The "Smoothie" Data Base Model for the Correct Modeling of Non-Linear Distortion in FET Devices

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***Abstract*—Currently available data base model implementations fail to correctly model intermodulation products at small to medium signal power levels. In this paper we present the "Smoothie" data base model for FET devices. The model is implemented within Agilent's Advanced Design System (ADS) and is based on the smoothing splines approximation of the device Y-parameters. All four the main functions (i.e. the port currents and charges) are found by analytical integration of the Y-parameters smoothing spline approximations.**

The use of the smoothing splines approximation compared to the conventional spline interpolation reduces the influence of measurement noise and yields to well behaved continuous higher order derivatives, which are essential in the simulation of circuit linearity. By choosing a proper set of splines control parameters, the user can influence the tradeoff between closeness and smoothness of the approximation. In this work we give an overview of the capabilities of "Smoothie" and compare it to the HP Root data base model.

I. Introduction

Since the compact model development is always following device processing innovations at some distance, compact models are not quite up to date and due to their inherent approximate character, often less fit to model the level of intermodulation distortion products correctly. This is especially true when considering modern circuit applications using younger device types like LDMOS and VDMOS.

To avoid the problems, an alternative would be the use of a mixed level simulator (e.g. [1] and [2]). Although accurate, and providing additional information on the device physics, this proves to be a very time consuming and computationally expensive way to go. In practice the use of these tools quite often results in unworkable long simulation times when considering circuit linearity.

In order to facilitate circuit design while utilizing the latest device innovations, people have developed the so-called data base models. Data base models are, in general, based on stored measured device data (e.g. currents, s-parameters, etc.) at discrete points taken over the bias range of interest. During the circuit simulation, interpolation techniques are used to provide the branch currents, charges and their partial derivatives to the circuit simulator at each bias condition.

Although data interpolation may seem a trivial task, it are these algorithms which determinate the fitness of the data base model to correctly predict the amount of intermodulation at low and medium signal power levels.

In this work, we will compare our newly developed data base model "Smoothie" with the well-known HP Root model [3]. Both models have been implemented in Agilent's Advanced Design System (ADS) [4] and utilize the same set of measured data.

II. The Database Model Smoothie

The data base model Smoothie is based on the 2D smoothing spline approximation of the device Y-parameters, yielding accurate and continuous higher order derivatives for the main functions. Another beneficial effect of the use of smoothing spline approximation is the elimination of the measurement noise on the fitted data. The device Y-parameter data can be either measured or simulated using a device simulator.

A. The smoothing spline approximation

In more detail, for a one-dimensional set of n data points, we can write:

$$f(x_i) = y_i \qquad (1)$$

In 1 $[x_i, y_i]$ are the data points. The function **f** is in the form:

$$f(x) = a_n x^n + a_{n-1} x^{n-1} + ... + a_1 x + a_0 \qquad (2)$$

Equation 2 becomes difficult to use when the number of data points becomes large, resulting in a very high order for the function f(x). The spline interpolation technique solves the problem by dividing the independent variable axis in several sub-intervals, each of them containing few data points. The division is performed by the introduction of boundary points, which are called "knots". In each sub-interval an interpolating, low degree, polynomial is used which satisfies equation 2 only at the data points enclosed by the sub-interval. In this technique, additional constrains are added to guarantee the continuity and lower-order derivability at the knots.

Problems arise when considering the higher order derivatives. Not only at the boundary knots where discontinuities are present, but also between the data points, where the interpolation can exhibit an almost oscillating nature. The smoothing spline approximation technique solves for this problem by approximating the data points rather then interpolating them (Figure 1). During the approximation, the polynomials are optimized by minimizing an error function which is directly related to the higher order derivatives (Eq. 3). A successful optimization results in a much smoother function with continuous higher order derivatives.

$$\eta = \int_{x_1}^{x_n} (\frac{d^n f(x)}{dx^m})^2 \quad (3)$$

The value of η in Eq. 3 is an indication of the smoothness of the approximating function. Another important parameter is the so "smoothing factor", usually denoted as S. This parameter represents the tradeoff between smoothness and accuracy (Eq. 4).

$$\sum_{i=0}^{n-1} (w_i(y_i - f(x_i)))^2 \leq S \quad (4)$$

In Eq. 4, the coefficients wi are the so-called "weighting factors" for each data point. They can be used to make the fit more accurate or to the contrary to be more smooth for a specific region.

The advantage of the smoothing spline approximation becomes the most clear when the measured data is noisy. (Figure 1).

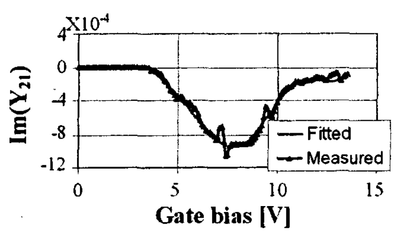

Fig. 1. Smoothing spline approximation of noisy Im(Y_{21}) data. The data is taken for a Philips LDMOS device as function of the gate voltage at f = 2.5 Ghz.

In our discussion so far, we have only considered one-dimensional data. The algorithm, however, can be easily extended for two or three-dimensional data points. In these cases, the advantages of the smoothing spline approximation technique are even more relevant.

B. The Model Implementation

In our database model implementation we have used the *Fitpck* package as provided by P. Dierckx (University of Leuven, Belgium) [5]. We have implemented the model in ADS, using the "user compiled model interface", as a two-port device model (2).

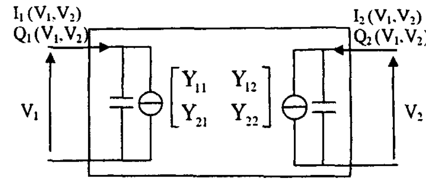

Fig. 2. Generic representation of the Smoothie model.

All four main functions (Id, Ig, Qd and Qg) depend on both port voltages (Vgs and Vds) and are found by analytical line integration of the spline approximation of the Y-parameters along the two possible integration paths shown in Fig. 3. For instance, if path 1 is used, the four main functions are calculated as:

$$I_g = \int_{V_{g0}}^{V_g} Re(Y_{11}) dV_g + \int_{V_{d0}}^{V_d} Re(Y_{12}) dV_d + I_0 \quad (5)$$

$$I_d = \int_{V_{g0}}^{V_g} Re(Y_{21}) dV_g + \int_{V_{d0}}^{V_d} Re(Y_{22}) dV_d + I_0 \quad (6)$$

$$Q_g = \int_{V_{g0}}^{V_g} \frac{Im(Y_{11})}{\omega} dV_g + \int_{V_{d0}}^{V_d} \frac{Im(Y_{12})}{\omega} dV_d \quad (7)$$

$$Q_d = \int_{V_{g0}}^{V_g} \frac{Im(Y_{21})}{\omega} dV_g + \int_{V_{d0}}^{V_d} \frac{Im(Y_{12})}{\omega} dV_d \quad (8)$$

If the integration path 2 of Fig. 3 is used, the expressions in eq. 5 - 8 slightly change.

The values V_{g0} and V_{d0} are the lower boundaries of the optimized (most accurate) region, as shown in Fig. 3. Note that in contrast to current computation, there is no need for a particular integration constant in the charge functions since only charge perturbations are relevant in circuit analysis. The upper implementation yields a very consistent relation between main functions and partial derivatives under the condition that the y-parameters are conservative [5]. In other words, the choice of the integration path between two bias points, should not affect the outcome for the main functions. Furthermore, the chosen frequency is assumed to have no influence on the results. In contrast to other data base models, also the currents in addition to the charges are found by analytical integration of the real part of the y-parameters, rather than fitting the DC current directly. The benefit of this implementation is, that it automatically yields a more accurate behavior of the higher order partial derivatives than a direct fit of the DC currents can provide[1]. By the means of control

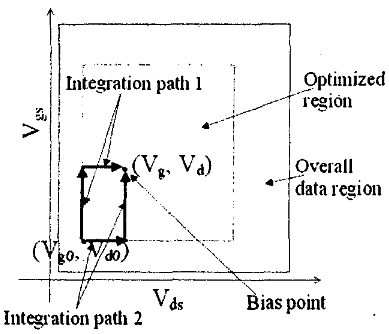

Fig. 3. Integration path used to compute the device currents and charges.

parameters the user can obtain an excellent tradeoff between the accuracy and the smoothness of the spline approximation. In addition, the user can specify an "optimized region", i.e. the region in the V_{gs}-V_{ds} plane where the fit is required to be the most accurate, as shown in Fig. 3. The fitting / initialization step for the data approximation is prior to the simulation and has to be done only once. If the result is satisfactory, the spline coefficients are stored in files that are reused in all successive simulations. This model implementation significantly reduces the overall simulation time.

III. Results

By manipulating the control parameters, the user can obtain a very good accuracy in the fit of the Y-parameters and currents. As an example, Fig. 4 compares the original and approximated trans-conductance and drain current of a 1mm gate-width LDMOS device. The original data has been obtained from MEDICI [7] simulations.

IV. Comparison of Models

As mentioned before, the advantages of Smoothie become clear when we focus on the behavior of the higher-order derivatives. These higher order derivatives are of major importance since they determinate if the model is fit to correctly model the intermodulation distortion products. For this purpose we have computed (using numerical differentiation within ADS) the higher order derivatives of Smoothie

[1]In [6] a combination of DC data and y-parameters is used in order to handle thermal and trap time constants but this approach will be less accurate for the higher order derivatives.

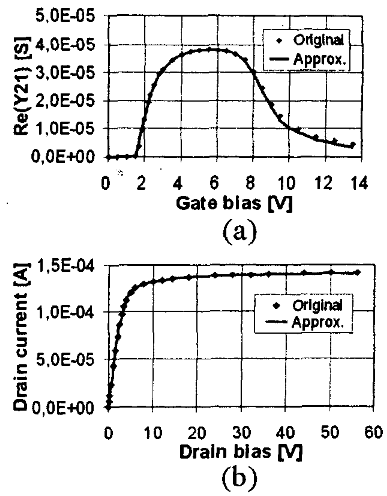

Fig. 4. Comparison of the original (Simulated using MEDICI) and "Smoothie" approximated trans-conductance (a) and drain current (b) of an experimental LDMOS device.

and the HP Root model. Both models use the same data set in their approximation / interpolation. Fig. 5 shows the Taylor coefficients as function of gate voltage at a fixed drain voltage in the saturation region.

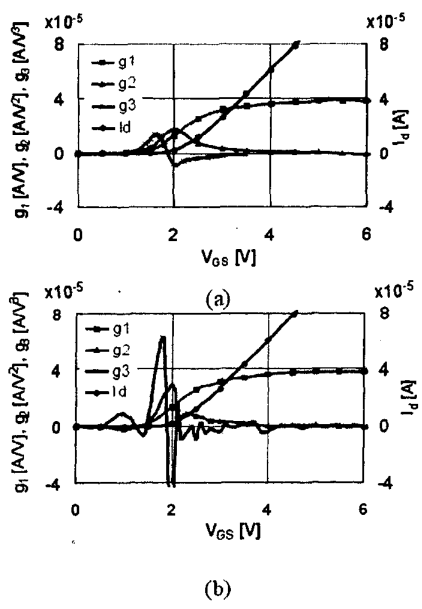

Fig. 5. Drain current and its first 3 Taylor coefficients as provided by Smoothie (a) and by HP Root model (b).

The continuous higher order derivatives of Smoothie facilitate the reliable simulation of third order intermodulation (IM3) distortion products at low and medium input power levels. Fig. 6a reveals the typical behavior of constant OIP3 contours in the output $I_d(V_d)$ plane for an LDMOS device. Fig. 6b shows the results of the same simulation when using the HP Root model. The result is less clear and does not follow the physical behavior of a LDMOS device.

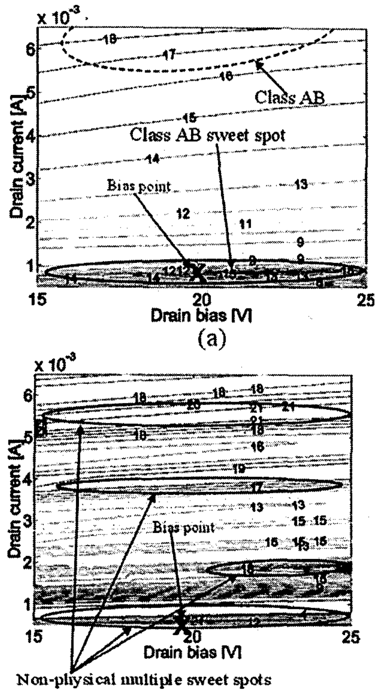

Fig. 6. Constant OIP3 contour plot in the Id(Vd) plane as produced by Smoothie (a) and by HP Root model (b). The markers (X) indicate the bias conditions used for the results in Fig. 7. The plots refer to a 200mm device with a input tone power of -15 dBm.

Using the insights provided by Fig. 6a, it is possible to choose a proper bias condition for optimum device linearity in class AB operation. In practical applications the IM3 versus power is an important measure for the amplifier performance. When we perform this simulation using the previously selected bias point, Smoothie provides well-behaved IM3 as function of the input tone power, which is shown in Fig. 7. Using HP Root model, problems occur at low and medium power levels. Currently, model verification with experimental LDMOS data is in progress.

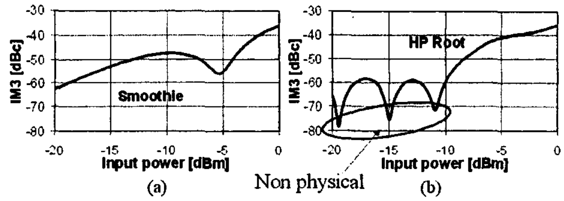

Fig. 7. Two tone third order intermodulation products (IM3) in dBc versus the input power as provided by the Smoothie model (b) and the HP Root model (b). The markers (X) in Fig. 6 indicate the DC bias conditions for this simulation.

V. Conclusions

In this work we have presented a new flexible data base model, named "Smoothie", for FET devices. The model is based on the smoothing spline approximations of the device Y-parameters. The main functions (i.e. the currents and the charges) are obtained by the analytical integration of the spline approximation of the device Y parameters. The model is implemented within ADS. The use of the smoothing splines reduces the influence of measurement noise and leads to continuous higher order derivatives. The latter aspect is a major advantage of Smoothie over other data base model implementations and facilitates the correct prediction of intermodulation distortion at low to medium signal power levels.

VI. Acknowledgements

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