Continuous-Time Model Identification of RF Power Amplifiers

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Abstract

The Radio Frequency Power Amplifier is the major source of the nonlinear distortion which affect the signal modulated in the Radiocommunication transmission system. To analyse and treat the distortion caused to the amplified signal, this paper presents the parameters estimation of a behavioral model. Based on baseband signals, this model includes a polynomial function representing AM/AM and AM/PM characteristics in addition with MIMO continuous filter to describe the PA dynamics. Using the baseband input and output data, model parameters are obtained recursively by an iterative identification algorithm based on Output Error method. Initialization and excitation problems are resolved by an association of a new technique using initial values extraction with a multi-level binary sequence input exciting all PA dynamics. Finally, the proposed estimation method is tested and validated on experimental data.

Index Terms

Nonlinear distortions, power amplifier, linear filter, continuous time domain, identification algorithm, Output Error technique.

I. Introduction

Non-linear system identification of microwave components and RF circuits becomes a challenge and potential useful problem in the radiocommunications system researches area. Interest for Power Amplifier modeling is motivated by the increasing growth of the wireless communications system which has lead to use digital modulation techniques such as (BPSK, QPSK, QAM, ...) with non-constant envelope to improve spectral efficiency[1][2]. As a result of the variable envelope modulation schemes, the PA effects become very important in the mobile communication system. This is due to the nonlinear distortions and dynamical effects which caused the increase of the bit error rate and generate unwanted harmonics in the spectrum signal transmitted.

Numerous approaches of modeling PA nonlinearities have been developed in this research area to characterize the input to output complex envelope relationship [3][4][5][6]. The model forms used in identification are generally classified into three methods depending on the physical knowledge of the system : black box, grey box and white box. A black box model is a system where no physical insight and prior information where available. This approach have been widely used in many research studies to predict the output of the Nonlinear Power Amplifier such as neural networks [7][8], Wiener and Volterra series [9][10][11][12]. However, this method suffer from the high number of parameters and the time consuming in computation for complex system. On the opposite, white box model is a system where the mathematical representation, under some assumptions, is perfectly known. The main advantages of this model is that the resulting parameters have physical significance like gain conversion, damping coefficient and cut-off frequency in electrical systems [19]. For these reasons, the model considered in this paper is a white box class described on continuous-time domain. This structure is similar to PA discrete-time representation including nonlinear transfer functions and multivariable continuous filter [3][4]. The first block is set to a memoryless complex amplitude (AM/AM) and phase (AM/PM) conversion. Conventionally, a power series model is used to consider these transfer functions. To describe PA dynamics, an n^{th} MIMO filter is inserted. This element operates on modulating input and represents a low-pass equivalent in envelope signals [20]. With this structure, the electronics engineer can interpret immediately the model in physical terms.

Model parameters are achieved using an iterative identification algorithm based on Output Error method.

During last two decades, there has been a new interest in Output Error techniques [13]. An overview of approaches is given in [14][15]. Output Error (OE) methods are based on iterative minimization of an output error quadratic criterion by a Non Linear Programming (NLP) algorithm. This technique requires much more computation and do not converge to an unique optimum. But, OE methods present very attractive features, because the simulation of the output model is based only on the knowledge of the input, so the parameter estimates are unbiased [16][17][18]. Moreover, OE methods can be used to identify non linear systems. For these advantages, the OE methods are more appropriate in microwave systems characterization [19][20].

For PA identification, the parameters initialization and input excitation are very important to ensure global convergence. Then, we propose a new procedure for initialization search based on estimation of the nonlinear (AM/AM) and (AM/PM) functions decoupled from filter identification. A resulting value gives a good approximation of model parameters. Associated with a multi-level input excitation, this technique allows a fast convergence to the optimal values. Such an identification procedure for continuous-time domain in PA modeling does not seem to have been used previously.

The validation of this PA model is obtained for some experimental digital modulation techniques. Measured and estimated output signal are compared. Results show a good agreement and demonstrate the possibility to PA characterization using continuous-time representation.

II. PA Model description

The nonlinear amplifier model used in this paper is an extension of the discrete time-model at continuous one [4]. The major disadvantage of the discrete representation systems is that the parameters used have no physical significance, contrary to continuous one where parameters keep their real aspect [13]. This is very important when advanced PA applications are considered such as linearization or real time control.

The nonlinear block presented here operates on baseband quadrature I/Q time-domain waveforms. The complex low-pass equivalent (LPE) representation of the communication signal is used to avoid the high sampling rate required at the carrier frequency.

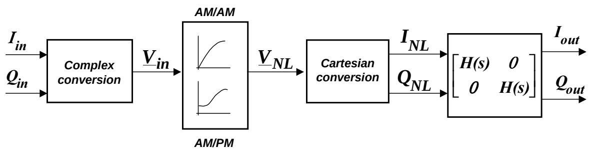


Fig. 1. Radio frequency power amplifier model

As shown in fig. 1, the two-box MIMO model includes a memoryless nonlinearity prior to an n^{th} order Laplace filter. In this model, the first box is the AM/AM and AM/PM conversions described PA nonlinearities. The second box is the frequency response operates on the two baseband inputs I/Q.

A. Nonlinear Static functions

To take into account simultaneous gain and phase characteristics, amplifiers are traditionally modeled with a complex polynomial series [11][22]. Then, the complex envelope of the non linear output signal is approximated with the following baseband input/output relationship:

$$\underline{V}_{NL} = \underline{V}_{in} \cdot \sum_{k=0}^{P} \underline{c}_{2k+1} \cdot |\underline{V}_{in}|^{2k} \tag{1}$$

$\underline{V}_{in}$ and $\underline{V}_{NL}$ are respectively the complex input and output voltage translated in baseband and expressed according the direct and quadrature I/Q signals as:

$$\begin{cases} \underline{V}_{in} &= I_{in} + j\, Q_{in} \\ \underline{V}_{NL} &= I_{NL} + j\, Q_{NL} \end{cases} \tag{2}$$

In equation (1), the second term is the non-linear transfer characteristic of the amplifier, dependent of the squared magnitude of the input $\underline{V}_{in}$. It is expressed with a polynomial function composed of even terms which produce harmonic distortions inside the PA bandpass. The parameters $\underline{c}_{2k+1}$ are the complex power series coefficients such as:

$$\underline{c}_{2k+1} = \alpha_{2k+1} + j\, \beta_{2k+1} \tag{3}$$

The previous equations give the relationship between input and output baseband signals :

$$\begin{cases} \underline{I}_{NL} = \sum_{k=0}^{P} (\alpha_{2k+1}\, I_{in} - \beta_{2k+1}\, Q_{in}) \cdot |V_{in}|^{2\,k} \\ \underline{Q}_{NL} = \sum_{k=0}^{P} (\alpha_{2k+1}\, Q_{in} + \beta_{2k+1}\, I_{in}) \cdot |V_{in}|^{2\,k} \end{cases} \tag{4}$$

The output quadrature signals depend on the both input quadrature terms and on the instantaneous input power.

B. Continuous filter

The dynamical effect caused by the PA system behavioral may be expressed with a differential equation. As shown in figure (1), the input to output relationships of this n^{th} order filter can be written as:

$$\left\{ \begin{array}{l} \frac{d^n}{dt^n} I_{out} + \sum_{k=0}^{n-1} a_k \frac{d^k}{dt^k} I_{out} = \sum_{k=0}^{m} b_k \frac{d^k}{dt^k} I_{NL} \\ \frac{d^n}{dt^n} Q_{out} + \sum_{k=0}^{n-1} a_k \frac{d^k}{dt^k} Q_{out} = \sum_{k=0}^{m} b_k \frac{d^k}{dt^k} Q_{NL} \end{array} \right. \tag{5}$$

where $I_{out}(t)$ and $Q_{out}(t)$ are the filter outputs.
The coefficients $\{a_k\}$ and $\{b_k\}$ are real scalars that define the model. Note that the filter structure is the same on the two axes I and Q, which gives a decoupled MIMO plant. Thus, the input-output relation can be expressed in Laplace-domain with the transfer-function $H(s)$, as so:

$$H(s) = \frac{\sum_{k=0}^{m} b_k \cdot s^k}{s^n + \sum_{k=0}^{n-1} a_k \, s^k} \tag{6}$$

where s denotes the differential operator $s = \frac{d}{dt}$.

III. Parameter identification of the PA model

The problem of system identification is a major field in control and signal processing. For their simplicity, the Equation Error (EE) techniques like least squares is regarded as the most suitable method for estimating the coefficients in a regression model. However, there are severe drawbacks, not acceptable in PA characterization, especially for the identification of physical parameters, such as the residual error caused by the output noise and the modeling errors [23].
Output Error (OE) methods have become a wide-spread technique for non linear system identification [18][17]. Usually, for these methods, parameter estimates are found iteratively using optimization algorithms. The simulation of the output model is based only on the knowledge of the input, so the parameter estimation is unbiased [16].

A. Identification algorithm

Parameter identification is based on the definition of a model. For power amplifier, we consider the previous mathematical model (Eqs. 1-6) and we define the parameter vector:

$$\underline{\theta} = \left[a_0 \ \cdots \ a_{n-1} \ \ b_0 \ \cdots \ b_m \ \ \underline{c}_1 \ \cdots \ \underline{c}_{2P+1} \right]^T \tag{7}$$

where $[.]^T$ denotes transposition operation.
Assume that we have measured K values of input vector $(I_{in}(t), Q_{in}(t))$ and output vector $(I^*_{out}(t), Q^*_{out}(t))$ with $t = k \cdot T_e$ and $1/T_e$ is the sampling rate, the identification problem is then to estimate the values of the parameters $\underline{\theta}$. Thus, we define the output prediction errors:

$$\left\{ \begin{array}{l} \varepsilon_{I_k} = I^*_{out_k} - \hat{I}_{out_k}(\hat{\underline{\theta}}, I_{in}, Q_{in}) \\ \varepsilon_{Q_k} = Q^*_{out_k} - \hat{Q}_{out_k}(\hat{\underline{\theta}}, I_{in}, Q_{in}) \end{array} \right. \tag{8}$$

where predicted outputs $\hat{I}_{out_k}$ and $\hat{Q}_{out_k}$ are obtained by numerical simulations of the PA model and $\hat{\underline{\theta}}$ is an estimation of true parameter vector $\underline{\theta}$.

As a general rule, parameter estimation with OE technique is based on minimization of a quadratic multivariable criterion defined as :

$$J = \sum_{k=1}^{K} ({\varepsilon_I}_k^2 + {\varepsilon_Q}_k^2) = \underline{\varepsilon}_I^T \, \underline{\varepsilon}_I + \underline{\varepsilon}_Q^T \, \underline{\varepsilon}_Q \tag{9}$$

We obtain the optimal values of $\underline{\theta}$ by Non Linear Programming techniques. Practically, we use Marquardt's algorithm [21][23] for off-line estimation:

$$\hat{\underline{\theta}}_{i+1} = \hat{\underline{\theta}}_i - \{[J''_{\theta\theta} + \lambda \cdot \mathbb{I}]^{-1}.J'_\theta\}_{\hat{\underline{\theta}} = \underline{\theta}_i} \tag{10}$$

J'_θ and $J''_{\theta\theta}$ are respectively gradient and hessian such as:
$J'_\theta = -2 \sum_{k=1}^{K} \left(\underline{\varepsilon}_{I_k}^T \cdot \underline{\sigma}_{I_{k,\underline{\theta}}} + \underline{\varepsilon}_{Q_k}^T \cdot \underline{\sigma}_{Q_{k,\underline{\theta}}} \right)$
$J''_{\theta\theta} \approx 2 \sum_{k=1}^{K} \left(\underline{\sigma}_{I_{k,\underline{\theta}}} \cdot \underline{\sigma}_{I_{k,\underline{\theta}}}^T + \underline{\sigma}_{Q_{k,\underline{\theta}}} \cdot \underline{\sigma}_{Q_{k,\underline{\theta}}}^T \right)$
λ is the monitoring parameter,

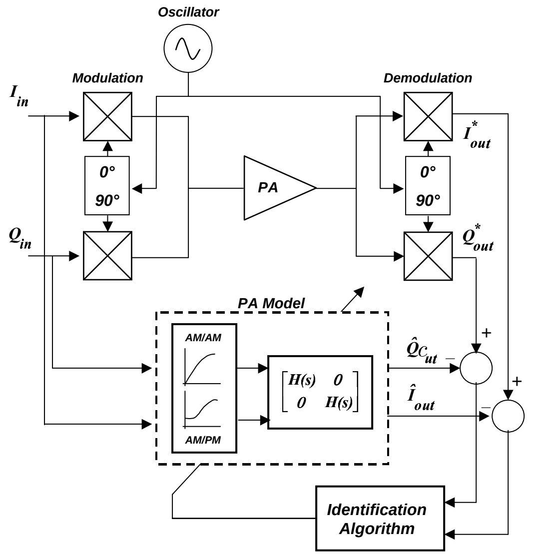


Fig. 2. PA identification scheme

$\underline{\sigma}_{I_{k,\underline{\theta}}} = \frac{\partial \hat{I}_{out}}{\partial \underline{\theta}}$ an output sensitivity on I axis,
and $\underline{\sigma}_{Q_{k,\underline{\theta}}} = \frac{\partial \hat{Q}_{out}}{\partial \underline{\theta}}$ an output sensitivity on Q axis.
The sensitivity functions $\underline{\sigma}$ are obtained, for each parameter, by numerical integration of their differential system [23].

All discrete-time models are deduced from the continuous one by second order serie expansion of the transition matrix.

B. Initialization problems

Usually, for engineering process, one has good knowledge on physical parameters, necessary to initializing the recursive algorithm (Eq. 10). In our case, PA users have not sufficient information on parameter vector $\underline{\theta}$, especially on AM/AM and AM/PM parameters. It is then essential to define a global strategy which makes it possible to obtain approximative values of parameters. So we propose an optimal search method based on Equation Error techniques to achieve initial values of PA non linear and filter parameters.

1) Non linear parameters initialization:

The first step consists in searching approximation of the complex parameters $\underline{c}_{2k+1}$ using the envelope magnitude and phase distorsions (Eq. 1). Thus, the AM/AM and AM/PM characteristic are used to optimize a polynomial function by Least Mean Square (LMS) algorithm [16]. A solution for the coefficients is obtained by minimizing the mean-squared error between the measured (I^*_{out}, Q^*_{out}) and the modeled output (I_{out}, Q_{out}) under low frequency signal such as:

$$\underline{\hat{\theta}}_{NL} = (\phi^H\, \phi)^{-1}\, \phi^H\, \underline{V}^*_{out} \tag{11}$$

where :
$(.)^H$ denotes transpose-conjugate transformation
$\underline{\hat{\theta}}_{NL} = [\,\underline{c}_1 \;\; \underline{c}_3 \;\; \cdots \;\; \underline{c}_{2P+1}\,]^T$ is the vector of polynomial parameters,
V^*_{out} is the measured output,
$\phi = [\,\underline{\varphi}_1 \;\; \underline{\varphi}_2 \;\; \cdots \;\; \underline{\varphi}_K\,]$ is the regression matrix,
$\underline{\varphi}_k = [\,V_{in_k} \;\; V_{in_k}|V_{in_k}|^2 \;\; \cdots \;\; V_{in_k}|V_{in_k}|^{2P}\,]^T$ is the regression vector,
and $\underline{V}_{in_k}$ is a k^{th} sampled input.

Noted that for these estimations, the regression vector $\underline{\varphi}_{k_c}$ is not correlated with the measured output $\underline{V}^*_{out}$.

In practice, the PA characteristics is performed by a sinusoidal excitation applied on baseband inputs I_{in} and Q_{in} at fixed low frequency and high input level. In these conditions, the PA filtering effects are assumed negligible according to non linear dynamics. The input-output curves are obtained by measuring the output gain and phase as a function of input level.

2) Filter parameters initialization:

The second step is the determination of initial values for the filter coefficients. They are obtained for an input signal with low input level and large frequency bandwidth. The signal distorsion is then negligible, which makes it possible to take into account only the linear filter effects. Thus, we define the filter parameter vector:

$$\underline{\theta}_f = [\, a_0 \;\; a_1 \;\; \cdots \;\; a_{n-1} \;\; b_0 \;\; b_1 \;\; \cdots \;\; b_m \,]^T \tag{12}$$

Parameter estimation is performed by iterative Instrumental Variable based on Reinitilized Partial Moments *RPM* method (see also [20][23]). Used to continuous filter identification, this technique is included in the integral methods class. The main idea of this class is to avoid the input-output time-derivatives calculation by performing integrations. In this class, the particularity of the *RPM* method[1] is the use of a time-shifting window for the integration and to perform an output noise filtering.
The main advantage of this estimation method to others is its relatively insensitivity to the initial conditions and rough system a priori knowledge.

IV. PA SETUP

The measurement setup is shown in Fig. 3. The power amplifier was a commercial ZHL-42 from MINI CIRCUITS manufacturer. Input and output data are obtained from YOKOGAWA DIGITAL OSCILLOSCOPE with a sampling period equal to 10 ns.

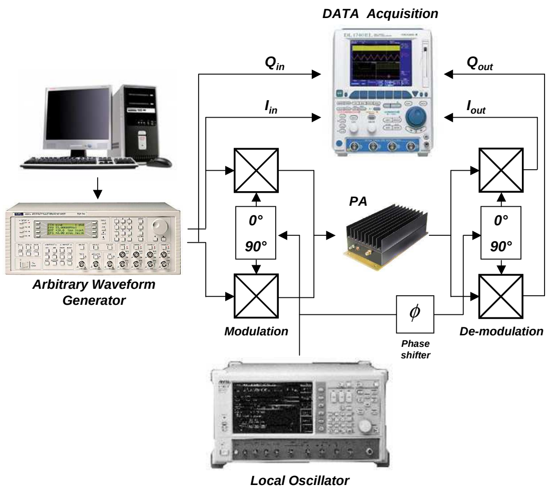


Fig. 3. PA setup

Filter identification algorithm needs large frequency bandwidth excitation signal to provide appropriate estimation. Indeed, modulated signals are required to excite both steady-state (low frequency) and process dynamics (medium to high frequency). This excitation is performed with a Pseudo Random Binary Sequence (P.R.B.S) baseband pulse as the input modulation to the transmitter. All data processing are carried using MATLAB MATHWORKS then are downloading to a BASEBAND WAVEFORM GENERATOR . The quadrature modulator AD8349 and demodulator AD8347 are inserted at the input and output of the PA. They are standard commercial units from Analog Devices.

Modulation signals I and Q are delivered by a TT*i* 40 MHz Arbitrary Waveform Generator connected to PC control. The local oscillator frequency is 900 MHz obtained from Digital Modulation Signal Generator (ANRITSU MG 3660A).

The identification procedure is performed in two steps : Initialization and global identification of the PA's model parameters.

A. Experimental results

Nonlinear parameters $\underline{c}_k$ are extracted from the input/output transfer function. The AM/AM and AM/PM measured characteristics are obtained by sweeping the power level of an input signal at a frequency located at the center of the PA bandwidth. In our case, we used the 3th order complex polynomial:

$$\underline{V}_{NL} = \left(\underline{c}_1 + \underline{c}_3 \cdot |\underline{V}_{in}|^2 + \underline{c}_5 \cdot |\underline{V}_{in}|^4 \right) \cdot \underline{V}_{in}$$

Thus, we define the estimated parameter complex vector:

$$\underline{\theta}_{NL} = [\, \underline{c}_1 \;\; \underline{c}_3 \;\; \underline{c}_5 \,]^T \tag{13}$$

After running a *LMS* algorithm (Eq. 11), we obtained :

$$\begin{cases} \hat{\underline{c}}_1 = 1.222 - 0.115\, j \\ \hat{\underline{c}}_3 = -0.0918 + 0.0299\, j \\ \hat{\underline{c}}_5 = 0.017\, 10^{-2} - 0.062\, 10^{-2}\, j \end{cases}$$

[1] CONTSID MATLAB TOOLBOX included the *RPM* estimation method can be downloaded from http://www.cran.uhp-nancy.fr/contsid/. The *ivrpm* function allows to obtain model estimation by iterative Instrumental Variable.

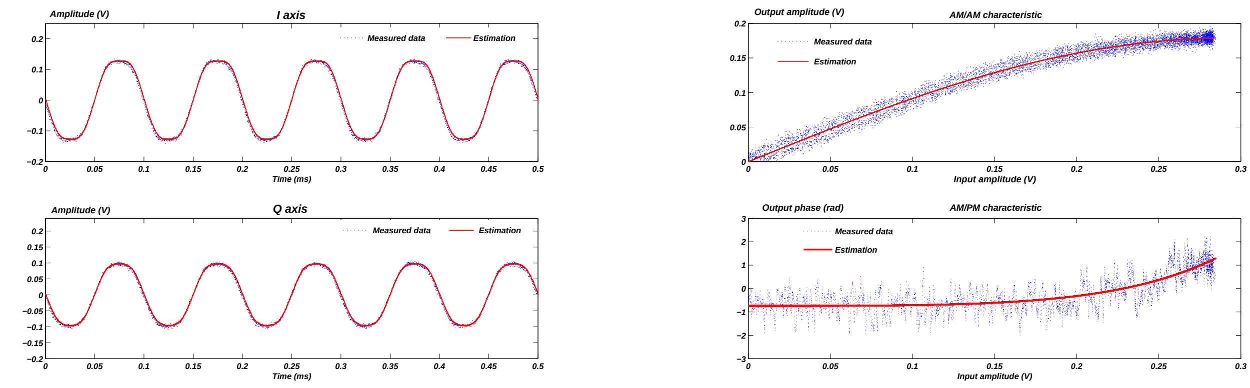


Fig. 4. (a) Comparison of time-domain measurement and estimation for sinusoïdal input (b) Comparison between the measured and estimated AM/AM and AM/PM functions

Figure (4. a) allows a comparison between measured I and Q outputs waveforms and their estimations. As can be seen, even if the amplifier is driven near saturation, the *LMS* algorithm converge to the optimum values with a maximum output estimation error less than 0.008 V.

AM/AM and AM/PM characteristics are given in figure (4. b). Thus, we can clearly see that the non linear behavioral of the amplifier is successfully described by a traditional third polynomial series.

A quadratic error comparison allows to obtain an appropriate order. Then, the 3^{rd} order filter are defined in the Laplace domain as:

$$H(s) = \frac{b_1\, s + b_0}{s^3 + a_2\, s^2 + a_1\, s + a_0} \tag{14}$$

Thus, we define the estimated parameter vector:

$$\underline{\theta}_f = [\, a_0 \;\; a_1 \;\; a_2 \;\; b_0 \;\; b_1 \,]^T$$

The *RPM* algorithm gives the parameters values:

$$\begin{cases} \underline{\hat{a}}_0 = 2.01 \cdot 10^{23} \\ \underline{\hat{a}}_1 = 6.11 \cdot 10^{23} \\ \underline{\hat{a}}_2 = 9.60 \cdot 10^{7} \\ \underline{\hat{b}}_0 = 1.51 \cdot 10^{23} \\ \underline{\hat{b}}_1 = -1.79 \cdot 10^{15} \end{cases}$$

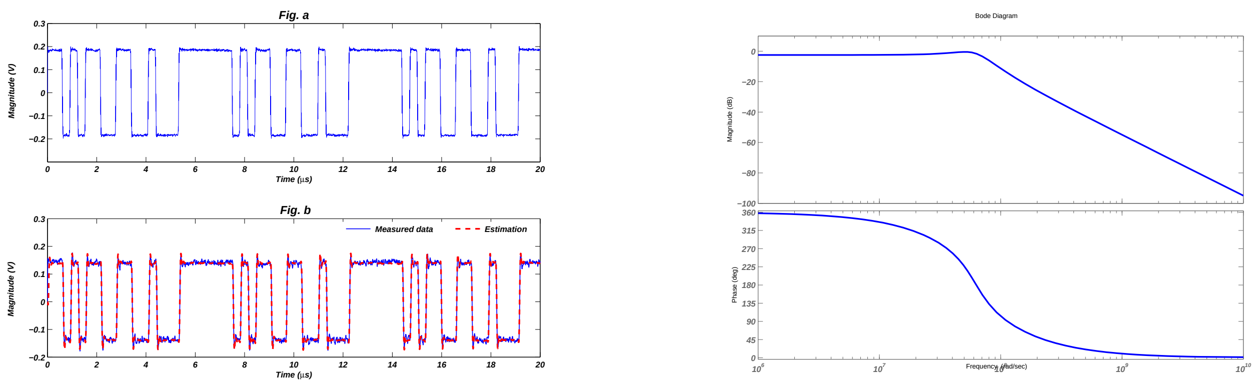


Fig. 5. (a) Comparison of time-domain measurement and estimation for binary sequence input (b) Frequency responses of the PA gain and the phase

For small power, figure (5. a) shows that the PA dynamic can be modeled as a $^{\text{rd}}$ order resonant system.

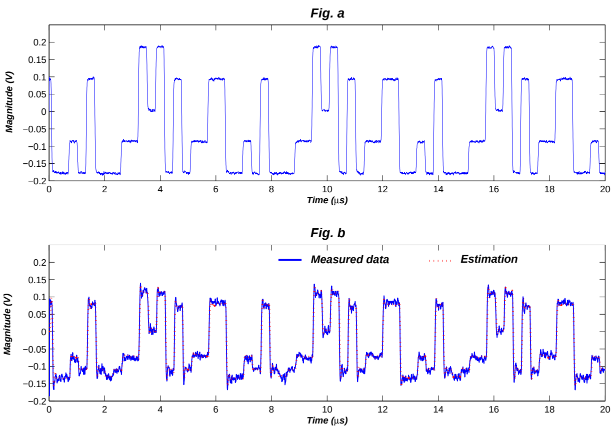
The dynamic behavioral of the PA system can be described by a MIMO filter. The filter characteristic is represented in figure (5. b) by the gain and phase curves. The resonnant frequency of the filter is around 9.8 MHz. Noted that the high order coefficients is due to the very low time-constant of the radio-communication system.

B. PA global identification :

The model parameters obtained in the previous section will be used to initialize the nonlinear identification algorithm. The unknown system in this case is the global PA model composed by both:

- non-linear complex polynomial functions.
- 3^{rd} order filter system.

The measurements are performed by an input signal obtained from the adding of some P.R.B.Sequences at different levels. The aim is to drive the amplifier in its overall level range (linear and non linear area). Figure (6) shows the input signal applied to perform global PA identification. After 8 iterations, we obtain the following parameters:



$$\underline{\hat{\theta}}_{NL} = \begin{cases} \underline{\hat{c}}_1 = 1.181 + 8.452 \cdot 10^{-3}\, j \\ \underline{\hat{c}}_3 = -0.042 - 0.023\, j \\ \underline{\hat{c}}_5 = -0.201 \cdot 10^{-2} + 0.316 \cdot 10^{-2}\, j \end{cases}$$

$$\underline{\hat{\theta}}_f = \begin{cases} \underline{\hat{a}}_0 = 2.01 \cdot 10^{23} \\ \underline{\hat{a}}_1 = 6.11 \cdot 10^{15} \\ \underline{\hat{a}}_2 = 9.65 \cdot 10^{7} \\ \underline{\hat{b}}_0 = 1.51 \cdot 10^{23} \\ \underline{\hat{b}}_1 = -1.79 \cdot 10^{15} \end{cases}$$

Fig. 6. Time-domain measurement and estimation for Multi-level binary sequence input

Model simulation with the achieved parameters exhibit good approximation of measured data (fig. 6).

C. Model validation

In this section, we validate the PA model by comparing predicted and measured outputs for different modulation schemes. As a test signal, we will use a QPSK digitally modulated signal shaped with a raised cosine filter with a *Rolloff factor* of $\alpha = 0.25$.

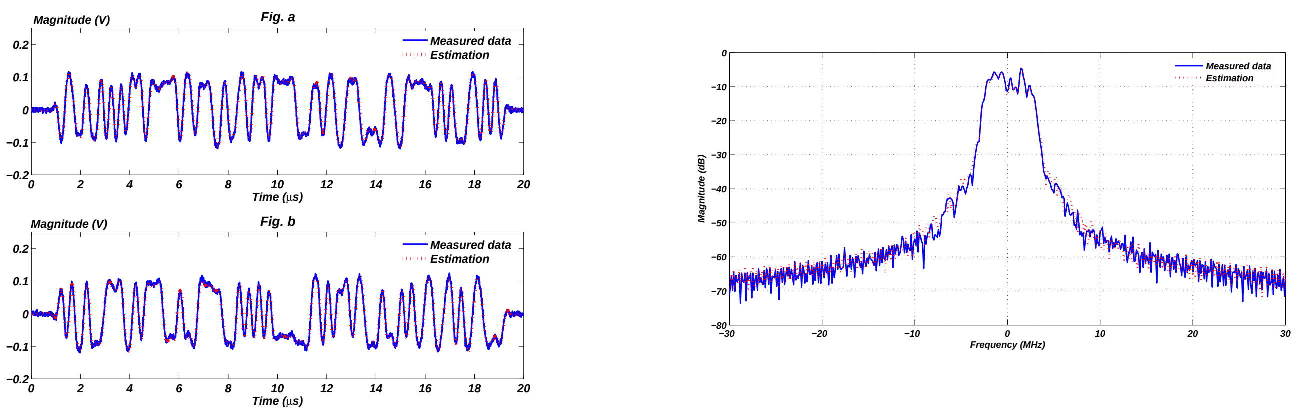


Fig. 7. (a) Time-domain measurement and estimation for QPSK modulation (b) Measured and estimated output spectrum

Figure (7.a) compare the simulated model output (dotted line) with the measured output for an excitation signal different of the one previously used for identification (solid line). It may be seen that the simulated output follows the measured one.

To validate the proposed model, figure (7.b) compares the measured and simulated output power spectral densities at specific frequencies.

V. CONCLUSION

A model based on continuous-time representation is described which offers a simple way to modeling PA dynamics. This model is able of accounting the magnitude and phase amplifier nonlinearities such as the saturation effects.
Test results illustrate the efficiency of this technique for use in off-line identification. The continuous approach was found to be accurate in predicting the dynamical response of the power amplifier. Estimation results show that the described amplifier acts like a resonant system coupled with a polynomial series.

The proposed technique is based on continuous time domain model. The model achieved can be used to develop a continuous baseband method for the compensation of nonlinearity of the RF front-end in a wireless transmitter.

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