Behavioral Modeling of RF Power Amplifiers Considering IMD and Spectral Regrowth Asymmetries

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***Abstract*—This paper proposes a new behavioral model to treat asymmetries between lower and upper intermodulation products and spectral regrowth in nonlinear power amplifiers (PAs). Asymmetric intermodulation distortion (IMD) phenomena has been attributed to long time constant envelope memory effects within the PA, and is known to be a limiting factor in predistortion linearization systems. The model developed in this paper is based on the previously developed memory polynomial model. The contribution made in this paper was to augment the memory polynomial model to include a weighted delay tap function that significantly reduces the parameter space required for accurate model identification. Using measured IMD from a 2.1 GHz 170 W PEP LDMOS PA, the coefficients of the 100 tap memory polynomial were extracted. The model is validated by comparing the measured and predicted results when the PA is excited by a two-tone signal with tone spacing extending from 10kHz to 5MHz. The proposed model reduces *rms* error up to 36% when compared to a conventional unit sample delay memory polynomial model.**

I. INTRODUCTION

When we measure intermodulation distortion (IMD) or spectral regrowth to characterize the nonlinear behavior of a power amplifier (PA), asymmetries in lower and upper sidebands are often seen. It is known that these effects come from memory effects, which may arise from thermal effect, and long time constants in DC bias networks. Several studies have recently been conducted to deal with the asymmetric effect in PA nonlinearity [1]-[4]. In [1], S. C. Cripps explained the asymmetric effects using an envelope domain phase shift that depends on the amplitude distortion and its interaction with the AM/AM and AM/PM functions. N. B. Carvalho *et al.* [2] explained the reasons for IMD asymmetry by analyzing nonlinear circuit in small- and large- signal regions. They attribute the reasons to the terminating impedances at the baseband, or difference frequencies. J. H. K. Vuolevi *et al.* [3] divided the memory effects into electrical memory effects and thermal memory effects, and attributed the reason for asymmetric IMD to the thermal memory effects. They suggested that the opposite phases of the thermal filter at the negative and positive envelope frequencies causes IMD power to add at one sideband, while subtracting at the other. D. J. Williams *et al.* [4] measured voltages and currents for IF and RF signals in the time domain and analyzed the asymmetric effects. Using active load-pull setup, they showed the envelope termination affects asymmetrical effects. Whatever reason may cause the asymmetric effects, a model to treat these phenomena is needed. If asymmetries are not considered in predistortion linearizer, the optimal sideband reduction cannot be achieved for PA with asymmetries. This severely degrades predistortion performance.

The traditional AM/AM and AM/PM based behavioral model only describes the symmetry IMD and spectral regrowth responses. In this paper, to take the asymmetric effects into consideration, a memory polynomial model with complex coefficients is used [5]. To model IMD asymmetry of wideband signals, a general memory polynomial model must have a large memory depth. In this paper, we propose to reduce the number of parameters by introducing a weighted delay tap model. The measured two-tone spectrum data, which consist of magnitudes and phases, are converted to complex envelope time domain data using an inverse fast Fourier transform (IFFT). The coefficients for memory polynomial are extracted using the least squares method. The derived model predicts asymmetric IMD phenomena over a wide frequency range compared to a general memory polynomial model. The weighted delay tap model can also applied to multi-tone signals and digitally modulated signals for predicting spectral regrowth.

II. PA IMD Simulation based on AM/AM and AM/PM

For the purposes of later comparison, memoryless PA response and modeling is reviewed in this section. A memoryless PA can be modeled with traditional AM/AM and AM/PM model. A 0.5 W low power amplifier manufactured by Sirenza is modeled with a complex polynomial to fit the measured AM/AM and AM/PM data at 1.9GHz carrier frequency. The two-tone fundamental, IM3, and IM5 are simulated based on this model by sweeping input power and plotted in Figs. 1 and 2. The result in Fig. 1 shows simulated lower and upper terms in complex 3-dimensional domain considering only the AM/AM function. Fig. 2 shows the same plot when both

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AM/AM and AM/PM functions are considered. The IMD products considering only AM/AM effects shows symmetric magnitude and phase for lower and upper terms. In contrast, the IMDs considering both AM/AM and AM/PM effects show symmetries in magnitude but show some offset between lower and upper phases. In this case, the phase of each term changes depending on the input signal magnitude. However, the magnitude of the sidebands is always equal. Thus, AM/AM and AM/PM models cannot explain the asymmetries in IMD magnitudes.

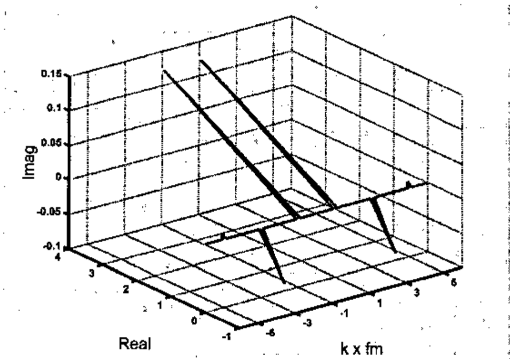

Fig. 1: Two-tone IMD considering AM/AM effect

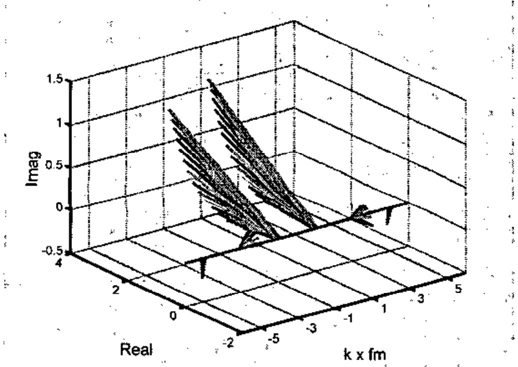

Fig. 2: Two-tone IMD considering AM/AM and AM/PM effects

III. Modeling of PA Considering Asymmetries

As shown in section 2, a real or complex polynomial cannot describe magnitude asymmetries. In this section, a memory polynomial is considered to model the asymmetry. The memory polynomial that consists of several delay taps and nonlinear static functions is a truncation of the general Volterra series [5], [6]. For the two-tone input signal $v(t)$ which has magnitude $A_i/2$ ($i=1,\dots,p$) and zero phase, and has tone spacings $2\omega_{md}$ ($d=1,\dots,s$) can be describes as

$$v(t)=\mathrm{Re}\{\tilde{v}(t,A_i,\omega_{md})e^{j\omega_o t}\} \qquad (1)$$

where ω_o is carrier frequency, and ω_{md} is modulation frequency. ($\omega_m << \omega_o$). The complex envelope is

$$\tilde{v}(t,A_i,\omega_{md})=\frac{A_i}{2}\cdot\left(e^{j\omega_{md}t}+e^{-j\omega_{md}t}\right) \qquad (2)$$

For this input, output signal $w(t)$ can be described as

$$w(t)=\mathrm{Re}\left[\sum_{k=-(n-1)}^{n} f_{(2k-1)}(A_i,\omega_{md})e^{j(2k-1)\omega_{md}t}e^{j\omega_o t}\right] \qquad (3)$$

where the vector $f_{(2k-1)}(A_i,\omega_{md})$ can be acquired from two-tone spectrum measurements. Spectrum analyzer measurements give only magnitude information. However, if we use extended setup as described in [7] and [8], the two-tone phase for each term can be acquired. The output complex envelope in (3) can be represented as follows:

$$\tilde{w}(t,A_i,\omega_{md})=\sum_{k=-(n-1)}^{n} f_{(2k-1)}(A_i,\omega_{md})e^{j(2k-1)\omega_{md}t} \qquad (4)$$

These complex envelope curve described by (4), when it is extracted from two-tone asymmetric IMD measurements, can be well fit with the memory polynomial that has $2n-1$ nonlinear order and Q memory depth size as follows:

$$\tilde{w}[l,A_i,\omega_{md}]=\sum_{k=1}^{n}\sum_{q=0}^{Q}a_{kq}\tilde{v}[l-r(q),A_i,\omega_{md}]\left|\tilde{v}[l-r(q),A_i,\omega_{md}]\right|^{2(k-1)} \qquad (5)$$

where $\tilde{v}[l,A_i,\omega_{md}]=\tilde{v}(t=lt_S,A_i,\omega_{md})$ $(l=1,2,\dots,N)$, $\tilde{w}[l,A_i,\omega_{md}]=\tilde{w}(t=lt_S,A_i,\omega_{md})$, and t_S is sampling time. $r(q)$ are the weighted delay tap functions. A conventional memory polynomial has $r(q)=q$. For the weighted memory polynomial, $r(q)=floor[N\cdot(q/Q)]$ is applied.

To get complex coefficients a_{kq}, Eq. (5) can be represented as matrix form for output data with N history

$$W=H\cdot a \qquad (6)$$

where

$$H=\begin{bmatrix} H(A_1,\omega_{m1}) \\ \vdots \\ H(A_P,\omega_{m1}) \\ H(A_1,\omega_{m2}) \\ \vdots \\ H(A_P,\omega_{m2}) \\ \vdots \\ H(A_1,\omega_{mS}) \\ \vdots \\ H(A_P,\omega_{mS}) \end{bmatrix},\quad W=\begin{bmatrix} W(A_1,\omega_{m1}) \\ \vdots \\ W(A_P,\omega_{m1}) \\ W(A_1,\omega_{m2}) \\ \vdots \\ W(A_P,\omega_{m2}) \\ \vdots \\ W(A_1,\omega_{mS}) \\ \vdots \\ W(A_P,\omega_{mS}) \end{bmatrix}, \qquad (7)$$

$$H(A_i,\omega_{md})=\begin{bmatrix} h_{10}(r(Q)+1,A_i,\omega_{md}) & h_{20}(r(Q)+1,A_i,\omega_{md}) & \cdots & h_{k0}(r(Q)+1,A_i,\omega_{md}) & \cdots & h_{1Q}(r(Q)+1,A_i,\omega_{md}) & \cdots & h_{nQ}(r(Q)+1,A_i,\omega_{md}) \\ h_{10}(r(Q)+2,A_i,\omega_{md}) & h_{20}(r(Q)+2,A_i,\omega_{md}) & \cdots & h_{k0}(r(Q)+2,A_i,\omega_{md}) & \cdots & h_{1Q}(r(Q)+2,A_i,\omega_{md}) & \cdots & h_{nQ}(r(Q)+2,A_i,\omega_{md}) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\ h_{10}(r(Q)+N,A_i,\omega_{md}) & h_{20}(r(Q)+N,A_i,\omega_{md}) & \cdots & h_{k0}(r(Q)+N,A_i,\omega_{md}) & \cdots & h_{1Q}(r(Q)+N,A_i,\omega_{md}) & \cdots & h_{nQ}(r(Q)+N,A_i,\omega_{md}) \end{bmatrix}, \qquad (8)$$

$$h_{kq}(l,A_i,\omega_{md}) = \tilde{v}[l-r(q),A_i,\omega_{md}]\left|\tilde{v}[l-r(q),A_i,\omega_{md}]\right|^{2(k-1)}, \tag{9}$$

$$W(A_i,\omega_{md}) = \begin{bmatrix} \tilde{w}[r(Q)+1,A_i,\omega_{md}] \\ \vdots \\ \tilde{w}[r(Q)+N,A_i,\omega_{md}] \end{bmatrix}, \tag{10}$$

and

$$a = \begin{bmatrix} a_{10} & a_{20} & \cdots & a_{n0} & \cdots & a_{1Q} & \cdots & a_{nQ} \end{bmatrix}^T . \tag{11}$$

W is a $(N \cdot p \cdot s \times 1)$ vector, H is a $(N \cdot p \cdot s \times (n(Q+1))$ matrix, and a is a $(n(Q+1) \times 1)$ vector.

The coefficient $\hat{a}$ can be derived from

$$\hat{a} = Pseudoinverse(H) \cdot W \tag{12}$$

The expected output from the model is

$$\hat{W} = H \cdot \hat{a} \tag{13}$$

The *rms* error for in-phase and quadrature of envelope signal can be defined as

$$rmse_{in} = \left\| \frac{\mathrm{Re}\{W-\hat{W}\}}{\sqrt{N \cdot p \cdot s}} \right\|_2 , \quad rmse_{quad} = \left\| \frac{\mathrm{Im}\{W-\hat{W}\}}{\sqrt{N \cdot p \cdot s}} \right\|_2 \tag{14}$$

IV. PA IMD Asymmetric Measurement and Simulation

Wideband and high power amplifiers are particularly vulnerable to memory effects because of self-heating effects and bias circuit frequency response. In this study, a 2.1GHz 170 W PEP LDMOS PA manufactured by Danam Communications, Inc. [9] was tested to investigate asymmetric IMD phenomena. A two-tone signal which has same magnitude and phase is applied to the input, and the output lower and upper terms are measured. Figs. 3 and 4 show the measured asymmetry results in IM3 and IM5 by sweeping two-tone spacings from 10 kHz to 5MHz and by sweeping input power from -17 dBm to -12 dBm. The difference between lower and upper fundamental terms is less than 0.2 dB, so PA frequency response is not an issue. Unlike the fundamental terms, the measured IM3 difference between upper and lower term ranges from -3dB to 2dB. The measured IM5 difference between upper and lower term ranges from -6dB to 2dB. The amount of the asymmetry depends on the input signal power and input signal tone-spacing.

The measured response was modeled with the memory polynomial described in section 3. The extracted memory polynomial has an order of 17 (odd terms only) and has a weighted memory depth of 100 taps. The measured and simulated results for IM3 and IM5 terms are plotted in Figs. 5 and 6. Fig. 5 is the result when two-tone spacing is 400kHz and Fig. 6 is the result when two-tone spacing is 4.8MHz.

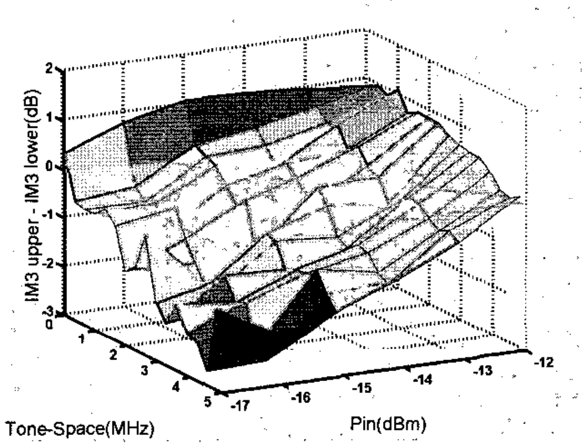

Fig. 3: Measured two-tone IM3 asymmetries for high wideband LDMOS PA

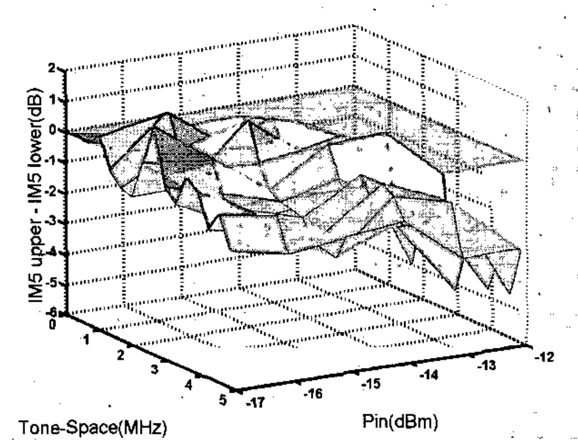

Fig. 4: Measured two-tone IM5 asymmetries for high wideband LDMOS PA

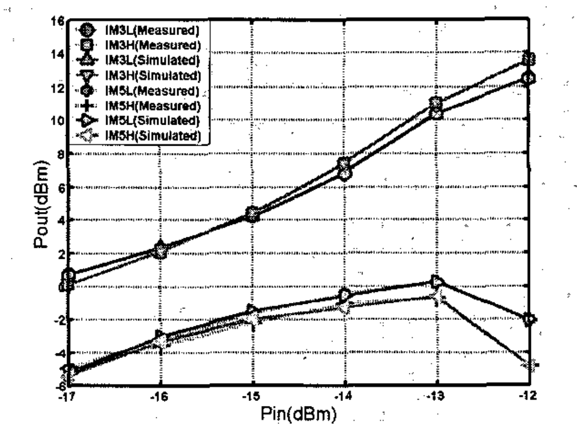

Fig. 5: Measured and simulated results for IM3 and IM5 asymmetries when tone-spacing is 400kHz

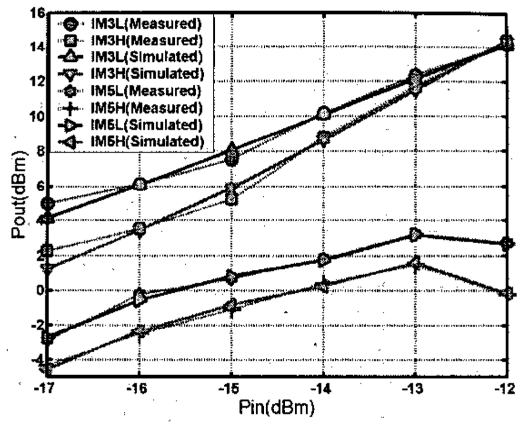

Fig. 6: Measured and simulated results for IM3 and IM5 asymmetries when tone-spacing is 4.8MHz

The extracted memory polynomial with weighted delay taps predicts each lower and upper term well in the wide range for two-tone spacings and the maximum error for IM3 terms is less than 1dB as shown in Figs. 5 and 6. The in-phase error and quadrature error of a general memory polynomial and weighted memory polynomial are calculated by sweeping memory depth size Q from 0 to 100. The *rms* errors were plotted and compared in Fig. 7. As shown in Fig 7, the weighted memory polynomial reduces *rms* error significantly when compared to a conventional memory polynomial.

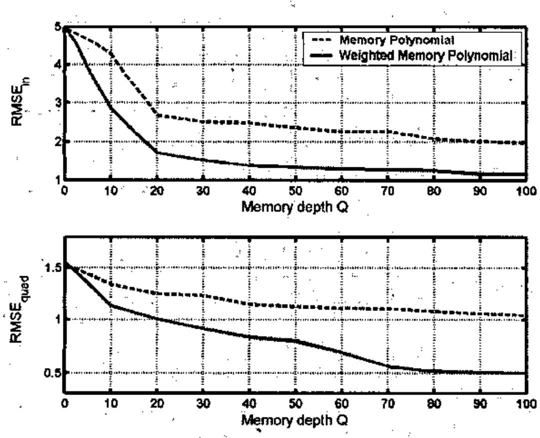

Fig. 7: In-phase and quadrature-phase *rms* error depending on memory depth

V. Conclusions

In this paper, a behavioral model of an RF power amplifier considering IMD and spectral regrowth asymmetries was proposed. A memory polynomial model was augmented with a weighted delay tap function to reduce memory depth requirements. To validate the proposed model, coefficients of a 100 tap memory polynomial model were extracted using measured IMD data from a 2.1 GHz 170 W PEP LDMOS PA. It was seen that the measurement results agree with the predicted results within 1 dB. The memory polynomial model with weighted tap delay reduces *rms* error about 15% for in-phase envelope and about 36% for quadrature envelope compared to a general memory polynomial with unit delay.

Further work is being carried out in order to apply this model to multi-tone signals and wideband digitally modulated signals. This work will allow the development of behavioral PA model considering asymmetric sidebands and their application to predistortion linearizer schemes.

Acknowledgement

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