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Modeling and identification of continuous-time system for RF amplifiers

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***Abstract*— In this paper, we present a new identification procedure for radio frequency Power Amplifier (PA) in the presence of nonlinear distortion and memory effects. The proposed procedure uses a continuous-time model where PA dynamics are modeled with a multivariable filter and a general polynomial function. Using the baseband input and output data, model parameters are obtained by an iterative identification algorithm. Finally, the proposed estimation method is tested and validated on experimental data by comparison of the quadrature IQ signals in time domain.**

I. Introduction

Numerous approaches in Power Amplifier identification area have been developed to characterize the input to output complex envelope relationship [1][2][3]. The model forms used in identification are generally classified into two methods depending on the physical knowledge of the system: discrete and continuous model.
A discrete model is a system where no physical insight and prior information available. This approach have been widely used in many research studies to predict and linearize the output of the Nonlinear PA such as neural networks and Volterra series [4][5][6][7]. However, this method suffer from the high number of parameters and the time consuming in computation. On the opposite, continuous model is a system where the mathematical representation, under some assumptions, is perfectly known. The drawback of this model is the complexity of the electrical modelling but the main advantage is that the resulting parameters have physical significance like gain conversion, damping coefficient and cut-off frequency [10].

The model considered in this paper is a Multi-Input/Multi-Output (MIMO) system described in continuous-time domain. This structure is similar to Hammerstein discrete-time model including nonlinear transfer functions and multivariable continuous filter.

Model parameters are achieved using an iterative identification algorithm based on Output Error (OE) method. This technique is based on minimization of a quadratic criterion by a Non Linear Programming (NLP) algorithm. This technique requires much more computation and do not converge to 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 [12]. Moreover, OE methods can be used to identify nonlinear systems. For these advantages, the OE methods are more appropriate in microwave systems characterization [10]. 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.

A special experimental setup dedicated to radio frequency with baseband transmission has been performed and used in order to validate this technique. Investigations exhibit good agreement and confirm the PA characterization accuracy 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 representation [1][9]. The nonlinear block presented here operates on baseband quadrature I/Q time-domain waveforms. The complex low-pass equivalent representation of the communication signal is used to avoid the high sampling rate required at the carrier frequency.

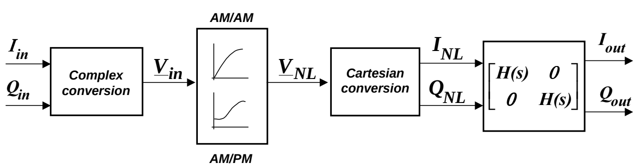

Fig. 1. Radio frequency power amplifier model

As shown in Fig. 1, the two-box model includes a memoryless nonlinearity and a Laplace filter matrix. The complex gain gives a nonlinear version $\underline{V}_{NL} = I_{NL} + j.Q_{NL}$ of the transmitted input signal $\underline{V}_{in} = I_{in} + j.Q_{in}$ according to the polynomial function composed by even terms which produces harmonic distortions inside the PA bandwidth:

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

where $\underline{c}_{2k+1}$ are the complex power series coefficients.

The dynamical model including memory effects caused by the PA may be expressed with a differential equation. As shown in Fig. 1, the input to output relationships of this n^{th} order filter can be written as:

$$\begin{cases} \frac{d^n}{dt^n} I_{out} = \sum_{k=0}^{m} b_k \frac{d^k}{dt^k} I_{NL} - \sum_{k=0}^{n-1} a_k \frac{d^k}{dt^k} I_{out} \\ \frac{d^n}{dt^n} Q_{out} = \sum_{k=0}^{m} b_k \frac{d^k}{dt^k} Q_{NL} - \sum_{k=0}^{n-1} a_k \frac{d^k}{dt^k} Q_{out} \end{cases} \tag{2}$$

where $I_{out}(t)$ and $Q_{out}(t)$ are the baseband PA outputs. The coefficients $\{a_k\}$ and $\{b_k\}$ are real scalars that define the model. The filter input-output relation can be expressed in Laplace-domain with the transfer-function $H(s)$, as so:

$$H(s) = \frac{\sum_{k=0}^{m} b_k \cdot s^k}{s^n + \sum_{k=0}^{n-1} a_k \, s^k} \tag{3}$$

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

III. Parameter identification of the PA model

A. Identification algorithm

Parameter identification is based on the definition of a model (Fig. 2). For power amplifier, we consider the previous mathematical model (Eqs. 1-3) and we define the transposed parameter vector:

$$\underline{\theta} = \left[\, a_0 \, \cdots \, a_{n-1} \;\; b_0 \, \cdots \, b_m \;\; \underline{c}_1 \, \cdots \, \underline{c}_{2P+1} \, \right]^T \tag{4}$$

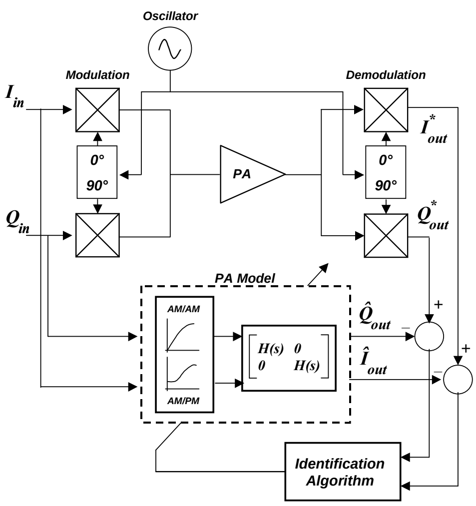

Fig. 2. PA identification scheme

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:

$$\begin{cases} \varepsilon_{I_k} = I^*_{out_k} - \hat{I}_{out_k}(\hat{\underline{\theta}}, I_{in}, Q_{in}) \\ \varepsilon_{Q_k} = Q^*_{out_k} - \hat{Q}_{out_k}(\hat{\underline{\theta}}, I_{in}, Q_{in}) \end{cases} \tag{5}$$

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 is based on minimization of a quadratic criterion defined as:

$$J = \sum_{k=1}^{K} ({\varepsilon_I}_k^2 + {\varepsilon_Q}_k^2) = \underline{\varepsilon}_I^T \, \underline{\varepsilon}_I + \underline{\varepsilon}_Q^T \, \underline{\varepsilon}_Q \tag{6}$$

We obtain the optimal values of $\underline{\theta}$ by Non Linear Programming techniques. Practically, we use Marquardt's algorithm [10] for off-line estimation:

$$\hat{\underline{\theta}}_{i+1} = \hat{\underline{\theta}}_i - \{[J''_{\theta\theta} + \lambda \cdot I]^{-1} . J''_{\theta}\}_{\hat{\underline{\theta}} = \underline{\theta}_i} \tag{7}$$

J'_{θ} and $J''_{\theta\theta}$ are respectively gradient and hessian [12] and λ is the monitoring parameter.

B. Initialization problems

An inherent problem of iterative search routines is that only convergence to a local minimum can be guaranteed. In order to converge to the global minimum, a good initial vector of parameters is important [8]. In our case, PA users have not sufficient information on parameter vector $\underline{\theta}$, especially on AM/AM and AM/PM coefficients. It is then essential to define a global strategy which makes it possible to obtain approximative initial values.
The first step consists in searching approximation of the complex parameters $\underline{c}_{2k+1}$ using the envelope magnitude and phase distortions (Eq. 1). 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:

$$\hat{\underline{\theta}}_{NL} = (\phi^H \, \phi)^{-1} \, \phi^H \, \underline{V}^*_{out} \tag{8}$$

where :

$(.)^H$ denotes transpose-conjugate transformation

$\hat{\underline{\theta}}_{NL} = [\, \underline{c}_1 \quad \underline{c}_3 \quad \cdots \quad \underline{c}_{2P+1} \,]^T$ is the vector of polynomial parameters,

$\phi = [\, \underline{\varphi}_1 \;\; \underline{\varphi}_2 \;\; \cdots \;\; \underline{\varphi}_K \,]$ is the regression matrix,

$\underline{\varphi}_k = [\, V_{in_k} \quad V_{in_k}|V_{in_k}|^2 \quad \cdots \quad V_{in_k}|V_{in_k}|^{2P} \,]^T$ is the regression vector.

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

For illustration, AM/AM and AM/PM characteristics are given in Fig. 3 for a following experimental setup (section IV). Thus, we can clearly see that the nonlinear behavioral of the amplifier is successfully described by a 5$^{\text{th}}$ polynomial series.

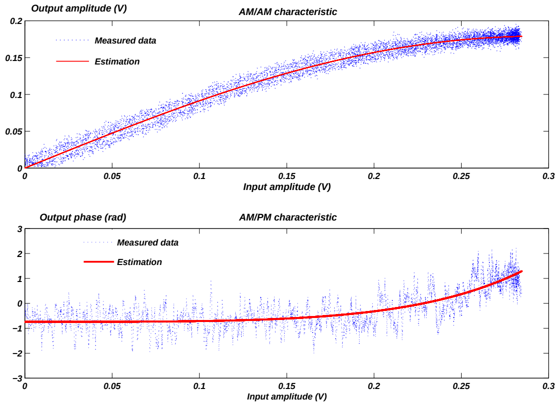

Fig. 3. Comparison between the measured and estimated AM/AM and AM/PM functions

The second step is the determination of initial values for the filter coefficients a_i and b_i. They are obtained for an input signal with low input level and large bandwidth. Parameter estimation is performed by iterative Instrumental Variable based on Reinitilized Partial Moments *RPM*[1] method (see also [10]).

IV. EXPERIMENTAL RESULTS

The measurement setup is shown in Fig. 4. The power amplifier is a commercial Class AB ZHL-42 from MINI CIRCUITS manufacturer. Input and output data are obtained from YOKOGAWA DIGITAL OSCILLOSCOPE with a sampling period equal to 10 ns.

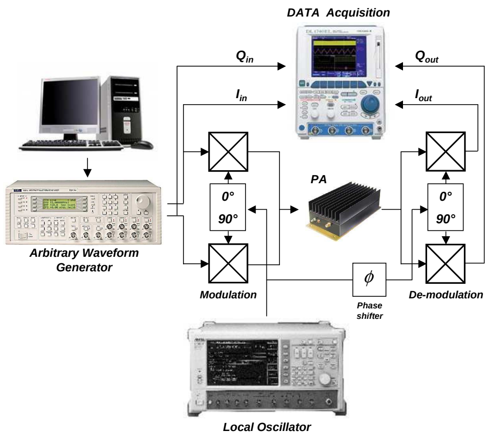

Fig. 4. PA setup

The quadrature modulator AD8349 and demodulator AD8347 are inserted at the input and output of the PA. Modulation signals I and Q are delivered by a TT*i* 40 MHz Arbitrary Waveform Generator connected to PC control. The modulation signal is a Pseudo Random Binary Sequence (P.R.B.S) processed using MATLAB MATHWORKS and downloaded to the BASEBAND WAVEFORM GENERATOR. The local oscillator frequency is 900 MHz obtained from Digital Modulation Signal Generator (ANRITSU MG 3660A).

A. Initialization results

Nonlinear parameters $\underline{c}_{2k+1}$ 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 carrier frequency located at the center of the PA bandwidth. In our case, we used the 5^{th} order complex polynomial. After running a *LMS* algorithm (Eq. 8), the following complex coefficients are achieved:

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

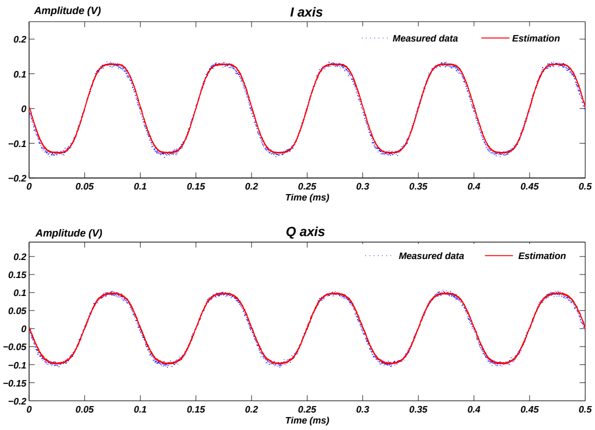

Fig. 5. Comparison of time-domain measurement and estimation

Fig. (5) 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 converges to the optimum values with a maximum output estimation error lower than 0.008 V.

The initial values of the linear filter parameters are obtained by applying a P.R.B. Sequence with small amplitude level. After optimization by a quadratic error comparison, we obtain an ideal filter composed with three poles and one zero:

$$H(s) = \frac{b_1\,s + b_0}{s^3 + a_2\,s^2 + a_1\,s + a_0} \tag{9}$$

The *RPM* algorithm gives the following parameter values:

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

[1] CONTSID MATLAB TOOLBOX including 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.

For small level power, Fig. 6 shows that the PA dynamic can be modeled as a 3^{rd} order system with the resonant frequency around 9.8 MHz.

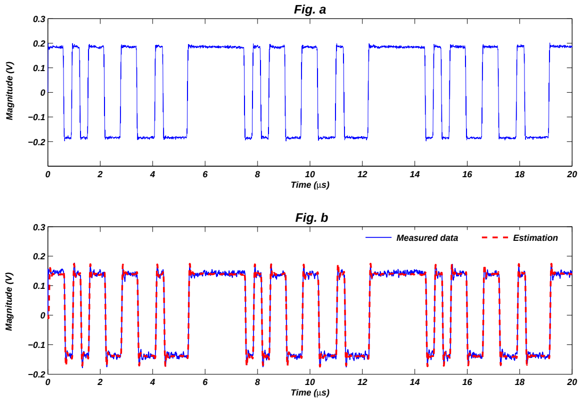

Fig. 6. (a) Input signal. (b) Comparison of time-domain measurement and estimation

B. PA global identification :

The model parameters obtained in the previous section will be used to initialize the nonlinear identification algorithm (7). The measurements are performed by an input signal obtained from addition of P.R.B.Sequences at different levels. The aim is to drive the amplifier in its overall level range (linear and non linear area). After 8 iterations, the following parameters are achieved:

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

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

Model validation is validated by comparing predicted and measured outputs for different QPSK digitally modulated signals shaped with a raised cosine filter having *Rolloff factor* of $\alpha = 0.25$.

Figures (7.a) and (7.b) 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 can be seen that the simulated output follows the measured one.

V. Conclusion

The proposed technique uses respectively wide band and high level modulation signal to characterize the dynamic and nonlinear behavior of the power amplifier. The time domain data achieved are used in nonlinear identification algorithm to establish the parameters of a continuous time domain model of the amplifier.

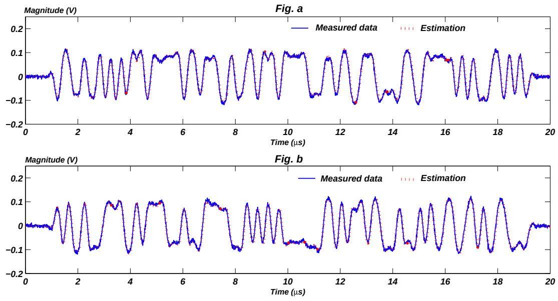

Fig. 7. Comparison of I/Q time-domain measurement and estimation for QPSK modulation

This model is able of accounting the magnitude and phase 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 method can be implemented in a baseband signal processing for real-time modeling and compensation of transmitter nonlinearity.

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