ON THE USE OF THE AUXILIARY GENERATOR TECHNIQUE TO IMPROVE NONLINEAR MICROWAVE CIRCUIT ANALYSIS AND DESIGN

José Luis Flores, Almudena Suárez
joseluis@muwavetech.com, almudena.suarez@unican.es

We present a simulation technique which is very easily implemented in AWRDE Microwave Office and can help Harmonic Balance to converge to a new set of stationary solutions, which may be present in a real circuit but do not show up during normal simulations due to intrinsic limitations of the frequency domain methods such as the Harmonic Balance algorithm. We discuss non convergence problems with Harmonic Balance and likely causes for differences between simulated and measured results. We give some basic insights into the different approaches of the time domain and frequency domain analysis tools.

It is not unusual, when testing a circuit in the laboratory, to observe some behaviour that was not obtained in simulation and which may seem strange and difficult -even impossible- to reproduce with the circuit simulator; it is the case with unwanted oscillations, sub-harmonics, hysteresis, discontinuities and memory effects associated with frequency or power sweeps. In such cases we may distrust our simulations, the nonlinear models, or even the prototype circuit. While these causes can be responsible for significant differences between simulation and measurements, there is an additional explanation which is inherent in the intrinsic nature of the nonlinear systems. It is important to understand these processes in order to prevent undesired phenomena from appearing in a circuit. Let's take a look at the two basic approaches to nonlinear circuit simulation.

Frequency or Time Domain analysis?

Every circuit containing inductors, capacitors or transmission line elements is described by differential equations. When non linear elements are also present, the resulting differential equation is non linear and does not have an explicit solution; it then must be solved through numerical integration methods in time domain. Numerical integration always converges to a unique solution for a given initial condition, (provided there are not numerical integration errors caused by a poor time resolution, or bandwidth limited device models). But long transients need usually be simulated before reaching the stationary regime. Frequency domain methods, on the other hand, converge directly to stationary solutions, but they may not be unique, even after setting up specific initial conditions.

It is natural and not strange, for a nonlinear circuit to have more than one stationary solution corresponding to the same set of input parameters. Some of these solutions have no physical existence and will not be observable in practice; they are just mathematical solutions to the set of Non Linear Ordinary Differential Equations describing the circuit function. But some other solutions can be physically observable and coexist; showing up one or the other depending on the previous value of the circuit's state variables, such as node voltages and branch currents; they show up with hysteresis.

There are four basic types of stationary solutions to nonlinear circuits: Continuous (DC), Periodic (fundamental + harmonics), Quasi-Periodic (two or more independent frequencies plus their harmonics and mixing products) or Chaotic (continuous wideband spectrum, non periodic).

There is no reason to assume that a nonlinear system shall have a periodic response to a periodic excitation; this is true for forced circuits such as amplifier, mixer, injected oscillator or frequency divider/multiplier. The same applies when there is no excitation at all; for example in autonomous free running oscillators.

Harmonic Balance -HB- is the preferred analysis method for these types of circuit, as it is powerful and straightforward to use for finding stationary solutions. But it is important to understand that it only converges for solutions containing the frequencies of the signal generators present in the circuit description, plus their harmonics, and this makes it difficult finding more elaborate responses that may exist (containing other wanted or unwanted frequencies). In addition, the signal generators lead to circuit solutions which always have mathematical existence, and HB will converge to them even though they might be unstable (not physically observable). Please note that we are always referring to the stability of the solutions and not of the circuits. As an example, an oscillating amplifier is a nonlinear circuit in which the oscillatory solution is stable and the amplified input signal is unstable. A well designed oscillator has an unstable DC output and a stable oscillation. Unstable solutions do not withstand the natural fluctuations produced by the noise sources present in real circuits, as opposed to stable (robust) solutions which continuously recover from small signal perturbations [1]. Harmonic Balance is insensitive to the stability of a mathematical solution so it can converge to observable as well as non observable solutions, depending on which one is the easiest to find.

Because the signal generators included in the circuit description (schematic) impose the type of response to which HB will converge; the easiest solution for a free running oscillator is DC (as it contains no signal generators), and an amplifier will always show a periodic output of the same fundamental frequency as the input generator's. In a mixer, HB will find solutions containing the input frequencies (f_{in} and f_{LO}) plus their products ($m \cdot f_{in} \pm n \cdot f_{LO}$). These are the solutions that we can expect from an analysis with HB, but in practice other solutions are sometimes observed, like input level induced oscillations in power amplifiers, sub-harmonics or even chaos. They may show up in any nonlinear active circuit, and it is worth knowing how to reproduce them in simulation, in order to make them unstable (if they are unwanted) or to guarantee their stability (if they are the wanted solution).

The HB algorithm is a frequency domain method; it basically solves for the *Kirchoff*'s laws in a circuit, creating a set of nonlinear equations and imposing an initial value to the harmonics of the node voltages or branch currents based on the input or internal generators available in the circuit description. That initial value is usually not a solution to the set of equations and it results an error voltage (or current) associated to it. A *Newton-Raphson* convergence method is then applied to minimize that error vector by optimizing the amplitude and phase of the initial solution harmonics, but <u>not</u> their frequency! Thus in no way we can reproduce an oscillation from an autonomous circuit (without input signal generators) or sub-harmonic and non-harmonically related frequencies from the output of an amplifier. No fundamental frequency will show up from an HB analysis which is not present in the internal or external signal generators used in the non linear circuit's description. In order to explore other solutions from a nonlinear system we need to add external elements to the circuit description in the schematic window; one example is the OSCAPROBE element, used in oscillator analysis, of which the Auxiliary Generator described hereafter is a more versatile version.

Time domain integration methods do not presume any particular type of solution and can robustly converge to any physically observable signal, including cases with stationary chaos. But time domain integration is not always practical for tuned circuits because transients can be very long, particularly in high-Q circuits. Also the amount of time samples required can be very high when low and high frequency signals coexist in the simulation, as we need to integrate over a sufficient time to observe the stationary regime of the lowest frequencies. This leads to very long and complex simulations; also convergence problems may arise in the integration method, associated to the distributed elements models.

A very common phenomenon observed in non linear circuits is hysteresis or memory effects in their response; an oscillation may show up or not for a same value of the VCO control voltage, depending on its sweep direction. Or different output power levels may be observed for the same input power to an amplifier, depending on the previous P_{in} value. This behaviour is not well reproduced by time domain integration methods, as they always start at $t=0$ and keep no memory from the previous state, unless it is imposed by the designer as an initial condition.

On the other hand, frequency domain's Harmonic Balance, when properly used can converge to stationary solutions of the DC, Periodic or Quasi-Periodic type, but can not predict stationary Chaos nor give any assurance about the stability (physical existence) of the converged solutions. When exploring the stability of a solution, large signal stability analysis techniques need to be used to complement the HB simulations.

Harmonic Balance is best suited for the optimization of non linear tuned circuits, but a time domain integration simulator (transient), when applicable, can be very useful to extract information about the stability of the wanted solution. Both simulation techniques are complementary in non linear microwave circuit design.

The Auxiliary Generator Technique

By introducing properly chosen probes into a nonlinear circuit, autonomous and synchronization (phase-locked) regimes can be evaluated. This technique, known as the Auxiliary Generator (AG), was first used in [2], and further improved in [3-5]. It is currently applied to the analysis of Periodic and Quasi-Periodic stationary solutions in nonlinear microwave circuits [6].

A probe is an independent voltage source added to the circuit and connected to one of its nodes. This probe can be set to a new frequency (to search for autonomous oscillations inside the circuit) or to the same frequency as the input, or a subharmonic of it, in order to search for synchronous solutions. It is a single tone source, so to prevent short circuiting higher harmonics at the node to which it is connected; an ideal filter is inserted between the voltage source and the circuit node, so that the source is disconnected from the node at every frequency, except its fundamental. If the frequency and complex voltage imposed by the Auxiliary Generator, at the connecting node, are equal to the fundamental spectral line of an existing solution, no current will flow between the node and source, and this is equivalent to the source being disconnected from the circuit. Usually the nodes close to device nonlinearities are good connection points because of their sensitivity [7], but there is no need to access the intrinsic elements in a model.

In order to perform an optimization on the frequency f_{AG} and complex voltage V_{AG} of the Auxiliary Generator, we must impose a non perturbation condition, which is expressed as:

$$\text{(1)} \qquad \mathrm{Y}_S = \frac{I_{AG}}{V_{AG}} = 0 + j \cdot 0$$

By means of the Auxiliary Generator, it is possible for the HB algorithm to converge to a solution containing the new f_{AG} frequency. The probe variables, such as amplitude, phase, or frequency, are optimized to satisfy the non perturbation equation. One of these variables can always be fixed in advance according to the regime to be simulated. Including the node voltage in the denominator of (1) prevents HB from converging towards the trivial solution $V_{AG} = 0$.

The OSCAPROBE element, available in AWRDE to simulate free running oscillators, works on a similar manner; the phase is fixed (the phase reference is undefined in an autonomous circuit) and the amplitude and frequency of the first harmonic are optimized.

But the Auxiliary Generator allows for a greater flexibility as any one of its parameters can be fixed while the two other are optimized. It is also possible to fix some or all of the three AG parameters to a desired solution, and optimize any other circuit parameter or component value. Having access to the three AG parameters (Voltage, Frequency and Phase) makes possible the optimization of circuits in order to produce desired solutions; such as damping unwanted oscillations, increasing the locking bandwidth in synchronized regimes, or fixing a particular free running frequency.

Discontinuities or *jumps* in a response can sometimes be observed when performing a parametric sweep (in frequency, power, control voltage, a component value ...), regardless of how fine we set the sweep step. With the aid of an Auxiliary Generator we may find solution points that are hidden by normal HB sweeps, because they belong to sections of infinite slope in their curve. When arriving at a point of infinite slope, the simulator jumps and converges to a different point. Jumps are also observed in physical circuits, when there are sections in a curve that belong to unstable (non observable) solutions. In such cases, more than one solution usually exists for the same parameter value; some are stable and others are not. Sometimes only one solution is stable, but there can also be two observable solutions, and depending on the sweep direction, one or the other will show up, leading to the well known hysteresis phenomena. The hysteresis is associated with multivalued curves and points of infinite slope, as the ones we will see in the next example.

It may also happen that a solution splits in two at a given point in a sweep. This is known as a *bifurcation.* Bifurcation points mark the border between different behaviours of the nonlinear system, such as synchronization between oscillators, generation of subharmonics or the apparition and interruption of a Voltage Controlled Oscillation.

The Van der Pol oscillator

As a practical example to show the powerfulness of the simulations with Auxiliary Generators we will simulate a forced *Van der Pol* oscillator; this simple topology (see Fig.1) contains the basic elements found in any non linear tuned circuit: a resonance, a non linearity and a signal source. The non linear conductance is of cubic order and shows negative values at low voltage amplitudes, $i(v) = -0.03 \cdot v + 0.01 \cdot v^3$. The parallel resonator has the element values L = 1 nH, C = 9 pF and R = 100 Ω. The paralleled structure is fed by an independent current source whose equivalent admittance is included in R, together with the resonator loss conductance.

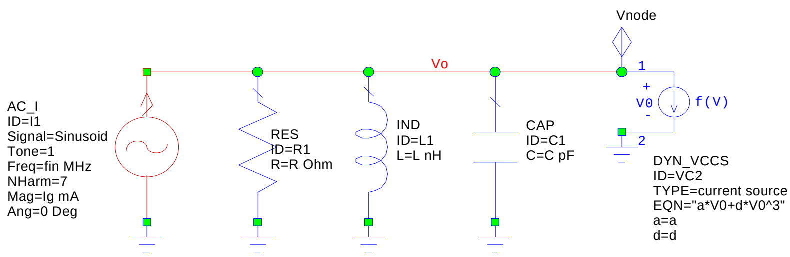

Fig.1. Forced non linear circuit; the Van der Pol oscillator

This structure represents no lose of generality for our purposes and thanks to its simplicity it is rapidly simulated in Time Domain. We use Aplac Transient. Its results will be compared with the predictions of Harmonic Balance and Aplac-HB simulators to evaluate the benefits of introducing non perturbing elements, such as the OSCAPROBE and the Auxiliary Generator, in the Frequency Domain analysis.

Time Domain Integration Analysis (Aplac Trans)

Interesting phenomena are observed for different values of the current generator's frequency and amplitude in the forced *Van der Pol* oscillator. In Fig.2 we observe that, for 5 mA amplitude of the input current, two different voltage waveforms are obtained depending on the input frequency. But the left side waveform can not be expanded as a harmonic series on f_{in}. Another frequency is involved. Where does it come from? The time domain integration performed by Aplac Transient has converged towards a quasi-periodic solution known as Self Oscillating Mixer (SOM) mode.

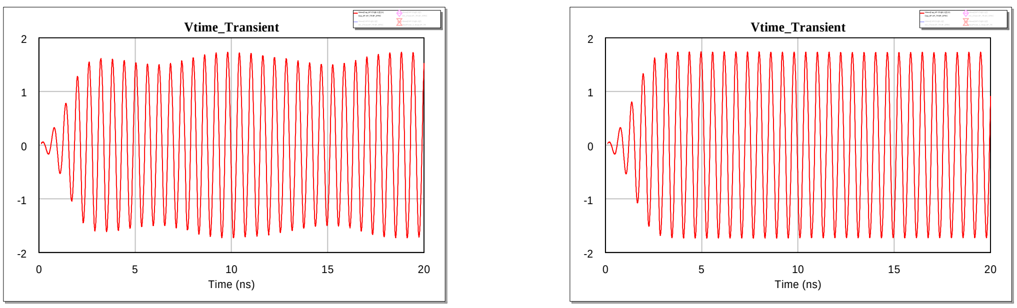

Fig.2. Time domain solutions for Ig = 5 mA with fin = 1550 MHz (left) and fin = 1650 MHz (right)

Self Oscillating Mixer modes are produced because an internal autonomous oscillation f_a has started and mixes with the input signal f_{in}. This autonomous oscillation is originated by the LC resonator and the negative conductance in Fig.1, and although its frequency is generally affected by the input current amplitude and frequency, both f_{in} and f_a are, in general, not harmonically related or non-commensurate.

In the circuit of Fig.1, when the input frequency f_{in} approaches the circuit's resonance, synchronization occurs and the solution becomes periodic (right side waveform in Fig.2). The voltage waveform contains only f_{in} and its harmonics. The frequency range in which synchronization takes place depends on the input generator's amplitude; it is wider for high I_g values, and narrower for lower current values.

When the input frequency is higher than the circuit's resonance, but close to one of its harmonics, synchronization can also take place in the form $f_{in} = N \cdot f_a$. In that case the subharmonic $f_a = f_{in}/N$ is observed in the periodic solution; this is the working principle of the Analog Frequency Dividers.

Frequency Domain Analysis

The Frequency Domain solutions of the circuit in Fig.1 are very different from the Time Domain results in Fig.2. Using the Harmonic Balance and the Aplac-HB simulators we have plotted the first harmonic voltage amplitudes in the frequency range 1.5-1.85 GHz, and for three different input current levels of 5, 10 and 15 mA as shown in Fig.3.

We observe that the solutions with Ig=5 mA at 1550 MHz and 1650 MHz have much lower amplitudes than those simulated in Time Domain (Fig.2). Also both simulators differ in the solution corresponding to Ig=15 mA, and there are two discontinuities in the HB curve (blue diamond), which still persist even after increasing the frequency resolution (Fig.4).

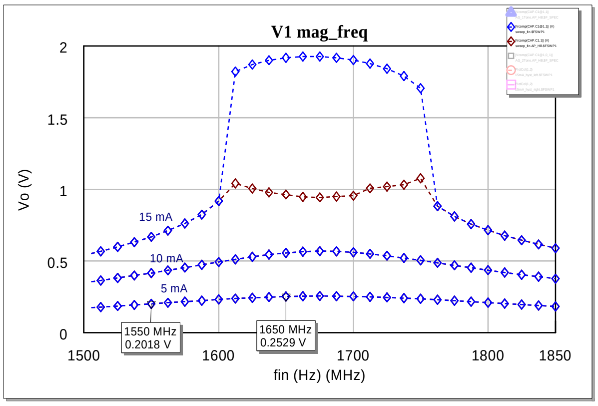

Fig.3. Frequency domain simulations at different input current levels using Harmonic Balance (blue) and Aplac-HB (brown). Different results are observed from both simulators at Ig=15 mA and a discontinuity appears in the HB solution. Frequency step size is 12.5 MHz and the current source is set with NHarm = 15.

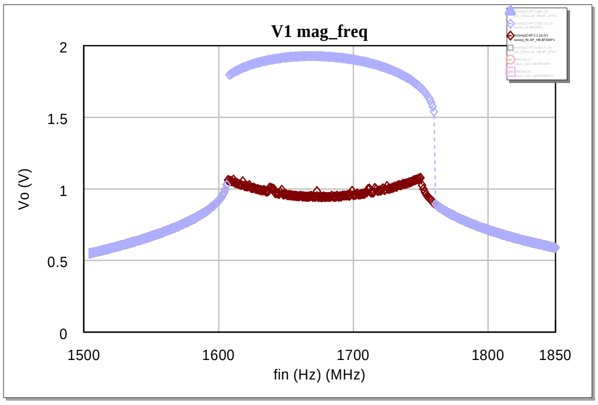

Fig.4. Repetition of the frequency domain simulations in Fig.3 for the case Ig = 15 mA with a frequency step size of 1 MHz. Discontinuity persists.

Let us explain the previous results. First, the solutions with Ig=5 mA have much lower amplitudes than those simulated in Time Domain because they represent the voltage developed by the low level input current across the equivalent impedance seen at V_o. The higher amplitude autonomous oscillations observed in Time Domain have not shown up here.

Second, the different results obtained with HB and Aplac-HB simulators over the frequency range 1610 – 1760 MHz do not reflect the natural behaviour of physical systems for which, the response to an input excitation must be unique and only depend on initial conditions. Also, the response to the continuous variation of a parameter must be continuous too.

Why then we are observing such results? Is there a problem with the simulators or the circuit? The answer is no. In this example, HB and Aplac-HB are showing different faces of a more complex reality; Results in Fig.3 and Fig.4 are a subset of the many possible solutions for this nonlinear circuit, showing a periodic output of the same fundamental frequency as the input source. We shall perform new HB simulations with the aid of an Auxiliary Generator.

Implementing the Auxiliary Generator in AWRDE

The Auxiliary Generator (AG) can be implemented with the Aplac frequency-dependent impedance element **Zblock_AP**. For use in Harmonic Balance simulations (with "Aplac HB"), this element is defined as

TONE = N H1 X1 ... HN XN

where N is the number of harmonics H1 to HN at which the impedances X1 to XN are specified. X_i can be real or complex (re, im).

In single tone HB analysis, H_i is an integer multiple of the fundamental frequency f1. Whereas in multi-tone HB, H_i is a vector [m,n] or [m,n,k] for 2-Tone and 3-Tone HB analysis respectively.

Zblock_AP can be seen as the parallel connection of X_i impedances, each having its value at only the exact frequency $f = m \cdot f_1 + n \cdot f_2 + k \cdot f_3$, and being infinite at any other frequency. This element is thus an open circuit at frequencies other than those specified by the tones H1 ... HN.

For the Auxiliary Generator configuration we choose N=1 and $X_1 = 0$, as shown in Fig.5. A NCONN element that we have named "Vnode" is used here for the connection of the AG to the circuit. Its use is optional, but as NCONN elements with a same name in a schematic represent the same circuit node, they are very useful to keep the schematic simple.

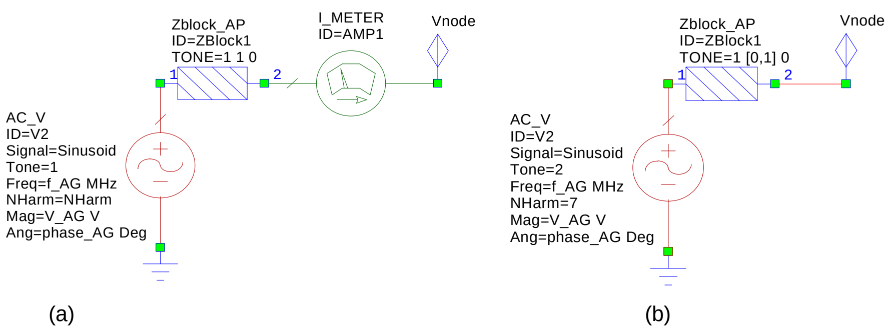

Fig.5. Two implementations of the Auxiliary Generator: (a) Single tone HB analysis with f_AG = f1 (fundamental), and (b) Two tone HB analysis with f_AG = f2 (second tone). The I_METER is an optional element as the admittance can also be simulated using the Large Signal Admittance (Ycomp) measurement in AWRDE.

Frequency Domain Analysis with Auxiliary Generator

a) Periodic solutions

There are no jumps in nature. Nevertheless, jumps can be observed in simulation as well as during a real test. When such thing happens we are confronted to a response with *multivalued sections,* showing more than one output for the same input value. These sections comprise stable and unstable solutions, and also contain points of infinite slope, which can not be solved by the Newton-Raphson convergence algorithm used by Harmonic Balance.

With the aid of an Auxiliary Generator we can overcome this convergence problem by implementing a technique known as *parameter switching*. In the case of Fig.4, we can sweep the voltage of the AG source and solve for its frequency and phase, thus transforming the very high or infinite slopes of the voltage vs. frequency curves, into very low or zero slopes of the frequency vs. voltage curves, easily solved by HB. By applying the non-perturbing condition (1) during an optimization with HB we have obtained the red circled curve in Fig.6.

Of the three parameters defining a single tone signal; Amplitude, Frequency and Phase, any of three can be set to sweep, leaving free the two others for an optimization with Aplac-HB. By sweeping the phase it is equally possible to solve for the multivalued sections of the curve, like the square-pink section of Fig.6. We observe that its bottom side differs slightly from the frequency sweep results obtained without an AG (brown diamonds). This difference is due to numerical errors in both simulations as the error function (Cost) for these points was much higher than in the rest of the curve. The most likely cause is that those points are not a solution. Sometimes, during an optimization, Harmonic Balance may converge close to a solution without reaching it; in this case the convergence error is high.

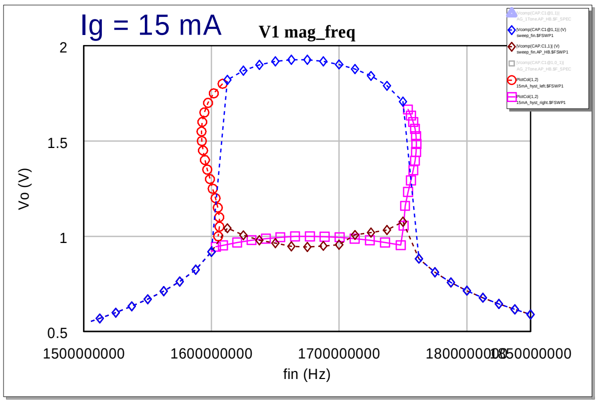

Fig.6. Voltage sweep (red circles) and Phase sweep (pink squares) performed with the aid of an auxiliary generator to find solutions in non converged sections of a curve. Each point is calculated by optimizing for |Ys| < 1e-7 with Simplex Optimizer and a maximum of 100 iterations.

One aspect to keep in mind when using the Auxiliary Generator technique is that it requires an interpretation of the convergence Error or Cost after each optimization; Values lower than 10E-10 or 10E-11 are adequate, while values of the order of 1E-8 or higher correspond to a bad convergence. The Cost is an internal function defined in AWRDE and may vary slightly from one optimizer to the other (see AWR documentation for this subject). Not to be confused with the optimization Goal which, in our example, is the maximum value permitted to $|Y_S|$ in order to verify the non-perturbing condition.

Phase sweeps are also performed to explore new solutions which may be hidden –not shown- after a frequency sweep with Harmonic Balance. It is the case with *synchronization curves* that are typical solutions in forced non linear systems, like *injected oscillators*. This injection mechanism may be wanted (coupled oscillators, frequency dividers, self-oscillating mixers) or unwanted, as is the case with odd mode oscillations in power amplifiers and other non linear instabilities.

A *synchronization curve* represents the locus of the solutions for which an internal oscillation develops and locks to the input signal, for all the possible phase shifts between them. The input signal comes from an independent source, and the synchronization may take place with the fundamental or any harmonic of the internal oscillation. Connecting an Auxiliary Generator at a given node and imposing $f_{AG} = f_{in}$, allowed us to sweep the phase difference between these two signals, and leave free for optimization the variables f_{in} and V_{AG}. By doing this we have reproduced the *synchronization curves* (red) in Fig.7.

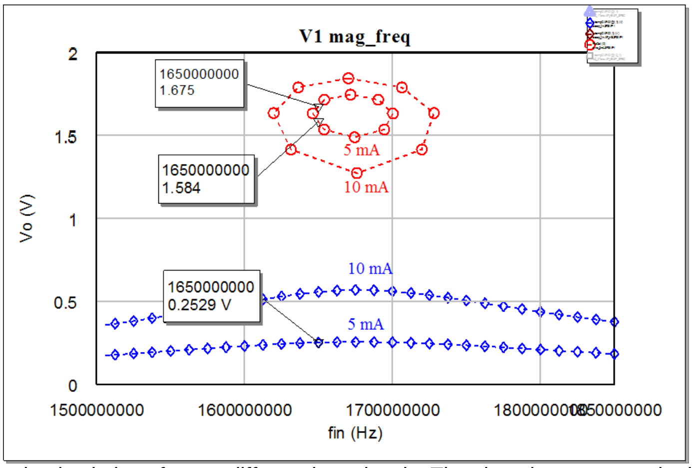

Fig.7. Synchronized solutions for two different input levels. The closed curves are obtained with an auxiliary generator, setting $f_a = f_{in}$. Three different solutions are obtained for Ig=5 mA and f_{in}=1650 MHz. Multi-valued sections are those with several outputs for the same input.

We observe multi-valued sections, with more than one voltage amplitude corresponding to the same input frequency; not more than one can have physical existence. From the time domain analysis in Fig.2 we deduce that 1.675V must be the stable solution at 1650 MHz. In forced circuits with greater complexity, when time domain integration is no longer viable, small signal perturbation analysis is usually applied to determine the stability of oscillatory solutions [5].

If we set Ig = 0 we would have a free running oscillator (autonomous system) with two solutions: the oscillation, represented by a single point (to where the closed curves seem to converge) and the trivial DC solution represented by V_o=0 (zero amplitude of the first harmonic). All free running oscillators have DC as a mathematical solution; in order for the oscillations to start up, the DC must be unstable and small signal analysis can be applied to verify it. The voltage and frequency of autonomous oscillatory solutions can be determined by nonlinear analysis using both; an AG or an OSCAPROBE element. But the stability of the large signal solution can not be addressed by small signal analysis; it requires the application of specific techniques [5] which are not compatible with OSCAPROBE elements and require the use of Auxiliary Generators.

In the case of the forced solutions with Ig > 0 (Fig.7), the frequency sweep (with no AG) shows $V_o \neq 0$ (blue curves) which are considered non-oscillating because they correspond to the voltage developed by the external independent current generator. On the other hand, the synchronization curves (red), obtained with an AG and imposing $f_{AG} = f_{in}$, represent oscillatory solutions. They also establish the *synchronization bandwidth* of this circuit, which depends on the input current amplitude Ig. Subharmonic solutions can be studied in the same way if we impose $f_{AG} = f_{in}/N$ for $N \geq 2$. The role of the AG is to excite the internal oscillation caused by the circuit's resonance, which under certain circumstances synchronizes with the external generator. The OSCAPROBE element is not compatible with the presence of independent signal generators in the circuit description.

b) Quasi-Periodic Solutions

So far we have searched for periodic solutions harmonically related to the input source, and the Auxiliary Generator proved useful to study multi-valued sections and regions of non convergence of HB. The AG is also very useful for finding Quasi-periodic solutions; they can be expressed by combining a finite number of non-commensurate (non-rationally related) fundamentals or periodic waveforms.

Although many different types of regimes are possible in nonlinear systems, in practice mixer-like behaviour with only two non-commensurate fundamentals is observed for a wide range of input frequencies and power levels ([1] pp.42-43).

In our example, a quasi-periodic solution is produced when the internal circuit oscillation is not synchronous with the input generator signal. This quasi-periodic solution with two fundamental frequencies is easily obtained by connecting to the circuit an auxiliary generator at the independent frequency f_a. The AG excites an internal oscillation mode and helps harmonic balance converge towards solutions with components $m \cdot f_{in} \pm n \cdot f_a$, being $|m|+|n|$ limited by the maximum harmonic order specified in the harmonic balance settings.

We have simulated the case Ig=15 mA with f_{in} = 1450 MHz and optimized the auxiliary generator's amplitude, frequency and phase for |Ys|<1e-7, using the Simplex Optimizer with 100 iterations followed by a 10 iteration Gradient with convergence tolerance better than 1e-5. The voltage waveform and frequency spectrum obtained with Aplac-HB are compared with those from the Aplac Transient simulation in Fig.8, showing an excellent agreement.

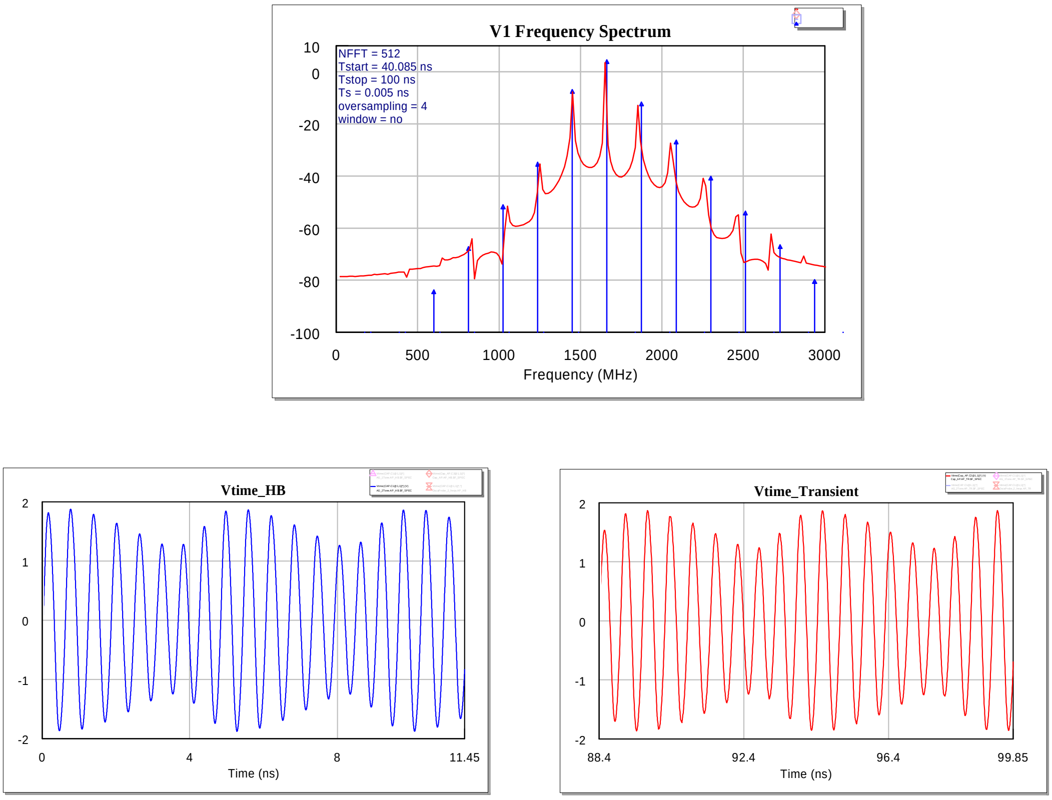

Fig.8. Results from the simulation of a quasi-periodic regime using the auxiliary generator with Aplac-HB (blue up and bottom left) and time domain integration with Aplac-Tansient (red up and bottom right). To represent the time domain spectrum (red up) we take an integer number of cycles from the steady-state part of the response.

In order to perform the Frequency Domain simulations, we have set the following Harmonic Balance Options:

Circuit Options/ Harmonic Balance/ Advanced/	
Solver Options	Continue sweep on failure
Convergence aids	Add conductance across nl elements Use saved results as the initial guess for harmonic balance Save results in project for use as a starting guess for harmonic balance

Circuit Options/ APLAC / Error and Convergence	
GMRES_ERR ShowNonconverged	1e-9 True

(*) All the simulations were performed with AWRDE (MWO-449), version 9.06r build 4997 Rev2 (73488)

Conclusion

Understanding the strengths and limitations of the different analysis tools available for microwave circuit design is critical for an efficient use and interpretation of their results. Nonlinear dynamics is the science that studies the behaviour of nonlinear systems, which include the great part of circuits employed in the radiofrequency and microwaves world. Analysis tools are continuously under evolution and we have presented here a technique that can be easily implemented in AWRDE to improve the simulation capabilities of Harmonic Balance by exploring a larger number of potential solutions from a circuit, including the synchronous (periodic) and self-oscillating mixer modes (quasi-periodic) observable through numerical integration in Time Domain, and in the real world.

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José Luis Flores received is Telecommunications Engineer Degree from the Polytechnic University of Catalonia in 1995. He has held various positions as a microwave design engineer at ESA, Alcatel Space Industries, Ommic, Alcatel R&I /Opto+, INTA and AT4 wireless. He has founded muWave Tech. & Co. with the aim to offer his expertise as an independent consultant on simulation, analysis and design of active microwave circuits. At this writing he is completing a Master's Thesis within the *Grupo de Ingeniería de Microondas y Sistemas de Radiocomunicación* at the University of Cantabria.

Almudena Suárez received the Electronic Physics and Ph.D. degrees from the Universidad de Cantabria (Spain), in 1987 and 1992, respectively, and the Ph.D. degree in electronics from the University of Limoges (France), in 1993. She is currently a Full Professor with the *Departamento de Ingeniería de Comunicaciones*, Universidad de Cantabria. Dr. Suárez is a member of the Technical Committees of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S), International Microwave Symposium (IMS) and the European Microwave Conference. She was an IEEE Distinguished Microwave Lecturer from 2006 to 2008.

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