CAD Identification and Validation of a Non-Linear Dynamic Model for Performance Analysis of Large-Signal Amplifiers

Corrado Florian*, Fabio Filicori*, Domenico Mirri°, Thomas Brazil‡, Michael Wren‡

*Dipartimento di Elettronica, Informatica e Sistemistica, Università di Bologna, Viale Risorgimento 2, Bologna, 40136, Italy

°Dipartimento di Ingegneria Elettrica, Univ. di Bologna, Viale Risorgimento 2, Bologna, 40136 Italy

‡Department of Electronic and Electrical Engineering, University College Dublin, Dublin 4 , Ireland

***Abstract* — We describe the CAD identification and software implementation of a Volterra-like integral series expansion for the behavioral-level simulation of communication amplifiers. The model represents an improvement with respect to the classical AM-AM AM-PM memoryless approach. The performance of the model is compared with both the AM-AM AM-PM approach and circuit-level CAD simulation.**

I. Introduction

The simulation of the performance of communication power amplifiers and nonlinear circuits is in general dependent on the availability of models capable of describing their behavior with a high level of accuracy.

In the environment of a CAD package, it is possible to choose between two different approaches, namely, circuit-level simulation or system-level simulation. The first approach is the most accurate, but needs a detailed description of all the circuit components by means of physical or electrical models: the solution is then carried out by solving the circuit equations for all these models and this is obviously quite complex and time-consuming.

On the contrary, system-level simulation utilizes models based on terminal measurements that are, by their nature, much more computationally efficient. This kind of mathematical black-box, or look-up table model, gives a description of the behavior of the nonlinear system from the point of view of its external ports.

When simulating the performance of a power amplifier in a communication link, we are particularly interested in the effects of the circuit nonlinearities on the spectrum of the transmitted signal. Being driven near its maximum output power and with broadband signals, the amplifier gain is usually affected by nonlinear distortion and nonlinear memory effects. Depending on the amplifier topology and technology (bias networks, RF matching, thermal effects) and on the nature of the input signal (bandwidth), the circuit behavior could vary from nonlinear quasi-memoryless to nonlinear with memory.

The classical behavioral description known as the AM-AM AM-PM model is well suited to describing a quasi-memoryless amplifier, that is to say a system with memory time constants (τ) significantly less than the period of the carrier $T=1/f_0$. In this case, the amplitude and phase distortion of the output signal at a certain time instant depends only on the input signal level close to the same instant, and this relationship is well described by the *Pin/Pout* amplifier characteristic (AM-AM conversion) and the amplitude-dependent phase shift characteristic (AM-PM conversion), computed by means of a power sweep of the carrier (f_0 frequency).

This is true for every kind of modulated input signal applied to such a system regardless of how large is its bandwidth. In fact denoting by $fmax$ the maximum frequency of the envelope bandwidth of the input signal, the memory time constants τ will be always negligible with respect the modulation bandwidth ($\tau << 1/fmax$) since they are already less than the period of the carrier.

This simple description is no longer appropriate when dealing with amplifiers that present longer memory time constants τ and when dealing with broadband signals. Indeed, when the memory effects are on the order of the period of the envelope signal ($1/fmax$), the system response depends not only on the input envelope amplitude but also on its frequency.

The classical demonstration of these phenomena is the situation where the two-tone intermodulation distortion (IMD) depends on the tone spacing, as can be made evident by varying the offset frequency between the tones in the envelope modulation bandwidth [1].

It is important to notice that the AM-AM AM-PM quasi-memoryless model can still be useful to describe

0-7803-7695-1/03/$17.00 © 2003 IEEE

this kind of system, but only in the presence of very narrowband signals for which the inequality $\tau << 1/fmax$ is satisfied.

However in many cases the modulated signals involved in modern communication systems have bandwidths that are not at all negligible with respect to the memory characteristics of the amplifier, and so a memoryless assumption fails to give the correct response. This has been observed to be particularly true for systems containing internal devices for distortion reduction through compensation of the nonlinear characteristics [1][2].

To address this type of application, a new dynamic non-linear amplifier model that takes account of distortions due to both the large amplitude and the large bandwidth of the input signal, has been formulated. The model, the full mathematical basis for which is described in [3], is based on a modified Volterra-like integral series, previously used for the modeling of PHEMT devices [4] and VCO circuits [5], and is especially oriented to the analysis of non-linear systems operating with modulated signals.

The main aim of this paper is the verification of the capabilities of this kind of model. To this end, we will briefly present the model formulation (Section II), and then we will describe a new frequency-oriented version of the model formula and the model identification process within the Agilent ADS2002 environment (Section III).

Section IV is focused on the implementation of the model in MATLAB 5.3 code, while in Section V the model performance will be discussed.

II. NON-LINEAR DYNAMIC MODEL

A more complete description of the mathematical development that leads to the present model formulation is contained in [3]. The basic idea of this approach is to develop an integral series expansion (Volterra series) around a well-behaved signal trajectory that should be chosen depending on the particular application [6]. In this way, and with quite general hypothesis, it is possible to reduce the Volterra formulation to a simplified and compact form, that consists of an instantaneous static non-linearity plus one or more convolution integrals nonlinearly dependent on the instantaneous amplitude and frequency of the input signal.

The important property of this approach is the separation of purely static nonlinear effects from memory effects, which are mixed in the classical Volterra approach. The model formulation starts from a general description of the relationship between the input and output signals of the amplifier:

$$u(t) = F\left[s(t \overset{+T_B}{\underset{0}{-}} \tau)\right] \tag{1}$$

Where it has been assumed that the output $u(t)$ of a large signal amplifier can be expressed as a generic functional of the input signal $s(t)$.

This means that the output signal depends non-linearly on the values of the input signal over a sufficiently large "memory interval" ($0 \le \tau \le T_B$) around the instant t at which the output is evaluated.

Starting form this general assumption, eventually the model formulation becomes [3]:

$$\begin{aligned} b(t) &= a(t)H\left(f_0, |a(t)|\right) + \\ &+ \int_0^{T_B} h_1(\tau_1)\cdot\left[a(t-\tau_1) - a(t)\right] e^{-j2\pi f_0 \tau_1} d\tau_1 + \\ &+ \int_0^{T_B} g_1(\tau_1, f_0, |a(t)|)\cdot\left[a(t-\tau_1) - a(t)\right] e^{-j2\pi f_0 \tau_1} d\tau_1 + \\ &+ a^2(t)\int_0^{T_B} g_2^*(\tau_1, f_0, |a(t)|)\cdot\left[a^*(t-\tau_1) - a^*(t)\right]\cdot e^{j2\pi f_0 \tau_1} d\tau_1 \end{aligned} \tag{2}$$

Where $b(t)$ is the complex modulation envelope of the first zonal output component around the carrier and $a(t)$ is the complex modulation envelope of the input signal.

An examination of Eq. (2) is very useful in identifying the different terms that contribute to the output in-band signal: the first term represents the non-linear memory-less contribution, the second term is the purely dynamic linear contribution, while the last two terms are the purely dynamic nonlinear contributions.

The function H simply corresponds to the AM-AM AM-PM amplifier characteristic. That characteristic is determined by driving the amplifier with a non-modulated carrier and sweeping the power level. This means that in practice, the AM-AM AM-FM plots represent just a zero-order approximation of the system behavior.

Thus, in the presence of a modulated signal, the AM-AM AM-PM characterization of the amplifier is sufficiently accurate only when the bandwidth of the complex modulation envelope of the input signal (*fmax*) is so small as to make the amplitude of the dynamic deviations $e(t-\tau_i) = a(t-\tau_i) - a(t)$ for each τ_i almost negligible in practice. The latter is true only for quasi-memoryless systems or systems where the memory time constants are negligible with respect to the reciprocal of the envelope modulation bandwidth $\tau << 1/f$max.

These constraints cannot be met in many practical cases, when dealing with large-bandwidth modulated signals.

In such cases the model of Equation 2 gives superior accuracy by taking into account more terms of the series expansion of the functional in Equation 1. In fact, even if the series is truncated to the first-order term ($n=1$), a considerable improvement in accuracy can be achieved compared to the coarser zero-order approximation of the conventional AM-AM AM-PM characteristic alone.

It is important to notice the hypothesis involved in performing a first order truncation ($n=1$): the bandwidth of the modulation envelope f_{max} must be small enough to make the product of the amplitude of the dynamic deviations $e(t,\tau_i)$ for each τ_i almost negligible in practice (3).

$$\left(\prod_{i=1}^{n} e(t,\tau_i)\right) \tag{3}$$

It should be clear [3] that this hypothesis is far less restrictive than the hypothesis $\tau << 1/f_{max}$ and can be satisfied in many applications of interest.

Furthermore, even if this approach remains inadequate for an accurate description of systems with particularly long memory phenomena such as those arising from thermal effects, it represents an improvement for such cases compared to the memoryless approach. Indeed when the duration of memory effects is sufficiently long to invalidate the hypothesis made in truncating the series to first-order, the model will take account of nonlinear memory phenomena as well, but in this case the truncation error introduced will be larger.

III. THE MODEL IDENTIFICATION

We can rewrite the model formulation of Eq. (2) in a frequency-oriented version, as follows:

$$\begin{aligned} b(t) &= a(t)H(f_0,|a(t)|)+\int_{-\infty}^{\infty}[H_1(f_0+f)-H_1(f_0)]A(f)e^{j2\pi ft}df+ \\ &+\int_{-\infty}^{\infty}[G_1(f_0+f,f_0,|a(t)|)-G_1(f_0,f_0,|a(t)|)]A(f)e^{j2\pi ft}df+ \\ &+a^2(t)\cdot\int_{-\infty}^{\infty}[G_2^*(-f_0-f,f_0,|a(t)|)-G_2^*(-f_0,f_0,|a(t)|)]A^*(f)e^{-j2\pi ft}df \end{aligned} \tag{4}$$

This is achieved by introducing the Fourier transforms $H1$, $G1$, $G2^*$ of the functions $h_1(\tau_1)$, $g_1(\tau_1,f_0,|a(t)|)$ and $g_2^*(\tau_1,f_0,|a(t)|)$ respectively, as well as the new functions:

$$\hat{H}_1(f_0,f)=H_1(f_0+f)-H_1(f_0) \tag{5}$$

$$\hat{G}_1(f_0+f,f_0,|a(t)|)=G_1(f_0+f,f_0,|a(t)|)-G_1(f_0,f_0,|a(t)|)$$

$$\hat{G}_2^*(-f_0-f,f_0,|a(t)|)=G_2^*(-f_0-f,f_0,|a(t)|)-G_2^*(-f_0,f_0,|a(t)|)$$

The final formulation for discrete spectrum signals becomes:

$$\begin{aligned} b(t) &= a(t)H(f_0,|a(t)|)+\sum_{p=-P}^{P}\hat{H}_1(f_0,f_p)\cdot A(f_p)e^{j2\pi f_p t}+ \\ &\sum_{p=-P}^{P}\hat{G}_1(f_0+f_p,f_0,|a(t)|)\cdot A(f_p)e^{j2\pi f_p t}+ \\ &+a^2(t)\cdot\sum_{p=-P}^{P}\hat{G}_2^*(-f_0-f_p,f_0,|a(t)|)\cdot A^*(f_p)e^{-j2\pi f_p t} \end{aligned} \tag{6}$$

We have developed an efficient model identification procedure based on this frequency-domain formulation using the Agilent ADS2002 Envelope simulator [7].

This simulator allows us to drive the amplifier with any generic modulated signal with complex envelope $a(t)$ and computes the corresponding in-band output modulation envelope $b(t)$, implementing the complex envelope modulator/demodulator system described in [3].

IV. MODEL IMPLEMENTATION

The model has been implemented in Matlab 5.3 environment. The Matlab code implements Eq. (6), reading from look-up tables that store the model functions. Instantaneous interpolations in the envelope amplitude and frequency domains are performed with Matlab interpolation functions. For comparison purposes, an AM-AM AM-PM model has also been developed.

The benchmark for our simulation results is the circuit level simulation performed with Agilent ADS2002 Envelope simulator. Even if, as we said before, there are some kind of linearised amplifiers that might be the best choice to make evident the deficiencies of the traditional compression/phase distortion model in modeling their dynamic behavior, as a first approach we choose a single-ended PHEMT amplifier (designed and realized at UCD in microstrip technology) for the validation of the proposed non-linear dynamic model.

V. SIMULATION RESULTS

As a first analysis of the model's broadband capabilities we chose a test signal that consists of two tones deliberately widely-spaced to 100MHz around the frequency f_0=2GHz. The output signal complex envelope is amplitude and frequency modulated. In Fig.1 and Fig.2 we can appreciate how the nonlinear dynamic model gives a prediction closer to the circuit-level simulation solution, both for the amplitude and phase modulation. In particular the AM-AM AM-PM gives only a rough estimation of the phase modulation.

The output spectrum data in Table 1 shows that the Nonlinear Dynamic Model predicts with very good accuracy the asymmetric response of the amplifier to the two tones, while obviously the narrowband AM-AM AM-PM model is not able to model the frequency dependence of the amplifier gain (the two output tones are predicted to be identical).

Other tests of the model with a W-CDMA signal (data rate 32Kbit/sec) generated within the ADS2002 DSP environment have been carried out with good results, which are omitted here due to space restrictions.

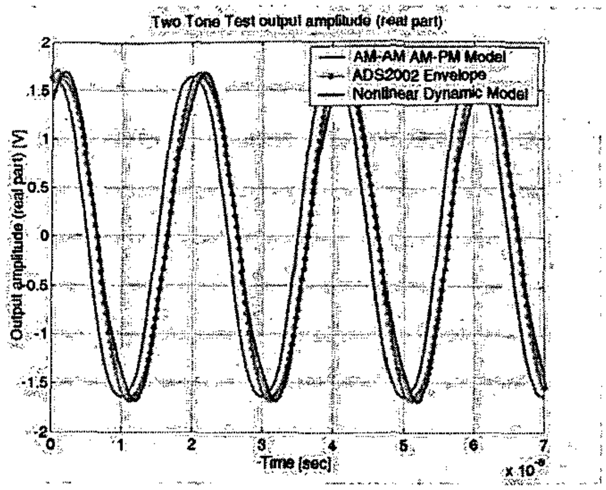

Fig.. 1. Complex Envelope Amplitude Modulation of the Output Signal: a Comparison Between the Three Approaches.

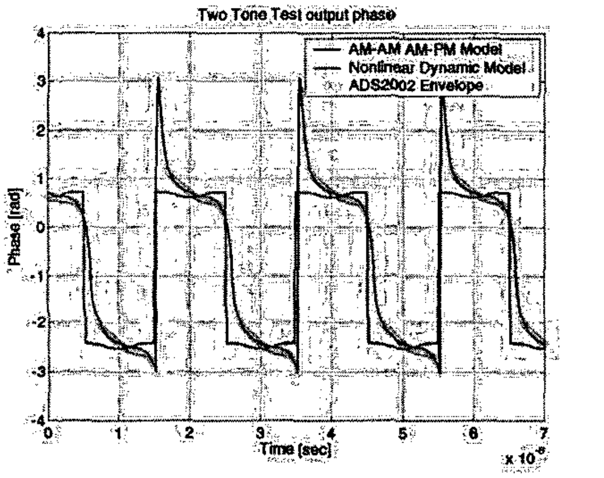

Fig. 2. Complex Envelope Phase Modulation of the Output Signal: a Comparison Between the Three Approaches

Two Tone Test Output Spectrum		
Simulator	Tones	
	-50MHz	50MHz
AM-AM AM-PM Model	10.8 dBm	10.8 dBm
ADS2002 Envelope	12.4 dBm	8.9 dBm
Nonlinear Dynamic Model	12.4 dBm	9.2 dBm

Table 1. Output Spectrum Resulting from the Two-Tone Test

VI. Conclusion and Future Activity

The implementation and the performance evaluation of a new kind of nonlinear dynamic model previously described by the authors have been presented. It has been shown that this modeling approach leads to an improvement in broadband behavioral modeling for a power amplifier compared to the classical memoryless AM-AM AM-PM approach.

Further investigations of the model's capabilities using different amplifier designs as well as an experimental implementation of the identification and validation set-up are planned for the near future. For this purpose, new instrumentation has recently been acquired at UCD allowing an experimental implementation of the identification bench described in [3]. The instrumentation consists of the Agilent E4438C Vector Signal Generator and the E4406A Vector Signal Analyzer Series Transmitter Tester, with which both the identification and the validation of the model can be carried out.

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