A, 1993.

[8] A.J.E.M. Janssen, “Fourier Analysis and Synthesis for a Mildly Non-Linear Quantizer”, *Nat.Lab. Report UR* 801/99, Einhoven, The Netherlands, 1999, publicly available as of June 1999.