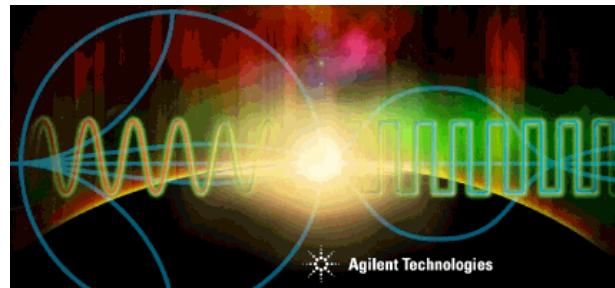


Topic 7:

Harmonic Balance



Harmonic Balance Simulation

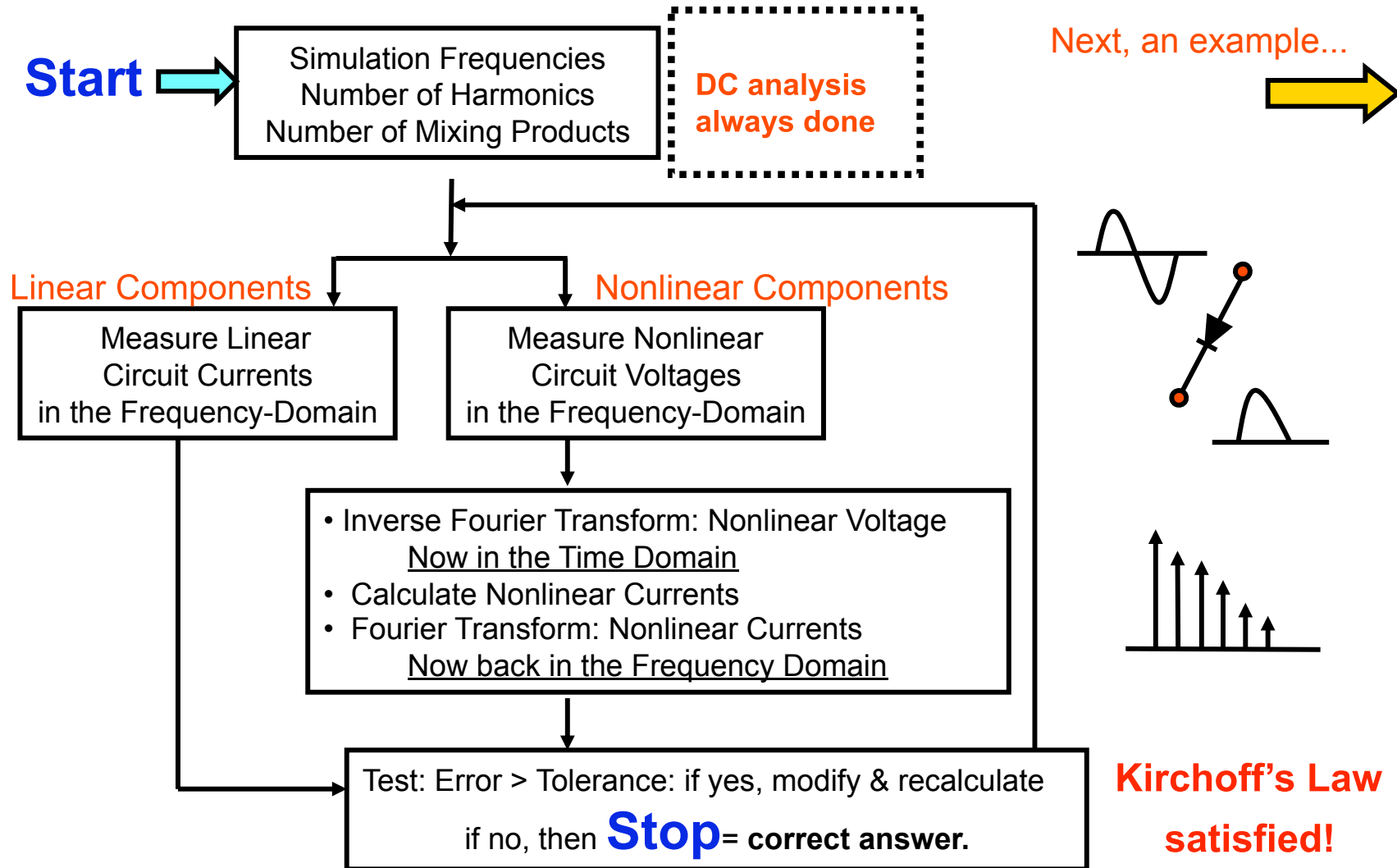
Analyze circuits with Linear and Non-linear components:

- You define the tones, harmonics, and power levels
- You get the spectrum: Amplitude vs. Frequency
- Use only Frequency domain sources
- Data can be transformed to time domain (ts function)
- Solutions use Newton-Raphson technique
- Automatically chooses best mode for convergence
- Transient can be run from HB controller (freq dividers)
- Similar to Spectrum Analyzer

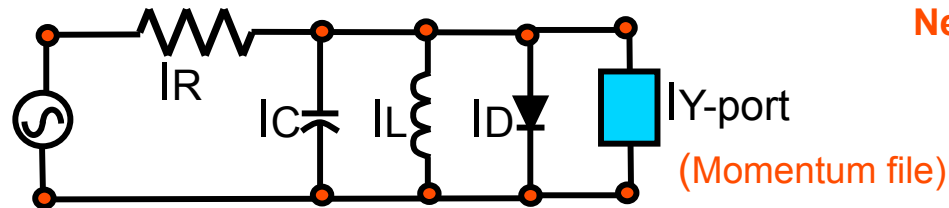
HB flowchart...



Harmonic Balance Simulation Flow Chart



Example Circuit: First and Last Iterations

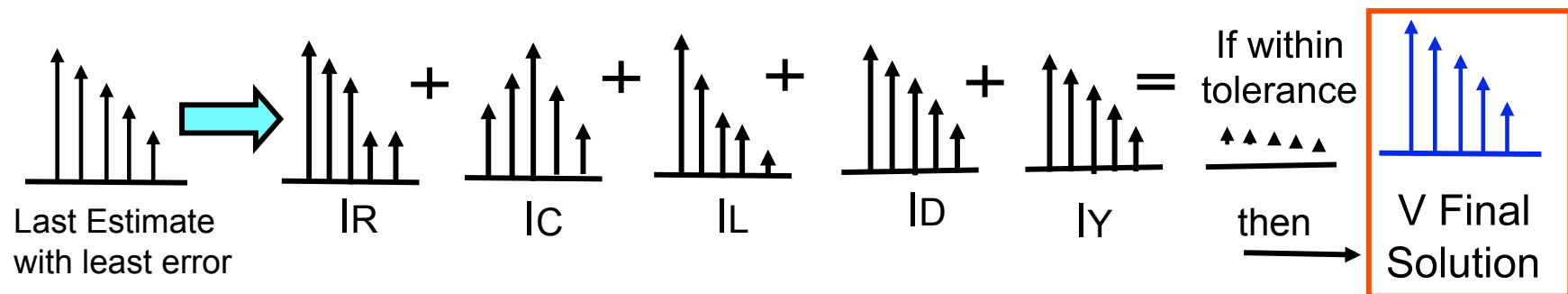
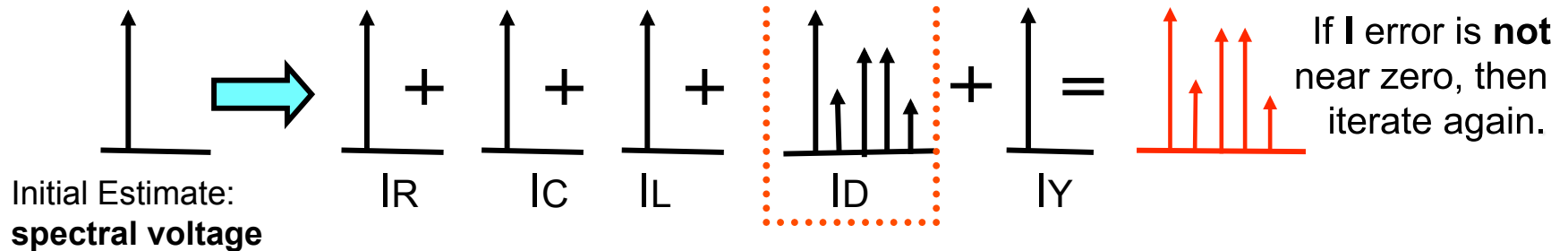


Start in the
Frequency Domain

Calculate currents

Convert: ts -> fs

Test uses
(Kirchoff's law):



NOTE: Try building the circuit, simulate, and write an equation to sum the currents.
The IY-port could be S-parameter data from Momentum or other NWA data.

Basic 1 Tone HB simulation setup

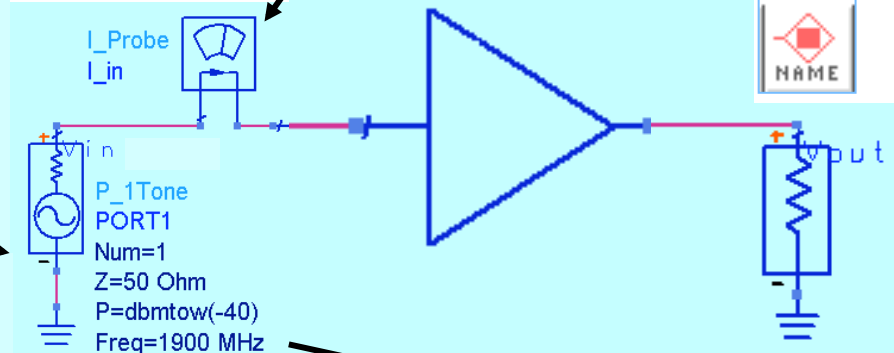
HB controller and source setup gives you spectral tones:



HARMONIC BALANCE

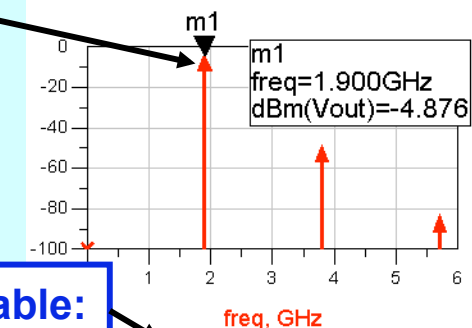
HarmonicBalance
HB1
Freq[1]=1900 MHz
Order[1]=3

Freq[1] is the fundamental tone you want HB to calculate. Freq[1] must match a tone in the circuit or you get a warning message.



Current Probe can be used for single current in dataset or use pin current for all values.

Order [1] = 3 means HB calculates 3 harmonics of Freq [1]



HB gives you a Mix table:

| freq | Vout | Mix |
|-----------|-------------------|-----|
| 0.0000 Hz | 0.000 / 0.000 | 0 |
| 1.900GHz | 0.180 / -14.199 | 1 |
| 3.800GHz | 0.001 / -170.939 | 2 |
| 5.700GHz | 1.963E-5 / 46.135 | 3 |

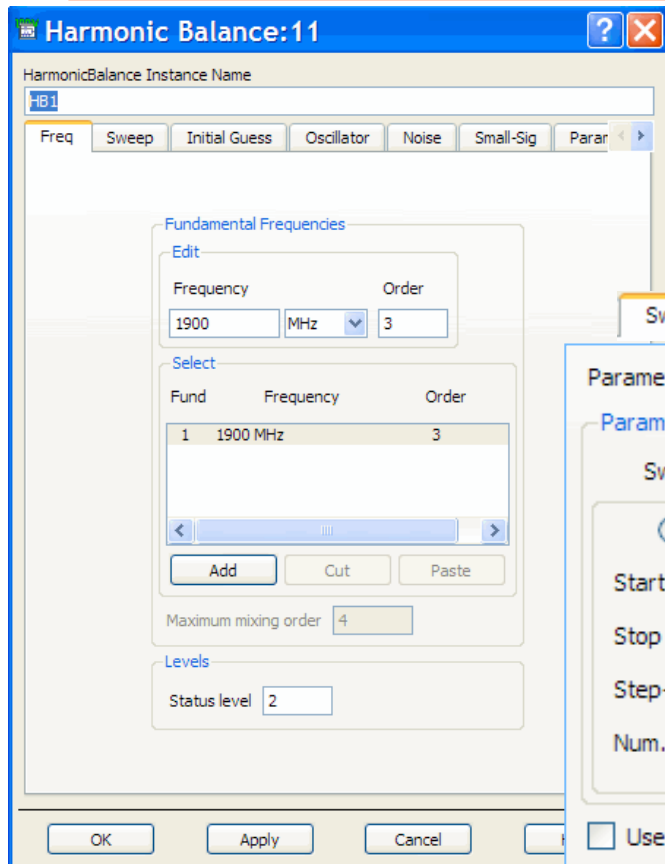
Numerous built-in sources and measurement equations.

Next, sweeping variables...

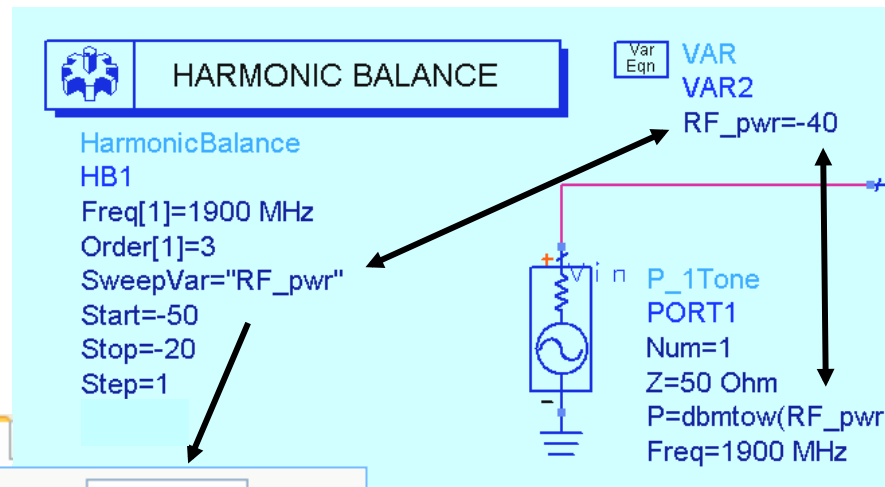


Swept variables in Harmonic Balance

Freq tab: specify tones (Freq), harmonics (Order), and mixing products (Max Order) if more than one Freq or source is used.



- 1) Initialize the VAR to sweep.
- 2) Specify the variable and range.



- 3) Be sure the VAR, the source, and simulation controller all have the same information.

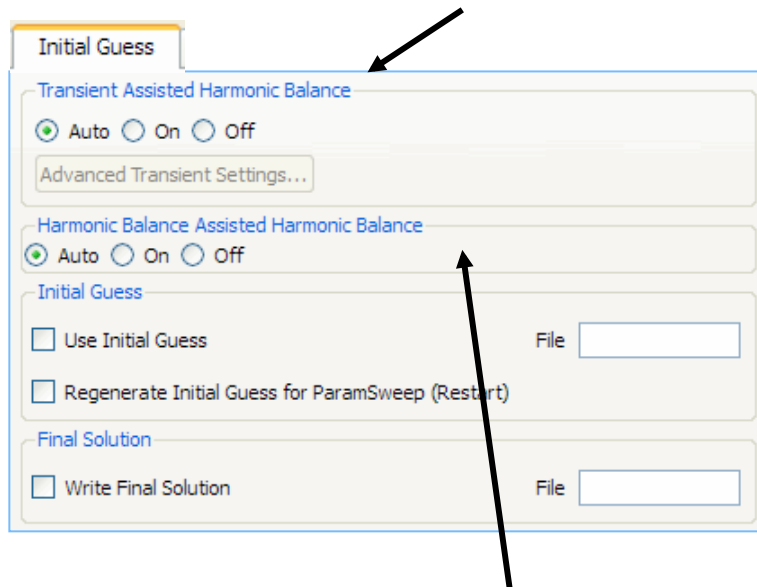
NOTE: Swept variables always go to the dataset.

Next, other tabs...



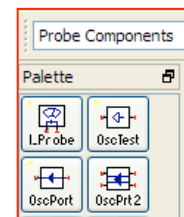
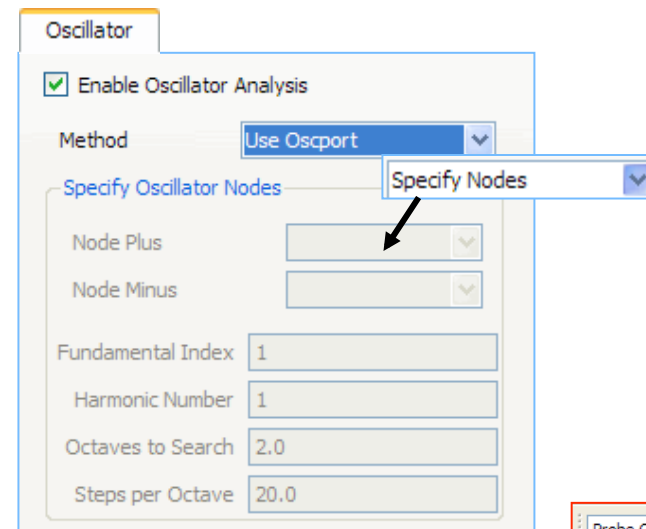
Other tabs in HB: Initial Guess & Oscillator

TAHB: The Auto setting will detect if running Transient first is needed. Used mostly for non-converging divider circuits that often contain S-parameter models. Or, if you use Transient first to verify your circuit's waveform or to achieve a steady-state condition, you can then run HB using the initial guess from the Transient analysis.



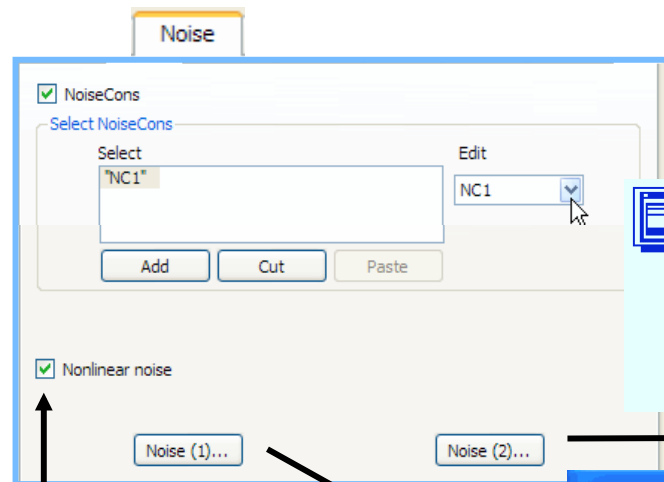
HBAHB: Auto setting will determine if it is needed. If used, HB uses fewer frequencies as initial guess to help achieve convergence.

Oscillator: For oscillator analysis, this will determine the oscillation frequency: specify node names or use an **Oscport** component.



NOTE: Oscillator testing: Use **OscTest** to determine if oscillation exists (S-param analysis). Use **OscPort** to determine the frequency of oscillation (HB analysis).

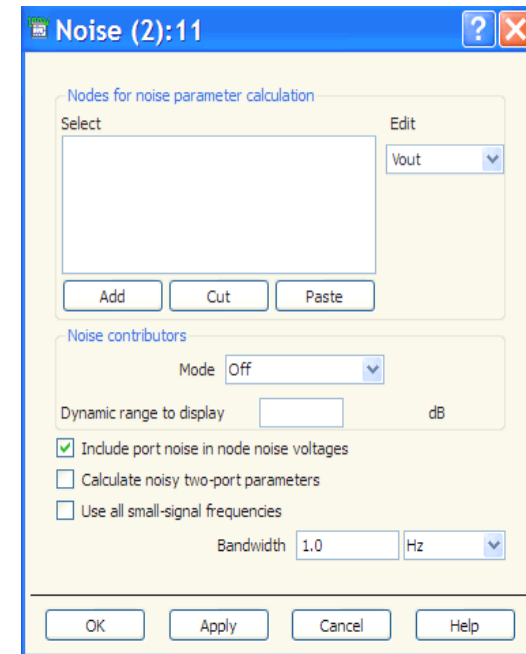
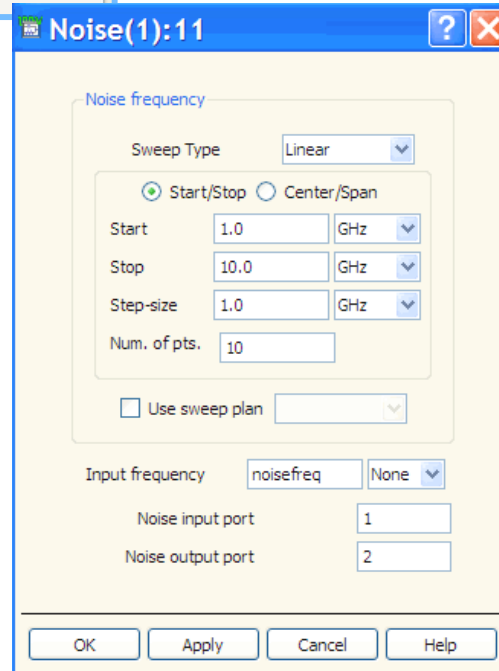
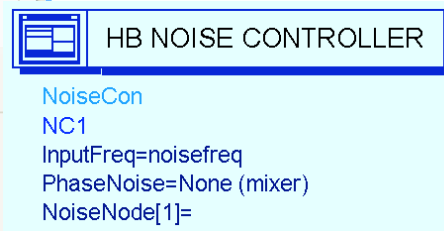
Other Tabs in HB: Noise



Click here to turn on Noise analysis and activate settings.

Noise buttons 1 and 2 are for setting up Noise analysis in the controller if not using a NoiseCon.

NoiseCon has the same settings as Noise buttons 1 and 2, plus it also has phase noise selections. And it is more convenient to use...



(1) Specify frequency range for noise sweep calculation – also specify port numbers for Terms.
(2) Add, Cut, Paste node names in schematic.

Other Tabs in HB: Solver & Output

HB will select the best method if Auto (default) is selected: Advanced or Basic.

The Solver tab contains three main sections: Convergence, Matrix Solver, and Memory Management. The Convergence section has radio buttons for 'Auto (Preferred)', 'Advanced (Robust)', and 'Basic (Fast)', with 'Auto' selected. Below are options for 'Max. Iterations' (Robust, Fast, Custom) and a button for 'Advanced Continuation Parameters...'. The Matrix Solver section has radio buttons for 'Solver Type' (Auto Select, Direct, Krylov) with 'Auto Select' selected, and 'Matrix Re-use' (Fast, Robust, Custom). It also has 'Krylov Restart Length' (Robust, Low Memory, Custom) and a button for 'Advanced Krylov Parameters...'. The Memory Management section has 'Matrix Bandwidth (GuardThresh)' (Fast, Robust, Custom) and 'FFT Options' (Minimize memory and runtime, Minimize aliasing) with 'Minimize memory and runtime' selected. At the bottom, there are checkboxes for 'Waveform Memory Reduction' (Use dynamic waveform recalculation, Use compact frequency map).

Krylov is for large circuits to reduce simulation time.

Memory Management and other settings are for problem circuits only.

Budget gives V & I at device pins. Oversample may help accuracy / convergence.

The Params tab includes a 'Device operating point level' section with radio buttons for 'None', 'Brief', and 'Detailed', with 'None' selected. Below is an 'FFT' section with a 'Fundamental Oversample' input field and a 'More...' button. The 'Budget' section has a checkbox for 'Perform Budget simulation'.

Select the desired data to be output to the dataset.

The Output tab has a 'Save by hierarchy' section with a table for selecting data to output. The table has columns for the data type and 'Maximum Depth'. The data types are 'Node Voltages', 'Measurement Equations', 'Branch Currents', and 'Pin Currents'. The depths are 2, 2, 999, and an empty field respectively. There is a 'For device type' dropdown set to 'All'. Below this is a 'Save by name' section with a list box containing 'Vin' and 'Vout'. At the bottom is an 'Add / Remove...' button. An arrow points from a text box to the 'Pin Currents' checkbox.

| | Maximum Depth |
|--|---------------|
| <input checked="" type="checkbox"/> Node Voltages: | 2 |
| <input checked="" type="checkbox"/> Measurement Equations: | 2 |
| <input checked="" type="checkbox"/> Branch Currents | 999 |
| <input type="checkbox"/> Pin Currents | |

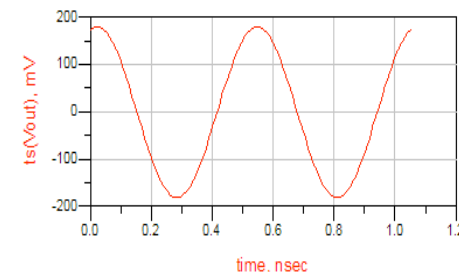
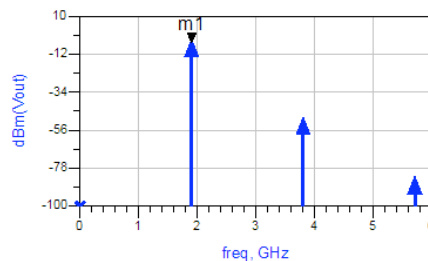
Check box to get currents

3 Related HB controllers: XDB and LSSP

Transform HB spectrum into the time domain with ts function: **ts(Vout)**.

HARMONIC BALANCE

HarmonicBalance
HB1
Freq[1]=1.9 GHz
Order[1]=3



LSSP

LSSP
HB2
Freq[1]=1.9 GHz
Order[1]=3
LSSP_FreqAtPort[1]=

| input_pwr | dB(S(2,1)) |
|-----------|------------|
| 1.000 | 4.704 |
| 2.000 | 3.847 |
| 3.000 | 2.991 |
| 4.000 | 2.118 |
| 5.000 | 1.238 |
| 6.000 | 0.329 |
| 7.000 | -0.667 |
| 8.000 | -1.674 |
| 9.000 | -2.682 |
| 10.000 | -3.692 |



GAIN COMPRESSION

XDB
HB2
Freq[1]=1.9 GHz
Order[1]=3
GC_XdB=1
GC_InputPort=1
GC_OutputPort=2
GC_InputFreq=1.9 GHz
GC_OutputFreq=1.9 GHz
GC_InputPowerTol=1e-3
GC_OutputPowerTol=1e-3
GC_MaxInputPower=100

XDB simulation results: 1 dB compression

| inpwr[1] | outpwr[1] |
|----------|-----------|
| -31.251 | -21.268 |

Next, sources...

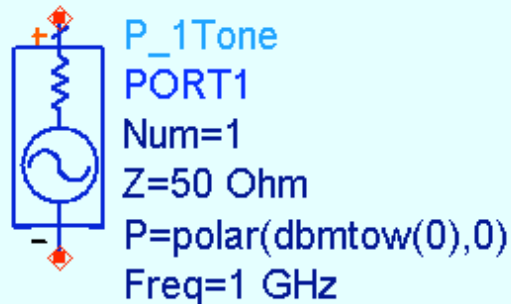


You will use HB and XDB in the lab!



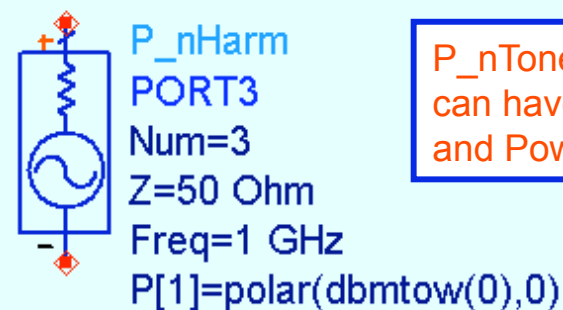
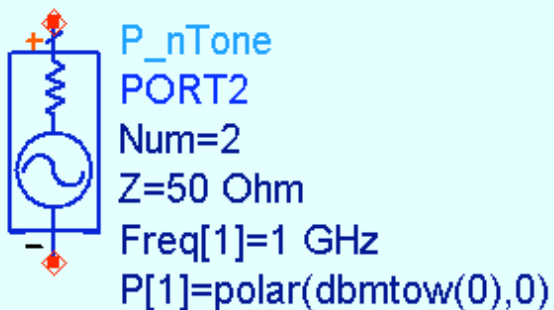
Types of Power Sources for HB

Default power function for these sources is **polar**,
but you can simplify it on the screen as: `dbmtow(0)`
Therefore, `dbmtow(0)` is the same as `polar(dbmtow(0),0)`



Notice that these sources are also **ports** (OK for S-param analysis).

Also, they can be considered **noiseless** like sources in a measurement system.



P_nTone and P_nHarm
can have multiple Freqs
and Power.

Next, a mixer example...



Example: HB simulation setup for a mixer with swept LO power

Mixer example:

Freq [1] fundamental tone (most power: LO for mixer)

Freq [2] fundamental tone (RF for mixer)

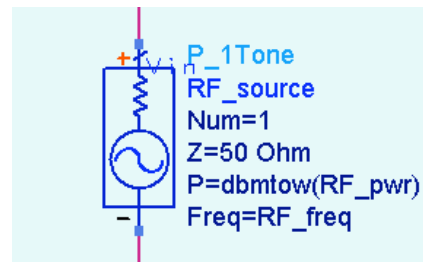
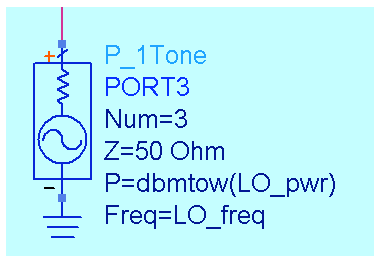
Order [1] number of harmonics for Freq [1]: LO.

Order [2] number of harmonics for Freq [2]: RF.


MaxOrder = mixing products, depends on Order[n].

NOTE: Here if MaxOrder = 9, you won't get 9th order product because Order[1] and [2] only go up to the 8th order.

LO and RF sources:



Do not do this: Freq = LO_freq MHz or MHz units will multiply.

**HARMONIC BALANCE**

HarmonicBalance
HB1
MaxOrder=8
Freq[1]=LO_freq
Freq[2]=RF_freq
Order[1]=5
Order[2]=3
StatusLevel=4
NLNoiseMode=yes
FreqForNoise=100 MHz
SweepVar="LO_pwr"
Start=-30
Stop=10
Step=1

Var
Eqn

VAR
mixer_vars
LO_freq=1800 MHz
RF_freq=1900 MHz
LO_pwr=-10
RF_pwr=-40

**LO_pwr goes to the dataset automatically.
RF_pwr can be sent using Output tab.**



Example data: use mix function on Mix table

DC term=0. Freq, harmonics [order], and products [max order] are indexed:

Mixer example: Max order=8
LO order=5 **RF order=3**

| freq | LO | Mix | RF |
|-----------|--------|-----|--------|
| | Mix(1) | | Mix(2) |
| 0.0000 Hz | | 0 | 0 |
| 100.0MHz | | -1 | 1 |
| 200.0MHz | | -2 | 2 |
| 300.0MHz | | -3 | 3 |
| 1.500GHz | | 4 | -3 |
| 1.600GHz | | 3 | -2 |
| 1.700GHz | | 2 | -1 |
| 1.800GHz | | 1 | 0 |
| 1.900GHz | | 0 | 1 |
| 2.000GHz | | -1 | 2 |
| 2.100GHz | | -2 | 3 |
| 3.300GHz | | 5 | -3 |

LO: Freq[1]=1800 MHz RF: Freq[2]=1900 MHz

To get dBm of IF (100 MHz) at Vout, use the mix () function:

```
MeasEqn
IF_100MHz_output
dbm_out=dBm (mix(Vout,{-1,1}))
```

Arguments in parentheses () and curly braces {generate the matrix }, required for **mix()** function.

8th order term uses +5th & -3th, but not: -3th & +5th (+5th of RF does not exist).

QUIZ: Can you use this equation: dBm(Vout[1]) for this data? Is it valid?

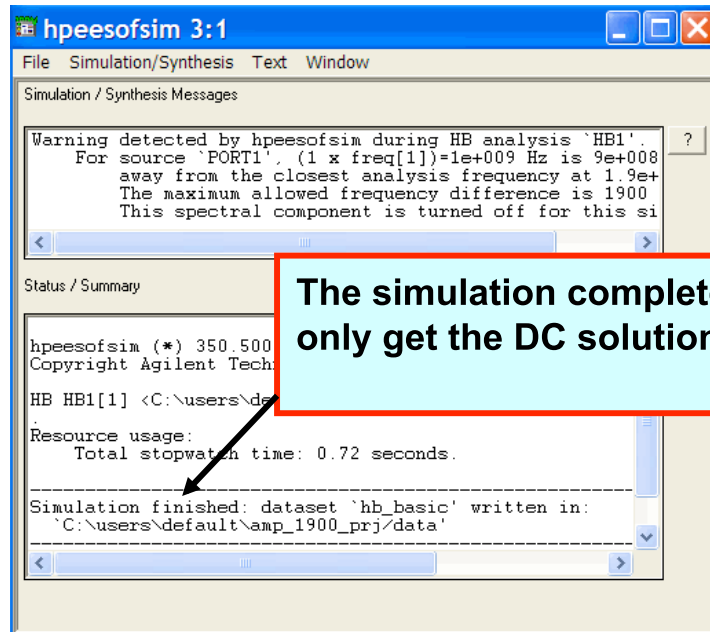
Answer: **YES** - if no other dependencies exist - it's the same as: **dBm(mix(Vout,{-1,1}))**

Next, HB convergence...



Harmonic Balance: messages & options

Freq [x] in each source must match Freq [x] in the controller or you get this message:

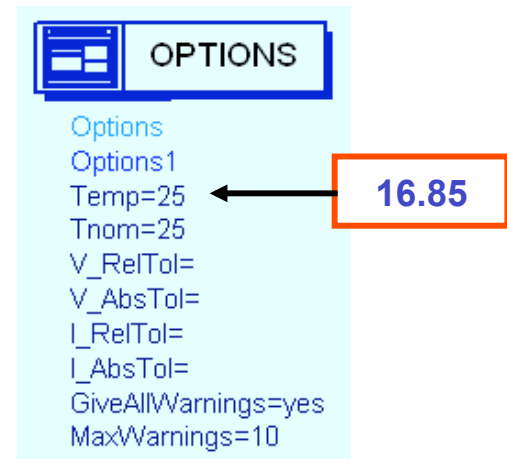


HB convergence error messages:
For all convergence errors: These messages will rarely appear with the new version of Harmonic Balance. However, if they do, go to the Help for Harmonic Balance and see Chapter 3: **Preventing Convergence Problems.**

NOISE TEMP error for all noise simulations: Set Temp=16.85 to eliminate any error message.



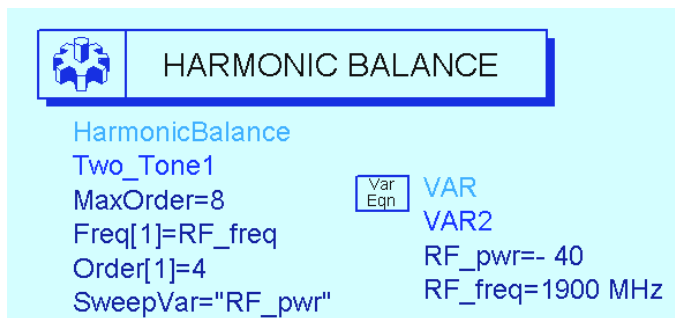
OPTIONS controller is in all simulation palettes. V and I values are simulator defaults but can be changed.



About “quotes”, brackets, braces, etc.

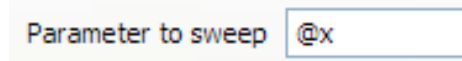
QUOTES:

- Only when editing on the screen for string value parameters, if necessary.
- When in doubt, double click and use the dialog boxes.



NOTE: Swept variables are always in quotes and controller names (“HB1”) in opt goals.

In dialog only: @ stops quotes when not needed.



If you see 2 quotes “X”, remove one set!

REVIEW: Parentheses, Brackets, Curly braces:



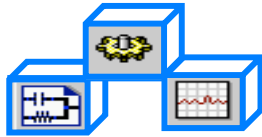
(parentheses) – use for function arguments and matrix elements

[brackets] – use for indexing multi-dimensional data

{curly braces} – use to define matrices, especially with mix function

Examples: dBm(Vout [1]) dBm(mix(Vout,{-1,1})) mag(Vout [1:: 6])

Double colon =
wildcard in ADS.



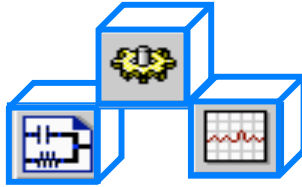
What the lab is about ...

Lab 7:

Harmonic Balance Simulations



Steps in the Design Process



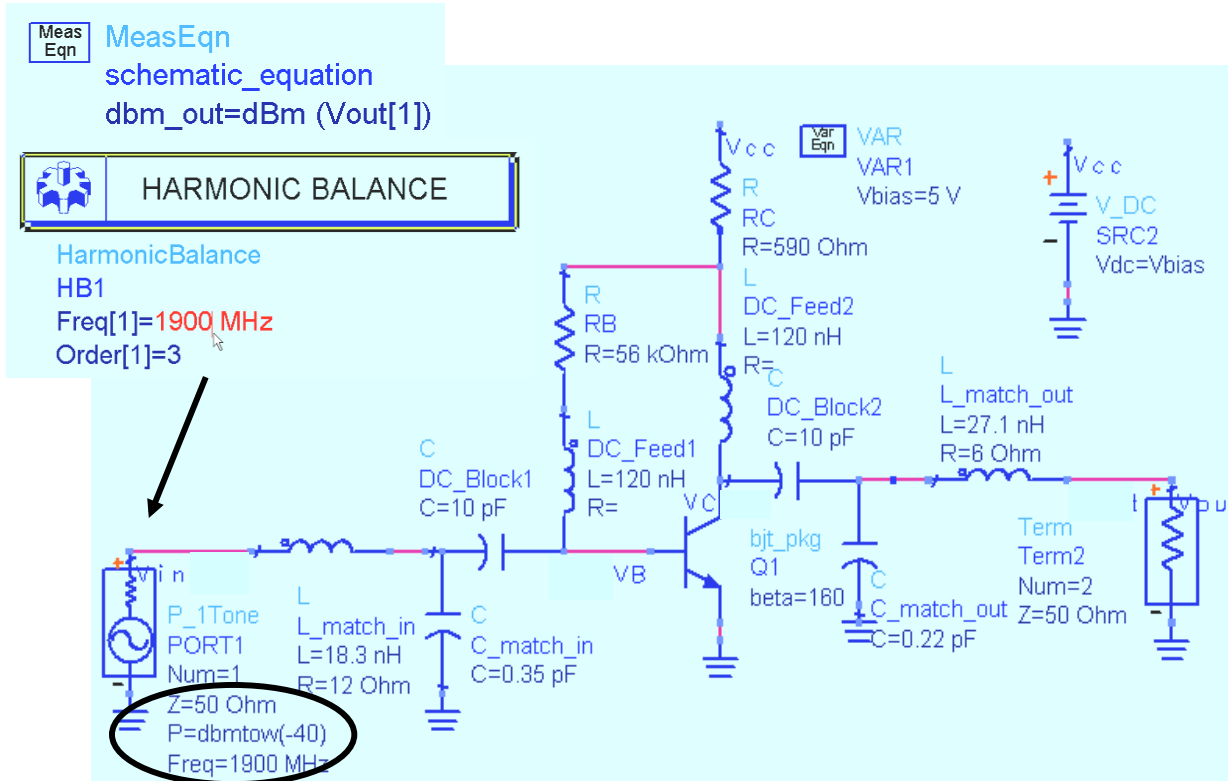
You are here:



- Design the RF sys behavioral model receiver
- Test conversion gain, spectrum, etc.
- Start amp_1900 design – subckt parasitics
- Simulate amp DC conditions & bias network
- Simulate amp AC response - verify gain
- Test amp noise contributions – tune parameters
- Simulate amp S-parameter response
- Create a matching topology
- Optimize the amp in & out matching networks
- Filter design – lumped 200MHz LPF
- Filter design – microstrip 1900 MHz BPF
- Transient and Momentum filter analysis
- **Amp spectrum, delivered power, Zin - HB**
- **Test amp comp, distortion, two-tone, TOI**
- CE basics for spectrum and baseband
- CE for amp_1900 with GSM source
- Replace amp and filters in rf_sys receiver
- Test conversion gain, NF, swept LO power
- Final CDMA system test CE with fancy DDS
- Co-simulation of behavioral system



First, one tone HB and Meas Eqn



Datasets and Equations

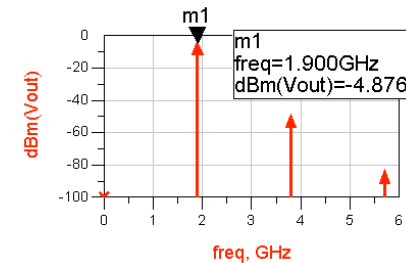
hb_basic

| |
|---------|
| dbm_out |
| freq |
| I_in.i |
| Mix |
| Mix(1) |
| SRC1.i |
| VB |

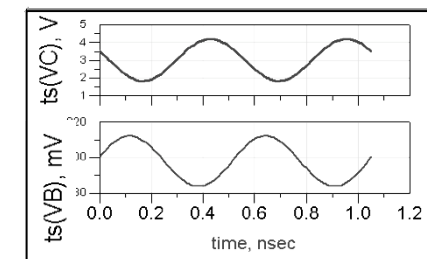
Dataset contains node voltages and Mix table.

| freq | Vout | Mix |
|-----------|-------------------|-----|
| 0.0000 Hz | 0.000 / 0.000 | 0 |
| 1.900GHz | 0.180 / -14.199 | 1 |
| 3.800GHz | 0.001 / -170.939 | 2 |
| 5.700GHz | 1.963E-5 / 46.135 | 3 |

Plot Spectrum



Use ts function



List MeasEqn results

| | |
|---------|--------|
| dbm_out | -4.876 |
|---------|--------|

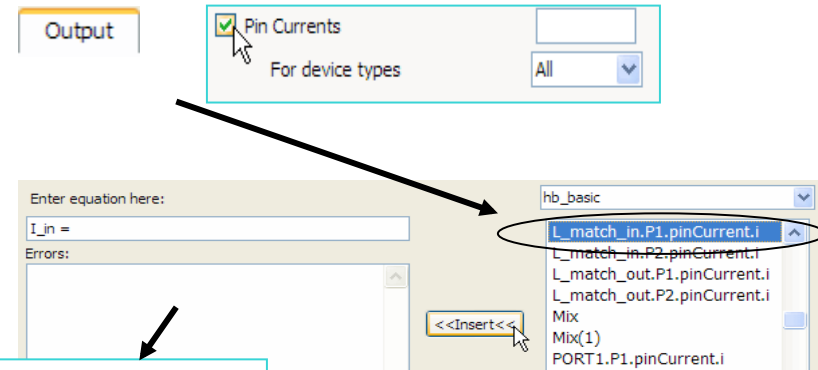
Equation uses Vout[1]



Next, simulate Power Delivered and Zin

Simulation Controller Output tab: check box and simulate = Pin Currents available in dataset (use instead of a current probe).

I_{in} = input current at 1900 MHz [1] and can now be used with $V_{in}[1]$ to calculate power and impedance Z :



$$\text{Eqn } I_{in} = L_match_in.P1.pinCurrent.i [1]$$

$$\text{Eqn } Z_{in} = V_{in}[1] / I_{in}$$

| Z_{in} |
|----------------|
| 47.619 / 0.686 |

Z_{in} at 1900 MHz is complex value. Also, Z_{in} is used in dBm argument instead of default of 50.

| $\text{dBm}(V_{in}[1], Z_{in})$ | $\text{dBm}(V_{in}[1])$ | P_del_dBm |
|---------------------------------|-------------------------|---------------|
| -40.003 | -40.214 | -40.003 |

P_del_dBm : delivered power at the input for 1900 MHz where 0.5 is for 1/2 peak value and +30 is for dBm (ref to 0.001 W):

$$\text{Eqn } P_del_dBm = 10 * \log(0.5 * \text{real}(V_{in}[1] * \text{conj}(I_{in}))) + 30$$

XDB and power swept compression

2 ways to simulate gain compression using HB

GAIN COMPRESSION

XDB
HB2
Freq[1]=1900 MHz
Order[1]=3
GC_XdB=1
GC_InputPort=1
GC_OutputPort=2
GC_InputFreq=1900 MHz
GC_OutputFreq=1900 MHz

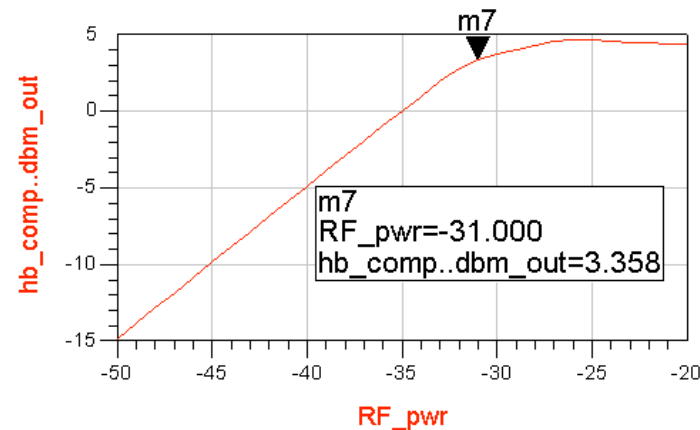
1 dB

| hb_xdb..inpwr[1] | hb_xdb..outpwr[1] |
|------------------|-------------------|
| -30.671 | 3.498 |

XDB can be set up very quickly for almost any circuit!

HARMONIC BALANCE

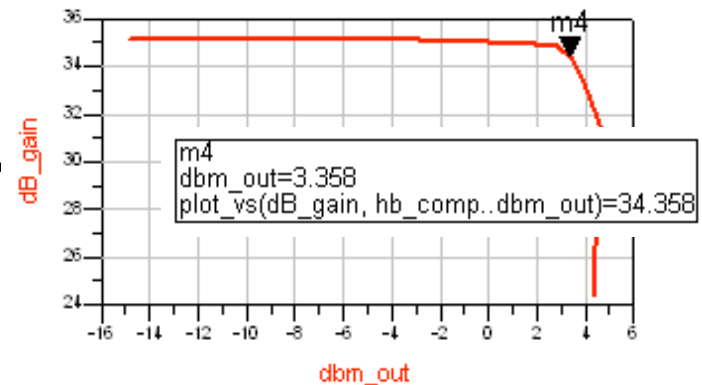
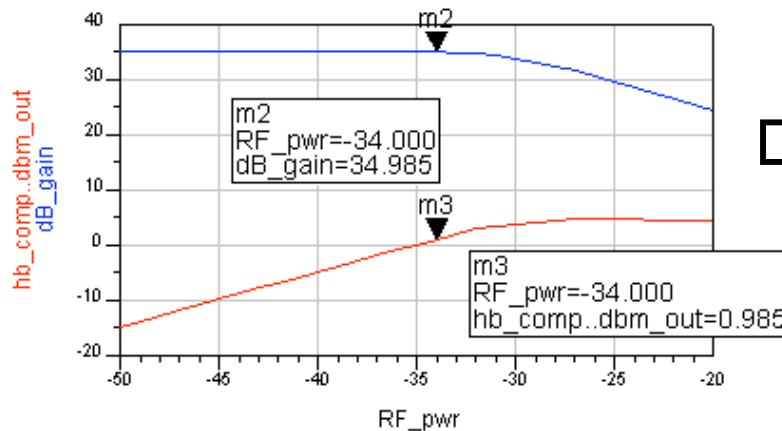
HarmonicBalance
HB1
Freq[1]=1900 MHz
Order[1]=3
SweepVar="RF_pwr"
Start=-50
Stop=-20
Step=1



Write equations using swept power data

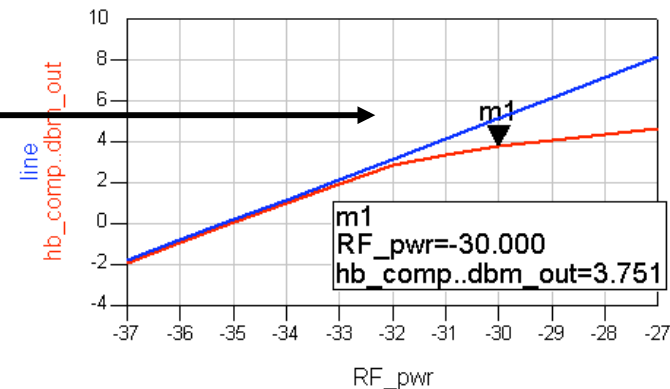
Eqn $\text{dB_gain} = \text{hb_comp}.\text{dbm_out} - \text{hb_comp}.\text{RF_pwr}$

Plot_vs function



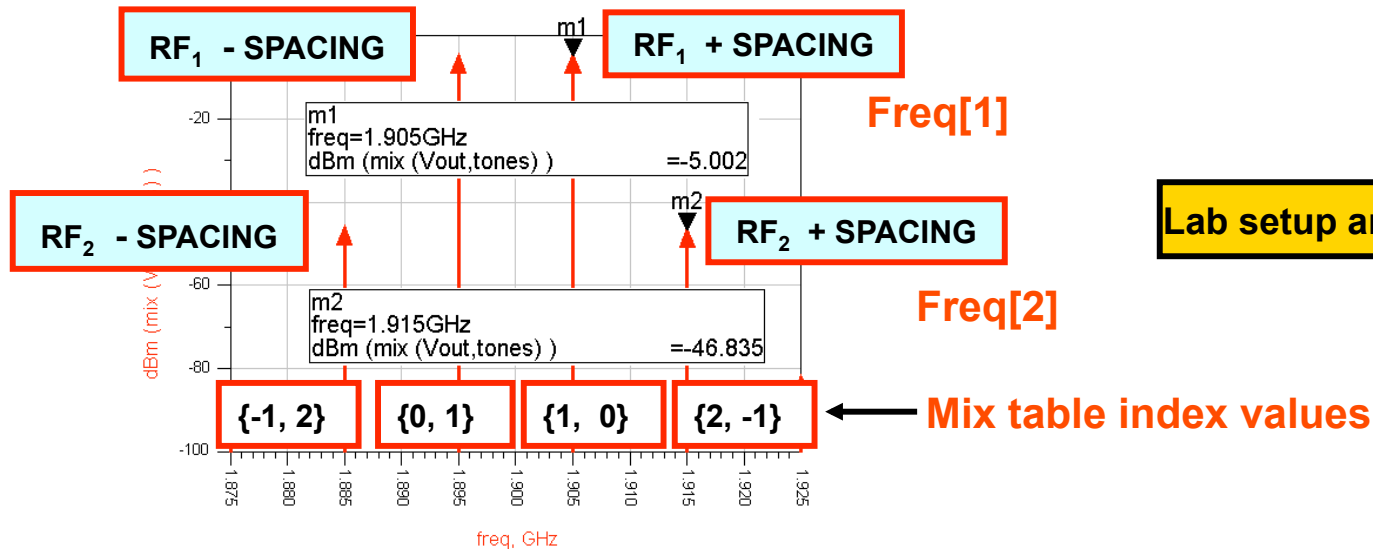
Create a line: nonlinear to linear

Eqn $\text{line} = \text{hb_comp}.\text{RF_pwr} + \text{dB_gain} [0]$



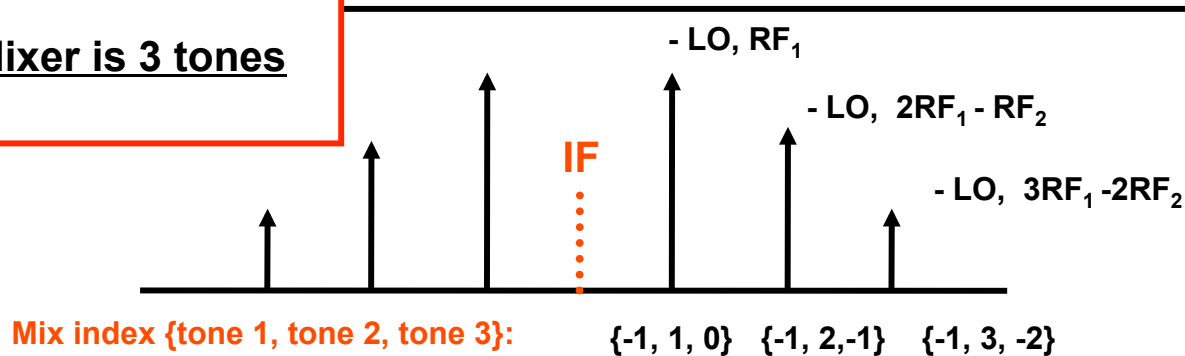
Simulating closely spaced tones...

Use 2 tones, such as RF +/- spacing (VAR)




Lab setup and data

Mixer is 3 tones



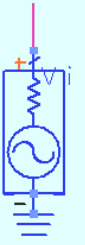
Two-tone HB simulation, data, DDS equation


HARMONIC BALANCE

Var Eqn

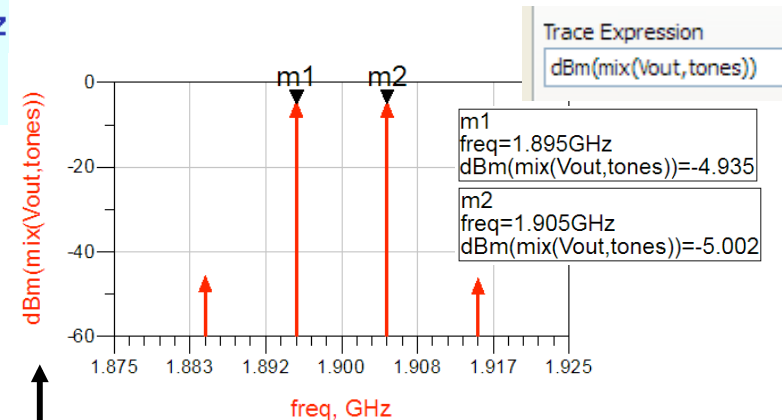
VAR
VAR1
Vbias=5 V
RF_freq=1900 MHz
RF_pwr=-40
spacing=10 MHz

HarmonicBalance
HB1
MaxOrder=8
Freq[1]=RF_freq + spacing / 2
Freq[2]=RF_freq - spacing / 2
Order[1]=4
Order[2]=4



P_nTone
nRF_source
Num=1
Z=50 Ohm
Freq[1]=RF_freq + spacing / 2
Freq[2]=RF_freq - spacing / 2
P[1]=dbmtow(RF_pwr)
P[2]=dbmtow(RF_pwr)

Spacing @ 10 MHz =
1.895 and 1.905 GHz



Eqn tones generates the index values!

Eqntones=[{1,0},{0,1},{2,-1},{1,-2}]

Traces

Trace Options...

dBm(Vout)

Trace Options: 1

Trace Type
Trace Options
Plot Axes
Trace Expression

Select Type

Auto

Bus

Linear

Scatter

Spectral

Histogram

Digital

Sampled

Density

Trace Expression

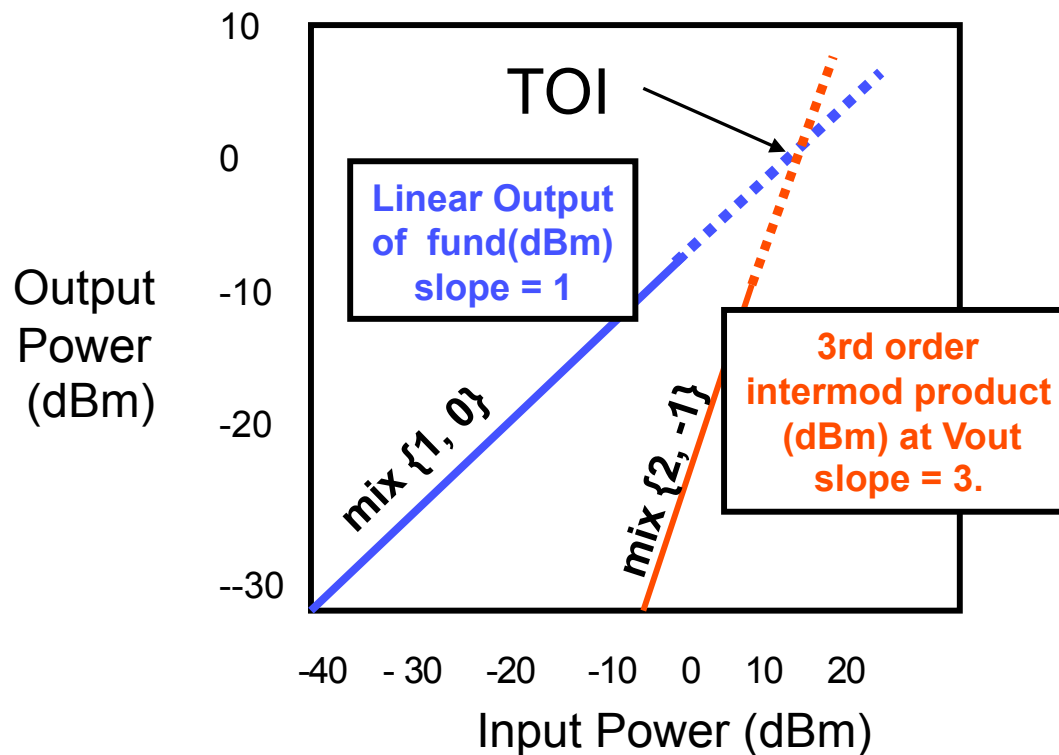
dBm(mix(Vout, tones))

Use [brackets to generate a matrix] and { curly braces to vector the data from Mix table}



TOI or IP3 Measurement

When the input power drives the non-linear device into saturation or distortion, third order products near the desired frequency can become large. The point at which 3rd order products intercept the linear rise in output power is the intercept point TOI or IP3.



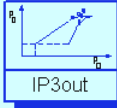
A measurement equation is used to get the answer...

Lab setup and data

NOTE for mixer 3 tones use:
mix{-1,1,0}
mix {-1, 2, -1}

TOI simulation setup using IP3 equations

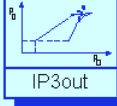
Built-in measurements use functions - you set the arguments.



IP3out

ipo_upper


upper_toi=ip3_out(Vout,{1,0},{2,-1},50)



IP3out

ipo_lower

lower_toi=ip3_out(Vout,{0,1},{-1,2},50)



HARMONIC BALANCE

HarmonicBalance

HB1

MaxOrder=8

Freq[1]=RF_freq + spacing / 2

Freq[2]=RF_freq - spacing / 2

Order[1]=4

Order[2]=4

2-tone Mix HB data

| | | |
|----------|----|----|
| 1.885GHz | -1 | 2 |
| 1.895GHz | 0 | 1 |
| 1.905GHz | 1 | 0 |
| 1.915GHz | 2 | -1 |

Result of IP3
eqns in DDS:

| lower_toi | upper_toi |
|-----------|-----------|
| 15.679 | 15.914 |

MIXERS: use this setup for 3 tone TOI.

HarmonicBalance
HB1
MaxOrder=10
Freq[1]=LO_freq
Freq[2]=RF_freq + f_spacing / 2
Freq[3]=RF_freq - f_spacing / 2
Order[1]=7
Order[2]=3
Order[3]=3

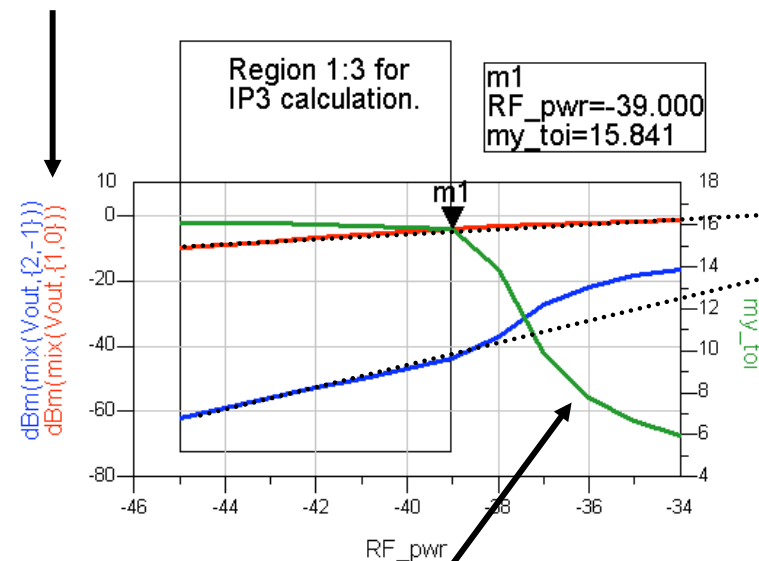


OPTIONAL: Sweep RF pwr vs TOI equation

Compare swept values to values in the TOI measurement range:

```
HARMONIC BALANCE
HarmonicBalance
Two_Tone
MaxOrder=8
Freq[1]=RF_freq + spacing / 2
Freq[2]=RF_freq - spacing / 2
Order[1]=4
Order[2]=4
SweepVar="RF_pwr"
Start=-45
Stop=-30
Step=1
```

Swept values used for IP3



Theoretical output power referred intercept point is approximately: -16 dBm.

Eqn my_toi = ip3_out(Vout,{1,0},{2,-1},50)

The Eqn, **my_toi**, is on the right Y axis.
When RF_pwr is greater than -39dBm, RF and third order slopes are no longer 1:3.

NOTE : The Extra Exercise is for HB with swept frequency!

