Validation of the High-Order Polynomial Models Used in Behavioral-Level Simulation

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Abstract – **Behavioral-level simulation techniques are very popular at the present time for the system-level simulation of RF and microwave communication systems. Appropriate models of nonlinear transfer characteristics of active (nonlinear) stages are required for the simulation. This paper begins with a brief discussion of such models. Their validation using measured data as well as harmonic balance (HB) simulation data are presented in detail. The discrete technique implemented in MathCAD was used for the simulation.**

Keywords - **Behavioral-level simulation, polynomial models, transfer characteristic.**

I. Introduction

Behavioral-level simulation techniques are widely used at the present time for simulation of RF and microwave communication systems [1-6]. They have a number of apparent advantages as compared with conventional circuit-level techniques or system-level semi-analytical analysis: an entire communication system can be modeled taking into account nonlinear effects, real-world signals can be used for the simulation, not only a single-tome stimuli (for instance, digitally modulated signals used in mobile communication systems), standard system parameters (power spectrum regrowth, error vector magnitude, adjacent channel power ratio) can be simulated in a reasonable time.

System-level models are used for transmitter and receiver stages during the simulation, which are presented by input-output transfer characteristics. Since nonlinear elements are usually modeled in the time domain, appropriate amplitude and instantaneous transfer characteristic models should be used. Amplitude (or envelope) transfer characteristic is the output fundamental tone amplitude as a function of input tone level (AM-AM); instantaneous transfer characteristic is the instantaneous output voltage as a function of instantaneous input voltage (valid for memoryless nonlinearity).

Simulation over wide frequency range requires for the instantaneous transfer characteristic and the use of the fast Fourier transform [5,6]. The use of high-order polynomial models has an advantage over other models in that it allows one to control the spectrum expansion (due to nonlinear signal transformation) and to avoid in this way the spectrum aliasing for any input signal [5,6].

It should be pointed out that we need polynomial models valid over an interval rather than at a small neighborhood of a point. So, we need to use curve fitting rather than the Taylor series expansion. The only difference between curve fitting and our approach is an approximation criterion: we need to maximize the accuracy of final simulation results rather than the approximation accuracy (note that the best approximation doesn't guarantee the best simulation accuracy).

Several methods can be used for the synthesis of polynomial models [8-11]. Here we consider two of them:

(1) synthesis of polynomial models using an analytical closed-form model and an interpolating polynomial [8, 10],
(2) synthesis of polynomial models using narrow-band measured data (amplitude-to-amplitude (AM-AM) and amplitude-to-phase (AM-PM) characteristics) and the integral equation technique [9, 12].

II. Polynomial models for behavioral-Level Simulation

The main idea of the 1st method is to use an intermediate analytical closed-form model for the instantaneous transfer characteristic. The synthesis process consists of 2 main steps:

1) an intermediate analytical model is chosen and its parameters are adjusted to fit the measured or circuit-level simulated AM-AM characteristic, or, alternatively, these parameters are calculated using some theoretical models [13],

2) interpolating polynomial is built using the intermediate model [8].

The "arctagent" intermediate model is used in this paper:

$$u_{out} = U_{st} \cdot \frac{2}{\pi} \cdot arctg\left(\frac{\pi}{2} u / U_{st,in}\right) , \qquad (1)$$

where U_{st} – output saturation level, $U_{st,in}$ – input saturation level, $U_{st,in} = U_{st}/k$, k – gain, u_{out} – output voltage, u – input voltage.

This approach allows one to use only few input parameters. Thus, the technique can be used at early design phase, when there is no detailed system data. We should note, however, that the model accuracy depends substantially on the parameters values (thus, they should be adjusted carefully) and, in general, this accuracy is worse than for the second method.

The second method consists of 3 main steps (we consider here only AM-AM characteristic, AM-PM one can be obtained in a similar way):

1) AM-AM characteristic is measured using a network analyzer in power sweep mode (spectrum analyzer or narrowband voltmeter may also be used),

2) instantaneous transfer characteristic is calculated using the measured data and the integral equation technique [9, 12, 17],

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3) polynomial model is built for the instantaneous characteristic.

Since we can not measure the instanteneous transfer characteristic (instanteneous voltage at the output versus instanteneous voltage at the input) but only envelope one (fundamental tone amplitude at the output versus the input amplitude), we have to calculate the instanteneous characteristic using the integral equation approach,

$$\frac{2}{\pi}\int_0^{\pi} v(u\cos(\varphi))\cos(\varphi)d\varphi = U_{env}(u) \qquad (2)$$

where u – is the input one-tone signal amplitude, $U_{env}(u)$ – is the envelope transfer characteristic, $v(u)$ – is the instanteneous transfer characteristic.

Note that eq. (2) gives us possibility to determine only the odd part of $v(u)$ and, consequentely, we can model only odd-order nonlinear products. In order to model even-order products, we need to measure (or simulate) second harmonic transfer characteristic (second harmonic ($2f_0$) voltage at the output versus input signal amplitude) and to use the following intergral equation:

$$\frac{2}{\pi}\int_0^{\pi} v(u\cos(\varphi))\cos(2\varphi)d\varphi = U_{env2}(u) \qquad (3)$$

where $U_{env2}(u)$ – is the 2nd harmonic envelope transfer characteristic (note that this equation allows one to determine only the even part of the instanteneous transfer characteristic). Thus, the complete instanteneous transfer characteristic is

$$v(u) = v_{odd}(u) + v_{even}(u) \qquad (4)$$

where v_{odd} and v_{even} are determined by eqs. (2) and (3) correspondingly.

In general, accuracy of this method is much better than the first one because an intermediate model is excluded and all the measured data are used during the polynomial synthesis.

In the present work, we used a slight modification of this technique, which allows to avoid numerical solution of the integral equations:

1) input-output amplitude (envelope) transfer characteristics of first and second-order are measured using a narrowband voltmeter and were simulated using a harmonic balance technique,

2) further, they are approximated by the Chebyshev polynomial series [11]:

$$U_{env}(u) = \sum_{i=0}^{n} a_{2\cdot i+1} T_{2\cdot i+1}(u), \qquad U_{env2}(u) = \sum_{i=0}^{n} a_{2\cdot i} T_{2\cdot i}(u) \qquad (5)$$

where a_i – are expansion coefficients, T_i – are the Chebyshev polynomials of the firs kind;

3) power series expansion coefficients b_i

$$U_{env}(u) = \sum_{i=0}^{n} b_{2\cdot i+1} u^{2i+1}, \qquad U_{env2}(u) = \sum_{i=0}^{n} b_{2\cdot i} u^{2i} \qquad (6)$$

are calculated using the Chebyshev expansion coefficients a_i by the well-known technique [14];

4) power series expansion coefficients c_i of the instanteneous transfer characteristic,

$$v(u) = \sum_{i=0}^{2n+1} c_i u^i \qquad (7)$$

are calculated using the expansion coefficients b_i of amplitude transfer characteristic,

$$c_{2\cdot i+1} = b_{2\cdot i+1} \cdot \frac{2^{2\cdot i}}{C^{i}_{2\cdot i+1}}, \quad c_{2\cdot i} = b_{2\cdot i} \cdot \frac{2^{2\cdot i-1}}{C^{i-1}_{2\cdot i}}, \qquad (8)$$

where C^i_j – are the binomial expansion coefficients. We should note that Bessel function expansion can also be used in this way.

III. Validation of the Models

In order to validate the polynomial models described above, amplitude characteristics and higher-order intermodulation products (IMP) have been measured for 4 amplifiers: 1) single-stage bipolar transistor amplifier, 2) single-stage field-effect transistor amplifier, 3) operational amplifier, 4) multi-stage microwave amplifier, and have been simulated by the harmonic balance (HB) technique [15] for a single stage microwave amplifier. A narrow-band voltmeter was used for IMP measurements.

The measured data were used for the synthesis of the polynomial models. First, 15-order model was built using method (1), and secondly, 21-order model was built using method (2). Then these models were used for the simulation and the simulation results (IMPs) were compared to the measured data. Error in IMP prediction for the first model is about 3 to 10 dB for 3rd order IMP, and up to 10 to 30 dB for 9-11 orders. Error in IMP prediction for the second model is about 1 to 4 dB for 3rd order IMP, and up to 10 to 20 dB for 9-11 order IMP. Fig.1 gives an example of simulated and measured IMPs at the amplifier output using the discrete technique and the models described.

On the second stage, a single-stage transistor microwave amplifier was simulated using the harmonic balance technique (circuit-level simulation). The simulated data were used for the synthesis of the polynomial models. Then behavioral-level simulation was carried out using these models and the results (IMP levels) were compared to the HB simulation data. Method b) was used for the synthesis of the 31th order polynomial model. The results (see Fig. 3and 4) are similar to the previous ones: error in IMP prediction is about 1 to 10 dB for 3rd and 5th orders, and about 10 to 30 dB for 7th and 9th

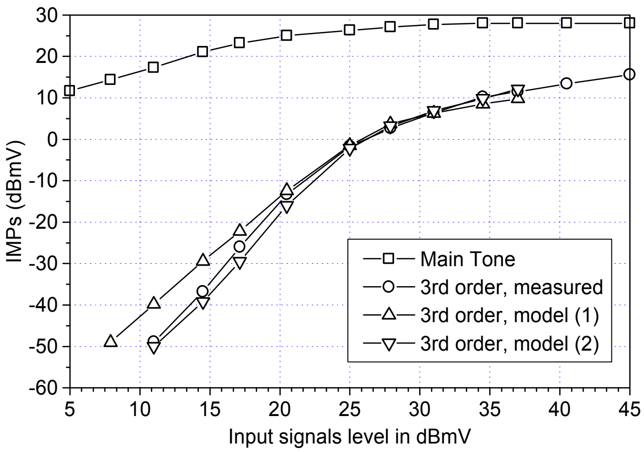

Figure1. Main tone and 3rd order IMP (calculated using the polynomial models (1) and (2) and measured) versus input level.

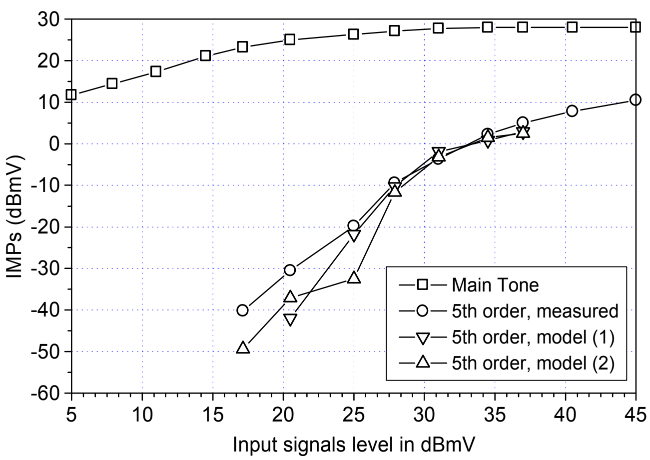

Figure2. Main tone and 5th order IMP (calculated using the polynomial models (1) and (2) and measured) versus input level.

orders (see Fig.2). The accuracy of even-order IMP prediction is worse than that of odd-order.

We should note that the computational time for the HB technique is several orders higher than for the discrete technique using the proposed models. HB simulation time increases also very substantially (exponentially) when the number of input tones increases and the discrete technique simulation time does not depend on the number of input tones (so, the time difference would be more large for larger number of input tones). Note also that the behavioral-level simulation works quite well over wide dynamic range (160 dB approximately).

Some discrepancy between the discrete technique simulation using the polynomial model (2) and the HB technique simulation can be attributed to the bias decoupling network effect [16], which we have not taken into account in the present consideration.

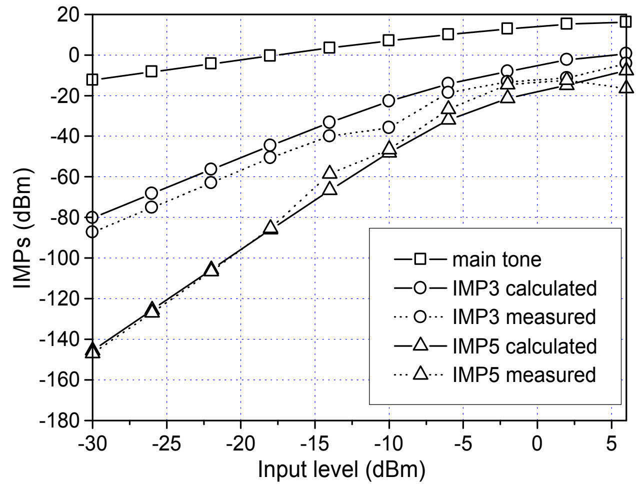

Figure3. 3rd and 5th order IMPs calculated by the harmonic balance (HB) technique and by the discrete technique using the polynomial model (2).

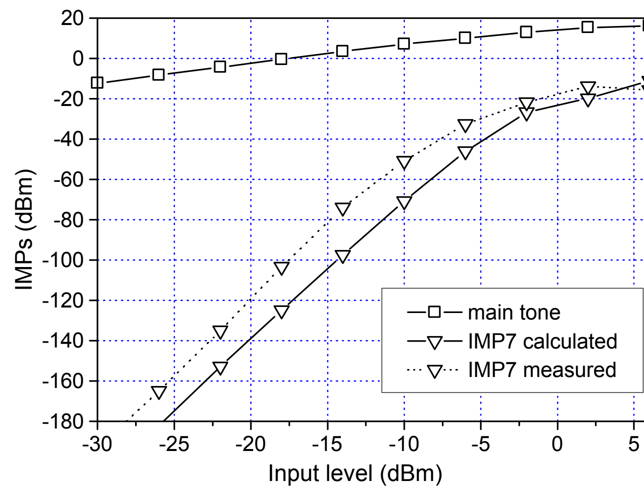

Figure 4. 7th order IMPs calculated by the harmonic balance (HB) technique and by the discrete technique using the polynomial model (2).

We should also point out that the accuracy of amplitude characteristic measurement is of great importance: small errors in the measurements may lead to large errors in simulation results. Thus, these characteristics should be measured as accurately as possible. Sometimes, time-averaging option may lead to more accurate results (since it allows to filter out measurement noise for small levels). Special care must be taken to exclude the influence of measurement setup nonlinearities (IMPs of generators during two-tone measurements, spectrum analyzer nonlinearity etc.) on the results.

In order to simulate a circuit accurately over wide frequency range, the circuit frequency response (usually, it is the frequency response of matching networks) must be measured and taken into account during simulation. Usually, the measured frequency response includes both the input matching network response and the output matching network response and we can not separate one from the other (we need these frequency responses in separate). The best solution in this case is to consider them to be equal.

IV. CONCLUSION

In this paper, we have studied two methods of the polynomial models synthesis: using an intermediate analytical model, and using a numerical procedure for the calculation of instantaneous transfer characteristic from the measured data. First method allows one to use few input parameters (suitable for early design phase). But the accuracy in nonlinear product prediction is not very nigh. The use of higher-order polynomials doesn't lead to accuracy increase due to the limited accuracy of the intermediate model. Besides, the simulation accuracy depends substantially on the intermediate model parameters, which should be adjusted carefully.

The second method is more complicated, but it is also more accurate. The simulation accuracy can be increased by increase in the measurement accuracy (and also in the number of measured points), and in the polynomial order. Besides, this method allows us to simulate even-order nonlinear products, which are very important for broadband systems, and for the simulation of bias decoupling network effect.

Some further work is desirable in order to improve models' accuracy, in particular, to take into account the bias decoupling network effect. More advanced forms of approximation technique can also be used to improve accuracy [18].

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