国外电子信息精品著作（影印版）

# ADC的动态特性

# Dynamic Characterisation of Analogue-to-Digital Converters

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## 内 容 简 介

在 ADCs 设计中，准确地知道其动态行为的特征参数非常重要。本书讨论了三种典型的测试 ADCs 的动态性能的方法，也给出了另外一种测试方法，这种方法避免了典型方法的限制。动态特性是衡量 ADC 性能的决定性指标之一，本书给出了测试方法、影响动态特性的因素以及解决方案。

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20 世纪 90 年代以来，信息科学技术成为世界经济的中坚力量。随着经济全球化的进一步发展，以微电子、计算机、通信和网络技术为代表的信息技术，成为人类社会进步过程中发展最快、渗透性最强、应用面最广的关键技术。信息技术的发展带动了微电子、计算机、通信、网络、超导等产业的发展，促进了生命科学、新材料、能源、航空航天等高新技术产业的成长。信息产业的发展水平不仅是社会物质生产、文化进步的基本要素和必备条件，也是衡量一个国家的综合国力、国际竞争力和发展水平的重要标志。在中国，信息产业在国民经济发展中占有举足轻重的地位，成为国民经济重要支柱产业。然而，中国的信息科学支持技术发展的力度不够，信息技术还处于比较落后的水平，因此，快速发展信息科学技术成为我国迫在眉睫的大事。

要使我国的信息技术更好地发展起来，需要科学工作者和工程技术人员付出艰辛的努力。此外，我们要从客观上为科学工作者和工程技术人员创造更有利于发展的环境，加强对信息技术的支持与投资力度，其中也包括与信息技术相关的图书出版工作。

从出版的角度考虑，除了较好较快地出版具有自主知识产权的成果外，引进国外的优秀出版物是大有裨益的。洋为中用，将国外的优秀著作引进到国内，促进最新的科技成就迅速转化为我们自己的智力成果，无疑是值得高度重视的。科学出版社引进一批国外知名出版社的优秀著作，使我国从事信息技术的广大科学工作者和工程技术人员能以较低的价格购买，对于推动我国信息技术领域的科研与教学是十分有益的事。

此次科学出版社在广泛征求专家意见的基础上，经过反复论证、仔细遴选，共引进了接近 30 本外版书，大体上可以分为两类，第一类是基础理论著作，第二类是工程应用方面的著作。所有的著作都涉及信息领域的最新成果，大多数是 2005 年后出版的，力求“层次高、内

容新、参考性强”。在内容和形式上都体现了科学出版社一贯奉行的严谨作风。

当然，这批书只能涵盖信息科学技术的一部分，所以这项工作还应该继续下去。对于一些读者面较广、观点新颖、国内缺乏的好书还应该翻译成中文出版，这有利于知识更好更快地传播。同时，我也希望广大读者提出好的建议，以改进和完善丛书的出版工作。

总之，我对科学出版社引进外版书这一举措表示热烈的支持，并盼望这一工作取得更大的成绩。

王越

中国科学院院士

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2006 年 12 月

# Preface

The present book is one of the outcomes of the project DYNAD - Methods and Draft Standards for the Dynamic Characterization and Testing of Analogue-to-Digital Converters. This project was held between 1997 and 2000, supported by the European Commission under the Standards, Measurements and Testing Programme, reference SMT4-CT98 2214, within the Framework IV activities. Its consortium comprised the University of Parma - Italy, the École Nationale Superieure d'Electronique, Informatique & Radiocommunications de Bordeaux - France, Thales (former TTM-Thomson CSF) - France, Italtel Spa - Italy, Infineon Technologies-Development Center Villach - Austria, and INESC-Porto - Portugal. Besides the authors of the different chapters of this book, other people contributed with their work to the start and success of the initiative. We acknowledge the efforts of Hubert Pernull, Otto Wiedenbauer, and Andreas Bertl from Infineon, Roberto Scotti from Italtel, Jorge Duarte and José Matos from INESC-Porto, M. Heuber and M. Zirnheld from Thales, and C. Rebai from ENSEIRB.

A state of the art overview of the methods and procedures employed for characterising the dynamic performance behaviour of analogue-to-digital converters using sinusoidal stimuli, is presented in this book. The three classical methods — histogram, sine wave fitting, and spectral analysis — are thoroughly described, and new approaches are proposed to circumvent some of their limitations.

This is a must-have compendium, which can be used by both academics and test professionals, to understand the fundamental mathematics underlining the algorithms of ADC testing, and as a handbook to help the engineer in the most important and critical details for their implementation.

DOMINIQUE DALLET, JOSÉ MACHADO DA SILVA

# Introduction

José Machado da Silva

ADCs are, eventually, the most pervasive analogue blocks in electronic systems. With the advent of powerful digital signal processing and digital communication techniques, ADCs are fast becoming critical components for system's performance and flexibility. Knowing accurately all the parameters that characterise their dynamic behaviour is crucial, on one hand to select the most adequate ADC architectures and characteristics for each end application, and on the other hand, to understand how they affect performance bottlenecks in the signal processing chain.

At present, most of the signal processing performed in electronic systems is becoming digital, and the role of the ADCs placed at the borders of the digital domain acquires a particular relevance, since the signal degradation introduced by these components cannot normally be recovered by subsequent processing. Both the markets of stand-alone ADCs and of ADC macrocells to be embedded in complex systems-on-chip, benefit from the availability of performance parameters accurately describing their expected behaviour, and of clearly specified test methods to be used for their measurement.

When the project DYNAD started, the standardization of ADC test procedures was not so well developed. Two standards existed, in particular, at that time — the IEC 60748 and the IEEE Std 1057. The former covers only quasi-static operation, while the second deals with dynamic testing but, being addressed at digital waveform recorders requires some adaptations to cover ADCs. A first aim of DYNAD project was then, to contribute to the improvement of the European rules concerning test methods for ADCs, by proposing an integration within IEC 60748 addressing the parameters specifying the dynamic behaviour of ADCs, measurement conditions, and data processing algorithms. By the end of year 2000 a working group from the IEEE Instrumentation and Measurement Society Technical Committee (TC-10) completed the IEEE 1241 Standard for Analog to Digital Converters. This standard, as well as contributions from the DYNAD project, are now being incorporated into an IEC standard on dynamic testing of ADCs. Other initiatives have been carried-out concerning standardization of ADC testing methods. One can also mention EUPAS (EUropean Project for ADC-based devices Standardization), and the IMEKO Technical Committee 4 (A/D and D/A Metrology WorkGroup).

The main objective of the DYNAD project was the study and evaluation of ADC testing methods based on the use of sinewave test stimulus. A second aim was to investigate and propose new test methods to circumvent the limits of the measurement instrumentation, which is strongly challenged by today's high resolution, high speed converters. Techniques for the measurement of parameters required by specific applications (e.g. audio hi-fi) and for the debugging of new converter designs were also investigated. Dissemination of the knowledge gathered during the activity was the third objective.

That work is now compiled in this book, which is structured in two main parts. Part one comprises chapters one to six. The first one provides an overview of the most important ADCs' architectures and respective fields of application. An introduction to the most relevant nomenclature and definitions of terms is also presented. Chapter two describes the generic architecture of an ADC test setup, and guidelines and best practice procedures are proposed in order to guarantee reliable test results. Chapters 3, 4, and 5 are devoted to the description of dynamic test techniques using sinewaves, respectively, sinewave fitting (time domain data analysis), discrete Fourier transform (frequency domain analysis), and code histogram test (statistical domain analysis). These techniques are thoroughly described, as well as the fundamental mathematical background behind the equations to be used to obtain ADCs' characterization parameters provided in each case. A comparison among these three methods is presented in chapter 6. The objective is not to find the best or the worst methods, but mainly to compare how they behave when test conditions are not ideal and to identify their requirements in terms of test time and volume of data. Examples of ATE implementation are also included.

The second part comprises chapters 7 to 10, which provide additional information to test for other relevant parameters, such as jitter, differential gain and phase, step and transient response, and hysteresis.

# GLOSSARY

$\varepsilon$ error, used for total error and error band

$\varepsilon_G(f)$ gain flatness error at frequency f

$\varepsilon$**[k]** difference between T[k] and the ideal T[k] computed from G and $V_{os}$

$\varepsilon_m(f)$ aliasing and first differencing magnitude errors

$\varepsilon_\theta(f)$ aliasing and first differencing phase errors

$\varepsilon_q$ quantisation error

$\varepsilon_{rms}$ root-mean-square value of $\varepsilon$

$\theta$ phase, expressed as radians

$\eta$**[n]** a record of noise data

$\eta_f$ noise floor

$\pi$ constant, ratio of the circumference to the diameter of a circle

$\rho$ reflection coefficient

$\sigma$ standard deviation; sometimes used as noise *rms* amplitude, which is the standard deviation of the random component of a signal

$\sigma_\sigma$ standard deviation of the standard deviation (for example, standard deviation of the noise amplitude)

$\sigma_j$ jitter

$\sigma_t$ aperture uncertainty

$\sigma^2$ variance; sometimes used to describe random noise power

$\tau$ sampling period, the inverse of $f_s$

$\omega$ angular frequency, expressed in radians per second

$\omega_i$ angular input frequency in radians/second

$\delta\mathbf{t}_{eq}$ sampling time error of equivalent time sampling

$\delta\mathbf{t}_{fi}$ input frequency inaccuracy

**A** sinusoidal amplitude

**B** test tolerance in fractions of the nominal least significant bit (Q). Also used as an amplitude

**BW** frequency bandwidth

**c** general purpose constant

**C** offset

**d[n]** dither component of output sample y[n]

**dest[n]** estimate of the dither component d[n]

**D** general purpose integer

**DFT** Discrete Fourier Transform

**DG** differential gain

**DNL[K]** differential non-linearity of code k

**DNL** maximum differential non-linearity over all k

**DP** differential phase

**DR** dynamic range

**ENBW** equivalent noise bandwidth

**f** frequency, Hz

**f(n)** sinewave component of output sample y[n]

$\mathbf{f}_{co}$ upper frequency for which the amplitude response is -3 dB

$\mathbf{f}_{d}$ sampling frequency of a record after decimation by some integer D

$\mathbf{f}_{eq}$ equivalent sampling rate

$\mathbf{f}_{h}$ frequency of an harmonic of the input frequency

$\mathbf{f}_{i}$ actual input frequency or approximate desired input frequency

$\mathbf{f}_{imf}$ frequency of intermodulation distortion products

$\mathbf{f}_{opt}$ optimum input frequency for testing

$\mathbf{f}_{m}$ frequency of the mth component of a magnitude spectrum

$\mathbf{f}_{r}$ input signal reference frequency or input signal repetition rate

$\mathbf{f}_{s}$ sampling frequency

$\mathbf{f}_{sp}$ frequency of a persistent spurious tone

**FR** frequency response

**G** static gain of the ADC under test

**G(f)** dynamic gain of the ADC under test as a function of frequency

**h** order of harmonic frequency

**H** average number of histogram samples received in two code bins sharing the same transition level

**H[f]** frequency response of the ADC under test

**H[i]** number of histogram samples in bin i

**Hc[j]** number in the jth bin of the cumulative histogram of samples

$\mathbf{H[f}_{k}\mathbf{]}$ DFT of h(n)

**h(n)** discrete time impulse response of a system

**i** general purpose index

**I** general purpose factor

**IMD** intermodulation distortion

**INL** integral non-linearity

**INL[k]** integral non-linearity at output code k

**J** number of cycles in a record

**k** code bin

**L** general purpose integer

**L(f)** phase noise spectral power density

**mse** mean square error

**M** number of sequential samples in a record

**$M^+(x)$, $M^-(x)$** number of measurements of the output value at the input value x for increasing and decreasing inputs respectively

**Md** number of samples in a record after decimation

**MD** number of samples in one period of pseudo-random dither

**n** sample index within a record

**N** number of bits

**$N_{ef}$** number of effective bits

**NDR** noise distortion ratio

**NPR** noise power ratio

**p** probability

**PG** processing gain

**Q** ideal code bin width, expressed in input units

**r** general purpose integer

**R** minimum number of records required

**S** set of samples collected over more than one record, also used as an error parameter or as total number of samples used in a histogram

**SFDR** spurious free dynamic range

**SINAD** signal to noise and distortion ratio

**SNR** signal to noise ratio

$S_x(f)$ spectral power density of quantity x

**$t_{eq}$** average equivalent time sampling period

**$t_f$** top to base transition time; falltime

**$t_r$** base to top transition time; risetime

**$t_n$** discrete sample times

**$t_{wc}$** the center point of the aperture time associated with an output sample

**T[k]** code transition level between codes k-1 and k

**$T_{nom}$[k]** nominal code transition level between codes k-1 and k

**$\widehat{THD}$** estimate of total harmonic distortion

**THD** total harmonic distortion

**TSD** total spurious distortion

**u** confidence level expressed as a fraction

**$V_{cm}$** common mode signal

**$V_{dm}$** differential mode signal

**$V_{fs}$** full scale range

**$V_{fsn}$** nominal full scale range

**$V_{ifs}$** full scale input signal

**$V_{OS}$** ADC input offset, ideally = 0

**$V_{OD}$** input signal overdrive; the amount by which an input signal exceeds the ADC full scale range

**$V_{rir}$** reduced ADC input range

**VSWR** voltage standing wave ratio

**w** estimated code error rate

**w'** worst-case code error rate

**w[n]** window function coefficient (for a DFT)

**W[k]** code bin width of code bin k

**x** ADC input signal value; or number of errors detected

**X** number of standard deviations of a Gaussian distribution

**$X_{avm}(f_m)$** the averaged magnitude spectral component at discrete frequency $f_m$ after a DFT

**y[n]** the nth output data sample within a record

**$\overline{y}$[n]** average of y[n] over M samples

**yn'** best fit points to a data record

**Y[k]** the k-point DFT of the M-sample record y[n]

**$Z_O$** transmission line impedance

**$Z_t$** ADC input impedance

**Zu/2** number of standard deviations that encompass 100(1-u) % of a Gaussian distribution about the center.

# Contents

# I

# ADC CHARACTERISATION BASED ON SINEWAVE ANALYSIS