AWR®
Nonlinear Modeling
White Paper

Malcolm Edwards
AWR Corporation
malcolm@awrcorp.com

AWR'S SUPPORT OF POLYHARMONIC DISTORTION AND NONLINEAR BEHAVIORAL MODELS

Linear and nonlinear device models are the building blocks of most RF and microwave designs. S-parameters are often used to represent linear devices. As a "black-box" model, they can easily be obtained using a vector network analyzer and distributed for simulation. S-parameters use superposition to equate the linear relationship between incident and reflected waves at all of the device's ports. Nonlinear devices, however, distort waveforms such that their behavior cannot be represented through superposition or S-parameters.

Historically, nonlinear devices have been represented in simulation by compact empirical or analytical SPICE models that operate in the time domain. Today's high-frequency circuit simulators analyze the linear portions of the network in the frequency domain and the nonlinear components in the time domain, resolving the two through an iterative technique called harmonic balance.

The process of developing a compact model, be it empirical or analytical, is costly, time consuming, and potentially exposes the device maker's intellectual property. More importantly, since most compact model parameters are extracted from linear 50 ohm S-parameters and DC IV (static and pulsed) data, their ability to predict behavior under extreme nonlinear conditions or non-50 ohm terminations may be questionable. The cost of model development is not trivial, and the resulting quality and availability varies among integrated device manufacturers.

This situation presents the high-frequency circuit designer with a bit of a dilemma. Fortunately, recent developments in measurement and modeling technology have focused on technology-independent, measurement-based black box models. This white paper examines the different nonlinear models and measurement systems available today and how they can be used with Microwave Office®, a leading high-frequency design environment from AWR Corporation.

CHARACTERIZING NONLINEAR DEVICES

Nonlinear models are most often used to describe the behavior of transistors, including the large-signal regime where power amplifiers and mixers operate. Large-signal computer models for devices are continually evolving in order to keep up with changes in semiconductor technology. To attempt standardization of model parameters used in different simulators, an industry working group of semiconductor vendor companies and EDA vendor companies called the Compact Model Council (CMC), has been formed to choose, maintain, and promote the use of standard models. An elusive goal in such modeling is prediction of next-generation circuit performance and the identification of technical direction for developing models capable of such predictions.

This requires the selection of operating conditions that define the nonlinear characteristics of devices, the nonlinear equations that replicate this behavior, and extraction of the parameters to be used in these model equations. An obvious alternative to using standard or evolving compact models to address the next-generation of devices would be to simply use the measured data directly, as is the case for S-parameters and linear devices.

This is the thought behind expanding the linear S-parameters into a more general form that could relay nonlinear behavior. Such a model would be a departure from a table of scalable parameters to be used by the compact model's intrinsic nonlinear equations, in favor of a data set that is directly based on the measured device behavior to a given stimulus and a set of terminal impedances. This measurement-based black-box model is the concept behind the current breed of commercial offerings known as Agilent Technologies' *X-parameters®, NMDG's S-functions, and the Mesuro Cardiff model. X-parameters and S-functions are the extension of the polyharmonic distortion modeling approach developed by Verspecht et al. They relate the spectra found at a device's terminals for a given set of stimuli and termination impedances. The Cardiff model, developed by Tasker et al., is a similar table-based model that relates IV waveform data at a device's terminals for a given stimuli and set of load/source impedances.

THE OPENWAVE FORUM

These evolving measurement-based nonlinear models and the measurement techniques required to extract them represent nearly 20 years of research and development among various commercial and academic organizations. Test and measurement vendors are all offering systems targeting microwave frequency nonlinear characterization systems. The Tektronix system is based on a sampling oscilloscope approach. The other vendors use nonlinear vector network analyzer techniques. Anritsu, Rohde & Schwarz, and Tektronix have partnered with various specialized technologists (HFE, NMDG and Mesuro) to develop their commercial nonlinear measurement and measurement-based model technologies. Together with AWR, these companies have formed the OpenWave Forum (OWF), an alliance to collaborate, create, and promote a unified and transparent data exchange format for large-signal simulations, measurements and models.

The benefits of the OpenWave Forum are:

- Provide the industry with a broader choice of vendors by offering a standard data format common to all tools, vendors, and solutions
- Reduce IP theft risk by providing flexible, non-proprietary data standards
- Offer greater accuracy by supplying device performance for simulation under exact operating conditions

This initiative supports AWR's open and flexible software architecture, which provides design automation across vendor tools. The AWR approach helps users maximize their productivity by enabling them to choose the best tool for each part of the design process. Similar to AWR's EM Socket™ Interface, which enables integration of its products with the industry's best EM tools, the OpenWave Forum will enable users to work with the test and measurement equipment vendor of their choice.

NONLINEAR BEHAVIOR

A periodic signal (CW or modulated) can be represented in the time or frequency domain. When such a signal drives a device into its nonlinear region, the shape of the IV waveform is distorted in such a way that it cannot be described simply by applying a scaling factor to the input signal. In the frequency domain, this behavior can be represented by changes to the harmonic and inter-modulation spectral components as functions of the changing stimuli and terminal impedances. The importance of having the nonlinear model replicate this behavior for each particular stimuli and terminal impedances cannot be understated.

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*X-parameter is a registered trademark of Agilent Technologies, Inc.

The polyharmonic distortion modeling approach is based on frequency-domain measurements and is identified from the responses of a device under test (DUT) stimulated by a set of harmonically related discrete tones, where the fundamental tone is dominant and the harmonically related tones are relatively small. Because the harmonically related tones are relatively small, the principle of harmonic superposition may be accurately applied. This principle asserts that the magnitude of the small test signals is such that the perturbation can be viewed as a linear process. This is analogous to mixer theory, whereby only the LO signal is large enough to bring a nonlinear device into a time-dependent linear operating mode when the injected small signal tones undergo multiplication in the time domain, i.e. frequency shifting. The general mixing equation is

$$\omega_{mix} = \pm N * \omega_{lo} \pm M * \omega_{rf} \qquad (1)$$

becomes…

$$\omega_{mix} = \pm N * \omega_{lo} \pm \omega_{rf} \qquad (2)$$

when the mixing process is limited to being linear.

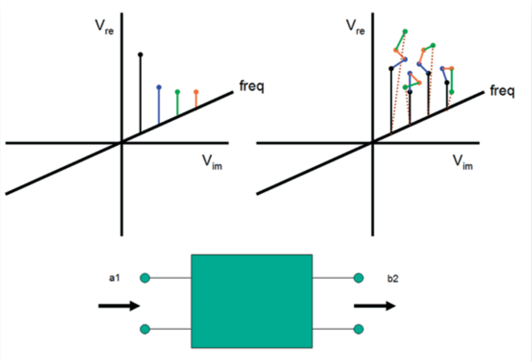


Figure 1. Graphical representation of the harmonic superposition principle utilized by PHD models.

The harmonic superposition principle is represented graphically in Figure 1. The fundamental tone that drives the DUT into a nonlinear operating mode is represented by the black tone. At the output port one can see the generated harmonic components (all black). The first small-signal test signal, a second harmonic tone (blue), is injected into port one, and this results in the perturbation of the four tones. The next small-signal test signal, the third harmonic (green), is injected into port one, and again this results in the perturbation of the four tones. This process continues until all harmonics and ports have been accounted for.

The DUT is connected to a large-signal network analyzer (LSNA) instrument, and a model is automatically extracted, accurately describing all aspects of nonlinear behavior, such as amplitude and phase of harmonics, compression characteristics, AM-PM, spectral re-growth, amplitude-dependent input, and output match. A real benefit of the approach is that it provides much more than figures of merit such as Psat, two tone third order intercept etc. The PHD model can be used in a computer-aided design (CAD) environment to consistently describe many different nonlinear characteristics and in the design and optimization of circuits utilizing the nonlinear device.

Commercial implementations of the PHD model include S-functions and X-parameters. They have been grouped together because they share the same genesis and, broadly speaking, target the same devices and subsystems. The two approaches currently have some major differences, which may become less pronounced in the future as these disparate techniques mature and converge.

S-FUNCTIONS

S-functions are an extension of S-parameters for nonlinear components, offering a simpler way to accelerate a system design process using nonlinear components by providing more complete system-level models. S-functions are able to predict harmonic and modulation behavior of nonlinear devices under different mismatch conditions. As with S-parameters, S-functions can be cascaded to predict nonlinear behavior of circuits and systems.

S-functions are easily determined with the modeling option of the NMDG VNAPlus extension kits. These kits extend various commercially available network analyzers (Agilent and

Rohde & Schwarz) using additional hardware and software to characterize nonlinear behavior. The characterization is done in the frequency domain (and can be converted into the time domain) under real life conditions for any terminal impedance by way of load/source-pull. Microwave Office can import this behavioral model to directly design larger circuits using the measured data or to provide more detailed data sheets.

THE CARDIFF MODEL

Unlike polyharmonic distortion approaches, which capture the amplitude and phase information of a DUT's spectral response, the Cardiff measurement system and associated model obtains the incident and reflected time domain current/voltage waveforms at the ports of the DUT. The test set-up is similar to a vector network analyzer but uses a sampling oscilloscope rather than harmonic mixing or sampling in the time domain. The resulting model uses four table-based nonlinear functions representing the corrected device currents and voltages to represent device behavior for a given input stimulus, bias, and terminating impedance. The system can employ single or multiple-tone large-signal measurements, including harmonic load-pull.

By controlling the load terminations at all harmonic frequencies while being able to view the voltage/current waveforms at the device's current-generating plane (in real-time), the engineer is able to shape the waveform to match the theoretical values that will produce optimum results. The resulting behavioral model, obtained under the load conditions that yielded optimum performance, can be extracted and invoked within Microwave Office. As a result, modeling and design engineers can fully characterize their devices or power-amplifiers for any signal level and impedance environment. For the same set of environmental conditions (power drive, bias and terminating impedance), such a model should be a more accurate representation of the device behavior compared to a (compact) model extracted outside of these operating parameters.

In their paper, "Highly Efficient Operation Modes in GaN Power Transistors Delivering Upwards of 81% Efficiency and 12W Output Power," Wright, Heikh, Roff, Tasker and Benedikt demonstrated how waveform engineering was used to optimize an inverse class-F power amplifier in order to achieve drain efficiencies above 81%, 12W output power at 0.9, and 2.1GHz using a wide band-gap gallium nitride (GaN) high electron mobility transistor (HEMT), as shown in Figure 2. Such capability allows engineers to understand the performance their device is capable of with the right matching networks. To design these networks or cascade devices into multi-stage amplifiers, a simulation environment is required. We now look at how Microwave Office works with these new classes of models.

The Cardiff Model is incorporated into a Microwave Office simulation using a netlist-based component (Figure 3) that is linked to the Cardiff current/voltage data table by means of the Microwave Data Interchange Format or MDIF file (Figure 4).

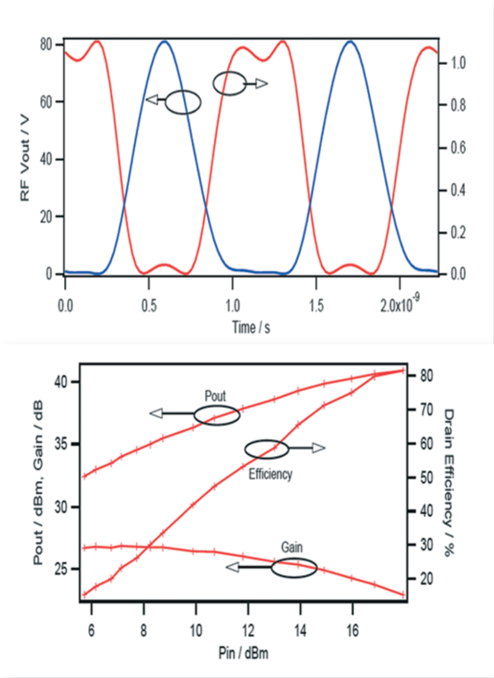


Figure 2. Current/Voltage waveforms at the device plane and resulting RF performance (Pout, Gain, PAE).

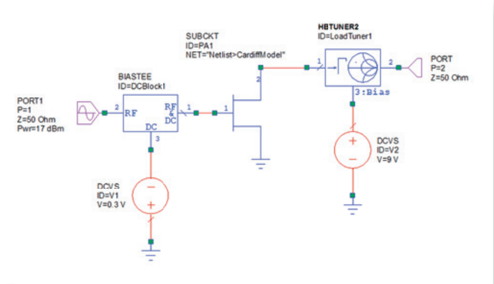
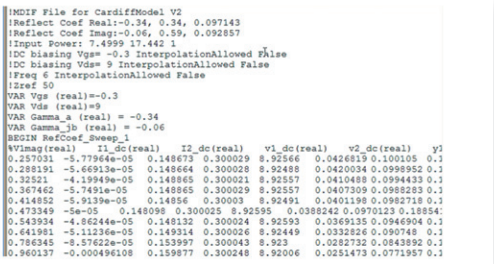


Figure 3. The Cardiff model with load pull elements in Microwave Office.



```
!MDIF File for CardiffModel V2
!Reflect Coef Real:-0.34, 0.34, 0.097143
!Reflect Coef Imag:-0.06, 0.59, 0.092857
!Input Power: 7.4999 17.442 1
!DC biasing Vgs= -0.3 InterpolationAllowed False
!DC biasing Vds= 9 InterpolationAllowed False
!Freq 6 InterpolationAllowed False
!Zref 50
VAR Vgs (real)=-0.3
VAR Vds (real)=9
VAR Gamma_a (real) = -0.34
VAR Gamma_jb (real) = -0.06
BEGIN RefCoef_Sweep_1
%V1mag(real)   I1_dc(real)    I2_dc(real)    v1_dc(real)    v2_dc(real)    y1
0.257031  -5.77964e-05   0.148673  0.300029  8.92566   0.0426819 0.100105  0.1
0.288191  -5.66913e-05   0.148664  0.300028  8.92488   0.0420034 0.0998952 0.1
0.32521   -4.19949e-05   0.148865  0.300021  8.92557   0.0410488 0.0994433 0.1
0.367462  -5.7491e-05    0.148865  0.300029  8.92557   0.0407309 0.0988283 0.1
0.414852  -5.9139e-05    0.14856   0.30003   8.92491   0.0401198 0.0982718 0.1
0.473349  -5e-05    0.148098  0.300025  8.92595   0.0388242 0.0970123 0.18854
0.543934  -4.86244e-05   0.148132  0.300024  8.92593   0.0369135 0.0946904 0.1
0.641981  -5.11236e-05   0.149314  0.300026  8.92449   0.0332826 0.090748  0.1
0.786345  -8.57622e-05   0.153997  0.300043  8.923     0.0282732 0.0843892 0.1
0.960137  -0.000496108   0.159877  0.300248  8.92006   0.0251473 0.0771957 0.1
```

Figure 4. Sample data inside an MDIF file containing the Cardiff model I/V data.

EXPLANATION OF HB TECHNIQUES

All high frequency simulators today use the harmonic balance (HB) algorithm to solve nonlinear networks. The HB algorithm splits the circuit/system into two sub-circuits, a linear sub-circuit and a nonlinear sub-circuit. The user selects the fundamental simulation frequency (otherwise known as input tone) which is a primary setting of the HB algorithm along with number of harmonic tones required for accurate representation of the nonlinear distortion. For a single tone HB solver only single frequency analyses such as pin/pout, power added efficiency (PAE), or gain compression are performed. With two tones available, the analyses can include the inter-modulation distortion (two tone) of an amplifier or perhaps mixer conversion loss with one tone used for the LO and the second for the RF. With three tones available, two tone inter-modulation distortion of a mixer can then be explored.

With the number of tones defined (along with some other HB settings of less importance to this description), the HB solver splits the circuit into two sub-groups, linear and nonlinear, and proposes a set of voltages at the interface of these subgroups. These voltages are defined in the frequency domain and of course reflect the magnitude of the user-defined voltage and current sources in the circuit description. For the linear section, the currents at the interface are simply obtained from a linear circuit solution. With the nonlinear sub-group, the voltages are transferred to the time domain and applied to the nonlinear models. The resultant currents are then transformed back to the frequency domain. Lastly, a comparison is made between the linear and nonlinear currents in the frequency domain at the linear/nonlinear interface. If the error is less than the user-specified amount, the task is complete and the data is stored. If the simulation is to be conducted over a frequency range, then the sources are appropriately updated and the algorithm is repeated until the frequency set is exhausted. The data is then sent to some graphics display to define the measurement traces.

USING A X-PARAMETER AND/OR S-FUNCTION MODEL

The nonlinear distortion is reflected in the model and the types of waveforms needed for model extraction and subsequent simulation. Because this approach maps spectral tones onto other spectral tones, simulators need general purpose elements to model these spectral relationships. This technique is typically applied for modeling microwave amplifiers with narrowband input signals. The narrowband constraint is not on the device itself, but on the input signal. It is perfectly possible, for example, to describe the distortion of a narrowband input signal for a wide range of carrier frequencies.

AWR offers model components that map spectral tone to spectral tone via equations. These frequency-domain-defined (FDD) devices are accessed through a netlist component that reads an MDIF file containing the spectral response information, as well as the operating conditions (power levels, bias, load impedances). This component internally supports interpolation of data sets. By definition this model is inherently steady state, used by the HB circuit solvers to support discrete harmonic tones and not general or arbitrary waveforms. This limitation is circumvented by coupling the HB solver with either circuit envelope or complex envelope solvers when more complex drive waveforms are needed for error vector magnitude (EVM) and adjacent channel power ratio (ACPR) analyses.

When a nonlinear element uses the FDD model, the transformation of data between frequency and time and vice versa has been obviated. This is a huge advantage in simulation run times and memory requirements. However, the FDD component is only cognizant of tones that have been declared explicitly in the MDIF file and by the user in the HB simulation. The HB algorithm analyzes the network based on the fundamental frequency and number of harmonics specified by the user. HB solvers also recognize the effects of inter-modulation; that is the interaction between predefined tones listed in the tone table. Note: the user defines the primary tones (F1, F2 … Fn), their maximum order of the tones created by the inter-modulation process.

MULTI-TONE INTER-MODULATION ANALYSIS

To keep the problem tractable, truncation of the inter-modulation frequency set is needed to limit the number of tones used to solve the HB algorithm. All this is accomplished by the user in the simulator settings window. In the current implementations of the nonlinear behavioral models being discussed, there is no explicit support for a multi-tone FDD description in the inter-modulation sense. This means that there is no direct way to investigate multiple tones around the main drive tone. However, there are other indirect methods that can be used to investigate inter-modulation.

These indirect methods are complex envelope or circuit envelope solvers, which in themselves imply certain assumptions. Both methods, complex envelope and circuit envelope, make use of the AM-AM and AM-PM information in the model and both assume that spectral widening is such that inter-modulation effects are narrow band centered about the carrier. In terms of what these models deliver, this is not perceived as a limitation that prevents their adoption. All models have limitations. These are all first-generation models and the work being conducted for their measurement, data extraction, support in simulations, and application scope is ongoing.

Currently all parties involved in PHD models (measurement, extraction, and simulation) are investigating additions to the modeling process to support inter-modulation within a steady-state solver without the need to invoke the complex envelope and circuit envelope solvers. Work is also being conducted on capturing memory effects, and several different approaches are being investigated.

CONCLUSION

Microwave Office is capable of simulating measurement-based, extracted nonlinear models just as well as any of the non-linear behavioral model varieties currently available. The model data, which is stored in an MDIF file format, is referenced through a netlist-based component directly within MWO. Spectral based models such as PHDs are addressed as frequency-domain devices in the simulator using spectral mapping. These model types eliminate the need to solve the nonlinear devices in the time domain, eliminating the need to harmonically balance the linear and nonlinear branches of the simulation network. Although not all nonlinear device measurements will incorporate load-pull data, all of these measurement-based models are fully capable of representing it to the simulator. This is a critical feature to ensure accuracy and to support efforts to optimize performance through the design of the external circuitry surrounding the DUT.

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AWR, 1960 East Grand Avenue, Suite 430, El Segundo, CA 90245, USA
Tel: +1 (310) 726-3000   Fax: +1 (310) 726-3005   www.awrcorp.com