Stability for Op Amps
Part 2 of 15: Op Amp Networks, SPICE Analysis

Tim Green, Strategic Development Engineer, Burr-Brown Products from Texas Instruments

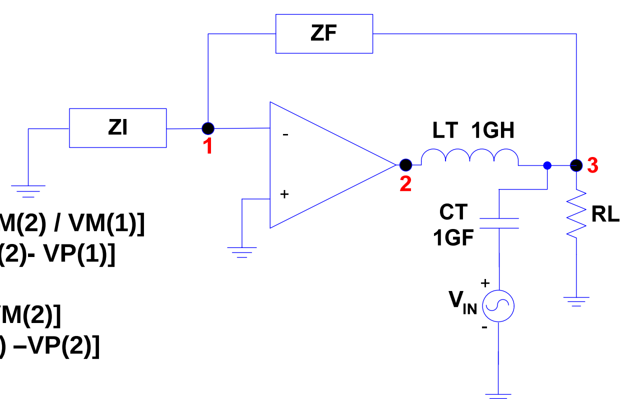
2.0 Introduction

Part 2 of this series focuses on analyzing op amp circuits for stability with a special emphasis on two common op amp networks. It is important first to perform 1st Order Analysis (hand analysis using mostly the thing between your ears) before moving on to SPICE simulation. Remember that GIGO (Garbage In Garbage Out) can result from circuit simulation programs if you do not know what you are looking before simulation. The SPICE Loop Gain Test technique will be presented which allows easy Bode plotting of Aol curves, 1/B curves, and Loop Gain curves. Also, an easy-to-build AC SPICE model for an Op Amp will be presented which allows for any op amp circuit to be quickly analyzed for AC stability.

Within this entire series we will be analyzing op amp circuits and presenting results using a versatile SPICE simulation software called TINA. Often we will refer to this as Tina SPICE. At www.designsoftware.com various versions of it can be previewed. Although some of the SPICE tricks presented are specific to TINA you will probably find that other SPICE simulators you use may also benefit from these shortcuts.

2.1 SPICE Loop Gain Test

The SPICE Loop Gain Test is detailed in Figure 2.0. LT provides a closed loop circuit for DC since every AC SPICE analysis requires a DC SPICE analysis. During an AC SPICE analysis, as frequency increases, CT becomes a short and LT becomes an open. With one SPICE run all information for AC stability can be obtained. Op Amp Aol, Loop Gain, and 1/β magnitude and phase plots are easily obtained from SPICE post-processing by using the equations as detailed in Figure 2.0. Although there are other techniques applicable to “break the loop” for an AC Analysis in SPICE the technique shown in Figure 2.0 has proven to be the least error-prone and least subject to mathematical nuances inside of SPICE.



Op Amp Aol Gain = dB[VM(2) / VM(1)]
Op Amp Aol Phase = [VP(2)- VP(1)]

Loop Gain = dB[VM(3) / VM(2)]
Loop Gain Phase = [VP(3) –VP(2)]

1/β = dB[VM(3) / VM(1)]
1/β Phase = VP(3) – VP(1)

Figure 2.0 SPICE Loop Gain Test

2.2 Op Amp Networks and 1/β

Two common op amp networks, ZI and ZF are shown in Figure 2.1. We will perform a 1st Order Analysis on each of these networks independently and then use Tina SPICE to simulate the op amp circuit and check if our predicted results agree! The key to our 1st Order Analysis will be to use our Intuitive Component Models from Part 1 of this series and a little intuition.

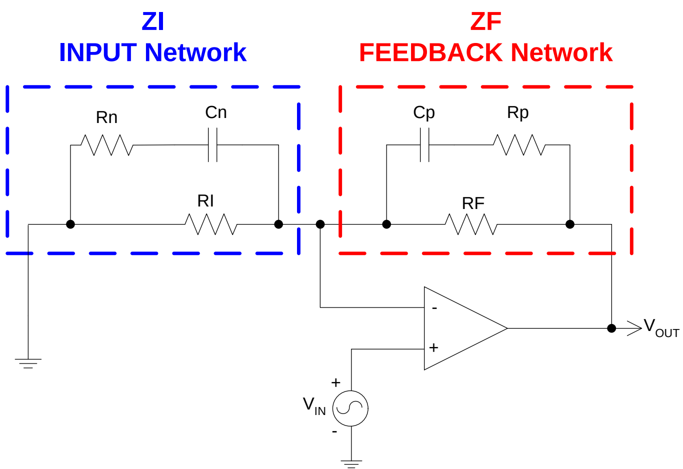
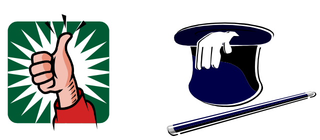
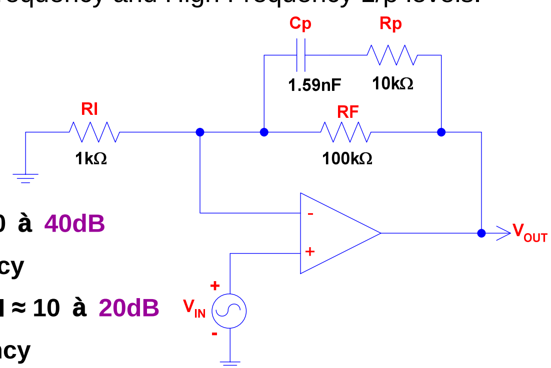


Figure 2.1 Two Common Op Amp Networks: ZI & ZF

2.2 Op Amp Network ZF

Let's perform our 1st Order Analysis for the ZF network shown in Figure 2.2. This is a feedback network in the op amp circuit. Cp is open at low frequency and the Low Frequency 1/β becomes simply RF/RI as shown. At the other frequency extreme, high frequency, Cp is a short and the High Frequency 1/β becomes (Rp//RF)/RI. However, when Cp is a short Rp<<RF and Rp should dominate the feedback resistance and so we approximate high frequency gain to be Rp/RI. We note there is a reactive element in the feedback path of the op amp, a capacitor, and therefore know there has to be some poles and/or zeros somewhere in the transfer function. At the frequency where the magnitude of Cp matches that of the parallel impedance with it (dominated here by RF) we anticipate a pole in the 1/β plot. Feedback resistance will be getting smaller and therefore VOUT must start to reduce. Now the frequency where the magnitude of Cp matches that of the impedance in series with it, Rp, we expect a zero since as Cp approaches a short the net feedback resistance can become no smaller and VOUT must flatten out as frequency increases. So we have predicted by our 1st order analysis where a pole and zero exists as well as the Low Frequency and High Frequency 1/β levels.





Ø **1/β Low Frequency = RF/RI = 100 à 40dB**

Cp = Open at Low Frequency

Ø **1/β High Frequency = (Rp//RF)/RI ≈ 10 à 20dB**

Cp = Short at High Frequency

Ø **Pole in 1/β when Magnitude of X_{Cp} = RF**

Magnitude X_{Cp} = 1/(2·Π·f·Cp)

fp = 1/(2·Π·RF·Cp) = 1kHz

Ø **Zero in 1/β when Magnitude of X_{Cp} = Rp**

fz = 1/(2·Π·Rp·Cp) = 10kHz

Figure 2.2 1/β 1st Order Analysis for ZF

To check our 1st Order Analysis our circuit for ZF analysis was built in Tina SPICE as shown in Figure 2.3. VIN is set for a DC value of 0V and an AC Source option is selected with the AC Amplitude set to 1. Our AC Analysis is set up to run from 10Hz to 10MHz with 100 points of data and Amplitude & Phase data requested to be saved for Post-Processing purposes. To perform our "SPICE Loop Gain Test" we use L1, C1 and VIN with convenient Voltage Probes placed as N1, N2, and N3. By inspection of this circuit we see Aol = N2/N1 and 1/Beta = N3/ N1.

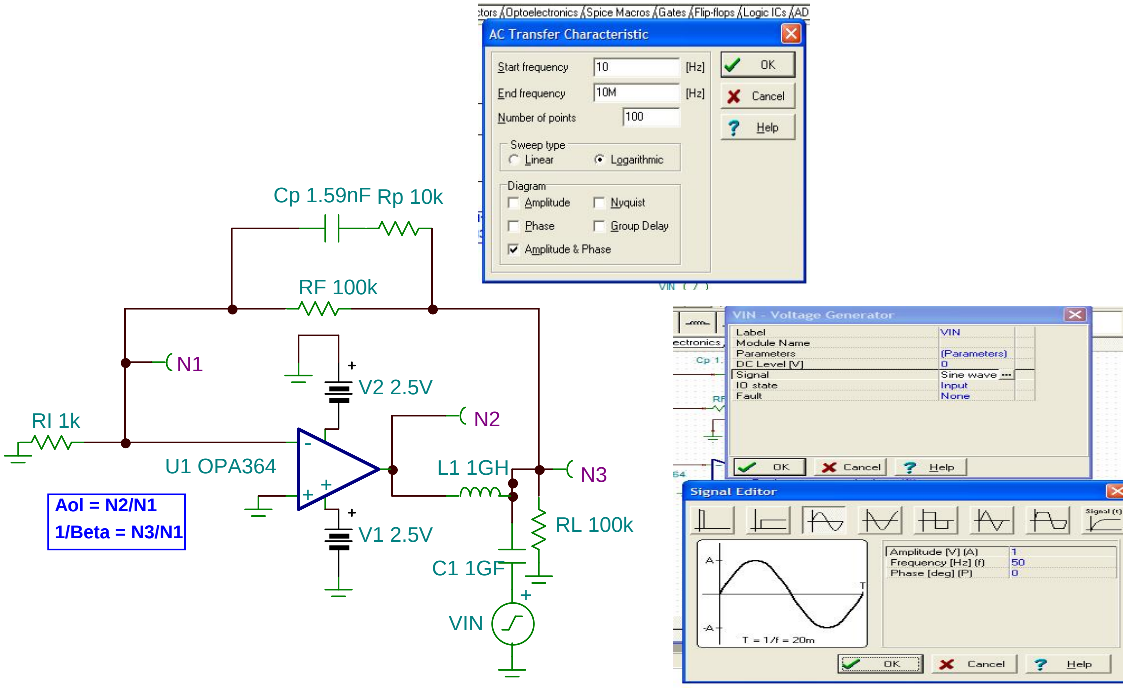


Figure 2.3 Tina SPICE Circuit for ZF Analysis

The "Default Results" of our Tina SPICE simulation are displayed in Figure 2.4. Not too valuable yet as we are interested in the 1/Beta Plot for ZF and the Op Amp Aol Curve.

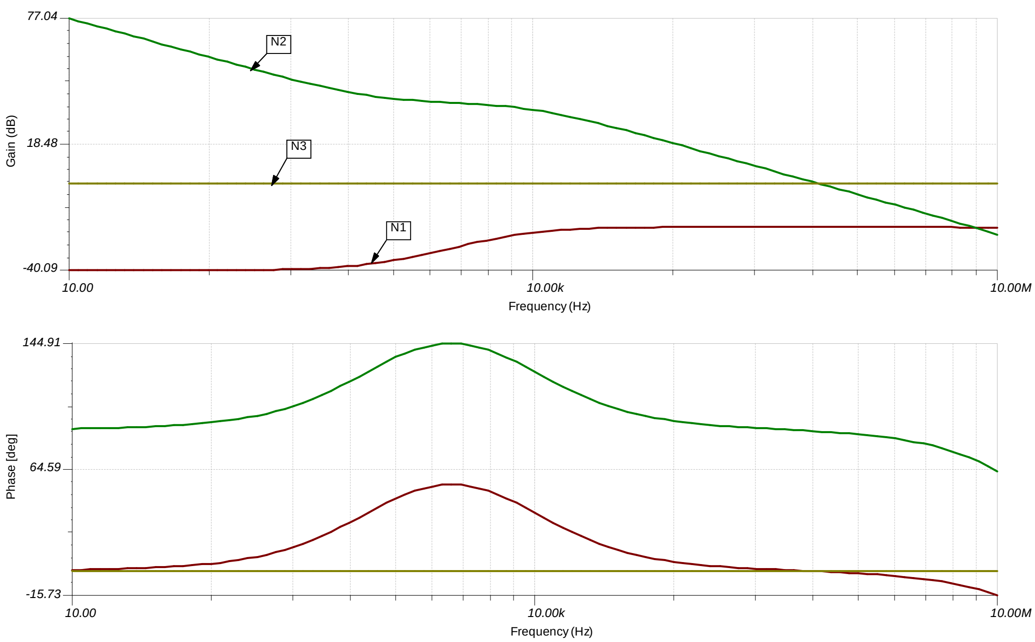


Figure 2.4Tina SPICE Default Results for ZF Analysis

So to obtain the desired plots we will perform "Post Processing Math" as shown in Figure 2.5. The User Defined function Aol has been assigned the math equation N2/N1 (for our Aol Plot) and Beta1 (so named because 1/Beta is not an accepted name in Tina SPICE) assigned the math equation N3/N1 (for our 1/Beta Plot).

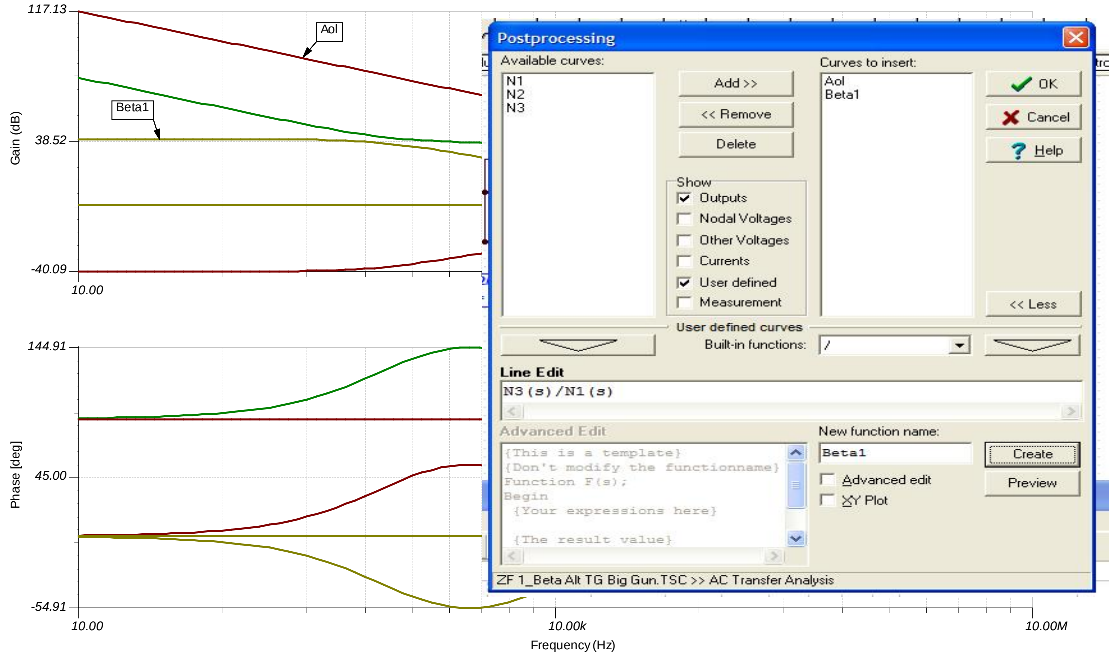


Figure 2.5 Tina SPICE Post Processing Math for ZF Analysis

Now we have generated the math results for Aol and Beta1 as shown in Figure 2.6. We can clean up our resultant Plot window by right-clicking on each waveform we no longer need (i.e. N1, N2, N3) in both the Magnitude and Phase Plots and deleting these unneeded waveforms. After this cleanup, right-click on the Y-Axis for each plot and select "Default Ranges". All looks good now EXCEPT our plots are not in familiar and useful scales that make it easy to see 20db/decade slopes in magnitude and 45 degree/decade slopes in phase.

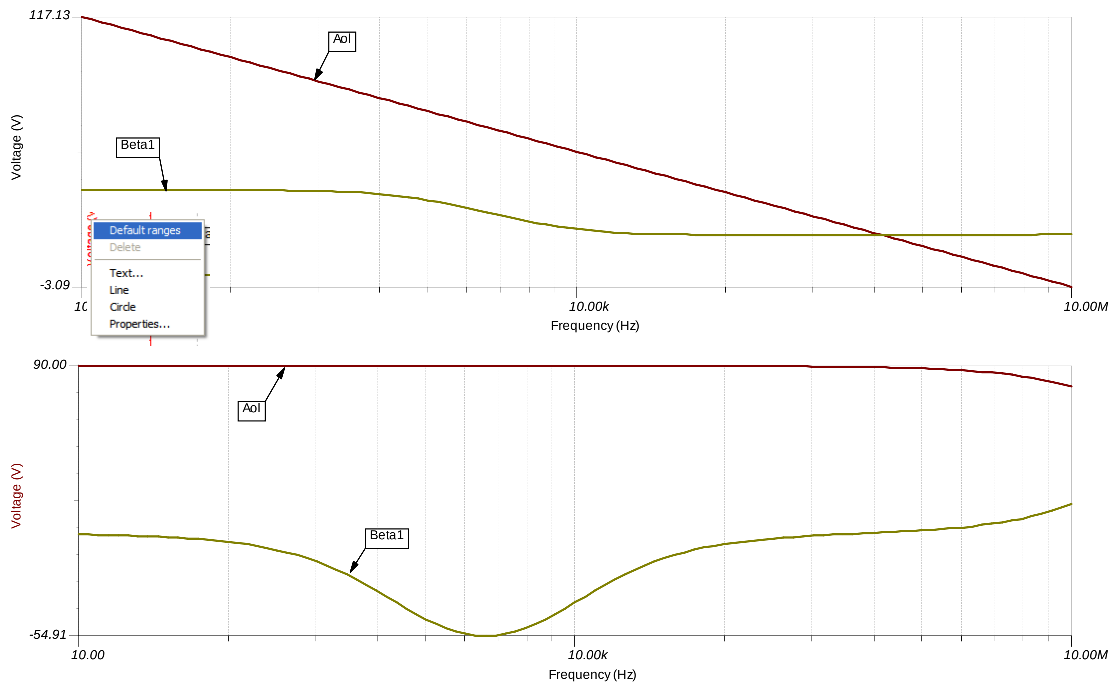


Figure 2.6Tina SPICE Default Scaling - Post Processing Math for ZF Analysis

As shown in Figure 2.7 there is a “Frequency Re-Scale” Trick which will allow us to conveniently get the best decade resolution of frequency on the x-axis. Right-click on the x-axis and select “Properties”. The pop-up window will appear as shown above. Now the secret to selecting the right number of “Ticks” for scaling is to count the number of decades within the frequency range plotted and add 1. As shown above for 10Hz -10MHz there are 6 decades (10 to 100, 100 to 1k, 1k to 10k, 10k to 100k, 100k to 1M, and 1M to 10M). Now our frequency axis looks like a familiar semi-log plot.

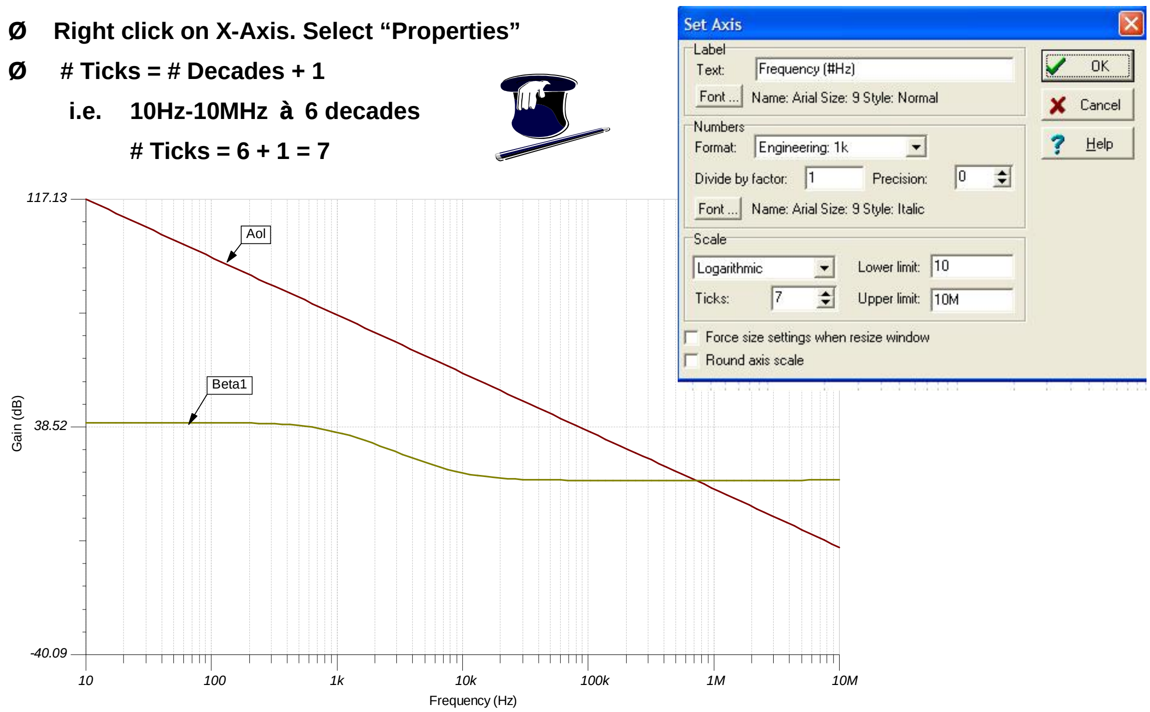


Figure 2.7 Tina SPICE Frequency Re-Scale for ZF Analysis

Now we wish to re-scale the y-axis on the magnitude plot to a more familiar 20dB/division. Our “Gain Re-Scale” Trick is shown in Figure 2.8. Right-click on the y-axis and select “Properties”. The pop-up window will appear as shown above. Now the secret to selecting the right number of “Ticks” for scaling is to first set the “Lower limit” to the nearest even increment of 20dB less than the default “Lower limit” shown. Now set the “Upper limit” to the nearest even increment of 20dB more than the default “Upper limit” shown. Subtract the new “Upper limit” from the new “Lower limit” and divide the result by 20. To this number add 1 and we have calculated the correct number of “Ticks” to set to get a familiar y-axis scaling of 20dB/division.

- Ø **Right click on Y-Axis again and select "Properties"**
- Ø **Lower Limit = Nearest 20dB < Min Gain (i.e. -20dB < Min Gain)**
- Ø **Upper Limit = Nearest 20dB > Max Gain (i.e 120dB > Max Gain)**
- Ø **# Ticks = [Upper Limit – Lower Limit]/20 + 1**

  # Ticks = [120- (-20)]/20 + 1 = 8

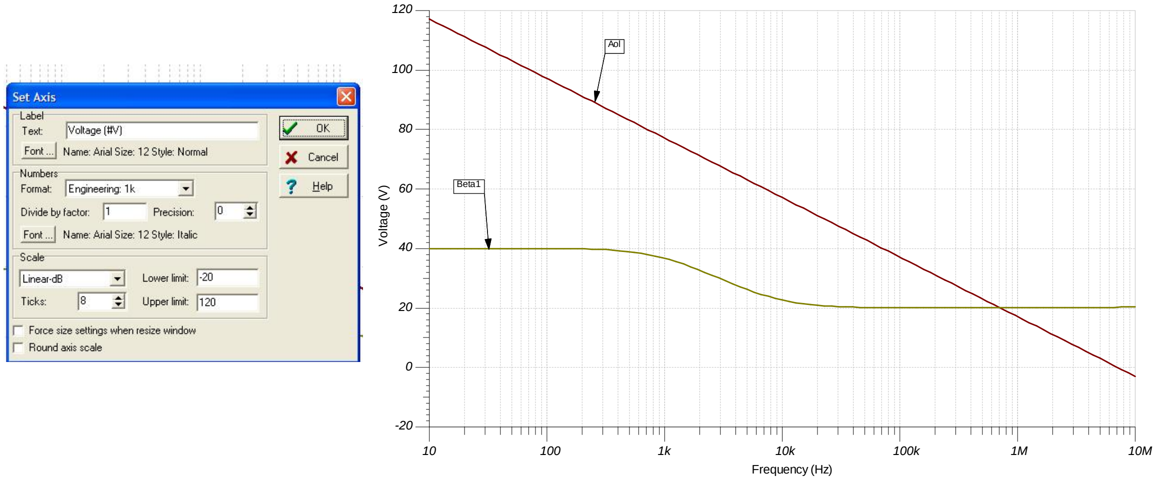


Figure 2.8 Tina SPICE Gain Re-Scale for ZF Analysis

Also, for ease of reading the phase plot, we will re-scale the y-axis to a more familiar 45 degrees/division. Our "Phase Re-Scale" Trick is shown in Figure 2.9. Right-click on the y-axis and select "Properties". The pop-up window will appear as shown above. Now the secret to selecting the right number of "Ticks" for scaling is to first set the "Lower limit" to the nearest even increment of 45 degrees less than the default "Lower limit" shown. Now set the "Upper limit" to the nearest even increment of 45 degrees more than the default "Upper limit" shown. Subtract the new "Upper limit" from the new "Lower limit" and dived the result by 45. To this number add 1 and we have calculated the correct number of "Ticks" to set to get a familiar y-axis scaling of 45 degrees/division.

- Ø **Right click on Y-Axis again and select "Properties"**
- Ø **Lower Limit = Nearest 45 degrees < Min Phase (i.e. -90 degrees < Min Phase)**
- Ø **Upper Limit = Nearest 45 degrees > Max Phase (i.e +180 degrees > Max Phase)**
- Ø **# Ticks = [Upper Limit – Lower Limit]/45 + 1**

  # Ticks = [90- (-90)]/45 + 1 = 5

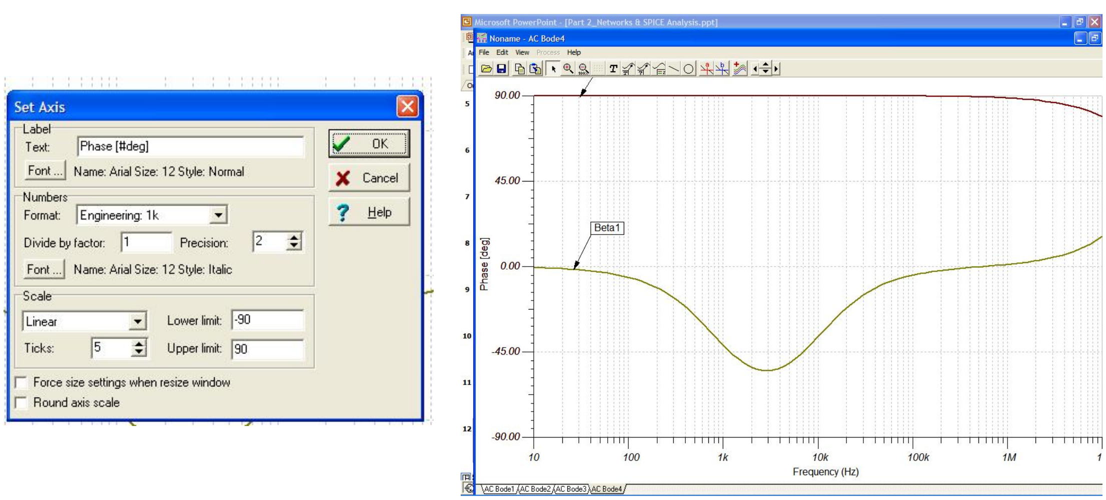


Figure 2.9 Tina SPICE Phase Re-Scale for ZF Analysis

Our optimally-scaled Tina SPICE simulation results for ZF are displayed in Figure 2.10. The purple colored text denotes our 1st Order Analysis predictions. The cursors are set for an exact amplitude difference of -3dB from the Low Frequency 1/Beta and +3dB from the High Frequency 1/Beta. Our 1st Order Analysis results and predictions are not exact but certainly more than acceptable for powerful and intuitive AC Stability Analysis.

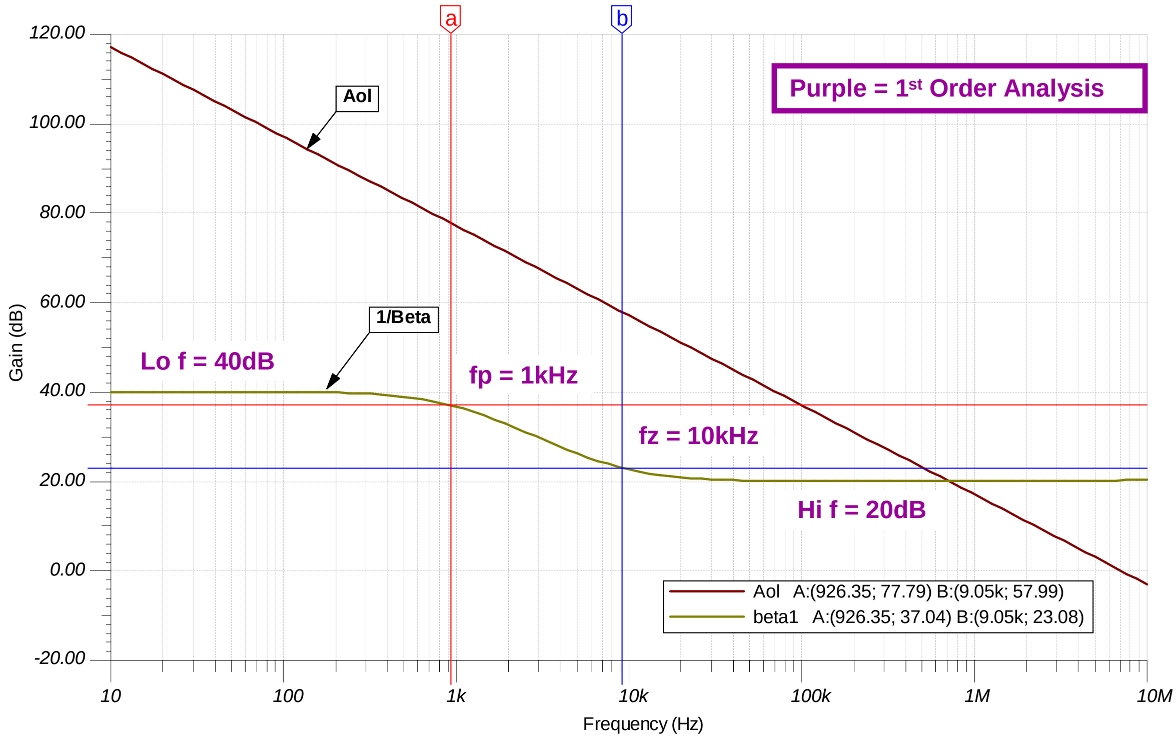
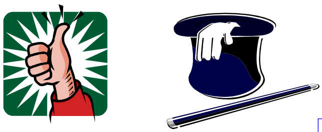
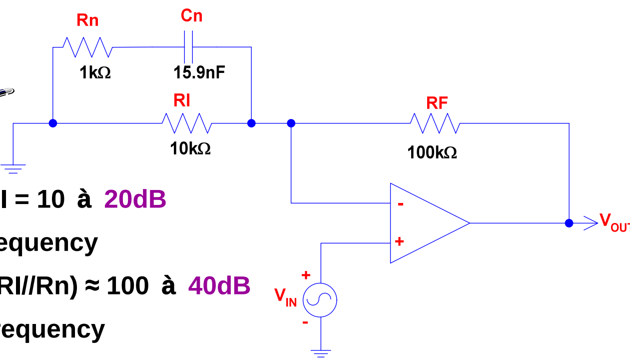


Figure 2.10 Tina SPICE Optimally-Scaled Results for ZF Analysis

2.2 Op Amp Network ZI

Let's perform our 1st Order Analysis for the ZI network in Figure 2.11. This is an input network in the op amp circuit. Cn is open at low frequency and the Low Frequency 1/β becomes simply RF/RI as shown. At the other frequency extreme, high frequency, Cn is a short and the High Frequency 1/β becomes RF/(RI//Rn). However, when Cp is a short Rn<<RI and Rn should dominate the input resistance and so we approximate high frequency gain to be RF/Rn. We note there is a reactive element in the input path of the op amp, a capacitor, and therefore know there has to be some poles and/or zeros somewhere in the transfer function. At the frequency where the magnitude of Cn matches that of the parallel impedance with it (dominated here by RI) we anticipate a zero in the 1/β plot. Input resistance will be getting smaller and therefore VOUT must start to increase. Now the frequency where the magnitude of Cn matches that of the impedance in series with it, Rn, we expect a pole since as Cn approaches a short the net input resistance can become no smaller and VOUT must flatten out as frequency increases. So we have predicted by our 1st order analysis where a pole and zero exists as well as the Low Frequency and High Frequency 1/β levels.





- Ø 1/β **Low Frequency = RF/RI = 10 à 20dB**

  Cn = Open at Low Frequency
- Ø **1/β High Frequency = RF/(RI//Rn) ≈ 100 à 40dB**

  Cn = Short at High Frequency
- Ø **Zero in 1/β when Magnitude of X_{Cn} = RI**

  Magnitude X_{Cn} = 1/(2·Π·f·Cn)

  fz = 1/(2·Π·RI·Cn) = 1kHz
- Ø **Pole in 1/β when Magnitude of X_{Cn} = Rn**

  fp = 1/(2·Π·Rn·Cn) = 10kHz

Figure 2.11 1/β 1st Order Analysis for ZI

To check our 1st Order Analysis our circuit for ZI analysis was built in Tina SPICE as shown in Figure 2.12. VIN is set for a DC value of 0V and an AC Source option is selected with the AC Amplitude set to 1. Our AC Analysis is set up to run from 10Hz to 10MHz with 100 points of data and Amplitude & Phase data requested to be saved for Post-Processing purposes. To perform our "SPICE Loop Gain Test" we use L1, C1 and VIN with convenient Voltage Probes placed as N1, N2, and N3. By inspection of this circuit we see Aol = N2/N1 and 1/Beta = N3/ N1.

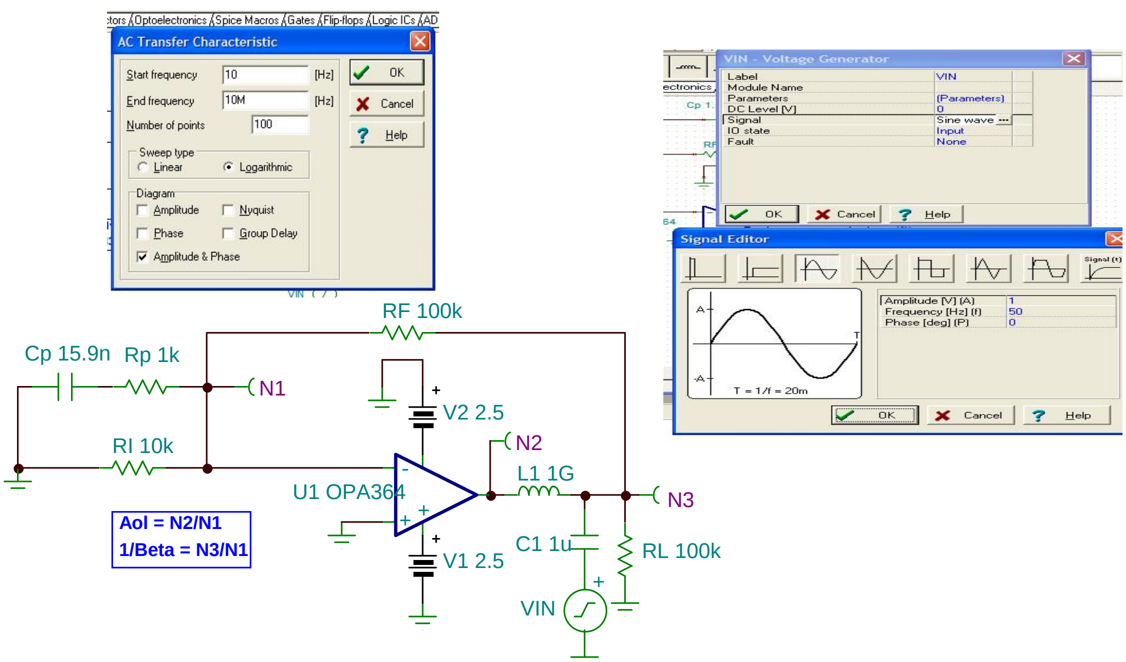


Figure 2.12 Tina SPICE Circuit for ZI Analysis

Our optimally-scaled Tina SPICE simulation results for ZI are displayed in Figure 2.13. The purple colored text denotes our 1st Order Analysis predictions. The cursors are set for an exact amplitude difference of +3dB from the Low Frequency 1/Beta and -3dB from the High Frequency 1/Beta. Our 1st Order Analysis results and predictions are not exact but certainly more than acceptable for powerful and intuitive AC Stability Analysis.

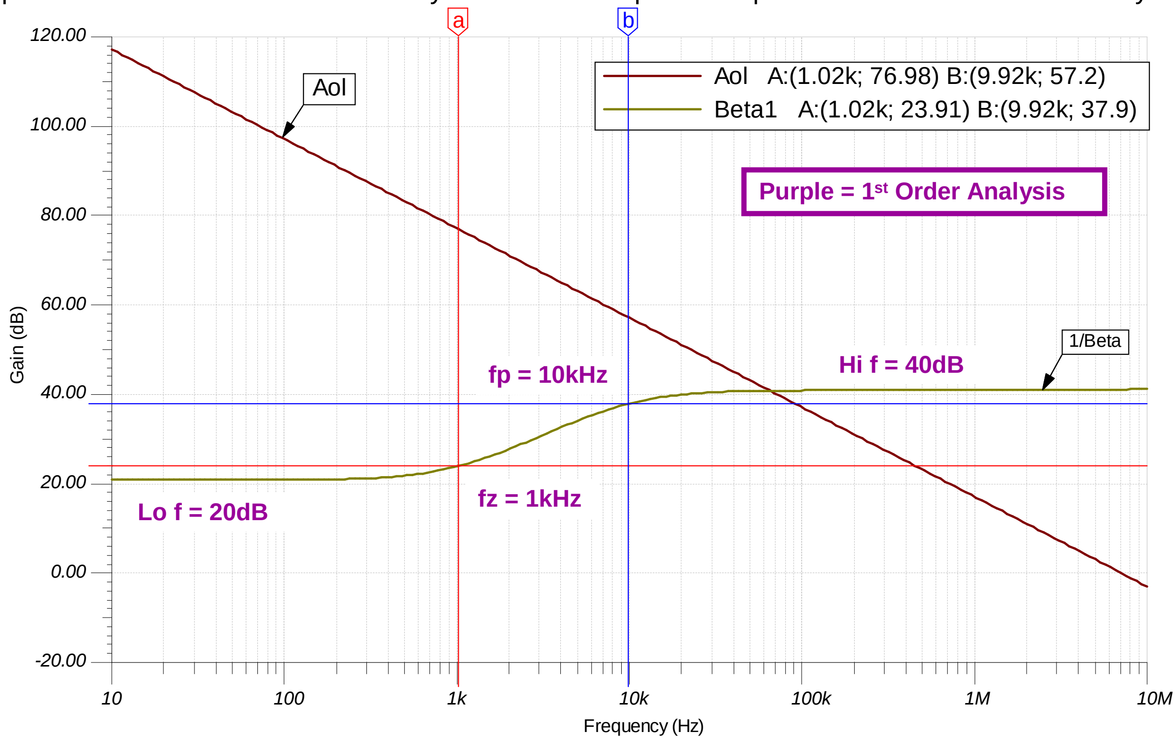


Figure 2.13 Tina SPICE Optimally-Scaled Results for ZI Analysis

2.3 Simple Op Amp AC SPICE Model

As we have seen SPICE can be a powerful analysis tool to check our 1st Order Analysis. However, for AC Stability Analysis it requires that we have an Op Amp Model to build our circuit with. Sometimes we do not have a SPICE model available but do have the data sheet for the Op Amp we are planning to use. For this example we will pretend we do not have an op amp model for the OPA364, a Single-Supply, RRIO, CMOS Op Amp (a Burr-Brown Product from Texas Instruments). The Open Loop Gain/Phase Plot from the data sheet is shown in Figure 2.14. A common characteristic of CMOS op amps is that the low frequency Open Loop Amplitude is Load dependent. This is illustrated above as the default 10kΩ load is shown as well as 100kΩ load. From the phase portion of the plot we use our “Log Scaling Technique” (see Part 1 of this series) to determine that at -45 degrees the frequency is 29Hz. The Unity Gain Bandwidth of the OPA364 is measured at 7.4MHz. We will first develop a Simple Op Amp AC SPICE Model using a two-pole approach. We will set the second pole, fp1 at the frequency where the phase dips to -135 degrees.

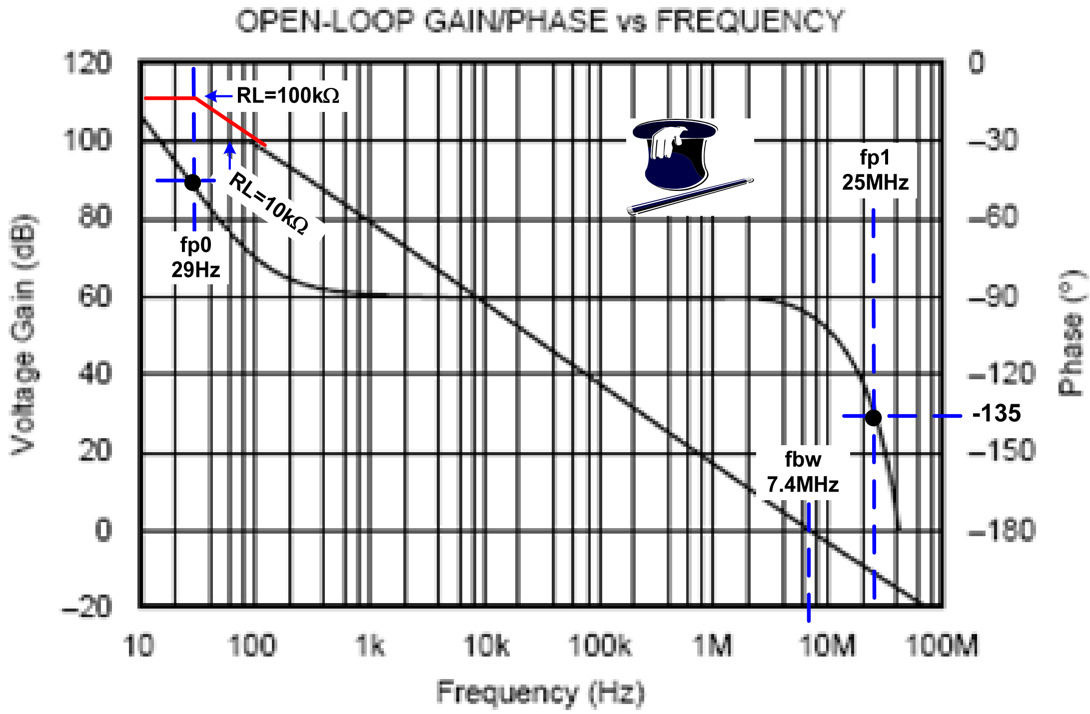


Figure 2.14 Simple Op Amp Model: OPA364 Data Sheet Curve

Shown in Figure 2.15 is our Simple Op Amp AC SPICE Model for the OPA364. The key frequency components are the elements used to form fp0 and fp1. Note that the Voltage-Controlled-Voltage Sources, VCV1, VCV2, and VCV3 provide perfect buffering between our frequency elements and prevent them from interacting with or loading down one another. The other important element is RO. RO is the Op Amps AC, Small-Signal, Open-Loop Output Impedance. We will study this in detail in Part 3 of this series where we will discuss how to obtain RO from either the manufacturer's data sheet or by measurement. For our current focus we will assign a value of 160 ohms to RO for this OPA364 AC Model. This model will run very quickly in SPICE and if our main concern is a good stable design then this will be about all we need. Also shown in Figure 2.15 is our use of "SPICE Loop Gain Test" through LT, CT and VIN with convenient Voltage Probes placed as VM, VOA, and VOUT. By inspection of this circuit we see Aol = VOA/VM.

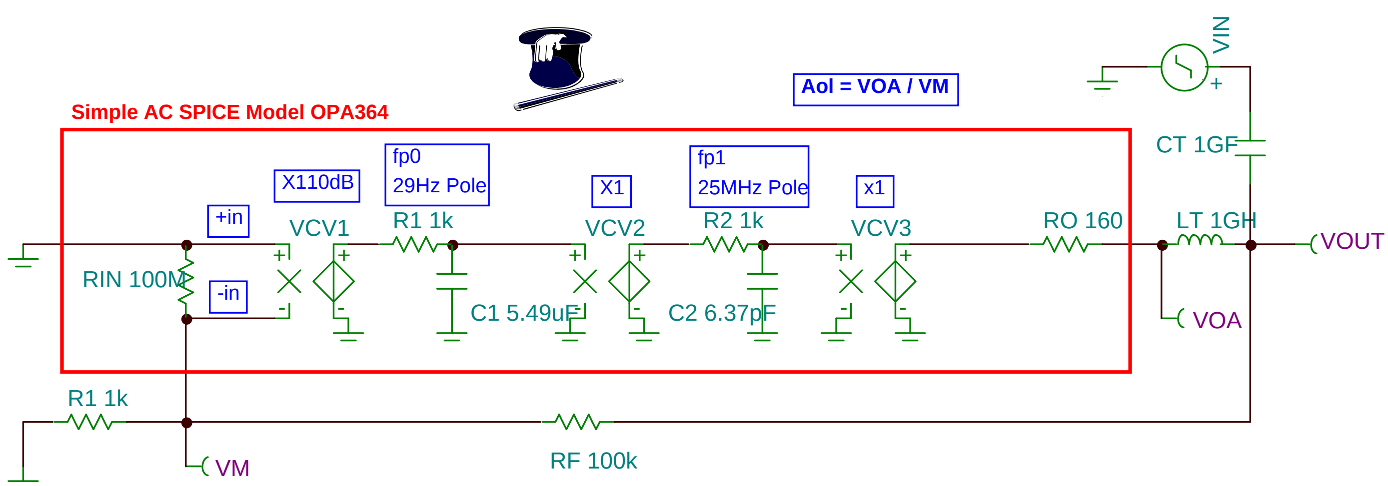


Figure 2.15 Simple Op Amp Model: AC SPICE Model

Our optimally-scaled Tina SPICE simulation results for the Simple Op Amp AC SPICE Model are shown in Figure 2.16. Our Phase results in SPICE start at 180 degrees and go down to 0 degrees. Typical data sheet curves show Phase starting at 0 degrees and going down to -180 degrees. This is because most of these plots are viewed as passing a signal through the non-inverting input of the op amp to the output. The Post Processing math performed by SPICE to yield our desired results ends up with a 180 degree phase factor since we are computing VOA (voltage out of the op amp) divided by VM (the inverting input of the op amp which implies a -1 factor or 180 degree phase shift). To view this in direct comparison with the data sheet subtract 180 degrees from each value on the y-axis. In the phase plot above we see that a 70.82 degree reading at the unity gain bandwidth frequency of 8.68MHz which would equate to -109.18 degrees (70.82 – 180) on a data sheet Open Loop Gain/Phase Plot. This looks close to the phase shift on the data sheet plot at fbw=7.4MHz from our previous slide. If we wanted our model to exactly match fbw=7.4Mhz we could reduce the low frequency Aol amplitude slightly.

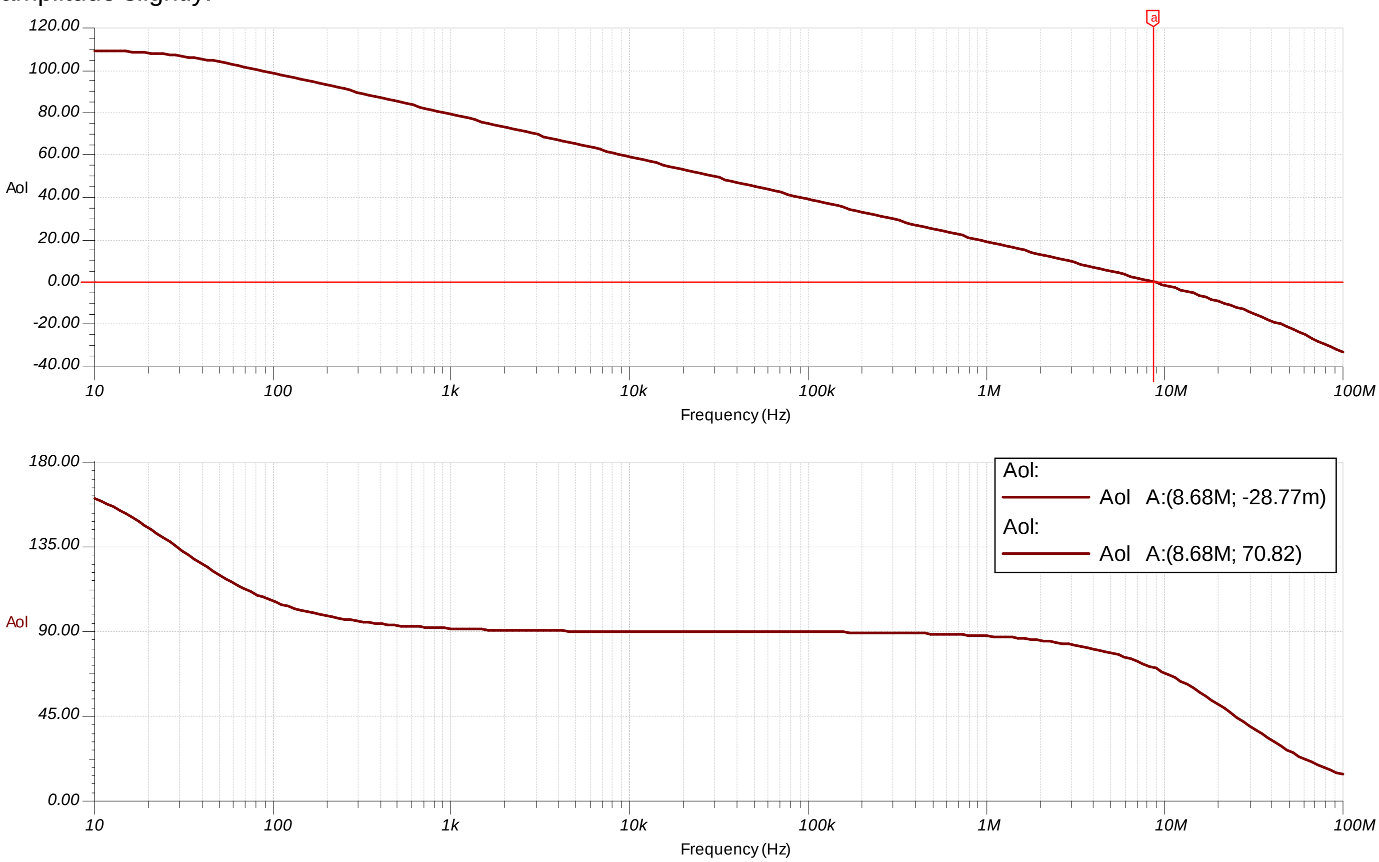


Figure 2.16 Simple Op Amp Model: AC SPICE Results

2.3 Detailed Op Amp AC SPICE Model

Now if we want to duplicate the high frequency phase effects of the OPA364 we can create a Detailed Op Amp SPICE Model. On the data sheet Open Loop Gain/Phase Plot in Figure 2.17 we draw phase slopes in ever-increasing multiples of -45 degrees/decade slopes. This information will allow us to compute where we want to place higher order poles to get the shown response.

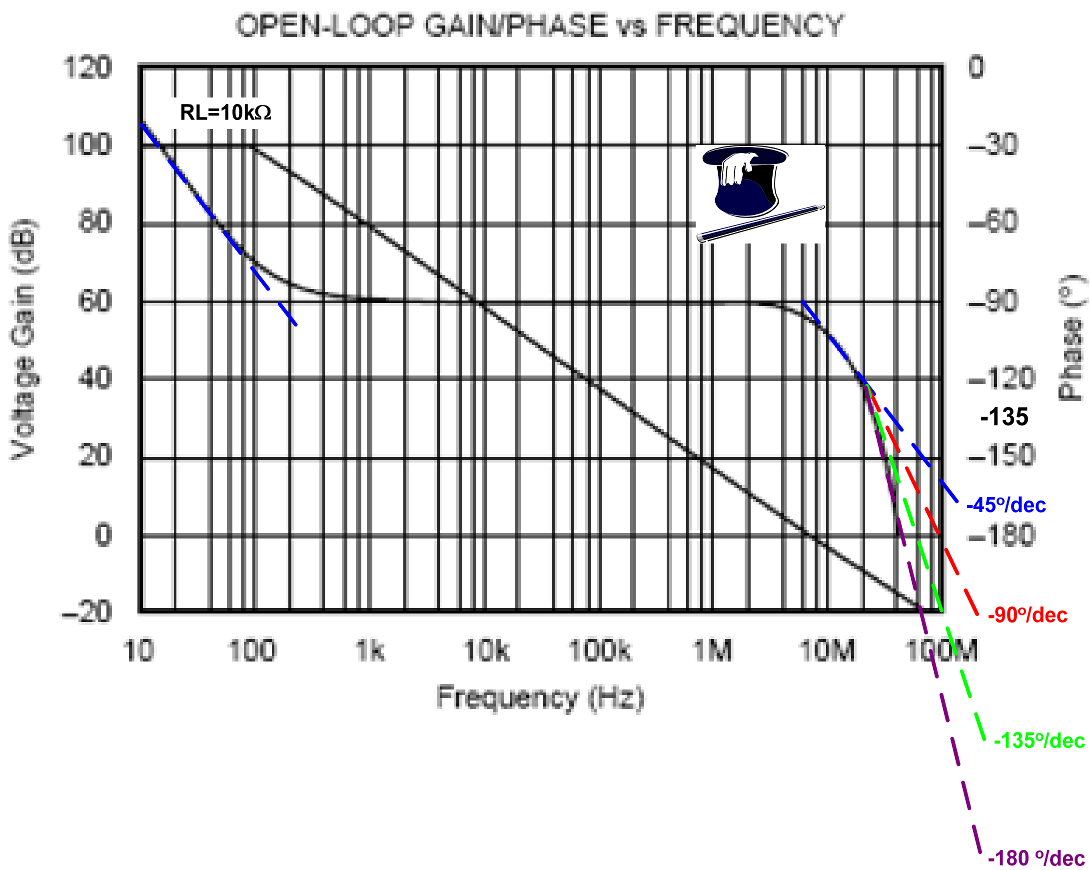


Figure 2.17 Detailed Op Amp Model: OPA364 Data Sheet Curve

From our Figure 2.17 we can transfer the phase slope information into components which can create such a response. In the Figure 2.18 we place fp0 at the frequency where the phase is -45 degrees on the data sheet plot in the previous slide. fp1 we place at the frequency where open loop phase is -135 degrees. From our Figure 2.17 we observe that starting at 20Mhz there must be a -180 degree/decade slope. -45 degrees/decade of this will come from fp1. Therefore, since a pole has phase impact a decade in frequency below and a decade in frequency above the actual location of the pole we know a decade above 20MHz we must have 3 additional poles to get the desired slope. Graphically this is shown above as ftp3 (triple pole at fp3). The slope starting at 20Mhz must be -45 degrees/decade and a decade away we will find the actual location of ftp3 (200MHz). This graphical technique allows us an easy way to synthesize the desired phase response and also plot the resultant summation of each pole and/or zero

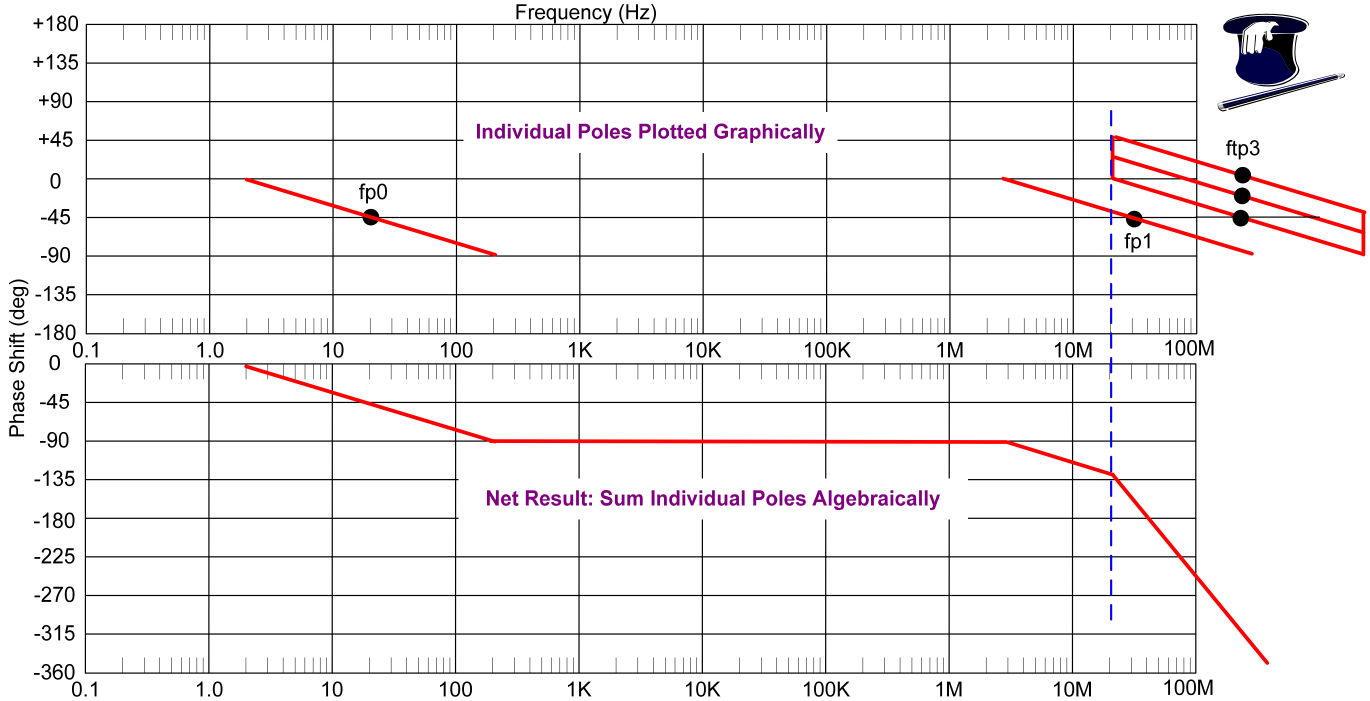


Figure 2.18 Detailed Op Amp Model: Graphing Aol Phase Response

The Detailed Op Amp AC SPICE Model adds 3 more high frequency poles to match the data sheet Open Loop Gain/Phase Plot. This is illustrated in the Figure 2.19.

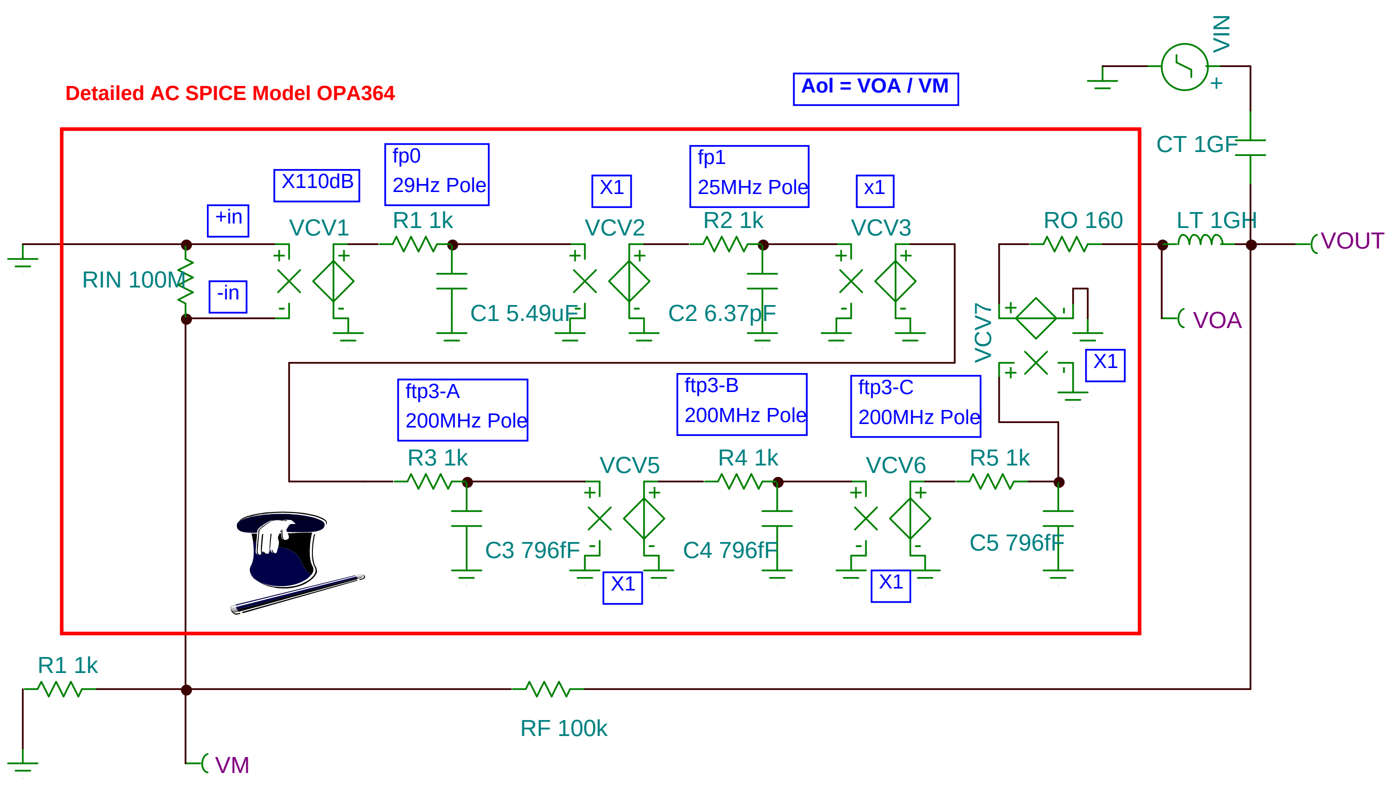


Figure 2.19 Detailed Op Amp Model: AC SPICE Model

Our optimally-scaled Tina SPICE simulation results for the Detailed Op Amp AC SPICE Model are shown in Figure 2.20. A close look at these results versus those of the data sheet Open Loop Gain/Phase Plot reveals a very accurate replication created in our Detailed Op Amp AC SPICE Model. For most op amp stability analyses the Simple Op Amp AC SPICE Model will suffice. However, for cases where performance and bandwidth are being pushed as wide as possible we have a way to rather accurately model the high frequency phase shifts of the op amp.

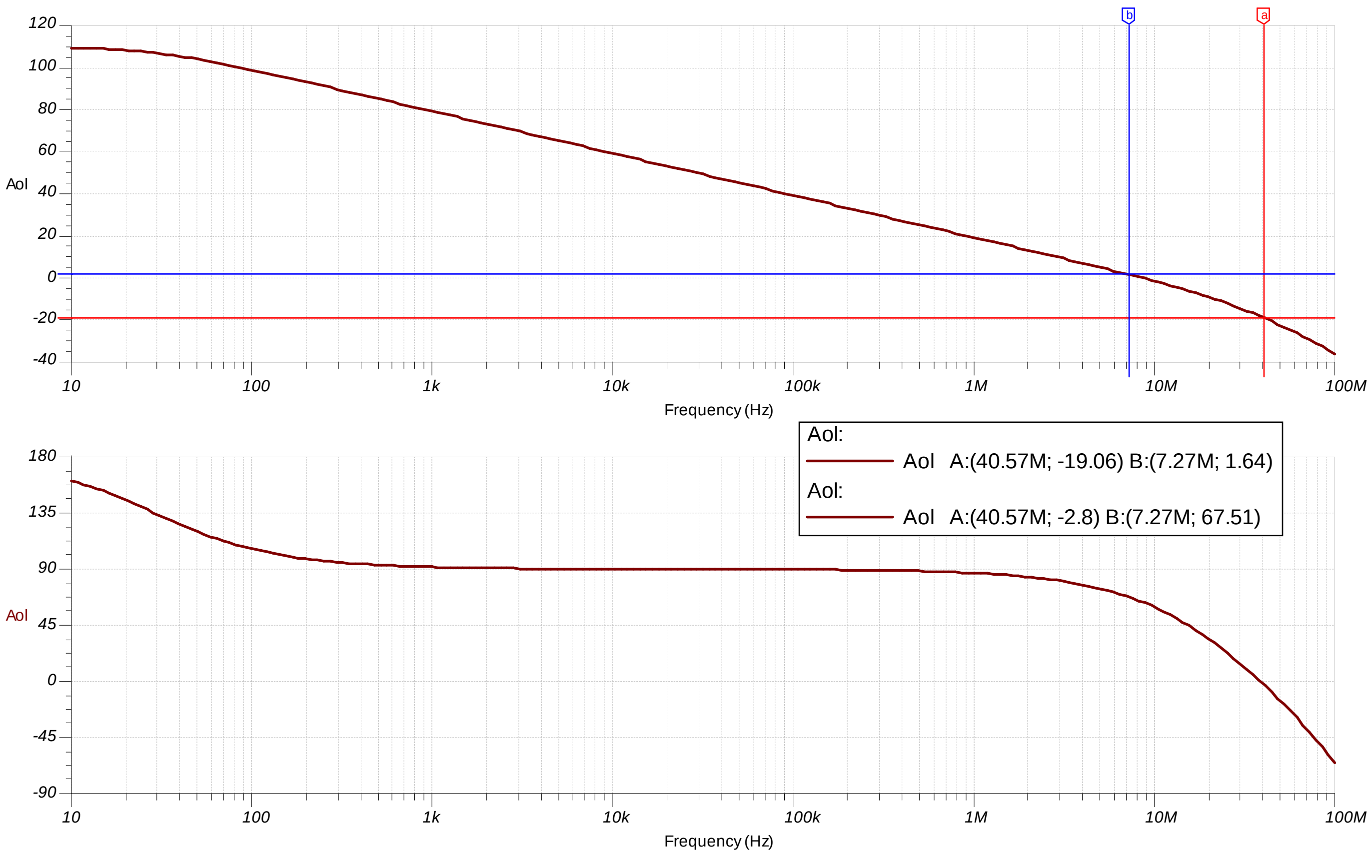
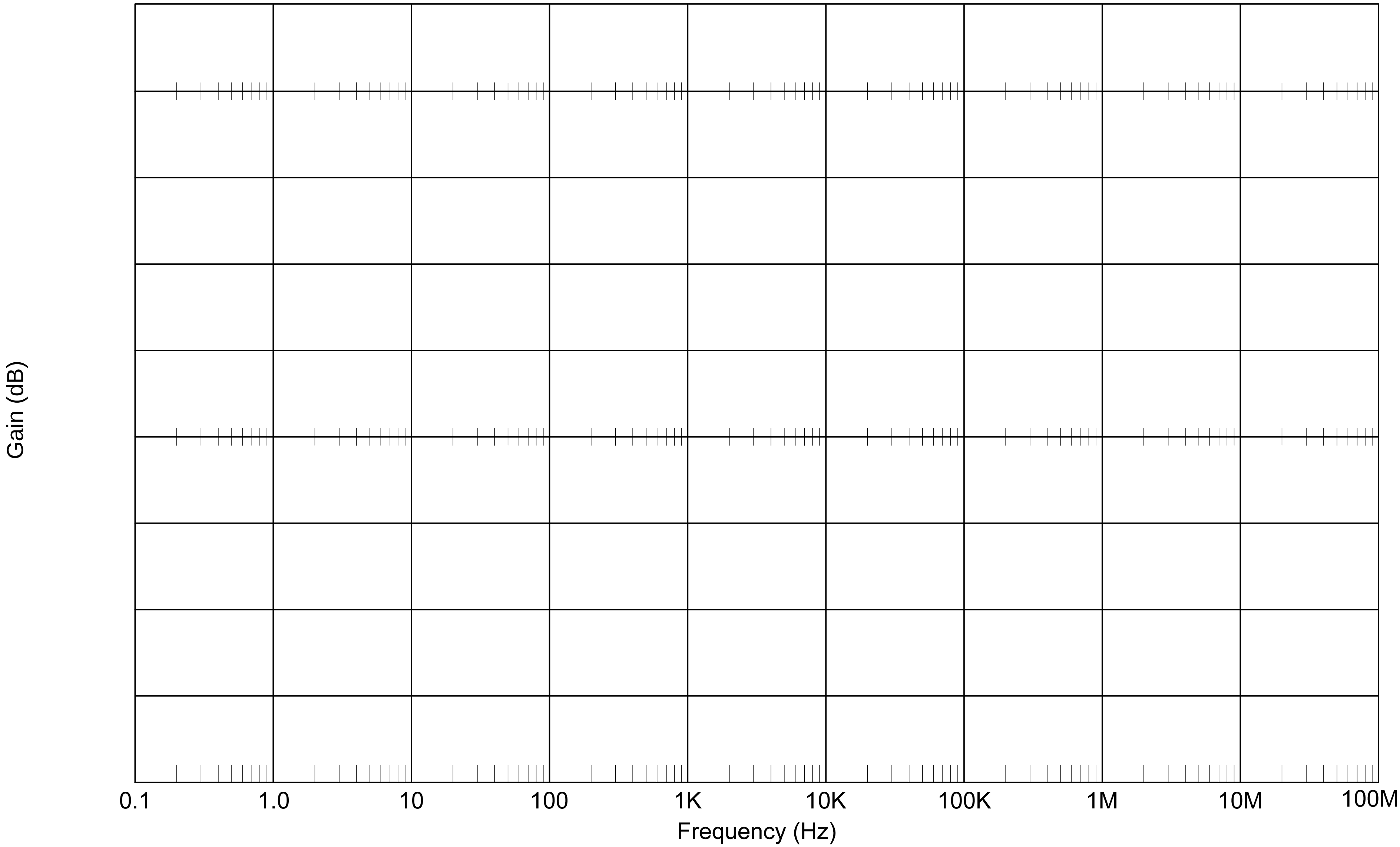
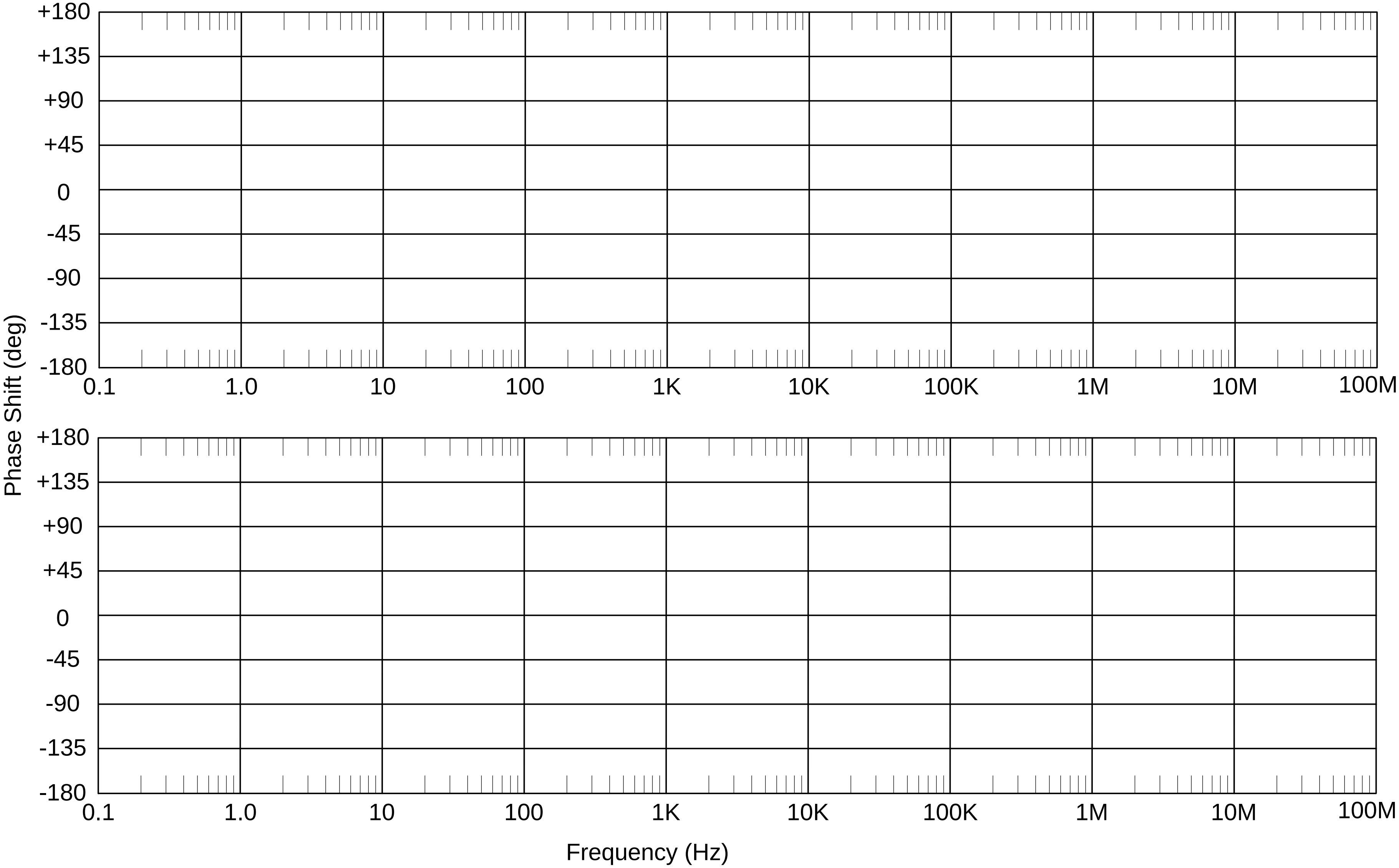


Figure 2.20 Detailed Op Amp Model: AC SPICE Results

2.4 Appendix: Blank Magnitude and Phase Plots

For ease of 1st Order Analysis the last two pages of this presentation contain a blank magnitude and blank phase plot.


Gain (dB)
0.1
1.0
10
100
1K
10K
100K
1M
10M
100M
Frequency (Hz)


Phase Shift (deg)
+180
+135
+90
+45
0
-45
-90
-135
-180
0.1
1.0
10
100
1K
10K
100K
1M
10M
100M
Frequency (Hz)