AWR®
MRHB™
White Paper

Circuit Simulation Technology for Highly Nonlinear and Complex Designs

THE ADVANTAGES OF MULTI-RATE HARMONIC BALANCE (MRHB) – ADVANCED, MULTI-TONE HARMONIC BALANCE TECHNOLOGY PIONEERED BY AWR

Harmonic balance (HB) analysis is a method used to calculate the nonlinear, steady-state frequency response of electrical circuits. It is extremely well-suited for designs in which transient simulation methods prove acceptable, such as dispersive transmission lines in which circuit time constants are large compared to the period of the simulation frequency, as well as for circuits that have a large number of reactive components. In particular, harmonic balance analysis works extremely well for microwave circuits that are excited with sinusoidal signals, such as mixers and power amplifiers.

Harmonic balance analysis has been the fundamental simulation solution for nonlinear frequency-domain simulation for more than 25 years, and the most advanced versions are more capable than ever. AWR's APLAC® HB simulator, for example, can efficiently solve designs with thousands of analysis frequencies, and its ability to scale in a near-linear fashion as circuit elements, nodes, and frequencies increase makes it highly productive.

The limitation of traditional harmonic balance analysis occurs when it is used to solve large circuits with many different signal sources because it requires long computational times and large amounts of computer memory. To make harmonic balance analysis viable when analyzing such circuits, AWR has developed a multi-rate harmonic balance (MRHB) technology within its APLAC family of harmonic balance and time-domain simulators. MRHB overcomes the aforementioned limitations, significantly reducing the solution time as well as the computer memory required when applied to frequency-rich nonlinear systems that have multiple signal sources. The capabilities provided with MRHB make it possible to solve entire complex subsystems such as mobile phone transceivers in a practical amount of time.

This white paper traces the use of harmonic balance in solving microwave problems, describes MRHB technology, and provides examples of its effectiveness when compared with traditional harmonic balance simulators.

HARMONIC BALANCE: A BRIEF HISTORY

Until the 1980s, SPICE and similar transient analysis techniques were the reigning champions for solving complex microwave circuits. However, as the decade progressed, harmonic balance rapidly displaced SPICE among RF and microwave designers because transient analysis required far too much time to reach a steady-state solution and quickly used up available memory even when presented with simple topologies containing distributed elements. Its limitations became glaringly obvious when solving mixers and other types of frequency-conversion devices in which frequencies change over a wide spectrum. In the world of analysis, these widely-separated frequencies are called tones.

Dr. Mike Heimlich
AWR Corporation
mike@awrcorp.com

Dr. Michael Heimlich, a well-known member of the RF/microwave industry, joined AWR in 2001.

Prior to AWR, he was the chief technology officer and founder of Smartlynx, an EDA interoperability company.

Earlier, Dr. Heimlich held several positions at MA/COM including CAE Manager for the IC Business Unit and principal engineer in IC product development. He also designed GaAs MMICs for Pacific Monolithics and designed space-qualified millimeter-wave mixers at Watkins Johnson. Dr. Heimlich earned his BSEE, MSEE, and PhD EE degrees from Renssalear Polytechnic.

CO-AUTHORS:

Taisto Tinttunen, director of engineering, AWR-APLAC Corporation
Ville Karanko, senior development engineer, AWR-APLAC Corporation

A technique called “multi-tone harmonic balance analysis” was developed that made it possible to consider analyzing receivers and transmitters. These early harmonic balance engines incorporated direct matrix methods that were very useful in steady-state analysis of a circuit with a few transistors. However, when they were presented with larger nonlinear circuits, the resulting dense conversion matrices devoured computer memory and required many hours of simulation time.

In the 1990s, harmonic balance technology got a much-needed boost when numerical analysis techniques appeared that were better-suited for solving large nonlinear problems. Direct matrix techniques were supplemented with iterative techniques and the naïve Newton iteration was replaced by so-called inexact Newton methods. The use of more advanced and better optimized fast Fourier transform (FFT) techniques produced great advances in how nonlinear device computations were performed.

A NEW OBSTACLE

Harmonic balance has been a true enabler of steady-state nonlinear analysis with distributed elements, but as the number of tones (independent frequencies) increases, the number of mathematical unknowns that must be solved grows geometrically. This occurs because in a multi-tone system, each circuit element must be solved not just at the harmonics of each tone, but also at many of their linear combinations as well. If the designer cannot constrain the harmonic balance analysis engine by limiting the number of frequency combinations per circuit element, the circuit must be analyzed for the same frequencies at every circuit node. In a typical multi-tone circuit, for example, this means that a lot of CPU time is consumed to refine a zero.

The number of analysis frequencies becomes a bottleneck when the number of tones grows above three, a phenomenon appropriately labeled by the numerical analysis community as the Curse of Dimension. Table 1 helps clarify the ramifications of the “curse,” and demonstrates what happens even in a moderately nonlinear simulation when the number of tones is increased. When fortified with the increased accuracy produced by “diamond truncation” (the strategy of selecting frequency linear combinations), the growth in the number of frequencies and hence the number of unknowns to be solved is almost an order of magnitude for every tone. This presents an untenable situation that renders most current harmonic balance solutions ineffective as they are faced with processing extraordinary amounts of information in order to achieve a result.

Number of tones	DIAMOND 5 truncation	BOX 5 truncation
1	6	6
2	31	61
3	116	666
4	341	7321
5	842	80526

Table 1. The Curse of Dimension.

AN INNOVATIVE NEW APPROACH - MRHB

To understand the sea change enabled by MRHB, it is important to remember its core concept: that operational blocks such as mixers, filters, and amplifiers in an RF system modify the frequency content. As traditional harmonic balance techniques assume that the relevant frequency content will be the same at every part (or block) in the circuit, it is essentially “out of sync” with how the circuit actually functions. Rather than perpetuating this concept, MRHB enables the designer to allow different parts of the circuit to have different dominating frequencies, and takes into consideration that some frequencies are important to solve while others are not. This intelligent, frequency-selective technique makes it possible to solve very complex circuits such as receivers with multiple stages of downconversion, multi-band power amplifiers, and complex high-frequency digital designs, an order of magnitude faster than with traditional harmonic balance.

MRHB dynamically forms its equations to solve for the multi-tone, multi-harmonic content of the circuit, adding the contribution of each element (block) only at the desired frequencies, which dramatically reduces the number of equations that must be solved. The analysis information is transferred from one element (block) to another via the shared frequencies, as illustrated in the simple example in Figure 1 in which a circuit has been divided into two blocks, each with single-tone frequency set. The first part (the red block) has eight harmonics and the second one (the blue block) has four. Communication between these two circuits occurs via the five frequencies they share, DC, and four harmonics. The first part is solved at all nine frequencies, which actually makes the results more accurate because of the greater number of harmonics.

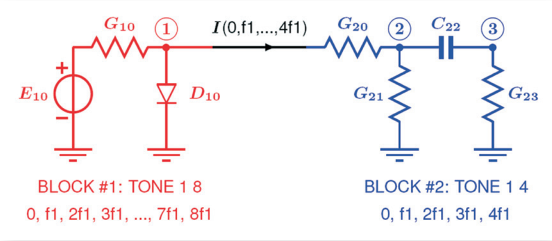

Figure 1. This simple, three-node circuit has two blocks with different frequency settings, both of which are single tone. Block 1 (red) has eight harmonics and Block 2 (blue) has four.

While the solution of such simple circuits generally achieves little by reducing frequency content at some parts of the circuit, many circuits require one of their nonlinear parts to be simulated more accurately. MRHB does not force this local accuracy requirement to affect the simulation of other parts of the circuit, so if a frequency divider requires more than 2,000 harmonics for a single-tone analysis, it can be simulated locally with a large single-tone frequency set without detrimentally impacting the two-tone frequency set used in the same simulation for the mixer.

In short, MRHB presumes that by intelligently addressing the fact that dominating frequencies differ in the various parts of a circuit, it is possible to realize more efficient, yet highly accurate harmonic balance analysis of the entire circuit. This remarkable feat is accomplished while at the same time consuming less memory and less simulation time than traditional harmonic balance techniques.

EXAMPLES TO ILLUSTRATE MRHB

Refer again to the simple circuit in Figure 1, in which the first block has a voltage source and a nonlinear diode, and the corresponding circuit equations are constructed for DC and eight harmonics. Assuming that the diode is being driven hard enough to generate significant harmonic content, an ordinary harmonic balance simulation would require the analysis of all circuit elements—nonlinear as well as linear—to be analyzed at all eight harmonics. The second part of the circuit implements a low-pass filter that would be expected to block the higher-order harmonics, introducing negligible signal energy at these frequencies to later elements in the circuit.

Using MRHB as the simulation engine for analyzing this circuit's behavior, the designer is able to individually set the analysis of the resistors and a capacitor to have a frequency set of only DC and four harmonics. The second block in the circuit does not exist in frequencies 5f1, 6f1, 7f1, and 8f1 and the current I flows from block 1 to block 2 only for the shared frequencies, i.e., DC, f1, 2f1, 3f1, and 4f1. So only the relevant frequencies and harmonics are solved on a block-by- block basis, making it possible to deliver simulation accuracy more efficiently, which in turn enables MRHB to address circuits of greater complexity.

Looking at the two relevant domains in which MRHB can be employed:

- In the single-tone, multiple-frequency domain of Figure 1, MRHB selects only the required nonlinear elements rather than all nonlinear harmonics propagated to all circuit elements
- In the multi-tone, multiple-frequency domain of Figure 2, MRHB reduces the overall tone-frequency solution space yet maintains high accuracy through the use of hybrid-tones

To illustrate the concept of hybrid tones, consider the QPSK receiver shown in Figure 2, which is a challenging circuit to solve at the circuit level with harmonic balance analysis because of its multiple tones and the need to employ many harmonics to tackle all the nonlinearities. The circuit consists of a transistor-level QPSK receiver with 130 transistors based on the BSIM3 model and more than 100 passive elements. Two-tone harmonic balance analysis would traditionally be used with a box-style truncation up to the seventh order at the RF frequency (fRF = 2.45 GHz) and the fourth order at the LO frequency (fLO = 2.44 GHz). However, by partitioning the blocks based on their frequency content, MRHB analysis can employ a multi-tone frequency set, which eliminates many of the harmonics in the circuit elements where they are clearly not a factor.

In the mixer within the circuit of Figure 2, the simulation results are achieved in half the time using half the memory with no difference in accuracy between measured versus simulated results when compared with traditional harmonic balance. For the differential-to-single-ended and Bessel filter blocks, the simulation consists of a single-tone, fourth-order analysis in which the fundamental frequency is constructed as an MRHB hybrid tone, fRF-fLO. By using this unique feature of MRHB in conjunction with the software's ability to set multi-tonal frequency analysis on a block-by-block basis, the resources necessary to analyze the receiver are reduced well beyond what is possible with traditional harmonic balance using either box or diamond truncation.

Table 2 summarizes the memory consumption and processor times of traditional harmonic balance versus MRHB simulation for this design. Voltage magnitude is plotted in Figure 3 from different parts of the circuit at selected frequencies (LO and RF), their second harmonics, and their third-order intermodulation products. Simulated data agrees very well with the actual circuit behavior and yet was achieved in nearly one-fourth the simulation time while using half the memory.

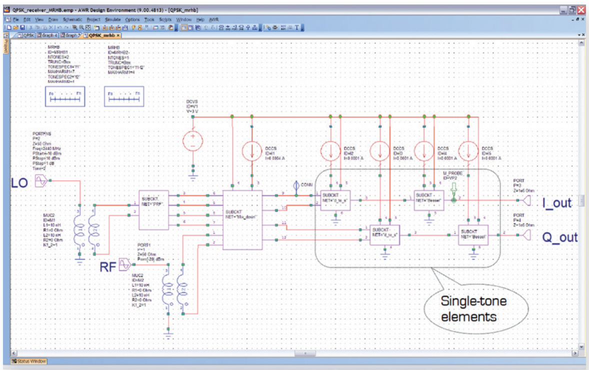

Figure 2. A QPSK receiver with 130 transistors and more than 100 passive components. The elements with single-tone frequency settings are shown in black and the rest of the elements belong to a block with a two-tone frequency set.

spec.	Traditional HB analysis	Multi-Rate HB analysis
CPU-time [s]	43.9	13.5
Memory usage [Mbytes]	50	23
GMRES iterations	71	71
Matrix-vector multiplies	189	189
Newton-Raphson iter.	71	71

Table 2. Performance comparison between traditional harmonic balance and MRHB for Figure 2 QPSK receiver.

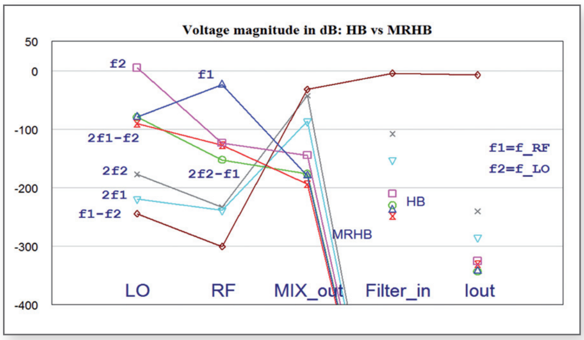

Figure 3. The mixer sub circuit of Figure 2 output spectrum from traditional harmonic balance (Δ) and MRHB (□).

EXAMPLE: MRHB SUCCEEDS WHERE HB FAILS

More than just speeding up traditional HB, with MRHB it is possible to simulate circuits that are impossible for harmonic balance to tackle due to the memory limitations of its formulation. A key feature of the MRHB technique is that the HB solution space can be defined on a block-by-block basis and, as such, limits the harmonics over which the simulator must solve. In other words, MRHB redefines the tones so as to advantageously direct the simulator to solve for only those tones that matter.

Compare, for example, a design that both HB and MRHB are able to tackle. Figure 4 shows a simple behavioral simulation for a GPS double-downconverter. The two mixing stages combined with the RF input yields three tones which, with default HB set-up parameters, requires less than 1000 harmonics for the HB simulator to solve over. Even though HB can handle this design, MRHB can be used to selectively prune this solution space by solving only at the necessary tones seen by each component. Because of this unique feature, the initial low noise amplifier (LNA) in the receive chain need only be analyzed at the input with the harmonics of the RF input signal—a one-tone solution. Similarly, those components seeing only the first mixing products are constrained by MRHB block 2 (see Figure 5) and the analysis is done only for the RF and first LO—a two-tone MRHB solution. Finally, with the second downconversion and the subsequent stages, components of all three tones are required. For the components in this part of the design, and only for these components, MRHB utilizes all three tones. While MRHB solves significantly faster for this design than traditional HB, it is also important to note that the results are virtually identical (Figure 6)

But MRHB provides an additional feature for this third MRHB block that makes its use even more intuitive. Rather than simply defining the three tones for the final MRHB block as the RF, first LO, and second LO, “solve” tones can be constructed from these three “simulation” tones that are of greater interest. In this case, for the LO leakage, which can compress this part of the design, two of the solve tones to be the LO tones are specified to the MRHB engine. For the third tone, tracking the GPS IF is most interesting and so the proper harmonic of RF, LO1 and LO2 is specified. The advantage of this specification is that MRHB can simulate using the precise number of harmonics of interest for the precise signals of interest (rather than the simulation tones). So, the user can control MRHB to focus on the IF even though there is no tonal source in the solution that directly corresponds to the IF. This capability of MRHB gives the designer the ability to have the solver track the tones of interest in each separate part of the design, corresponding to the MRHB blocks.

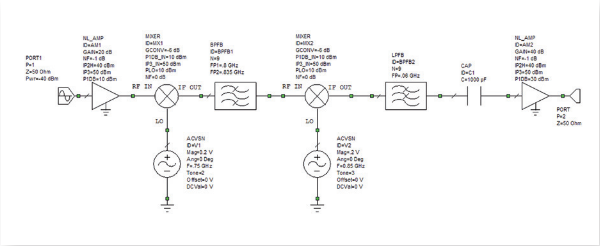

Figure 4. GPS double-downconverter for HB solution.

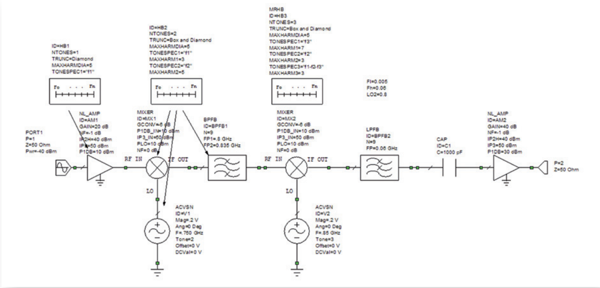

Figure 5. GPS double-downconverter for MRHB solution. MRHB blocks 1 and 2 show associated elements, the remaining elements are subject to MRHB block 3. Note that tone 3 of MRHB block 3 is created from the 3 simulation tones.

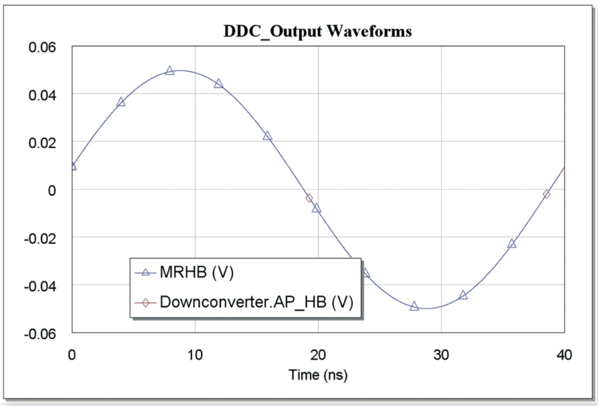

Figure 6. Time-domain results for MRHB and HB for GPS double-downconverter.

Pushing this notion further, a simple common-gate field-effect transistor (FET) (Figure 7) is added to the design to act as a sampling circuit, for example, to have the receiver feed a data acquisition system or analog-to-digital converter (ADC). With the default HB behavior, something on the order of 10,000 harmonics is required of the solution, which would cause most desktop PCs to fail to solve due to a lack of memory. The corresponding MRHB solution to this circuit not only solves, but does it in one-third the time that it takes the simple double-downconverter in Figure 5. (This is using what might be considered a default or non-aggressive MRHB simulation set-up)

In order to make HB work on this design, the number of harmonics considered must be drastically pared. For example, even reducing the number of harmonics from about 10,000 to 1,000 the solve time is still more than four times that of the default MRHB simulation. Although the HB simulation is solving at more harmonics than MRHB, MRHB is actually treating more of the harmonics that matter and accounting for more of the energy through explicit tonal and harmonic selection. Thus, MRHB accuracy is superior, as can be seen in the mismatch effects in Figure 8. While traditional HB still gives a reasonable answer, it can be seen that the accuracy degrades purely to get a solution on a standard PC.

To see this example demonstrated in AWR's Microwave Office® software, view the video on AWR.TV™ titled "Multi-Rate Harmonic Balance Tutorial."

CONCLUSION

Traditional harmonic balance analysis continues to be a core component in the designer's toolbox, but is limited in its ability to solve the large, high-frequency circuits with many signal sources that are becoming more and more prevalent in today's complex designs. The intelligent frequency selectivity and other innovative features within AWR's patent-pending MRHB technology transcend the shortcomings of traditional harmonic balance and enable designers to solve these complex circuits in significantly shorter time and with more accuracy.

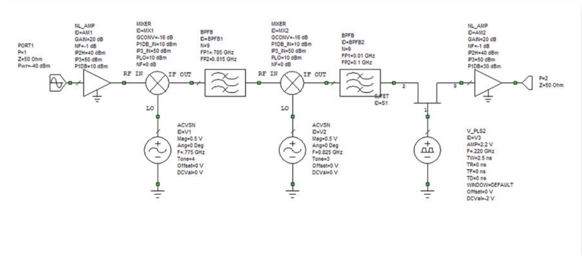

Figure 7. GPS double-downconverter with sampling FET for HB solution (MRHB solution is the same except with 4 MRHB control blocks similar to Figure 5). Standard HB default settings cause this simulation to run out of memory on a standard PC.

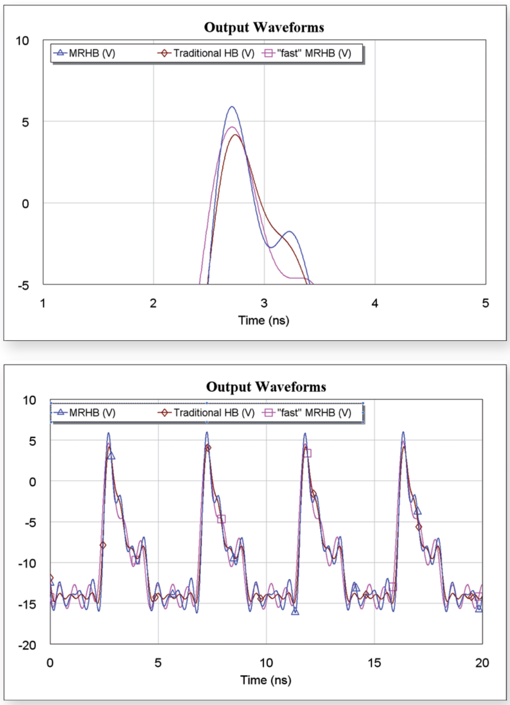

Figure 8. Results for sampling circuit + GPS double-downconverter, comparing high accuracy MRHB, fast MRHB, and HB made to run on a standard PC.

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