

This chapter shows how to use Harmonic Balance for two-tone measurements such as TOI, NF, and others.

Lab 7: Advanced Harmonic Balance Mixer Simulations

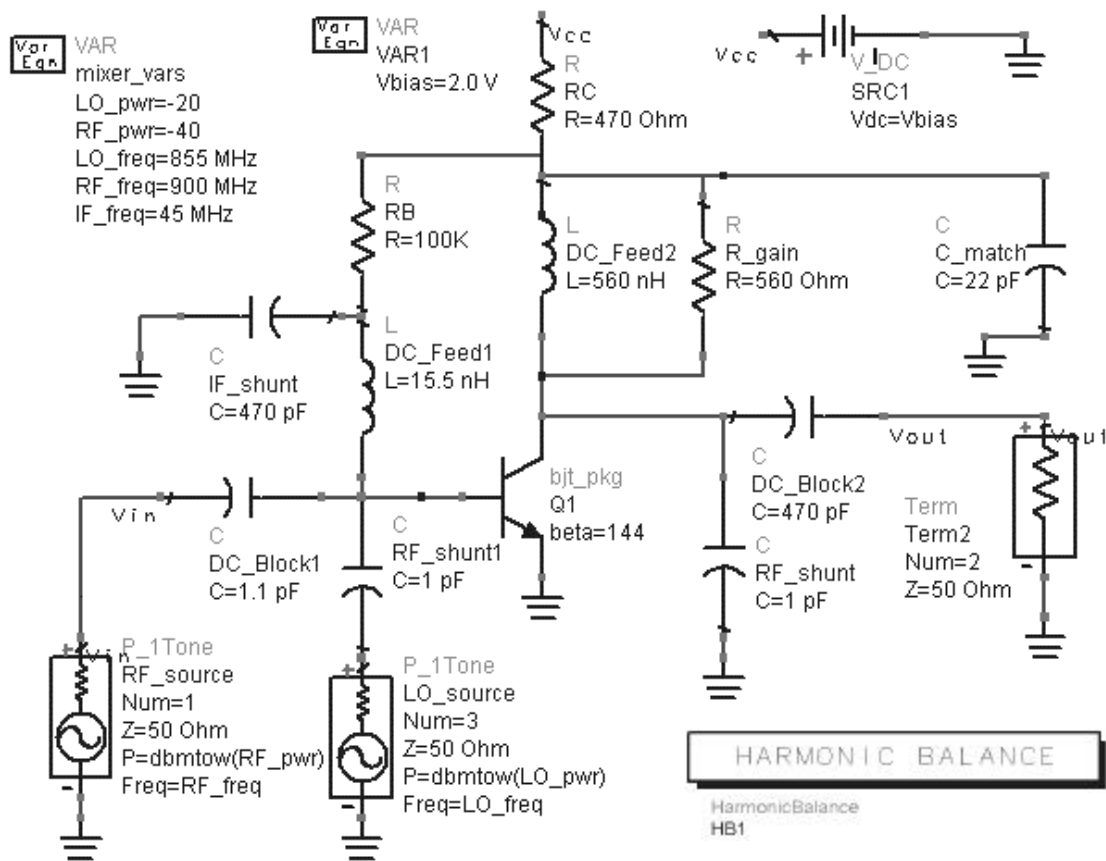
OBJECTIVES

- Perform more 2 tone simulations: TOI (IP3)
- Sweep LO power vs. NF and IF power
- Use functions and variables to control simulations and data

PROCEDURE

1. Create the schematic

- Save the last lab (hb_comp) with a new name: **hb_toi**
- Start with the schematic shown here from the previous lab - you can also keep the HB controller and VAR equation block but they will be modified during this lab:



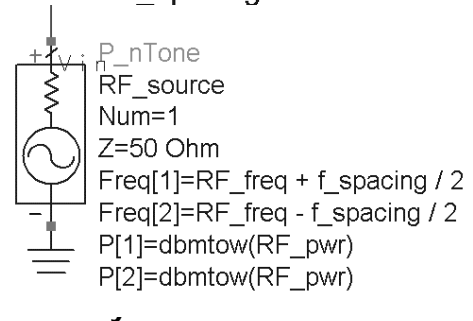
2. Modify the VAR block

For this lab, set up the following variable equations on the VAR block to initialize the values needed for the IP3 or TOI (third order) variable **f_spacing** is used to separate the 2 RF tones:

Var	Eqn	VAR	Il
		mixer_vars	he
		LO_pwr=-20	
		RF_pwr=-40	
		LO_freq=855 MHz	
		RF_freq=900 MHz	
		f_spacing=20 kHz	

3. Modify the RF source

Change the RF source to a P_nTone source as shown (specify any number of tones and their specific power) and add Freq[2] and power P[2]. Notice that the 10 KHz offset spacing from the RF, so the actual spacing is 10 KHz.



4. Set up the HB controller

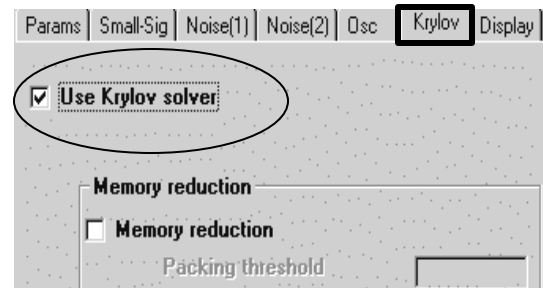
- Set the HB controller as shown here – you will need to **add the extra freq tones** and **to turn on** (shortens simulation time).
- In the HB controller **Display tab**: turn on the annotation shown. The SweepVar will not be used now but it will be used later. Be sure to turn on the **Other** setting and then type in the **Other=OutVar= "RF_pwr"** on the screen. You are using this feature to allow the RF_pwr variable to be sent to the dataset. **NOTE: Be sure to remove the sweep variable from the last lab if you copied this controller.**

HARMONIC BALANCE

```

HarmonicBalance
HB1
MaxOrder=9
Freq[1]=LO_freq
Freq[2]=RF_freq + f_spacing / 2
Freq[3]=RF_freq - f_spacing / 2
Order[1]=7
Order[2]=4
Order[3]=4
UseKrylov=yes
SweepVar=
Start=
Stop=
Step=
Other= OutVar = "RF_pwr"

```



Check these items in the Display Tab in the controller,

5. Set up the IP3out measurement equation (TOI)

IP3out is a built-in measurement equation that automatically computes the third order intercept point (TOI) as output power. This is one of several built-in measurement equations that operate with similar arguments and syntax. By learning to use this one, you will be able to use others. For this lab, you will use two IP3out equations – one for each of the two tones.

- a. From the HB palette, insert the built-in IP3out (Intercept Point 3rd order Output). Notice that the function requires a node voltage, indices for the mix function, and a reference impedance value of 50 ohms.



Meas
Eqn IP3out

ipo1

our_ipo=ip3_out(vout,{1,0},{2,-1},50)

NOTE: To read more about this function, edit the measurement equation and click the Help button. Close the Help box when you have finished.

- b. Edit the equation in the dialog or on the screen. Editing on the screen is usually faster in most cases. Rename the left hand side of the equation and type in the values shown where hi_toi represents the higher spaced tone (RF_freq + spacing/2). Note that **Vout** is a named node and must be spelled exactly like the node name (case sensitive means V is capitalized as in your schematic). The indexing of the mix function data will generate two tones: the IF and the 3rd order product. These are the same curly braces used before, except that now you have three frequencies to deal and two indices separated by commas:

Meas
Eqn IP3out

hi_toi

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

- c. Copy the equation using **Ctrl C** and set it up for the low side tone:

Meas
Eqn IP3out

lo_toi

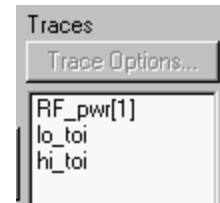
lo_toi=ip3_out(Vout,{-1, 0,1},{-1,-1,2},50)

6. Simulate and display the results

After the simulation is finished, open a new data display and insert a list with the results as shown:

- Add the two TOI values: lo and hi
- Add the outvar at one point: RF_pwr[1]
- Remove the check for: Display Indep Data
- Title the plot similar to the one shown here

123 4
567 8



☐ Display Indep. Data

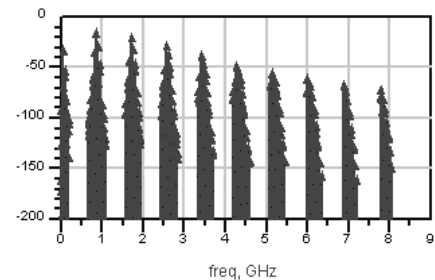
Two tone 3rd order intercept values at the output

hi_toi	lo_toi	RF_pwr[1]
-11.438	-11.384	-40.000

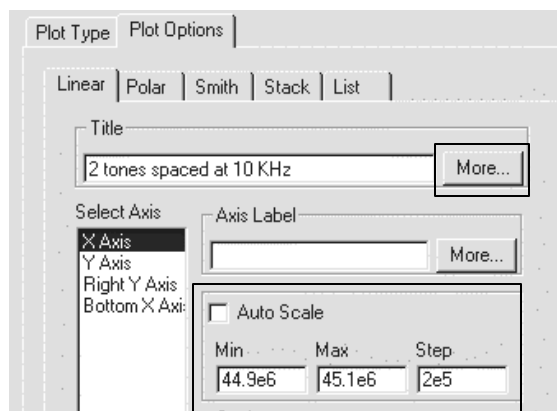
← Your list should look like this one.

7. Plot the spectrum of Vout in the band of interest

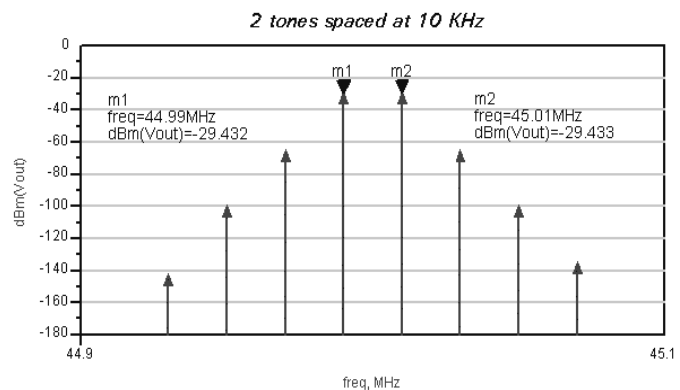
- Put the Vout data in dBm and you will see the inter-modulation products (max order) generated by the two-tone simulation.
- However, to see the tones of interest, use **Plot Options** and remove (uncheck) the Auto Scale feature from the X-axis. Enter a range of: **44.9e6** to **45.1e6**. This will scale the plot and you can add markers to the tones of interest. Also, try labeling the plot with a different font (**More** button) and position the markers text inside the grid as shown:



8. Data display calculations using expressions



Your plot should look like this:



This step shows you a more refined way to use the data display by setting up equations that pass values to expressions. In this case, you only use the curly braces in the equation one time. Also, you can apply this technique of passing values for other data display calculations.

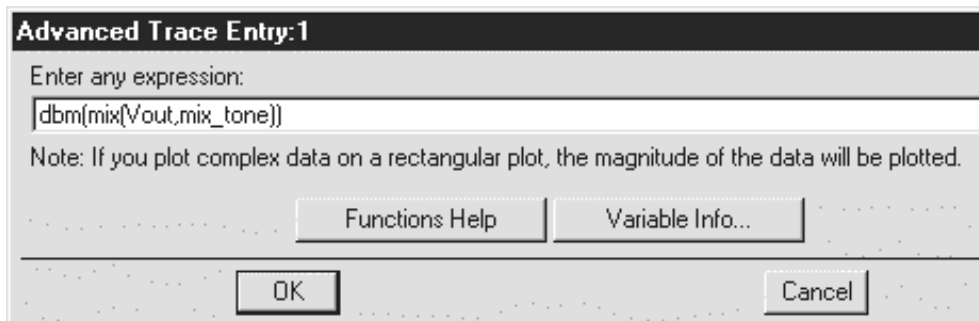
- a. In the current data display, write an equation that describes the index position of the lower IF product that appears in the mix data:

Eqn mix_tone={-1,0,1}

- b. **Insert a list** and when the dialog appears, click the **Advanced...** button.

Advanced...

- c. When the Advanced Trace dialog appears, write an expression to give the value in dBm of the mixing tone in your equation. Remember that this is different than listing an equation or editing a trace value. Here, you are writing the expression and you are passing the value from your equation (mix_tone) into the expression. This is one of the powerful data index capabilities in ADS: **dbm(mix(Vout, mix_tone))**.



After you click OK, you should see the data appear in a list along with the independent variable freq. Note that this is exactly the same data that appeared on the narrow spectrum you plotted in the previous major step.

freq	dbm(mix(Vout,mix_tone))
44.99MHz	-29.432

- d. Go back to the equation (mix_tone) and change the value to another frequency and notice that the list value is automatically updated.

Eqn mix_tone={-1,2,1}

freq	dbm(mix(Vout,mix_tone))
1.845GHz	-70.533

9. Sweep the LO power

- Edit the Harmonic Balance controller to sweep the variable **LO_pwr** from **-20 to 0 dBm in 4 dBm steps**.
- Set the **MaxOrder = 5** and set **Order = 3** for each of the three tones as show here.
- Setup a new dataset name: **hb_lo_swp** and **Simulate**.
- When the simulation is finished, copy the spectral tone plot of Vout (titled: 2 tones spaced at 10 KHz) using **Ctrl C / Ctrl V** and edit the **Trace Options** in the copied plot as follows:

HARMONIC BALANCE

```

HarmonicBalance
HB1
MaxOrder=5
Freq[1]=LO_freq
Freq[2]=RF_freq + f_spacing / 2
Freq[3]=RF_freq - f_spacing / 2
Order[1]=3
Order[2]=3
Order[3]=3
UseKrylov=yes
SweepVar="LO_pwr"
Start=-20
Stop=0
Step=4
Other= OutVar = "RF_pwr"

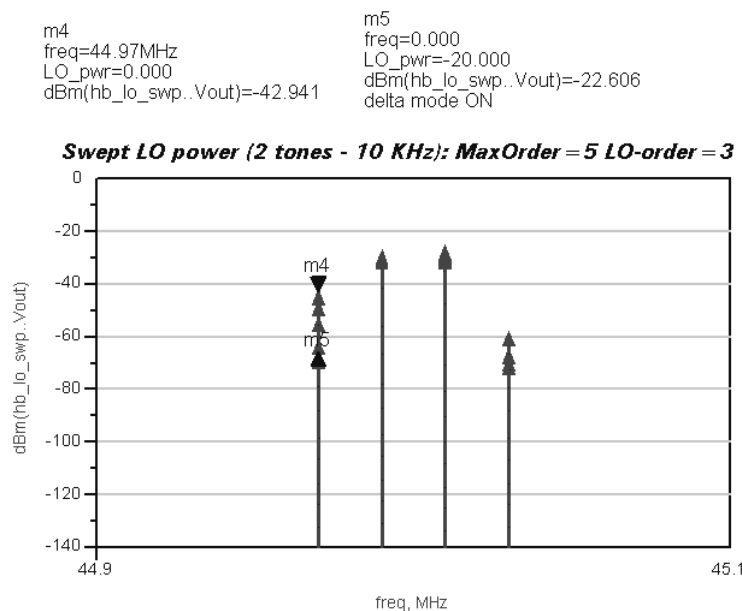
```

- In front of the Vout node name, type in the name of the dataset followed by **two dots**. This double dot operator is used in ADS to explicitly name the dataset path. In summary, your Trace Expression is: **dbm (hb_lo_swp..Vout)**

Trace Expression

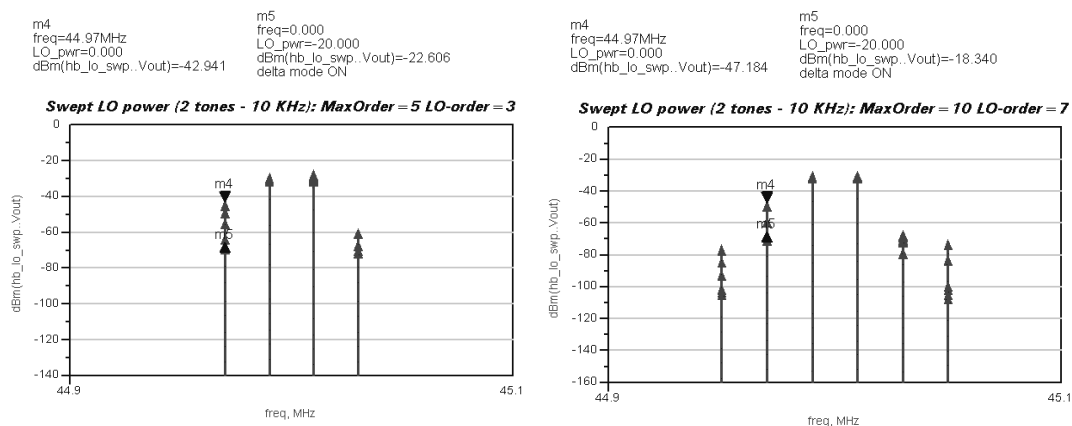
```
dbm(hb_lo_swp..Vout)
```

- Put markers on the swept power points 0 and -20 dBm which can be a little difficult. Then use marker Delta mode to show the difference which is about 22.6 dBm (shown here) for the lower 3rd order product:



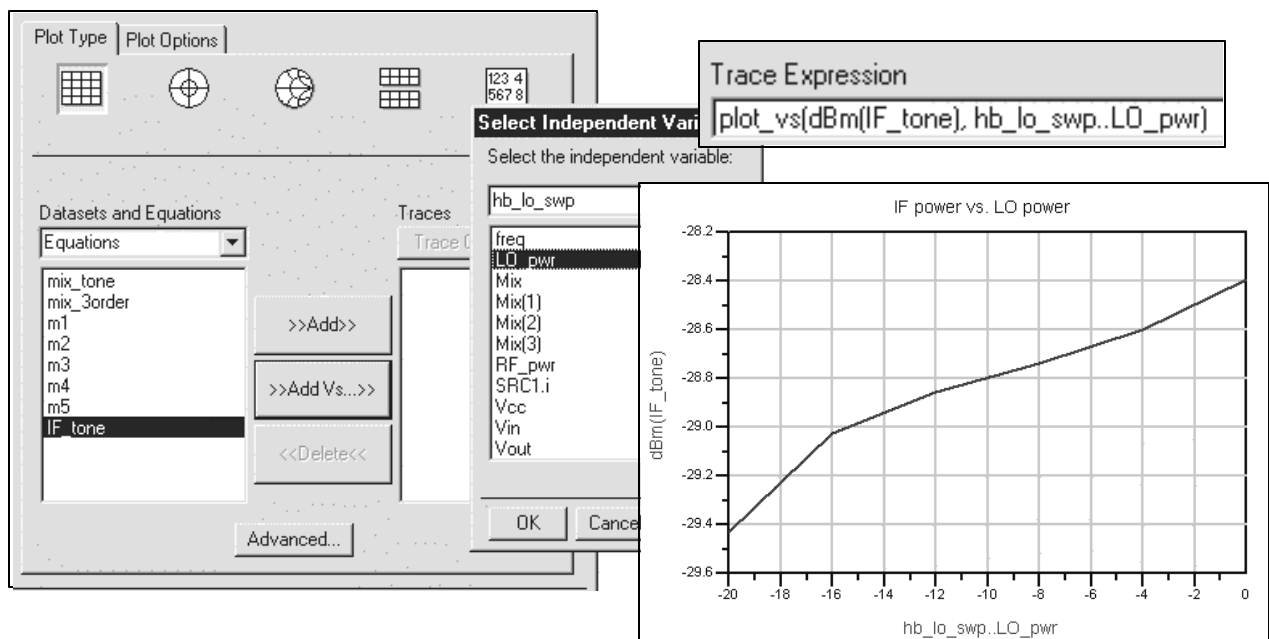
Non-symmetrical results may be due to max order or LO order set too low in simulation.

- e. **Increase the LO order = 7 and Max Order = 10** on the simulation controller and **Simulate** again. Immediately bring up the data display and watch the plot update - you may have to adjust the markers. Comparing the 3rd order products in the two simulations, you can see that the HB settings, Order and MaxOrder, have an effect on the data. However, with larger circuits this will take more computation time and in those cases, the Krylov solver should be used.



- f. **Plot IF power vs. LO power – this step will test your skills in using the data display:** write an equation for an IF product and pass that value to the mix function - then plot it versus (vs) LO power. The dialogs and the final Trace Expression are shown here. Note that the **plot_vs** feature in ADS is always: Y axis vs X axis:

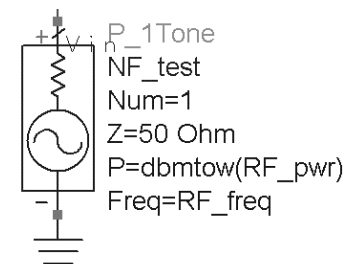
Eqn IF_tone=mix(hb_lo_swp..Vout, {-1,0,1})



10. Simulate NF (Noise Figure)

The NF (Noise Figure) measurement calculates the noise contributed by circuit for the given input frequency (RF). It does not account for image noise for frequency conversion. The calculation assumes a two port circuit and calculates the conversion gain according to the ports and frequencies you specify. In the following steps you will replace the two-tone RF source with a single tone which will require modifying the HB controller. Also, you will still sweep LO power and, after the simulation, plot NF vs. LO power on the same plot as the last step – this means you will see two Y axis components vs LO power.

- Deactivate** and **disconnect** the **RF source** and replace it with an RF source as shown here. The LO source remains from the last step.
- Deactivate** the current two-tone HB controller and set up a new HB controller as shown here – you can copy the other one if desired and modify it as shown here. To simplify the measurement and avoid any image frequencies mixing to the IF, set the **RF to Order[2] = 1**.



HARMONIC BALANCE

HarmonicBalance

HB_NF_test

MaxOrder=7

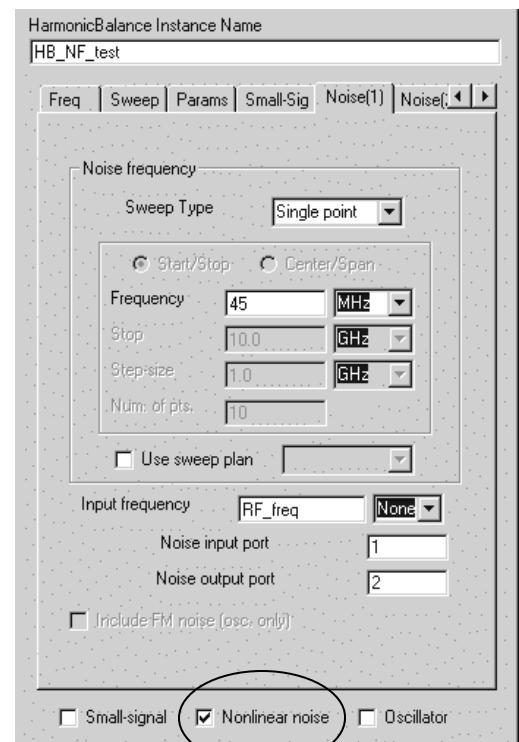
Freq[1]=LO_freq

Freq[2]=RF_freq

Order[1]=7

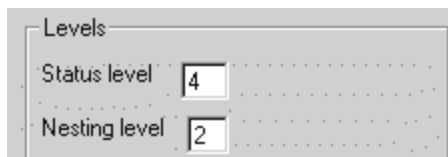
Order[2]=1

- Edit the HB controller and notice that there are tabs for Noise(1) and Noise(2). First, go to the **Noise(1)** tab. Click the box to activate the Nonlinear Noise measurement.
- In this tab, set the noise frequency sweep type to Single point and set the Noise frequency to 45 MHz. The Input Frequency is the RF variable with ports 1 and 2 corresponding to the RF input and IF output.



- e. Go to the Noise(2) tab. Add the **Vout** node which will give you the noise contributed at that point. Also, use **Sort by value** for the results. The Dynamic range is used mostly for large circuit. Check the box for using all small-signal frequencies – this will use all the side-band tones from the LO. Also, 1 Hz is the standard bandwidth for noise. Be sure to click the Apply / OK button as usual.

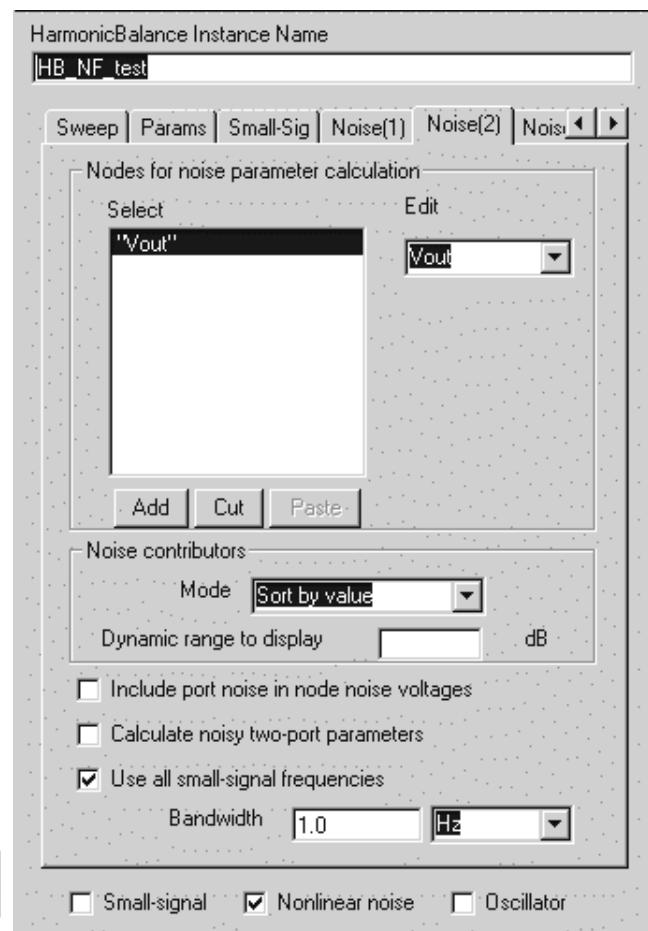
- f. In the HB controller **Params Tab**, set the status level to **4** as shown here so that the simulator will output the NF and other values to the Status window. This way you do not have to list the value in the Data Display. Also, turn of f Krylov.



HARMONIC BALANCE

```

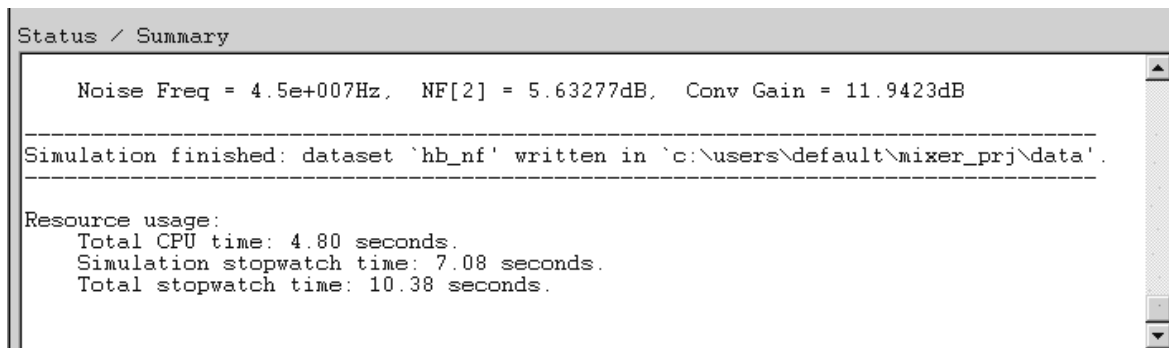
HarmonicBalance
HB_NF_test
MaxOrder=7
Freq[1]=LO_freq
Freq[2]=RF_freq
Order[1]=7
Order[2]=1
UseAllSS_Freqs=yes
InputFreq=RF_freq
FreqForNoise=45 MHz
NoiseInputPort=1
NoiseOutputPort=2
SweepVar="LO_pwr"
Start=-20
Stop=0
Step=4
    
```



- g. Finally, in the **Sweep** tab, set the LO power sweep like the previous simulation (shown here): **Start = -20, Stop=0, and Step=4.**
- h. Check the circuit and be sure to deactivate the IP3 equations if they are on the schematic.

11. Set up the dataset name and Simulate

- Set up a dataset name: **hb_nf**. Then position the Status window so you can see it – then **Simulate**.
- The results should be similar to those shown here. If you scroll up, you will get the values of NF and Conv Gain.



NOTE on noise warning messages: If the noise frequencies are the same as the HB simulation frequencies, you may get a warning message that can be disregarded. Or, simply offset the noise frequencies by a small amount.

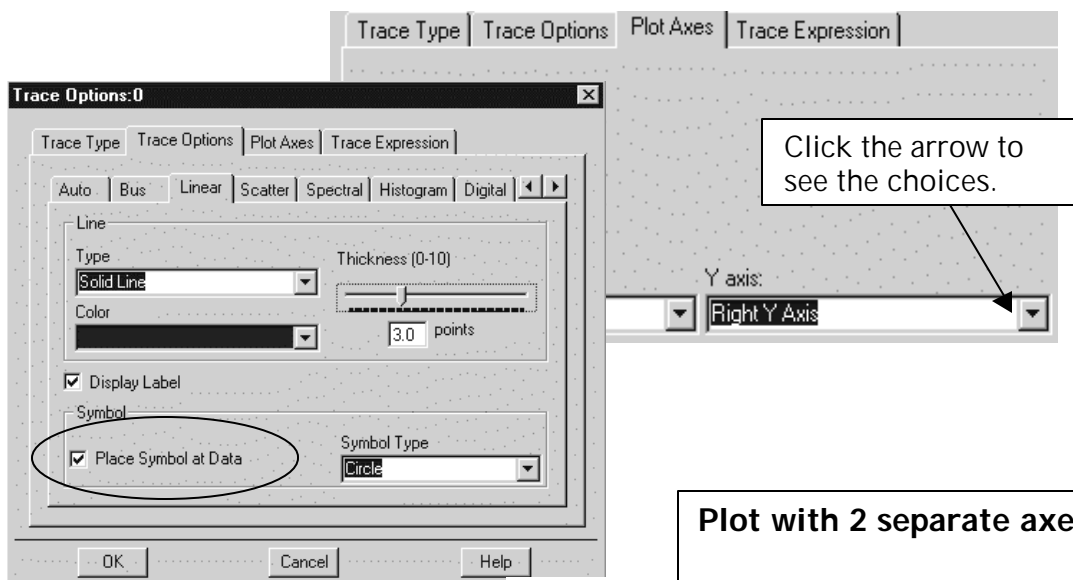
- Go to the data display and list the circuit noise contribution values for port 2 (specified in the controller) and the name so that you can identify them.

hb_NF..port2.NC.vnc	hb_NF..Vout.NC.name
LO_pwr=-20.000, noisefreq=45.00MHz	
1.257nV	total
1.173nV	Q1.BJT1
1.023nV	Q1.BJT1.ibe
574.2pV	Q1.BJT1.ice
318.8pV	RC
292.6pV	R_gain
131.3pV	RB
LO_pwr=-16.000, noisefreq=45.00MHz	
1.315nV	total
1.236nV	Q1.BJT1
1.097nV	Q1.BJT1.ibe
568.4pV	Q1.BJT1.ice
318.8pV	RC
292.6pV	R_gain
126.1pV	RB
LO_pwr=-12.000, noisefreq=45.00MHz	
1.358nV	total
1.282nV	Q1.BJT1
1.151nV	Q1.BJT1.ibe
563.4pV	Q1.BJT1.ice

- d. In the data display, go to the existing plot of the IF_tone vs. LO_power. Edit that plot, access the **hb_nf** dataset, and add the **nf (2)** data vs. LO_pwr to the plot. The trace expression is shown here:

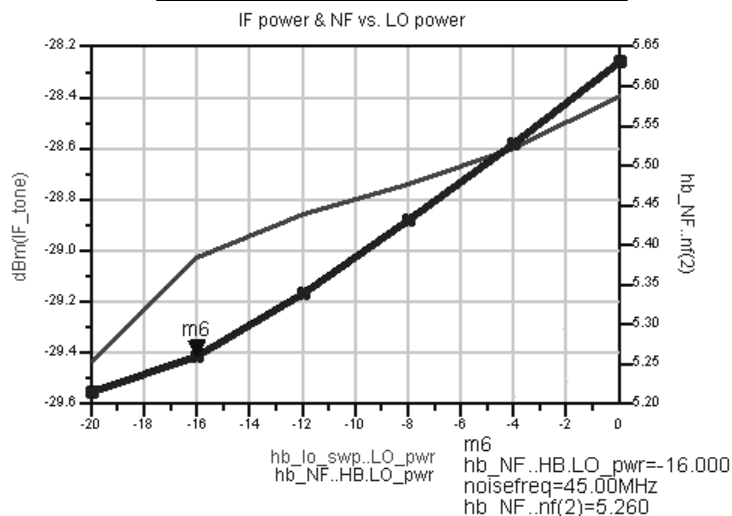
Trace Expression
`plot_vs(hb_NF..nf(2), hb_NF..HB.LO_pwr)`

- e. Now, edit the Trace and go to the Plot Axes tab. Set the Y axis as shown so that it uses a separate **Right Y axis** and click OK. You can also edit the trace so that it has a circle symbol at each point. The plot should look like the one here. Now, swept LO power is on the X axis and IF power and noise figure are on the two Y axes.



Plot with 2 separate axes

Mixer Design Note: At this point, the circuit should have met the NF specification of 6dB or better. However, there is still a lot of LO feed-through.



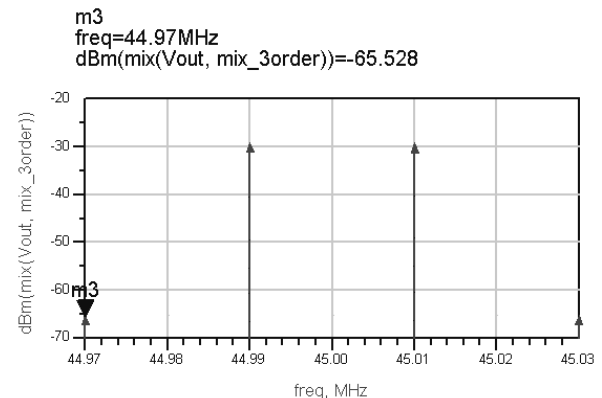
EXTRA EXERCISES:

1. In the TOI measurement, change the spacing, simulate, and notice any differences. Or, modify the equation for up conversion!
2. Perform an IP3in simulation. Insert the IP3in measurement equation and edit it similar to the IP3out, except that the second argument of the conversion gain is required. Here, the default is 0, but you need to enter the value in dB: use 10 or 11.

Meas IP3in
Eqn
ipi1
our_ipi=ip3_in(vout,0,{1,0},{2,-1},50)

Eqn mix_3order=[{-1,0,1},{-1,-1,2},{-1,1,0},{-1,2,-1}]

3. Try writing an equation to pass all the 3rd order products to a spectral plot. Then change the f_spacing to 30 KHz and simulate. Afterward, modify the equation to pass the 5th order products.



4. Insert a node name at the BJT collector and set the Noise(2) control to measure the noise at the device output at that point.
5. Perform a Harmonic Balance small signal analysis with noise and compare the results.
6. Try using a NoiseCon (Noise Controller) and use the HB NoiseCons tab. Do not set NLnoise in the HB controller. Also, insert an oscillator with phase noise in place of the LO but do not sweep the LO power.



OSCwPhNoise
OSC1
Freq=LO_freq
P=dbmtoW(LO_pwr)
Rout=50 Ohm
PhaseNoise=list(10 Hz, -40, 100 Hz, -60, 1 KHz, -80, 100 KHz, -120,

HB NOISE CONTROLLER

NoiseCon
NC1
InputFreq=RF_freq
FreqForNoise=IF_freq
NoiseInputPort=1
NoiseOutputPort=2
NoiseNode[1]=Vout

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