Time Domain Characterization of Power Amplifiers with Memory Effects

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Abstract — **Memory effects in power amplifier nonlinearity are frequently an impediment to amplifier linearization. In this paper, memory effects in a cellular phone power amplifier are characterized via time domain measurements, with waveforms including steps, triangular waveforms and CDMA signals. Memory effects found with different waveforms are shown to be consistent, and in agreement with measurements made with sinusoids in two-tone tests. The results are analyzed by considering gain modulation by a parameter varying at the baseband frequency in response to the signal envelope. For pseudorandom input signals, such as for CDMA, cross-correlation of gain residues with the signal envelope yields an impulse response associated with the memory effects.**

I. Introduction

Requirements for extended battery life and minimized distortion, spectral regrowth, and signal contamination in wireless communication systems have been driving the need for improved power amplifier performance. Accurate amplifier characterization and modeling is important, in order to enable linearization techniques to be effectively applied. Often, compression characteristics, or AM/AM & AM/PM models, are used to model amplifiers with little or no memory effect. A number of papers have been presented over the years [1-8] to extend this modeling approach, improve simulation times and enable effective modeling of the amplifier so that corrective measures can be accurately evaluated with simulation.

The presence of memory effects complicates this modeling procedure. Such memory effects can arise from multiple sources, including bias circuit effects, self-heating, and trapping effects [2]. Various approaches have been suggested to characterize the memory effects in power amplifiers, most often based on combinations of sinusoidal inputs. In this paper, we present a measurement approach to characterize memory effects using waveforms with complex time dependence, including steps, triangle and CDMA waveforms. In previous work, Silva [4] has used on-off power envelope measurements for the same purpose. The results of our measurements carried out on a commercial handset power amplifier provide a consistent picture, which also agrees with results obtained from two tone tests. Analysis is based on the assumption that gain is modulated by an unknown parameter, which is driven by the signal envelope at the baseband frequency. This approach is similar to the augmented behavioral characterization approach [7] in concept. In [7], the dependence of gain on the modulating parameter (e.g. power supply voltage, temperature, etc.) could be directly measured. In the present work, it is assumed the gain modulation cannot be measured directly, only inferred indirectly from the response of the amplifier gain to various excitations. We show that the step response associated with the memory effect can be inferred from measurements with pulsed power, and the corresponding impulse response emerges from the cross-correlation of the output gain residue with the input signal, for pseudorandom inputs such as CDMA signals. Here the gain residue is the normalized difference between the measured gain at a given time, and the gain expected on the basis of the instantaneous input power, as determined in quasi-static measurements.

II. Analytical Formulation

With the conventional behavioral model based on AM/AM and AM/PM measurements, the input signal is a continuous sinusoid at a specific frequency and the output signal magnitude and phase are characterized. This model assumes that the environment in which it is extracted (CW signal, harmonic terminations, temperature, signal dynamics, etc.) is a close approximation to the application environment. With modulation bandwidths of modern communication systems increasing, this assumption is being violated increasingly. As a result, "memory effects" appear in the component performance that cannot be captured by the conventional model.

In general, the input waveform can be represented as a modulated RF signal:

$$x_i(t) = x_{in}(t)\exp(j(2\pi f_o t + \varphi_{in}(t))) \qquad (1)$$

where $x_i(t)$ is the modulated RF signal, $x_{in}(t)$ is the amplitude of the envelope. When this signal is applied to an amplifier, the output complex envelope is described as:

$$x_{out}(t) = G(t)x_{in}(t)\exp(j\Theta(t)) \qquad (2)$$

where the function $G(t)$ is the describing function of the nonlinearity, and $\Theta(t)$ specifies the phase response. In memoryless cases, $G()$ is a function of $x_{in}(t)$ and can be easily measured, modeled, and utilized in simulation [1]. In other cases, it is a function of an additional parameter such as temperature or voltage, which can be measured and tabulated [7]. A more complete form of equation 2 is given as

$$x_{out}(t) = G(x_{in}(t), Z(t))x_{in}(t) \tag{3}$$

where the describing function *G()* is dependent on the current input signal and *Z(t)*, where *Z(t)* is a function of the historical input signal and some physical characteristic causing memory effects within the amplifier. Examples include $V_{cc}(t)$, $V_{bb}(t)$ and thermal characteristics which depend on the input power $x_{in}(t)$. In some cases where the parameter is inaccessible and memory effects exist, approximate relations can be derived from terminal measurements. The describing function can be approximated as a Taylor expansion for small excursions from a nominal location. The Taylor expansion is written for deviations of gain from the steady state values G_o and Z_∞ :

$$G(x_{in}, Z(t)) \approx G(x_{in}, Z_\infty) + \left.\frac{\partial G}{\partial Z}\right|_{|x_{in}|, Z_\infty} (Z(t) - Z_\infty(x_{in})) \tag{4}$$

By assuming a form for:

$$G_o(x_{in}) = G(x_{in}, Z = Z_\infty(x_{in})) \tag{5}$$

and

$$\left.\frac{\partial G}{\partial Z}\right|_{|x_{in}(t)|, Z_o} = G_o(x_{in}) \cdot k_g(x_{in}) \tag{6}$$

we get:

$$G(x_{in}, Z(t)) \approx G_o(x_{in}) \cdot (1 + k_g(x_{in}) \cdot (Z(t) - Z_\infty(x_{in}))) \tag{7}$$

and *Z(t)* is a function of x_{in}. As a first approximation, we will assume that *Z(t)* varies with the input excitation as a linear, time invariant system, although $Z_\infty(x_{in})$ may vary nonlinearly with x_{in}. As a result we have:

$$Z(t) - Z_\infty(x_{in}) = x_{in}(t) \otimes h_z(t) \tag{8}$$

where $h_z(t)$ is an impulse response function. This yields an expression we can use to extract and validate the nonlinear model:

$$G(x_{in}, Z(t)) \approx G_o(x_{in}) \cdot (1 + k_g h_z(t) \otimes x_{in}(t)) \tag{9}$$

The extraction procedure is to first measure $G_o(x_{in})$ under quasi static conditions then measure $G(x_{in}, Z(t))$ with a number of different modulated RF signals with time varying envelopes.

It has been observed that the impulse response function $h_z(t)$ changes when the component operated substantially outside it's normal operating range. This paper will focus on the regions of performance where $h_z(t)$ is nearly invariant.

III. Model Extraction

For the validation of this methodology, a commercial CDMA handset power amplifier module was used, biased with a Vref=3.1 volts and a Vcc=3.4 volts. The test environment included an Agilent ESG source providing arbitrary modulation envelope waveform capability, and an Agilent Vector Signal Analyzer with a PSA for detection of the signal.

The quasi-static $G_o(x_{in})$ is measured using a low frequency ramp such that memory effects are minimized. The power range of the ramp encompasses the weakly nonlinear, gain expansion and compression regions of operation. The slow ramp period is 1 mS. The ramp power range for the input signal is from -35dBm and up to 5dBm. Figure 1 illustrates the quasi-static gain and phase characteristics obtained in this fashion.

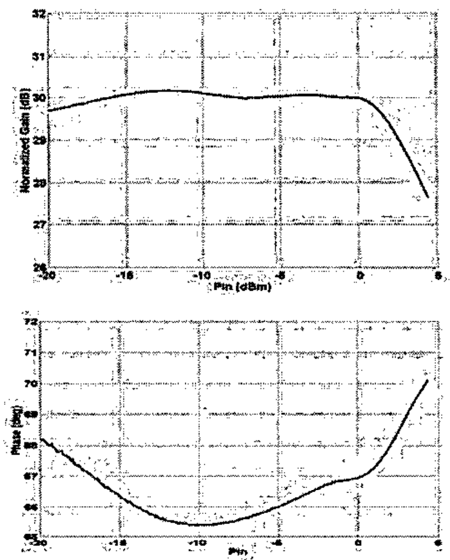

Fig. 1. Quasi static $G_o(x_{in})$ and phase characteristics from VSA slow ramp.

The measurements used to extract the remaining terms of $G(x_{in}, Z(t))$ are pulsed RF signals, where the minimum and maximum values of the pulsed signal are within the range of the extracted $G_o(x_{in})$ values and the envelope of the input RF signal $x_{in}(t)$ is a step function $\Delta x_{in} \cdot u_{-1}(t)$. From (9) we can see that:

$$k_g \cdot h_z(t) \otimes \Delta x_{in} u_{-1}(t) |= \frac{\left|\frac{x_{out}}{x_{in}}\right|}{G_o(x_{in})} - 1 \tag{10}$$

By applying a number of pulsed RF signals with different initial and final power levels (Fig. 2), and extracting the associated step responses we can extract the normalized transfer function $h_z(t)$, which can be accurately fit to characterize the system response (Fig. 3).

The results indicate that this amplifier displays pronounced memory effects that have a characteristic low frequency ringing behavior, most likely associated with bias circuits within the module. The gain is modulated at the level of several percent.

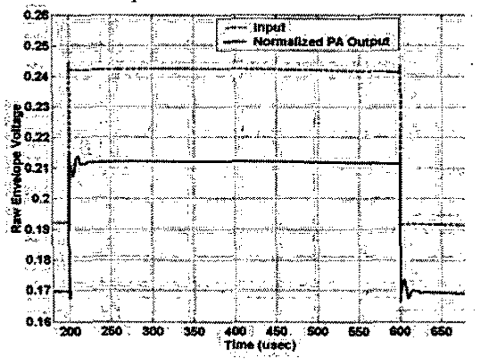

Fig. 2. Pulsed RF envelope voltages $x_{in}(t)$ and $x_{out}(t)$.

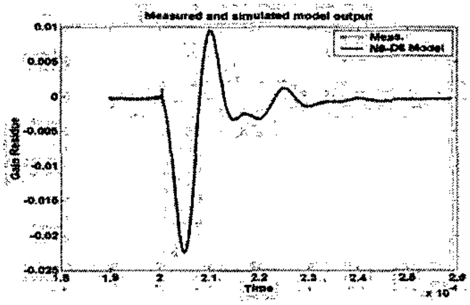

Fig. 3. Transfer function (modeled and measured) versus time.

IV. Model Validation

A number of arbitrary waveforms and signal conditions have been presented to the amplifier and simulated to determine the model accuracy. The signals used included triangular waveforms, sinusoids (in two-tone tests) and CDMA signals.

A. Triangle-wave Modulated RF input Signal

By using a triangle waveform envelope similar to the one used for the extraction of $G_0(x_{in})$ under quasi-static conditions but reducing the period, the impact of memory effects are observed as hysteresis in the Pin vs Pout plot. The results correspond to a dramatically larger hysteresis at a resonant frequency. Modeled results exhibit a corresponding resonance.

B. Two Tone, IM3 Response

Generating two sinusoidal signals, separated by Δf, and applying them to the input of the amplifier, we can observe the IM3 products and evaluate their deviations. In a memoryless amplifier, the IM3 tones will be symmetric with the high side tone matching the power level of the low side tone and their response will be independent of Δf. In the case of our example amplifier, the IM3 terms are not independent of Δf, nor are they symmetric (Fig. 5) Early simulations show reasonable agreement between modeled and measured dynamics and asymmetric characteristics.

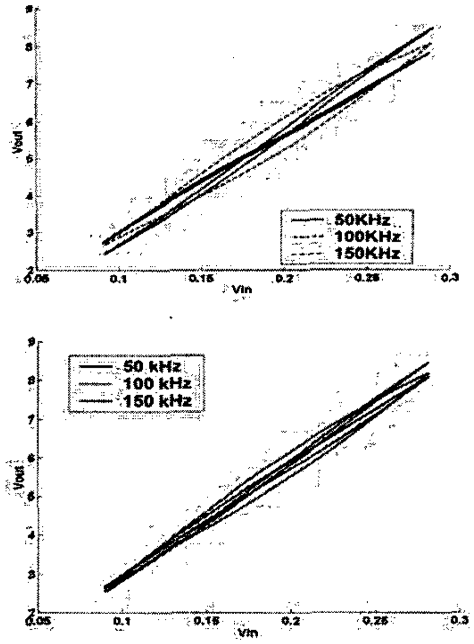

Fig. 4. Output and input voltage obtained with triangle waveform modulated RF signals with different periods: (top) measured, (bottom) modeled.

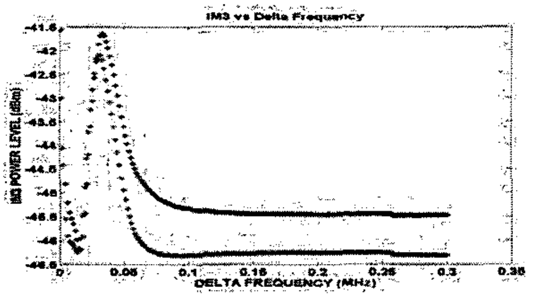

Fig. 5(a). Measured high side and low side IM3 products as Δf is swept.

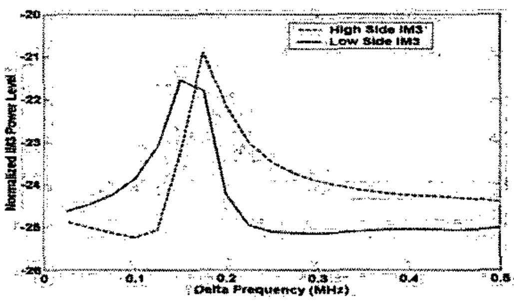

Fig. 5(b). Measured High side and low side IM3 products as Δf is swept.

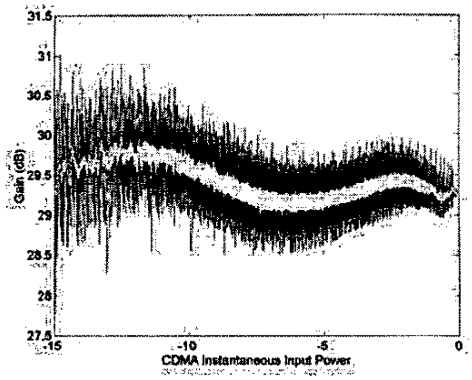

Fig. 6 Gain versus instantaneous input power measured with CDMA signal. The average gain is also shown.

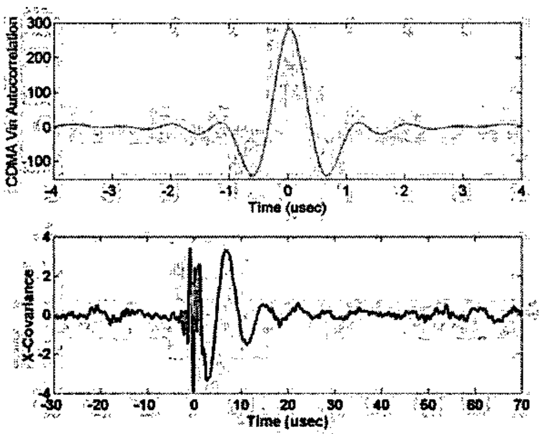

Fig. 7 Top plot: CDMA signal autocorrelation function, bottom plot: cross covariance of gain residue γ(t) with CDMA input signal.

C. CDMA Response

By comparing the amplifier input and output (after accurate time alignment) it is possible to determine instantaneous values of amplifier gain and phase response with CDMA signals. Fig. 6 shows, for example, the effective gain plotted against the instantaneous input signal amplitude level. The values inferred exhibit considerable deviations from their average value at a given power level (which is not equivalent to the quasi-static gain since it corresponds to a response after a shorter time [3]). In part these gain deviations correspond to measurement noise, and in part they correspond to deviations of gain resulting from the dependence of gain on the past history of the signal. We compute the normalized gain residue, γ(t), according to:

$$\gamma(t) = \frac{\left|\frac{x_{out}}{x_{in}}\right|}{G_{ave}(x_{in})} - 1 \qquad (11)$$

According to equation (9) we expect

$$\gamma(t) = k_g \cdot h_z(t) \otimes x_{in}(t) \qquad (12)$$

To demonstrate this relationship, we form the cross-correlation between the normalized gain residue γ(t) and the input signal. For a linear system, the cross-correlation of the output and input is given by the convolution of the impulse response of the system and the autocorrelation function of the input. For CDMA signals, the autocorrelation function is largely confined to the neighborhood of t=0 (as pictured in fig. 7 inset). The cross-correlation of γ(t) and xin(t) (after eliminating the mean of xin(t)) is shown in fig. 7. The results clearly show the oscillatory behavior of the impulse response as measured with step inputs.

V. CONCLUSION

Time domain measurements with step, triangular and CDMA inputs can be used to characterize the memory effects in a power amplifier. The response to different waveforms can be analyzed with a straightforward model. We show that the memory effects can be characterized by cross-correlation of the gain residue and input signal for pseudorandom inputs.

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