Operational Amplifier Stability
Part 6 of 15: Capacitance-Load Stability: R_{ISO}, High Gain & CF, Noise Gain

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Part 6 of this series is the beginning of a new electrical engineering tune "There must be six ways to leave your capacitive load stable". The six ways are R_{ISO}, high gain & CF, noise gain, noise gain & CF, output pin compensation, and R_{ISO} with dual feedback. Part 6 focuses on the first three of these stability techniques for capacitive loading on the output of an op amp. Parts 7 & 8 will cover the remaining techniques in detail. Each technique presented will use familiar tools from our stability analysis tool kit and each technique will be presented by first-order analysis, confirmed through Tina SPICE loop-stability simulation, checked by the V_{OUT}/V_{IN} ac transfer function analysis in Tina SPICE and finally sanity-checked by the Transient Real World Stability Test run in Tina SPICE. Each of the techniques has been confirmed to work as predicted in real-world, actually-built circuits at some time over the last 23 years. However, due to resource limitations, each circuit specifically presented here has not been built, but rather is left to the reader as an exercise or the application of each technique to his/her own individual application (ie analyze, synthesize, simulate, build and test).

Op Amp Examples And Computing R_O

Our op amp of the day for the stability examples in this part will be a high voltage, up to ±40V, operational amplifier, the OPA452. Such a "power op amp" is often used for driving piezoelectric actuators which, as you may have guessed, are mostly purely capacitive in nature. A few key specifications for this amplifier are listed in Fig. 6.1. The one key parameter missing is R_O, the small-signal ac open-loop output resistance, which is *EXTREMELY* key to simplifying stability analysis when driving capacitive loads. Since the data sheet does not have this parameter listed in any form we will need to extract the value for R_O through measurement. Since the SPICE model for this amplifier was built by W K Sands of Analog & RF Models http://www.home.earthlink.net/%7Ewksands/ we are going to measure R_O using Tina SPICE. The W K Sands SPICE models have been proven time and time again to be very accurate to the data sheet specifications and, even more importantly, the actual silicon part!

OPA452
Supply: +/-10V to +/-40V
Slew Rate: +7.2V/us, -10V/us
Vout Saturation:
Io=50mA, (V-)+5V, (V+)-5.5V
Io=10mA, (V-)+2V, (V+)-2V

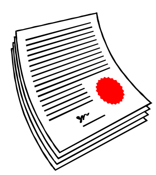


Fig. 6.1: OPA542 Key Specifications

In Fig. 6.2 we mark on an open-loop gain and phase vs frequency plot of the OPA452 the "test point" for measuring R_O. By testing for R_{OUT} at this operating point (a frequency and gain point where there is no loop gain) $R_{OUT} = R_O$ (see Part 3 of this series for a detailed discussion of R_O and R_{OUT}).

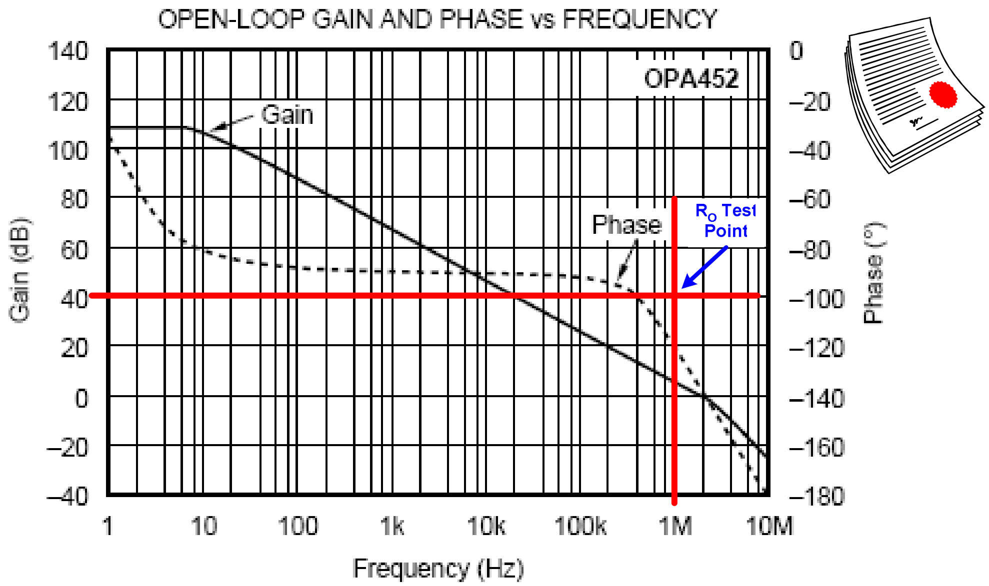


Fig. 6.2: OPA542 Aol Curve With R_O Measurement "Operating Point"

Since we are only testing for R_O in Tina SPICE there is a yet-to-be-introduced "trick" that works well in SPICE (see Fig. 6.3. First, we set the amplifier circuit to our selected gain point of 100. We ac-couple our source through C1 and limit the maximum current driven into the op amp output through R3. Next a current meter, A1, is inserted in series with our excitation source. By placing a voltage probe, VOA, on the output of the op amp we can easily calculate R_{OUT}, which is R_O in our test configuration. This is a variation on the "Measuring R_O -- Drive Method" presented in Part 3.

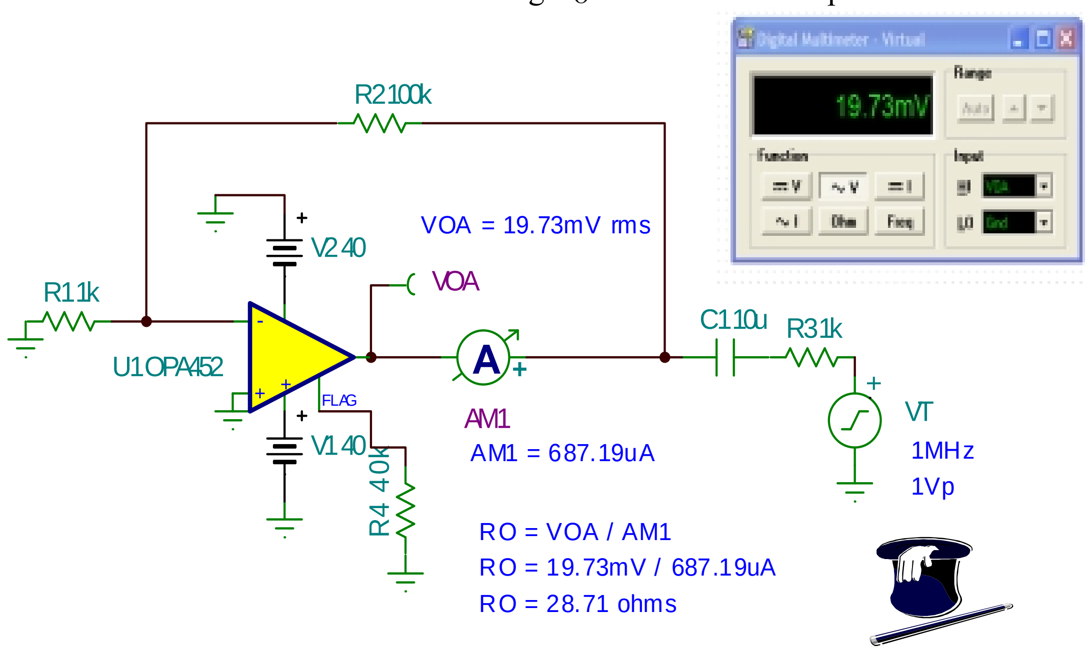


Fig. 6.3: Tina SPICE: R_O Test Technique Nr 1

As a double check of our R_O measurement we will use the "Measuring R_O -- Load Method" from Part 3 measure R_O (see Fig. 6.4). The trick we present here is that it can all be done in one SPICE run by using one ac signal source, VT, and two identical amplifiers, U1 and U2, with one amplifier, U1, unloaded and the other op amp, U2, loaded. The result shown of $R_O = 28.67\ \Omega$ agrees with our technique used for measuring R_O in Fig. 6.3. We will use R_O=28.7 Ω for the OPA452.

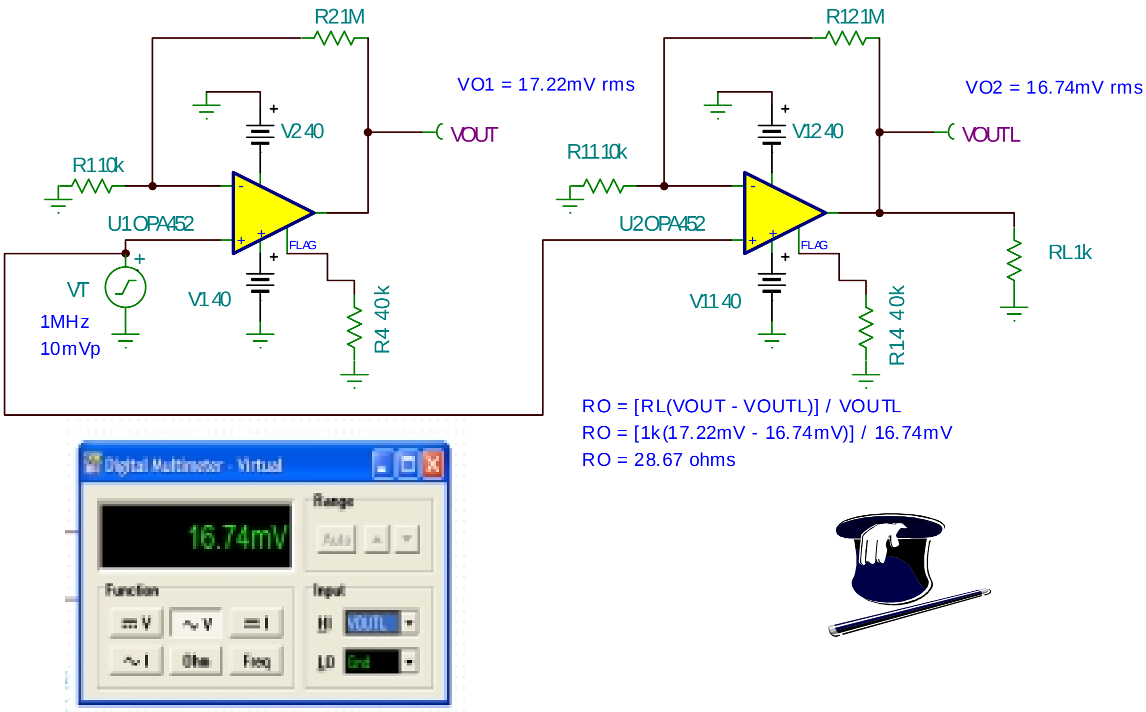


Fig. 6.4: Tina SPICE: R_O Test Technique Nr 2

Modified Aol Model

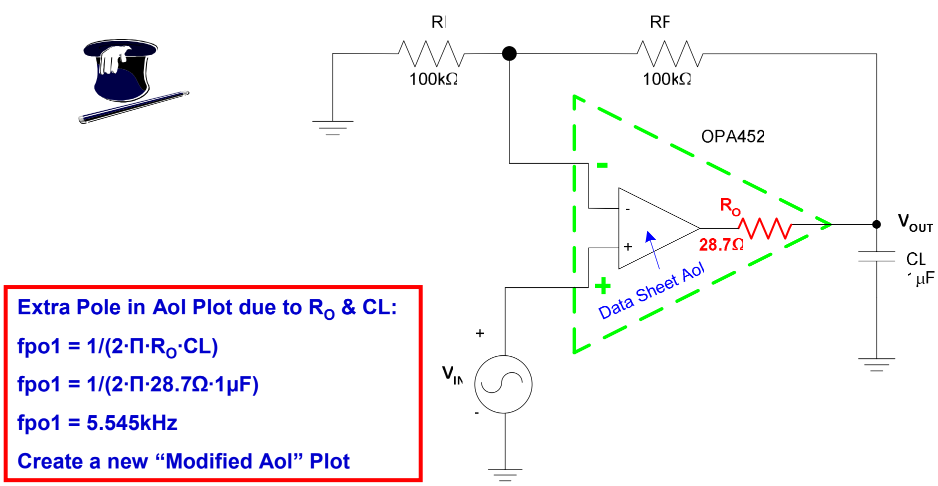


Fig. 6.5: Modified Aol Model With CL

Our stability analysis of the effects of capacitive loading on an op amp will be simplified by the introduction of the "Modified Aol Model." The data sheet Aol curve (Fig. 6.5) is followed by the op amp output resistance, R_O. The capacitive load, CL, in conjunction with R_O will form an additional pole in the Aol plot and may be represented by a new "Modified Aol" plot (Fig. 6.6). We readily see that, with just resistive feedback and low gains, we have an UNSTABLE op amp circuit design since the 1/β curve intersects the "Modified Aol" curve at a rate-of-closure which is 40 dB/decade.

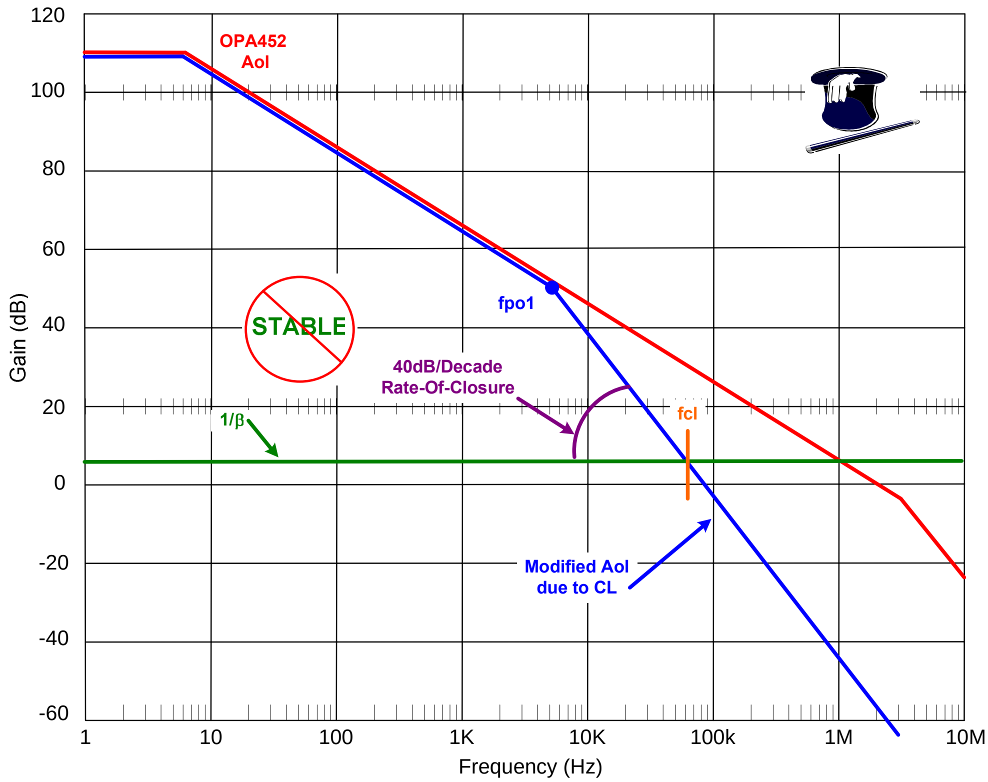


Fig. 6.6: First Order Analysis: OPA452 Modified Aol With CL

Now we will check our first-order analysis by using Tina SPICE. The circuit shown in Fig. 6.7 breaks the loop for a loop stability check by opening the loop for ac at the minus input of the op amp. This allows an easy way to plot the "Modified Aol" due to the CL load interacting with R_O.

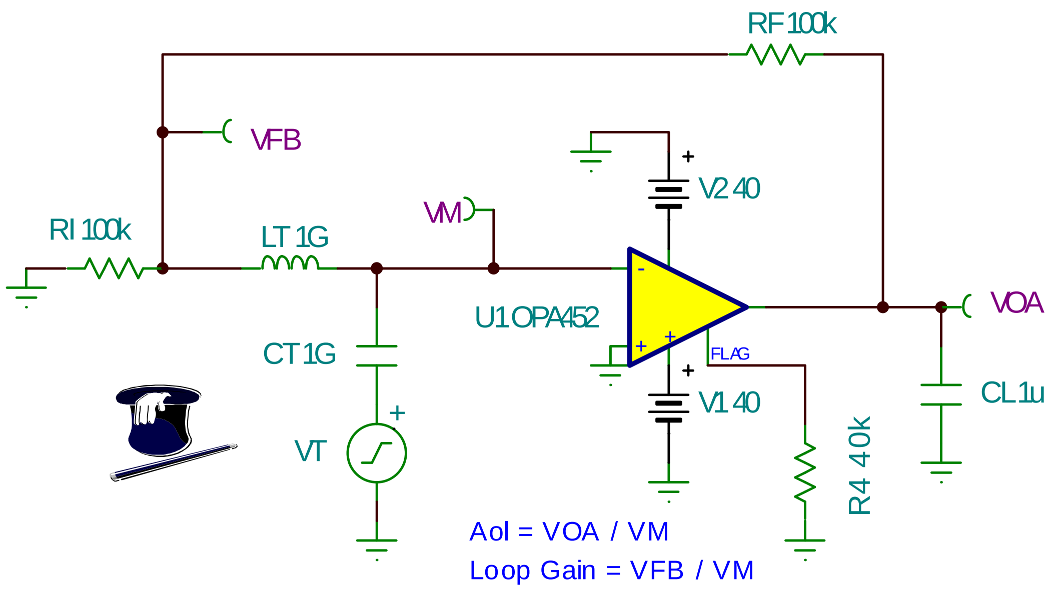


Fig. 6.7: Tina SPICE: Modified Aol Circuit With CL

We see that our first-order analysis (Fig. 6.8) is vindicated. The actual second pole in the "Modified Aol" plot is at 5.6 kHz when we had predicted a second pole due to CL at 5.45 kHz.

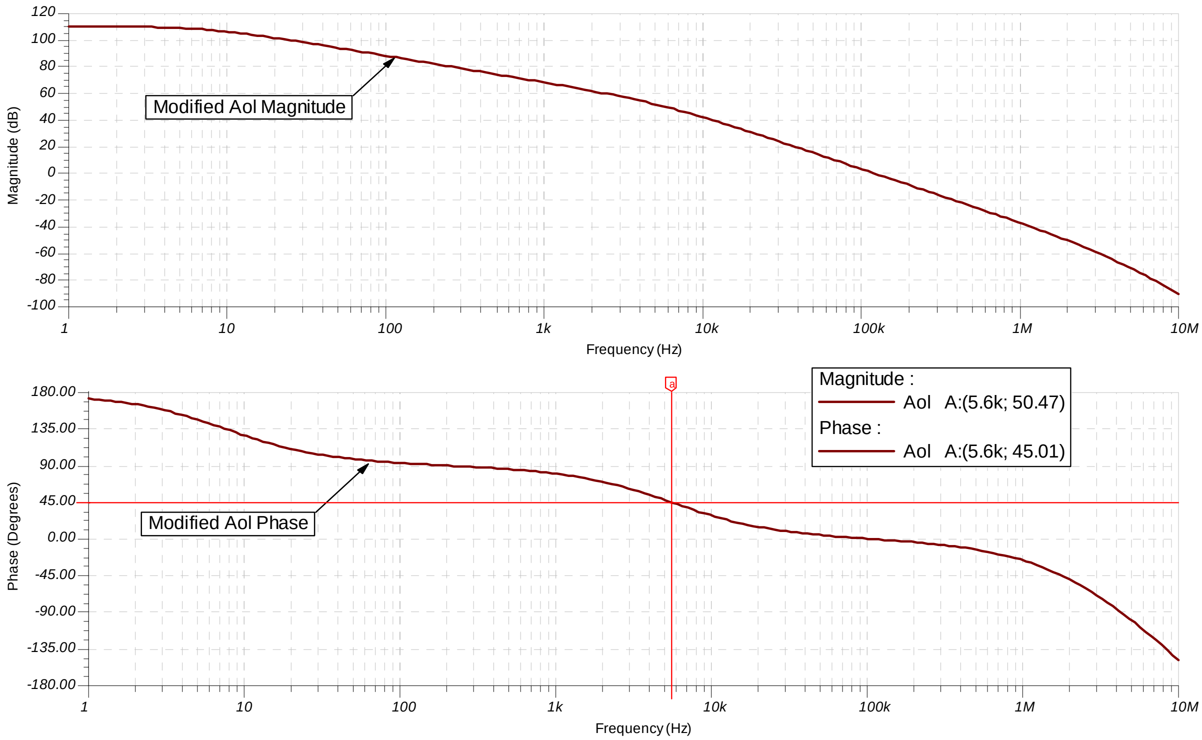


Fig. 6.8: Tina SPICE: Modified Aol Plots With CL

To enforce the idea that our first-order analysis was right in predicting instability a loop-gain analysis was performed (see Fig. 6.9) clearly indicating we are headed for trouble since it hits zero at fcl.

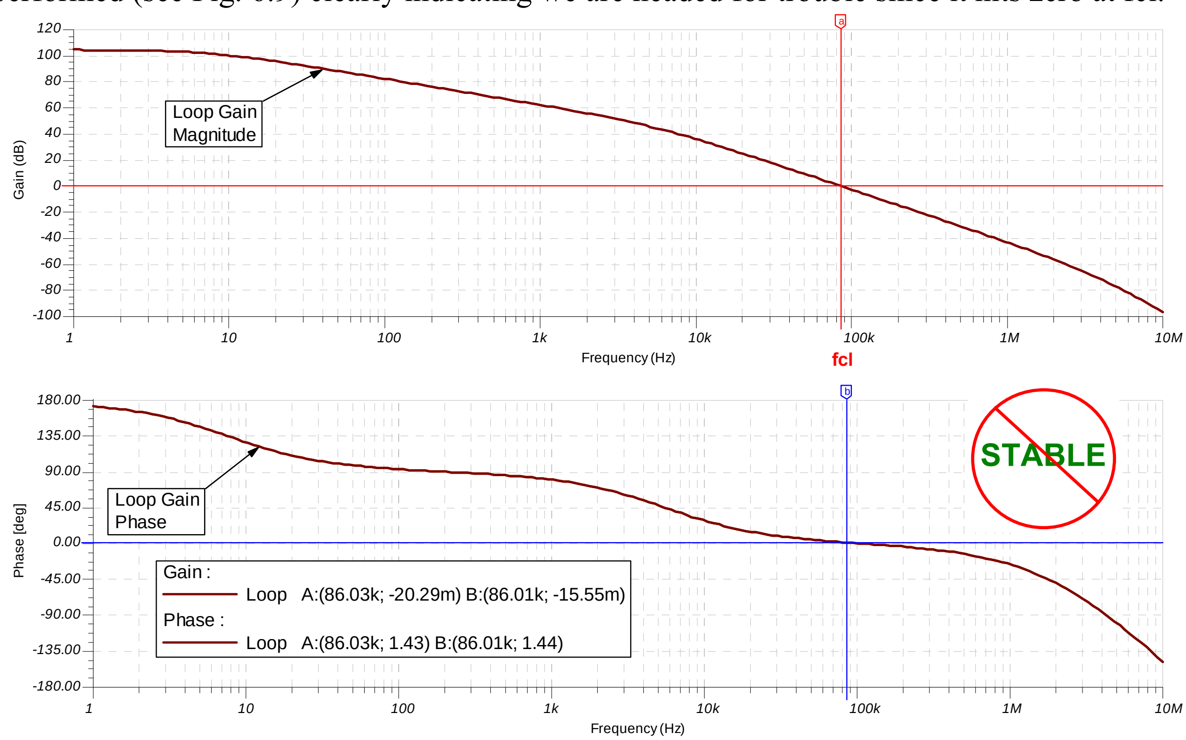


Fig. 6.9: Tina SPICE: Loop-Gain Plots With CL

We will run a Transient Real World Stability Test circuit (Fig. 6.10) in Tina SPICE. Our loop-gain plot predicts instability, as did our first-order analysis. For completeness we will look at the transient response of our circuit.

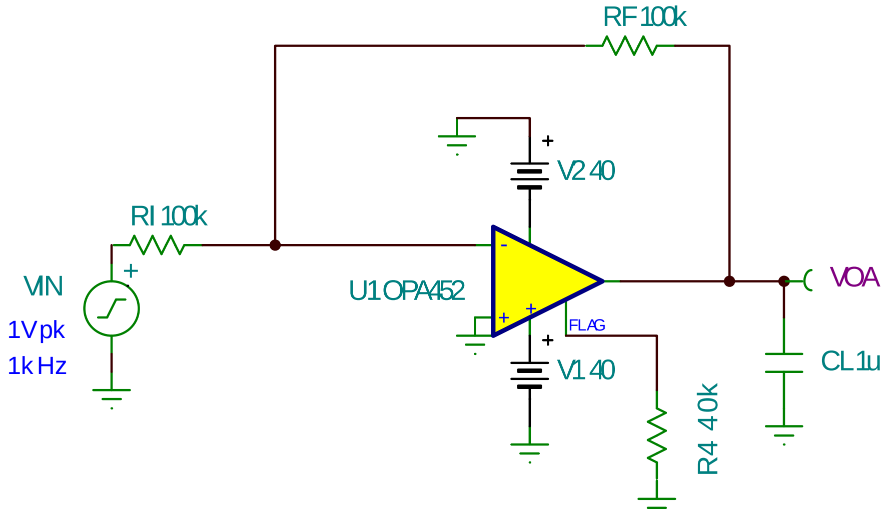


Fig. 6.10: Tina SPICE: Transient Test With CL

The results of our Transient Tina SPICE simulation in Fig 6.11 confirm that this circuit is in "stability-jeopardy" if we do not do something to make it stable.

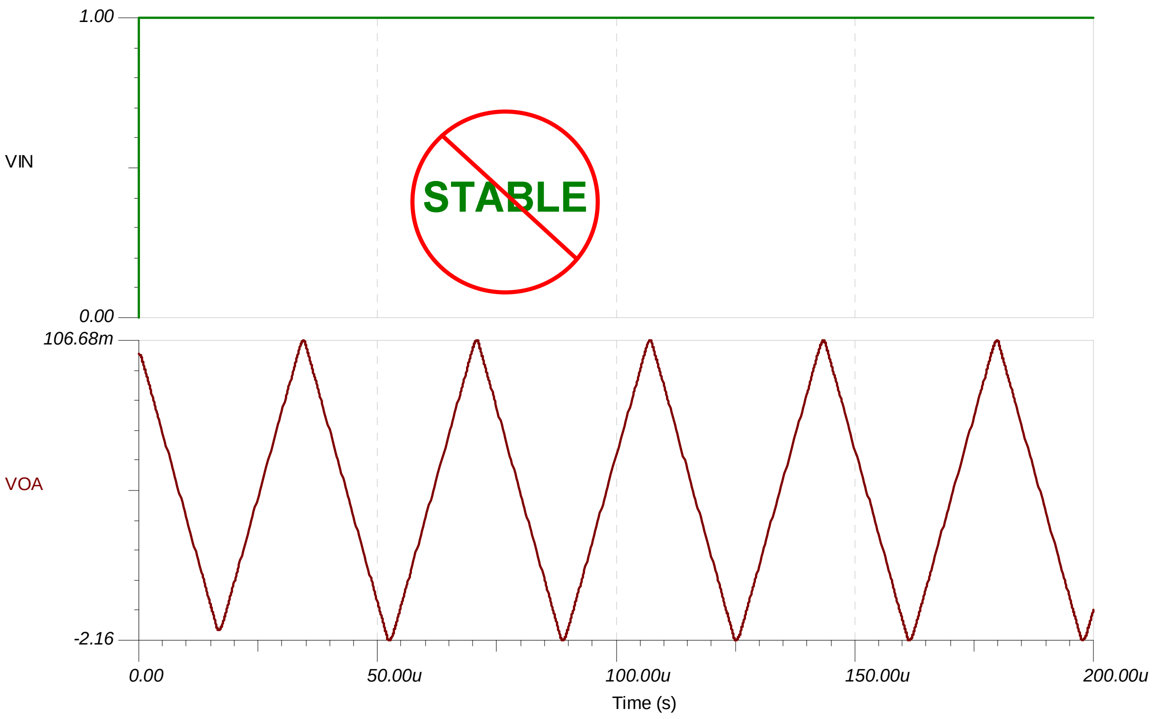


Fig. 6.11: Tina SPICE: Transient Test Results With CL

Before we try to compensate our unstable, capacitive-loaded op amp circuit we should consider if the load resistance will affect the location of the second pole in our "Modified Aol" plot due to R_O and CL. The effect of the load resistance, RL, (Fig. 6.12) is to appear in parallel with the op amp output resistance, R_O, which increases the frequency location of the pole. The final pole location will be now determined by the parallel combination of R_O and RL along with the load capacitance CL. From this we form a handy rule of thumb based on our favorite decade approach. If RL > $10R_O$ we can ignore the effect of RL and the second pole will be predominantly determined by R_O and CL.

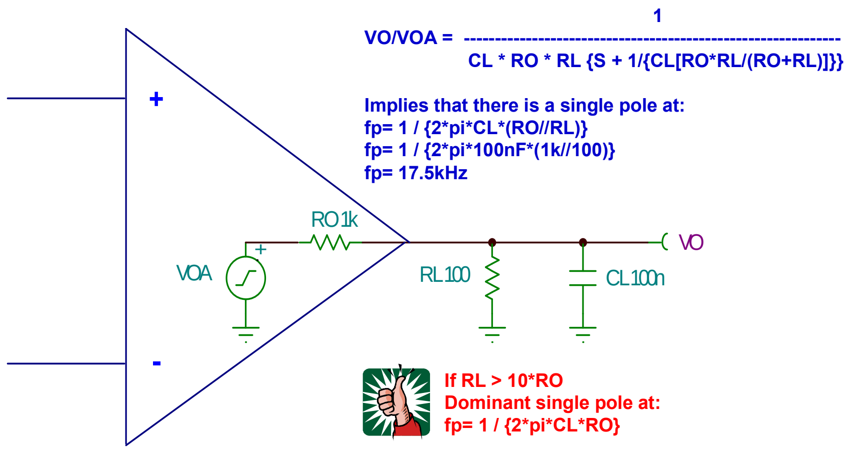


Fig. 6.12: Do We Need To Worry About RL?

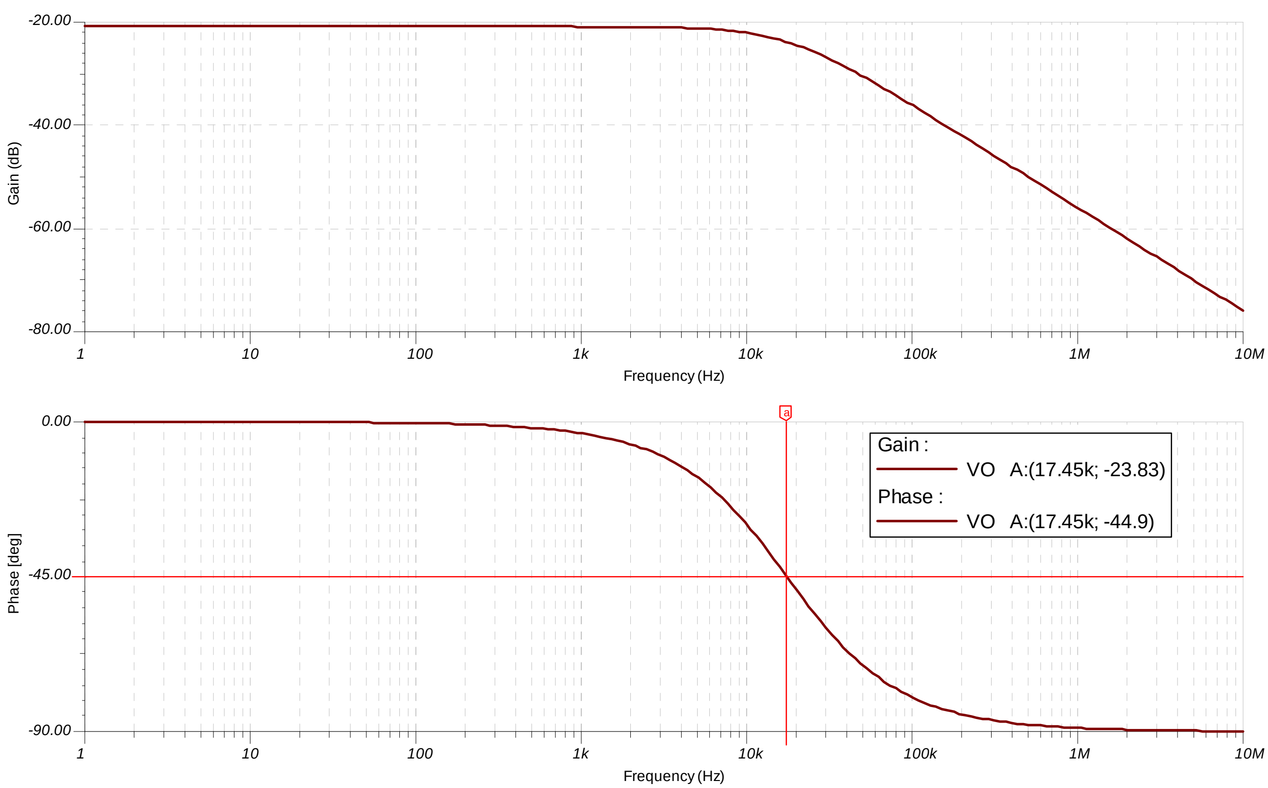


Fig. 6.13: Tina SPICE: R_O, RL, CL Pole Plot

Fig. 6.13 confirms our first-order analysis that for the configuration of R_O, RL and CL that the pole location is determined, as predicted, by the parallel combination of R_O and RL in conjunction with CL.

R_{ISO} & CL Compensation

Our first technique (Fig. 6.14) to stabilize an op amp driving a capacitive load is to use an isolation resistor, R_{ISO}, between the output of the op amp and the capacitive load, CL. Our point of feedback is taken directly at the output of the op amp. This will create for us, in the "Modified Aol" plot an additional pole and zero. One key consideration for this technique is the current flowing out of the op amp to the load through R_{ISO}. This current will cause an error in V_{OUT} compared with V_{OA}, which is the point of feedback for the op amp. A given application will determine if this error is acceptable.

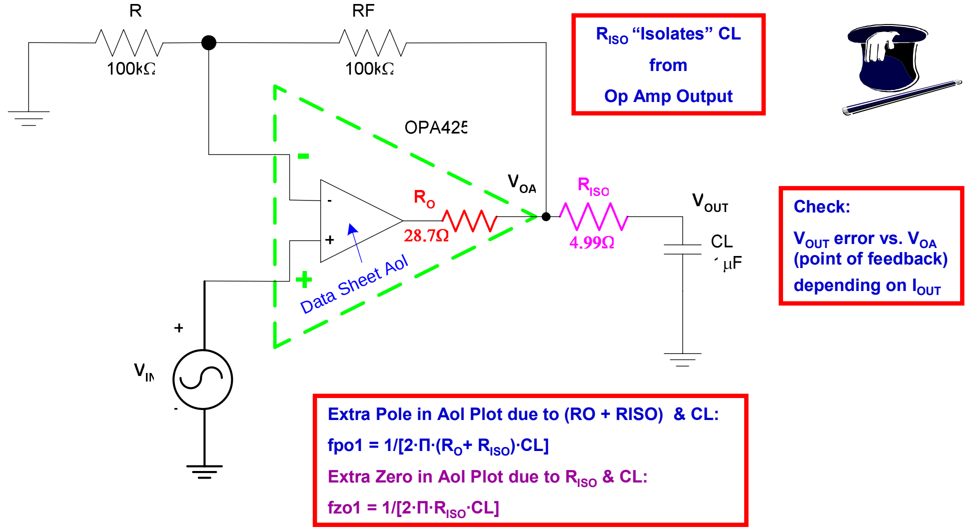


Fig. 6.14: R_{ISO} And CL Compensation

In our first-order analysis using the R_{ISO} & CL technique (Fig. 6.15) fpo1 is determined by the total sum of the resistance of R_O and R_{ISO} interacting with CL. fzo1 is determined by the combination of R_{ISO} and CL and for a $1/\beta$ of 6 dB we see that at fcl the rate-of-closure is 20 dB/decade and our first-order analysis predicts stability.

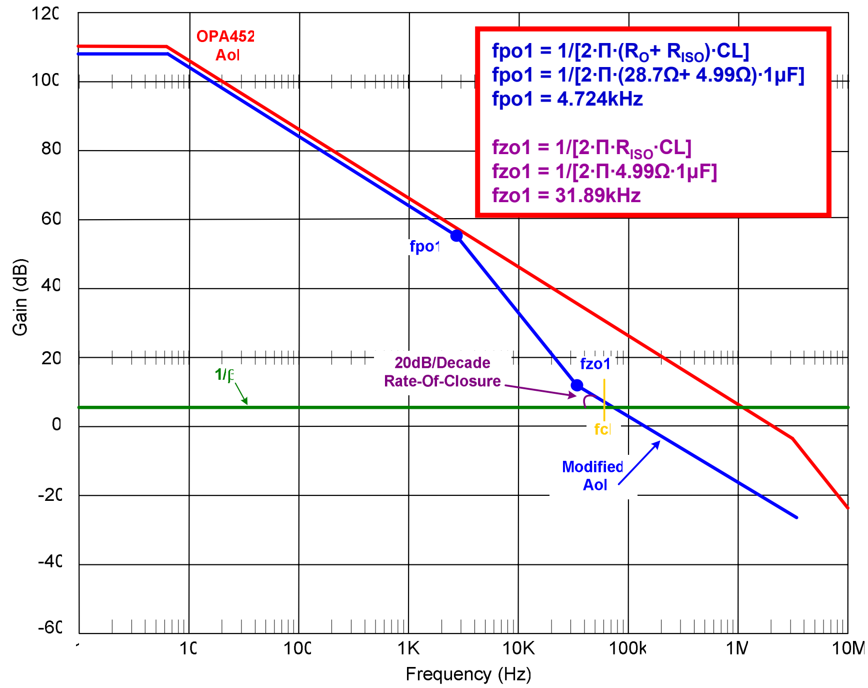


Fig. 6.15: First-Order Analysis: R_{ISO} And CL Modified Aol

We will use the Tina SPICE circuit (Fig. 6.16) to confirm our first-order analysis. Notice that we break the loop here at the minus input of the op amp which allows us to easily plot the "Modified Aol" curve and loop gain. 1/β, by inspection, will be x2 (6 dB).

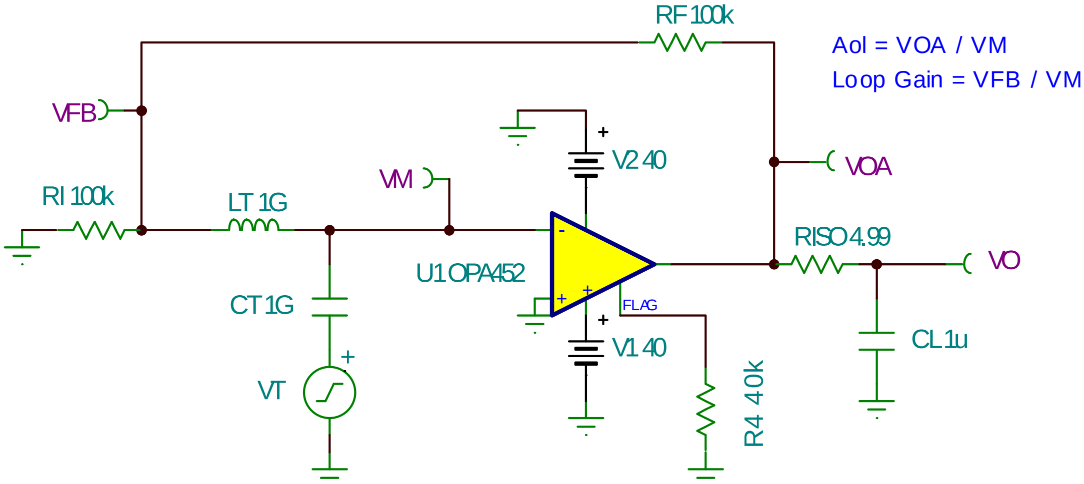


Fig. 6.16: Tina SPICE: R_{ISO} And CL Loop Circuit

The "Modified Aol" plot (Fig 6.17) shows poles and zeros close to our predicted fp01 = 4.724 kHz and fz01 = 31.89kHz.

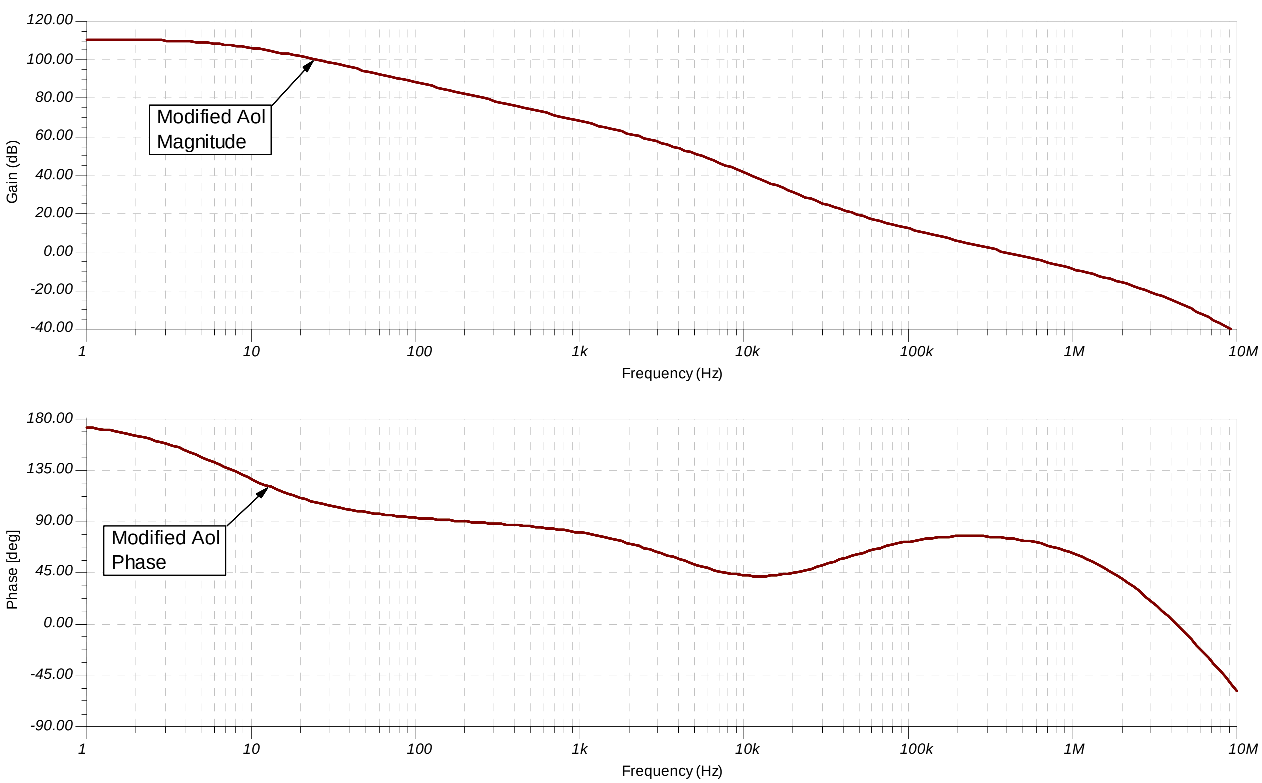


Fig. 6.17: Tina SPICE R_{ISO} And& CL "Modified Aol"

The loop-gain plots (Fig. 6.18) indicate good stability for the R_{ISO} & CL stability technique. From our synthesis rules-of-thumb we see phase margin never dipping below 45° from dc to fcl.

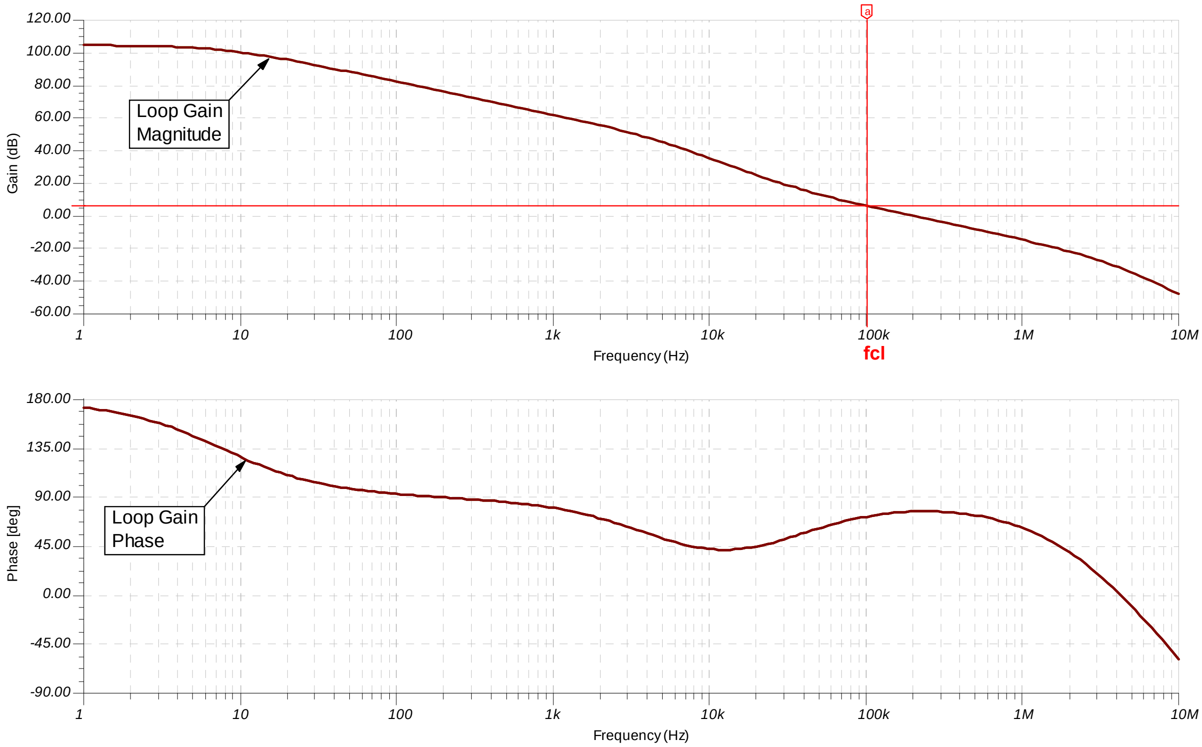


Fig. 6.18: Tina SPICE: R_{ISO} And CL Loop Gain

The Tina SPICE circuit (Fig 6.19) will be used to run our ac V_{OUT}/V_{IN} transfer function and rerun with V_{IN} changed for our transient analysis.

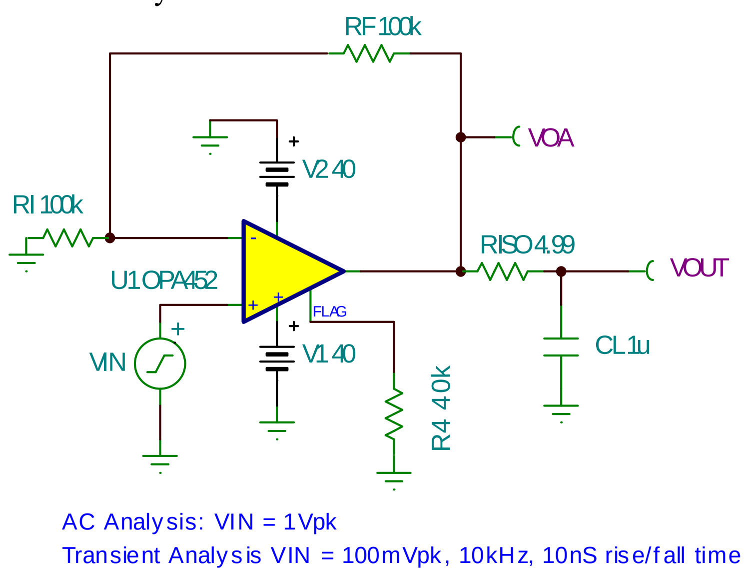


Fig. 6.19: Tina SPICE: R_{ISO} And CL V_{OUT}/V_{IN} Circuit

The V_{OUT}/V_{IN} ac transfer function for R_{ISO} & CL is a little bit tricky without some first-order analysis to help us understand how the frequency behavior of this circuit works.

We need to consider (Fig. 6.20) the V_{OA}/V_{IN} ac transfer function along with the V_{OUT}/V_{IN} ac transfer function. The point of feedback for this circuit is from V_{OA} and, therefore, V_{OA}/V_{IN} will be flat until the 1/β curve intersects the modified Aol plot. At fcl, V_{OA}/V_{IN} will follow the modified Aol curve on down since there is no loop gain left.

V_{OUT}/V_{IN} will be a little bit different. From dc to fzo1 V_{OUT}/V_{IN} will be flat. At fzo1, which is formed by R_{ISO} and CL, V_{OUT}/V_{IN} will roll-off at -20 dB/decade due to the single-pole effect of R_{ISO} and CL. At fcl loop gain is gone and V_{OA} begins to roll-off at -20 dB/decade due to the modified Aol curve. But V_{OUT}/V_{IN} contains the additional pole due to R_{ISO} and CL. So (Fig. 6.20) V_{OUT}/V_{IN} will have a 2-pole roll-off, or -40 dB/decade slope after fcl.

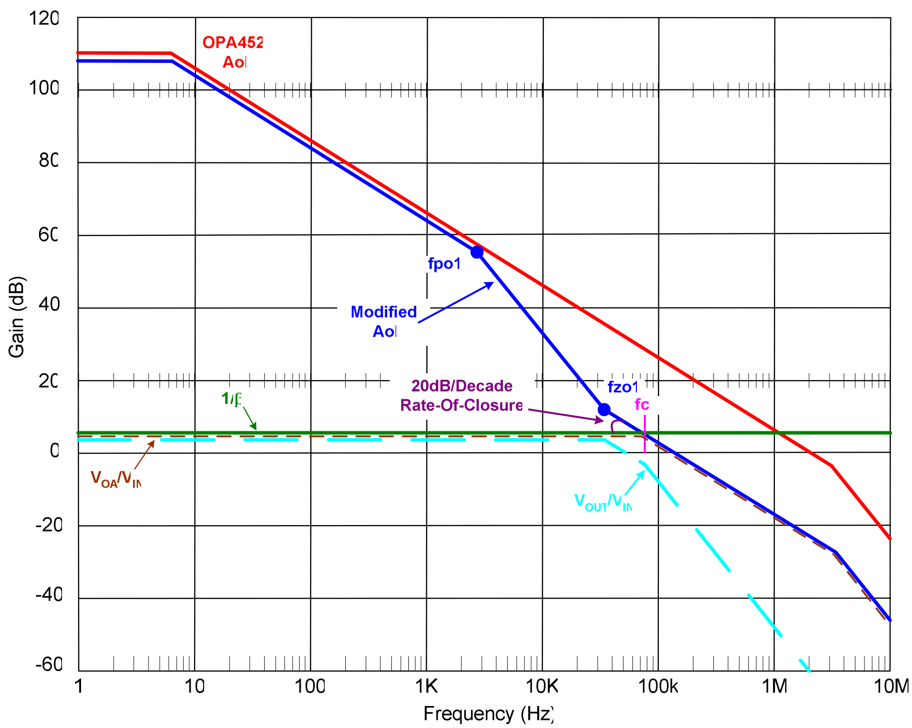


Fig. 6.20: First-Order Ac Analysis: R_{ISO} And CL V_{OUT}/V_{IN}

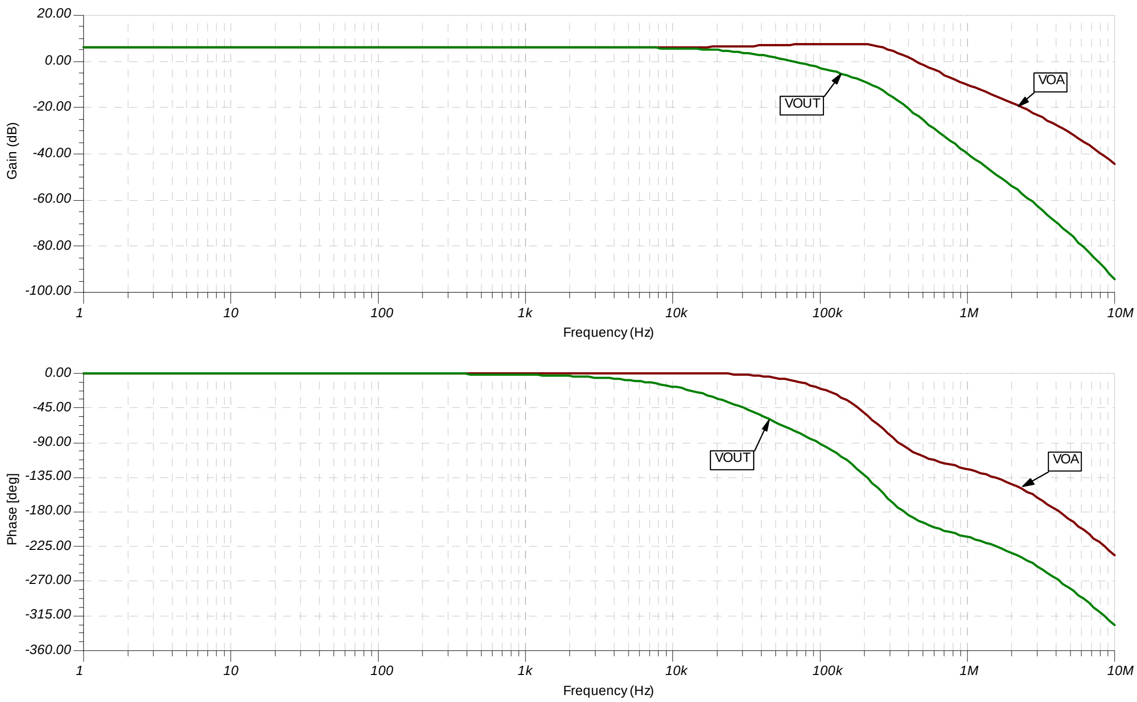


Fig. 6.21: Tina SPICE: R_{ISO} And CL V_{OUT}/V_{IN}

Our Tina SPICE simulations (Fig. 6.21) confirm our first-order analysis of V_{OUT}/V_{IN} and V_{OA}/V_{IN}.

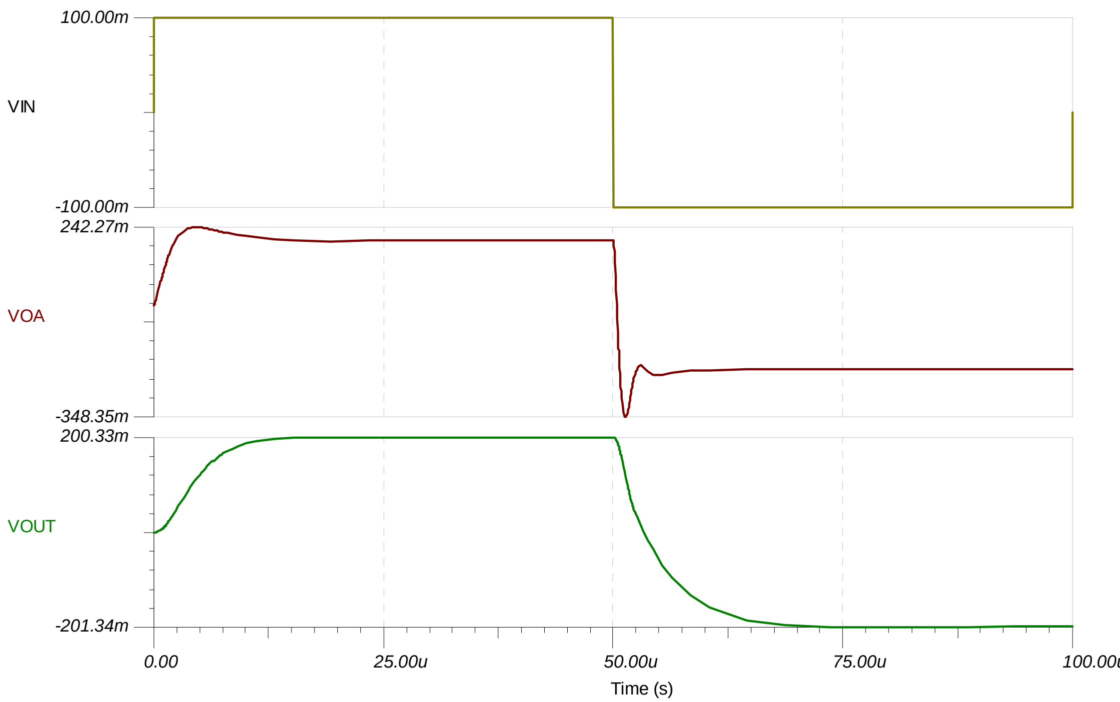


Fig. 6.22: Tina SPICE: R_{ISO} And CL V_{OUT}/V_{IN} Transient Analysis

For our final stability sanity check we run a transient analysis (Fig. 6.22). From V_{OA}, the point of feedback, the positive-going output predicts about 60° of loop-gain phase margin while the negative-going output has more than 45° (see Part 4). As this model matches the real IC for characteristics we see that the negative output stage is a bit different than the positive, but overall stability looks solid.

High Gain And CF Compensation

Our second technique to stabilize an op amp driving a capacitive load is to use high gain and a feedback capacitor, CF (Fig. 6.23). To see how this technique works we will plot a modified Aol curve with a second pole formed by R_O and CL. In the $1/\beta$ plot we add a pole at a frequency location to cause an intersection of the $1/\beta$ curve with the modified Aol curve at a rate-of-closure which is 20 dB/decade.

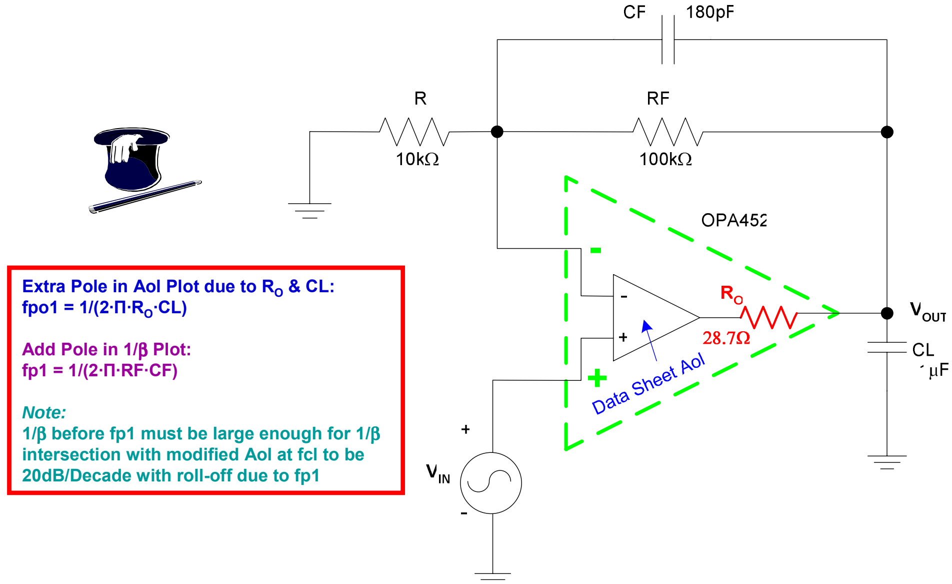


Fig. 6.23: High Gain And CF Compensation

Our first-order analysis plots the second pole, fp01, in the modified Aol curve (Fig. 6.24).

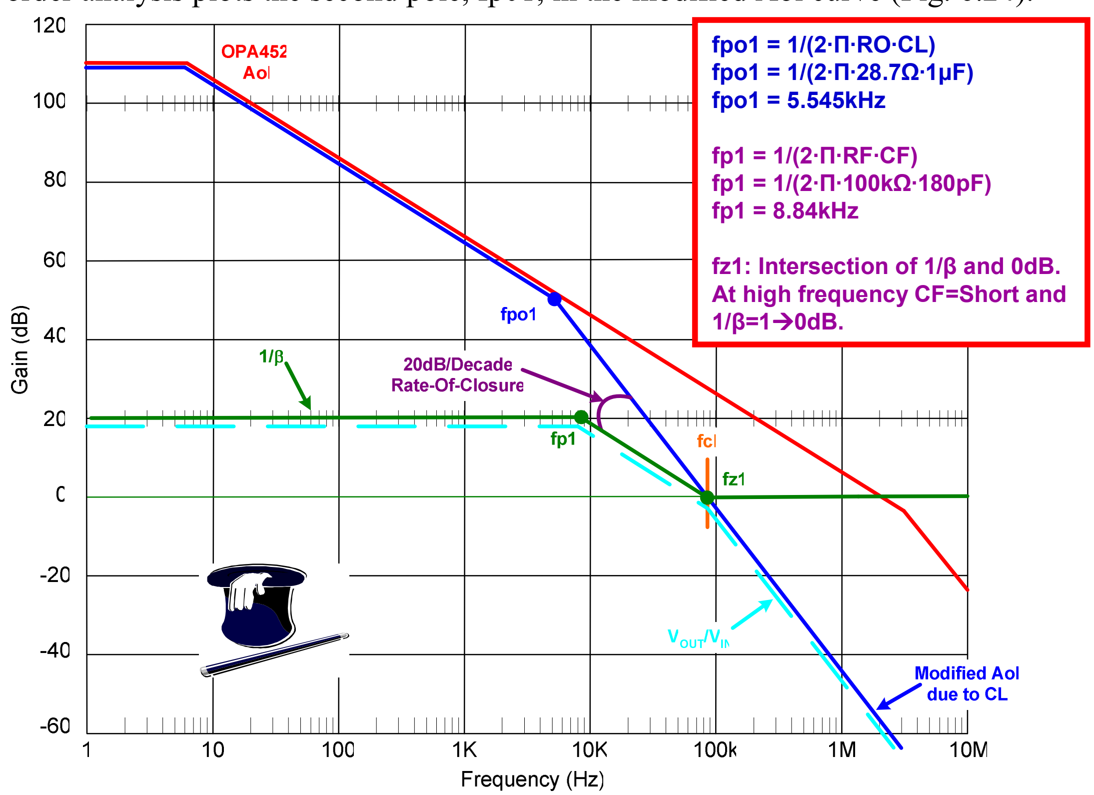


Fig. 6.24: First Order Analysis: High Gain And CF

We add a pole in the 1/β plot through the addition of CF in the op amp feedback. Note how fp1 was chosen to ensure the intersection of 1/β and the modified Aol curve to be 20 dB/decade rate-of-closure. The smallest value of 1/β will be 1 (0dB), by inspection, since at high frequencies CF is a short and V_{OUT} is fed back directly to the minus input of the op amp. From this first-order analysis we predict a stable circuit and since the point of feedback is directly at CL there will be no error in the V_{OUT}/V_{IN} transfer function. Our predicted V_{OUT}/V_{IN} ac transfer function will show a single pole roll-off at fp1, 8.84 kHz, due to the interaction of CF and RF. This will continue down at -20 dB/decade until fcl, where loop gain goes to zero, and then V_{OUT}/V_{IN} will follow on down the modified Aol curve. Our Tina SPICE circuit for the high-gain & CF loop test (Fig. 6.25) breaks the loop at the minus input to the op amp allows us to accurately plot the modified Aol curve.

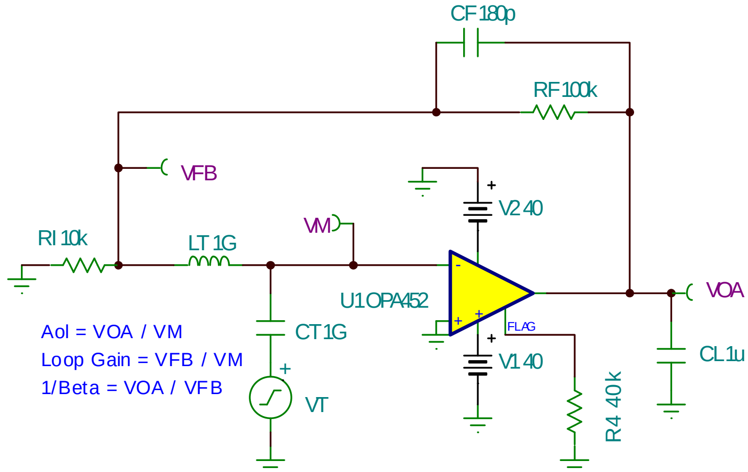


Fig. 6.25: Tina SPICE: High Gain And CF Loop Circuit

The 1/β plot and modified Aol plot (Fig. 6.26) correlate directly with our first-order predictions with a second Aol pole, fp, at about 5.45 kHz and a 1/β plot with a pole, fp1, at about 8.84 kHz. Notice how 1/β continues at a -20 dB/decade slope from 8.84 kHz until it intersects with 0 dB, where it remains.

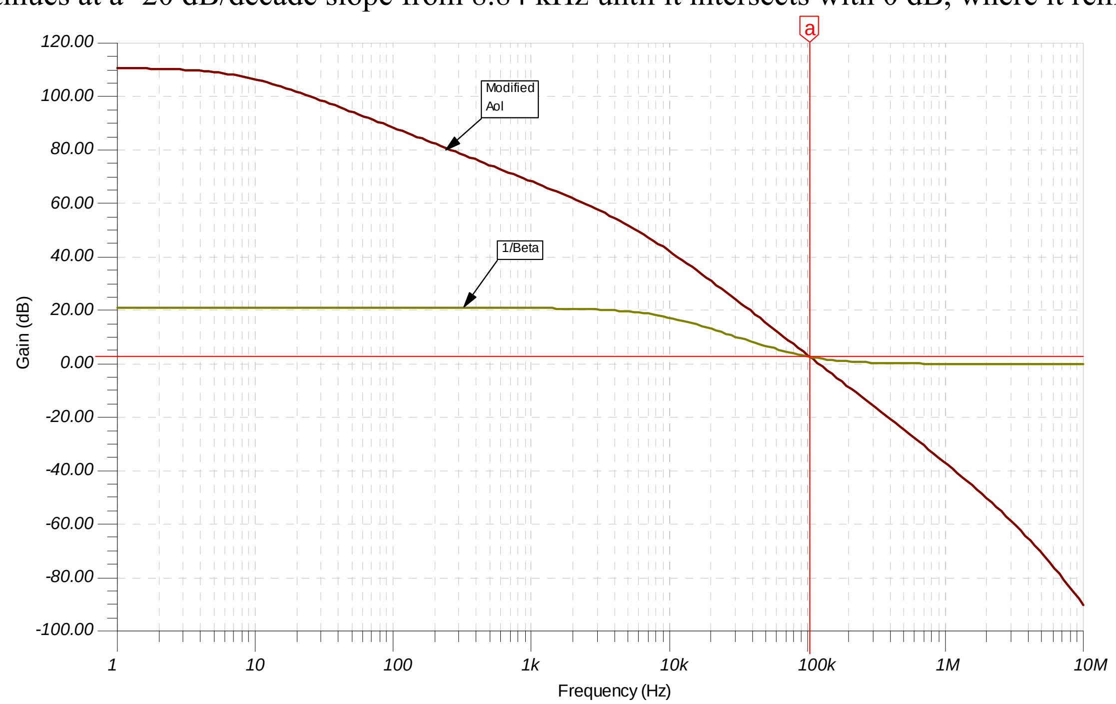


Fig. 6.26: Tina SPICE: High-Gain And CF-Modified Aol/1/β

Our loop gain plots for stability are shown in Fig 6.27 and phase-margin-wise, from dc to fcl our phase is >45° as desired. At fcl we see a phase margin of 38.53°. Let's see what the closed-loop ac response and transient analysis look like to determine if this is an acceptable circuit for us.

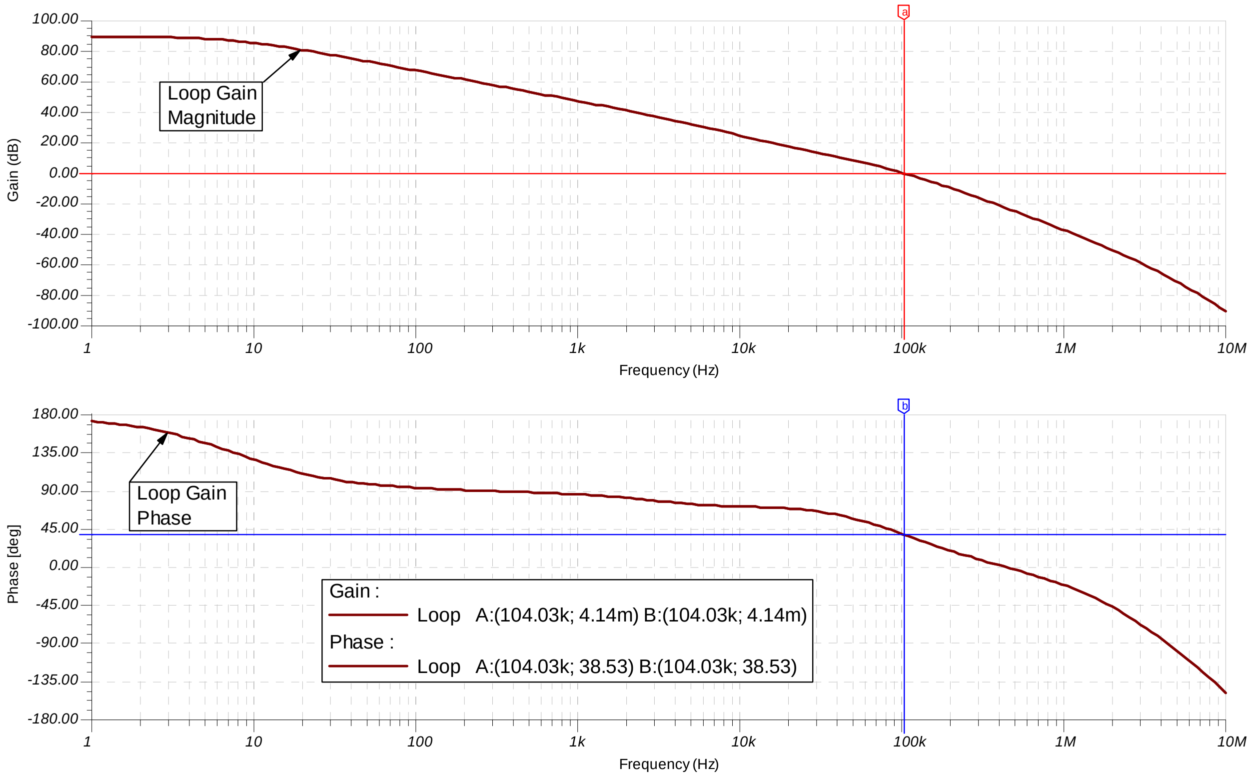


Fig. 6.27: Tina SPICE: High-Gain And CF Loop Gain

The V_{OUT}/V_{IN} tests will be conducted using the Tina SPICE circuit in Fig 6.28.

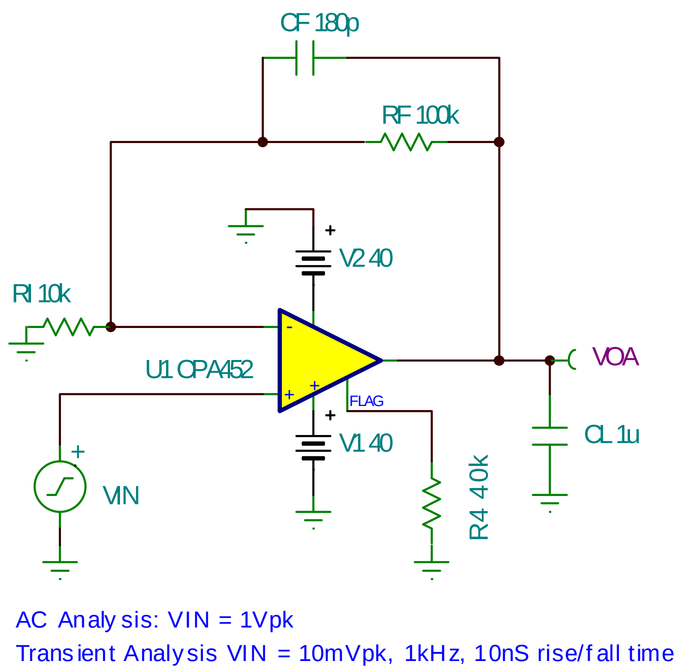


Fig. 6.28: Tina SPICE: High-Gain And CF V_{OUT}/V_{IN} Circuit

The V_{OUT}/V_{IN} ac transfer function is what we predicted by our first-order analysis (Fig. 6.29). A single pole roll-off around 10 kHz with a -40 dB/decade roll-off above 100 kHz (the flat spot is a predicted transition) where loop gain is zero and V_{OUT}/V_{IN} follows the modified Aol curve on down.

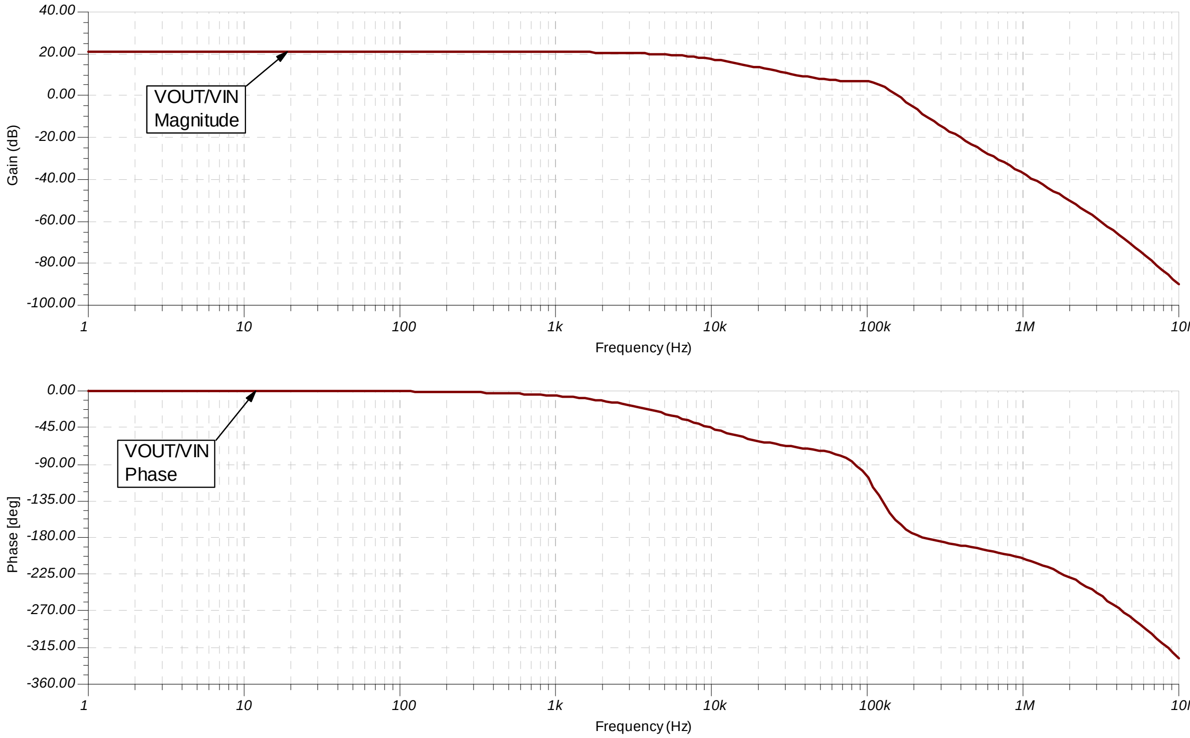


Fig. 6.29: Tina SPICE: High-Gain And CF V_{OUT}/V_{IN}

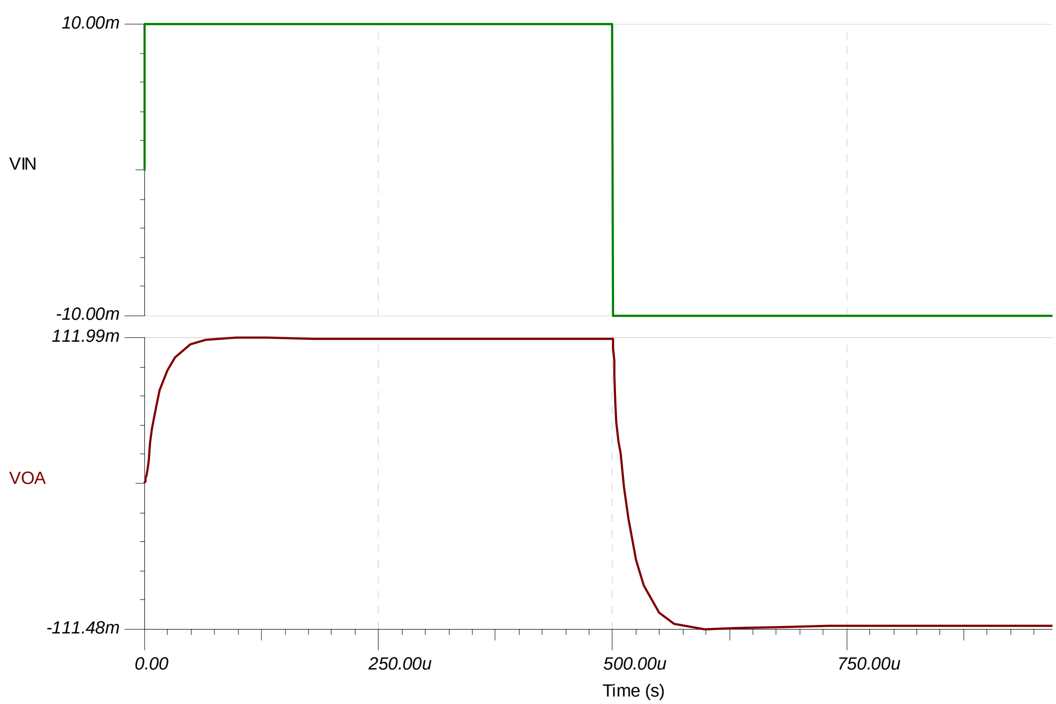


Fig. 6.30: Tina SPICE: High-Gain And CF Transient Analysis

A Tina SPICE transient V_{OUT}/V_{IN} analysis (Fig 6.30) shows a stable circuit with no overshoot/ringing.

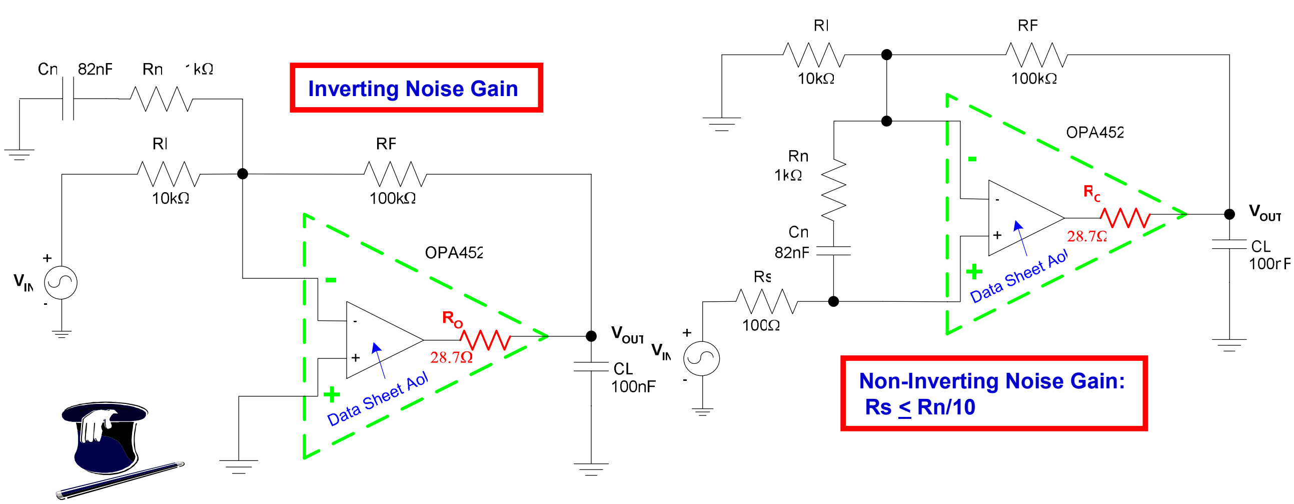
Noise Gain Compensation

Our third technique to stabilize an op amp driving a capacitive load is to "noise gain" (Fig. 6.31). To see how this technique works we will plot a modified Aol curve with a second pole formed by R_O and CL. In the 1/β plot we will add a pole and zero such that we will raise the 1/β gain at high frequencies to be above the second pole in the modified Aol curve. The added pole in the 1/β curve, fpn, is set by Rn and Cn, as shown. We do not need to compute the zero, fzn, since we can plot it graphically starting from fpn and going back down in frequency at a 20 dB/decade slope to the dc 1/β value.

This technique is called noise gain because it does increase the overall noise gain of the op amp circuit -- ie any noise internal to the op amp, usually referred to the input, is gained up to the output by the increase in gain over frequency of the 1/β curve.

For the inverting noise gain configuration this topology can be thought of as a summing amplifier. In this regard it is easy for us to see that V_{OUT}/V_{IN} is simply –RF/RI. The additional summation of ground into the Cn-Rn network results in no output voltage contribution but does limit the bandwidth of the overall circuit since it modifies the 1/β curve. *This clearly emphasizes the fact that to make an op amp circuit stable we must give up bandwidth.*

For the non-inverting noise gain configuration we must ensure that Rs, the input signal source impedance, is at least 10 times less than Rn to ensure that Rn will dominate in setting the high frequency 1/β gain. It is not as obvious that the non-inverting noise gain topology will yield V_{OUT}/V_{IN} = 1 + RF/RI. A derivation of this will be worthwhile.



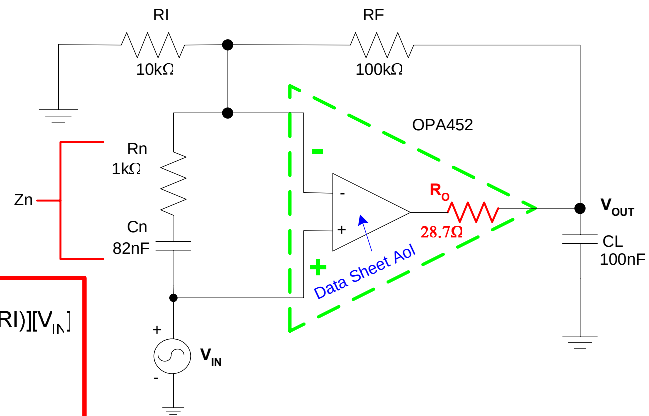
Extra Pole in Aol Plot due to R_O & CL:
fpo1 = 1/(2·Π·R_O·CL)

Add Noise Gain Zero & Pole in 1/β Plot:
1/β DC = RF/RI
1/β Hi-f = RF/Rn (Must intersect Modified Aol at 20dB/Decade)
fpn = 1/(2·Π·Rn·Cn)
fzn = Intersect of +20dB/decade slope from fpn down to 1/β DC value

V_{OUT}/V_{IN} = RF/RI
V_{OUT}/V_{IN} High Frequency Noise Gain increases to RF/Rn

Fig. 6.31: Noise Gain Compensation

We assign the Rn-Cn network (Fig. 6.32) a single variable name Zn to simplify our analysis of the V_{OUT}/V_{IN} ac transfer function. Using superposition (see Part 4) and classical op amp gain theory we can solve for V_{OUT} by treating the op amp as a summer-amplifier. The result is that V_{OUT}/V_{IN} is the simple 1 + RF/RI gain ratio for any non-inverting op amp configuration. However, Rn-Cn will impact $1/\beta$ and reduce the bandwidth of V_{OUT}/V_{IN} and increase the overall noise gain of the circuit.



Use Superposition:

$V_{OUT} = 0V(-RF/RI) + V_{IN}(-RF/Zn) + [1+ RF/(Zn//RI)][V_{IN}]$
$= -V_{IN}\,(RF/Zn) + V_{IN} + [RF/(Zn//RI)]\,V_{IN}$

$[RF/(Zn//RI)] = RF/[ZnRI/(ZN+RI)]$
$= (RF\,ZN + RI\,RF) / ZN\,RI$
$= RF\,ZN/ ZN\,RI + RI\,RF/RI\,Zn$
$= RF/RI + RF/Zn$

$V_{OUT} = -V_{IN}\,(RF/Zn) + V_{IN} + [RF/RI + RF/Zn]\,V_{IN}$
$= -V_{IN}\,(RF/Zn) + V_{IN} + V_{IN}(RF/RI) + V_{IN}(RF/Zn)$
$= V_{IN} + V_{IN}(RF/RI)$

$V_{OUT} = V_{IN}\,[1+(RF/RI)] \rightarrow V_{OUT}/V_{IN} = 1+(RF/RI)$

Fig. 6.32: Non-Inverting Noise Gain Compensation Derivation

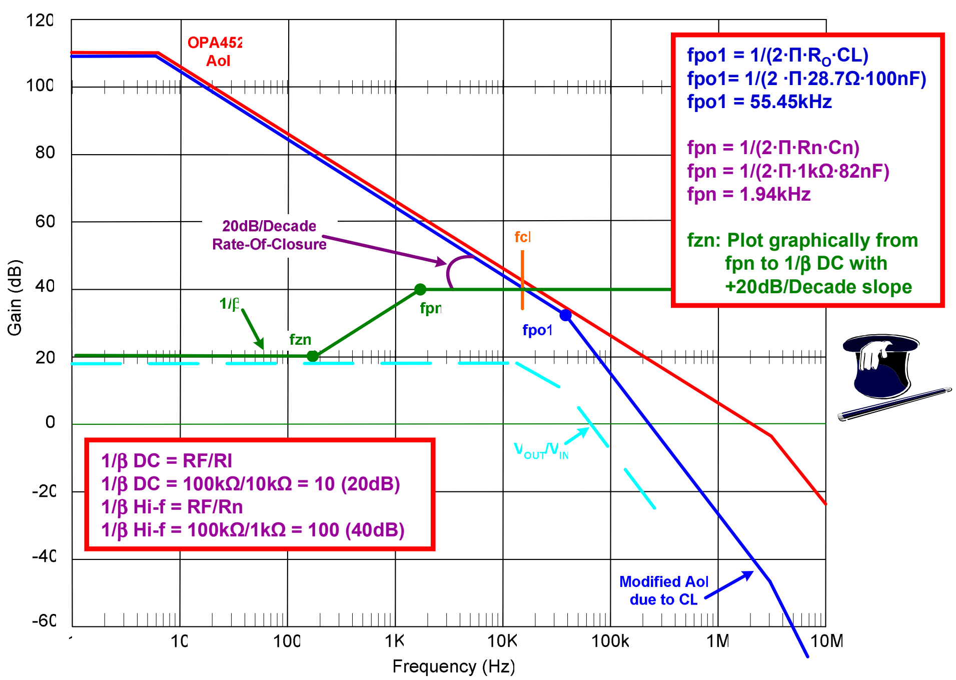


Fig. 6.33: First-Order Analysis: Noise Gain Compensation

To complete our first-order analysis for the noise gain example (Fig. 6.33) the modified Aol is first created. Our dc $1/\beta$ is known to be 10 (20 dB). We see that in order to intersect the modified Aol at a rate-of-closure that is 20 dB/decade we will need to set the high-frequency $1/\beta$ to 100 (40 dB). This is set by RF/Rn. We choose fpn about a decade less than fcl. This choice is to allow for Aol shift over temperature, operating conditions and IC process variations. Knowledgeable IC designers inform me that over process and temperature and operation Aol won't shift more than ½ of a decade. I prefer the easy-to-remember, conservative rule-of-thumb of one decade. If the modified Aol curve was to shift one decade to the left in frequency we would have 40 dB/decade rate-of-closure and instability!! fzn is simply found graphically by drawing a 20 dB/decade slope from fpn to the intersection of the low-frequency 1/β. Everything looks good from our many decade rules-of-thumb for spacing poles and zeros in the 1/β plot for good stability design. V_{OUT}/V_{IN} will be flat from dc to fcl where loop gain goes to zero. At that point V_{OUT}/V_{IN} will follow the modified Aol curve on down in amplitude.

In our Tina SPICE circuit (Fig. 6.34) to plot 1/β, modified Aol, and loop gain to check our first-order analysis we again break the loop at the minus input of the op amp for ease of modified Aol plotting.

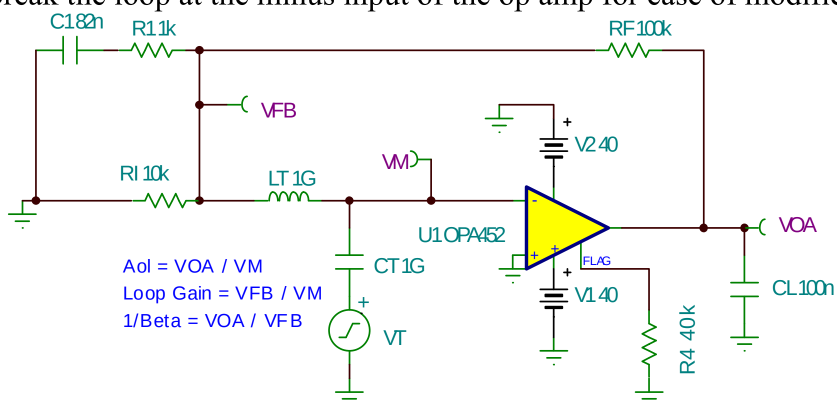


Fig. 6.34: Tina SPICE: Noise Gain Loop Circuit

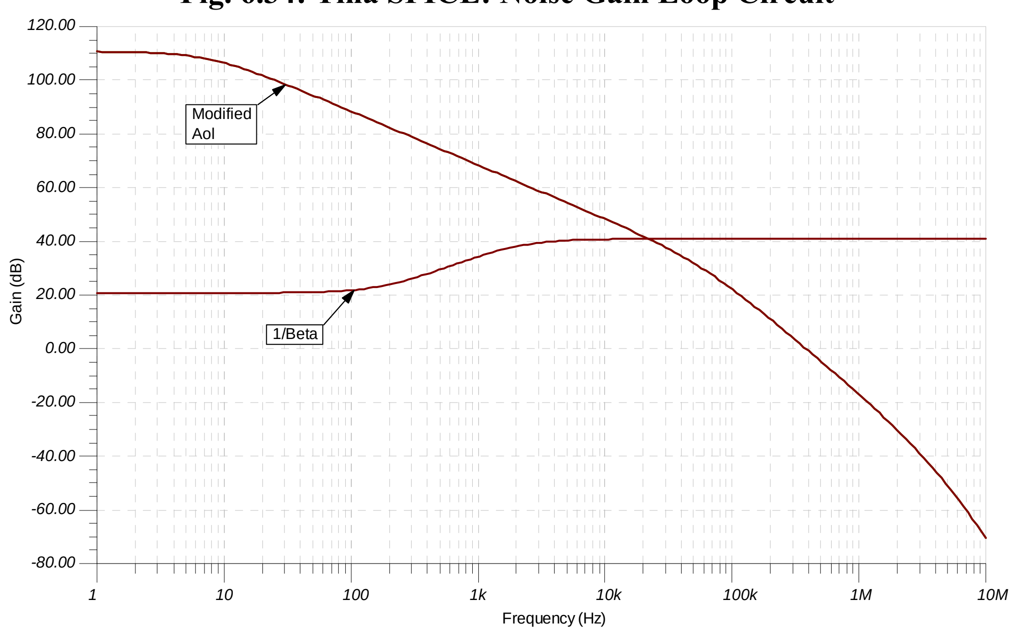


Fig. 6.35: Tina SPICE: Noise Gain Modified Aol And 1/β

Our Tina SPICE results once again match our first-order predictions. The modified Aol (Fig 6.35) contains a second pole at about 55.45 kHz. The 1/β plot is 20 dB at low frequencies, 40 dB at high frequencies, contains a pole at about 1.94 kHz and a zero at about 194 Hz. And at fcl, about 20 kHz, a 20 dB/decade rate-of-closure.

The loop gain plots (Fig 6.36) confirm a stable circuit with phase margin at fcl of 63.24°. There is a slight dip of phase to under 45° between 100 Hz and 1 kHz but not enough to cause concern.

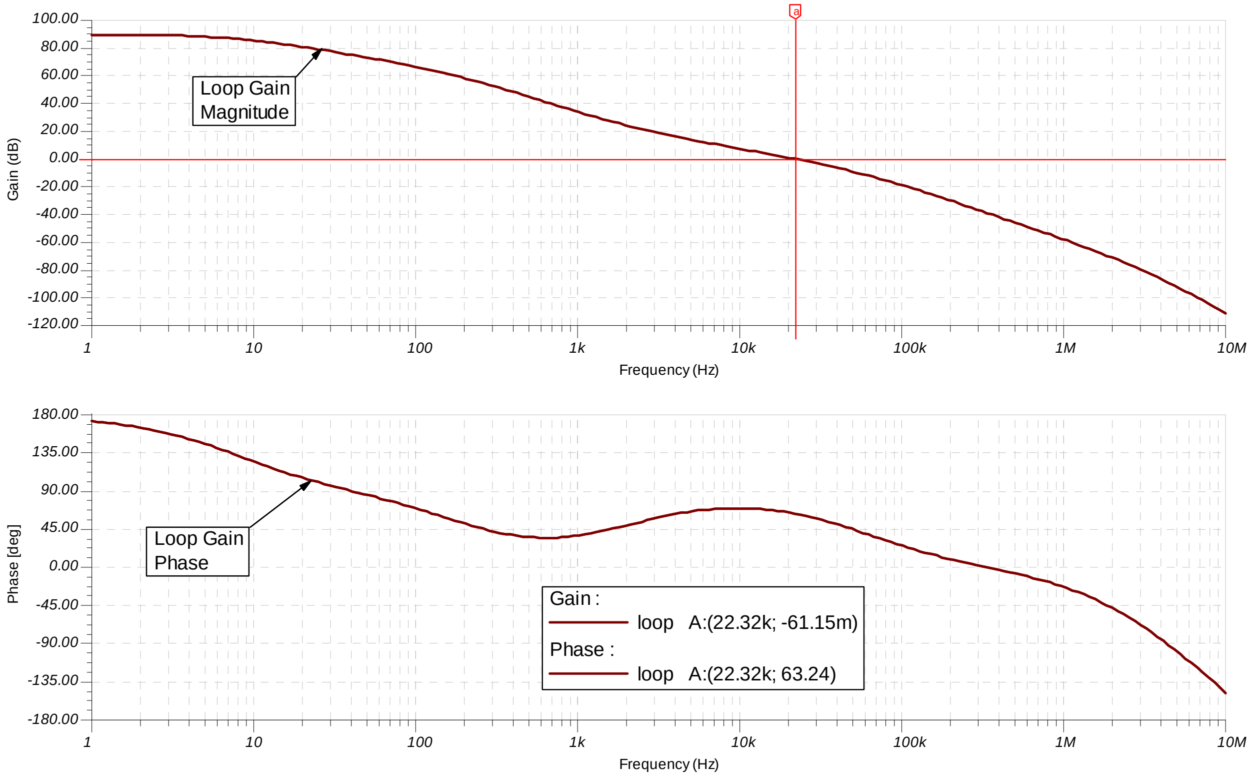


Fig. 6.36: Tina SPICE – Noise Gain Loop Gain

For our V_{OUT}/V_{IN} ac transfer test and transient test we will use the circuit in Fig 6.37.

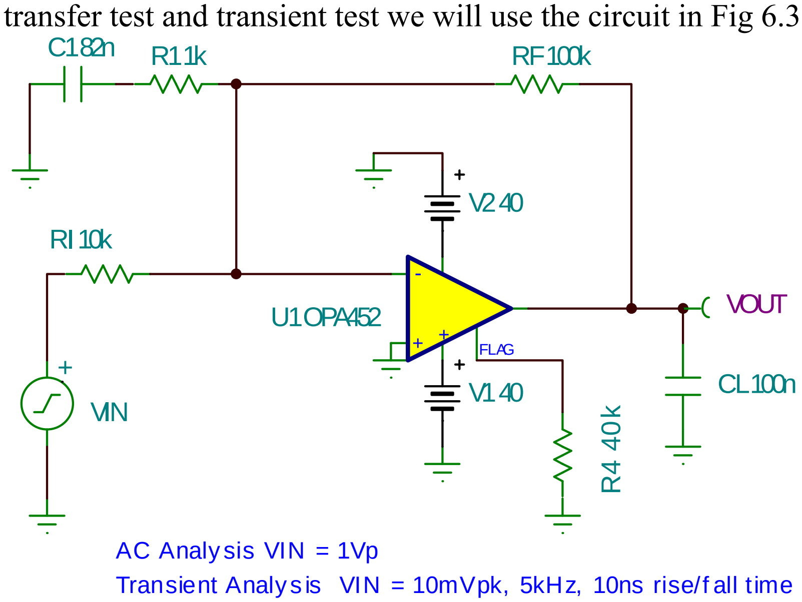


Fig. 6.37: Tina SPICE: Noise Gain V_{OUT}/V_{IN} Circuit

The V_{OUT}/V_{IN} ac transfer function (Fig 6.38) shows next-to-no peaking in its response and as we predicted a -20 dB/decade slope from about 20 kHz (where loop gain goes to zero) to about 50 kHz where the modified Aol breaks again to a -40 dB/decade slope.

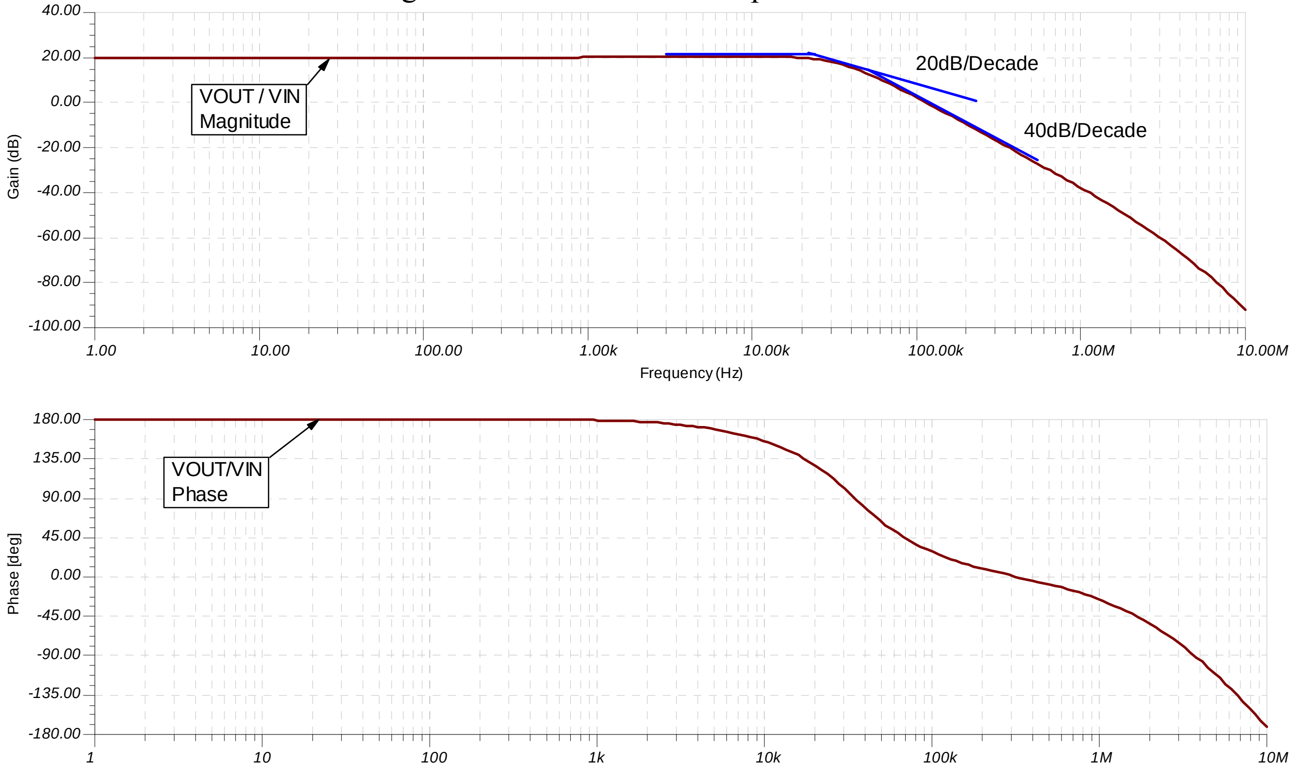


Fig. 6.38: Tina SPICE: Noise Gain V_{OUT}/V_{IN}

Based on the slight overshoot (Fig 6.39), and no undershoot, the transient V_{OUT}/V_{IN} test, phase margin correlates to about a 60° phase margin (see *Transient Real World Stability Test* in Part 4).

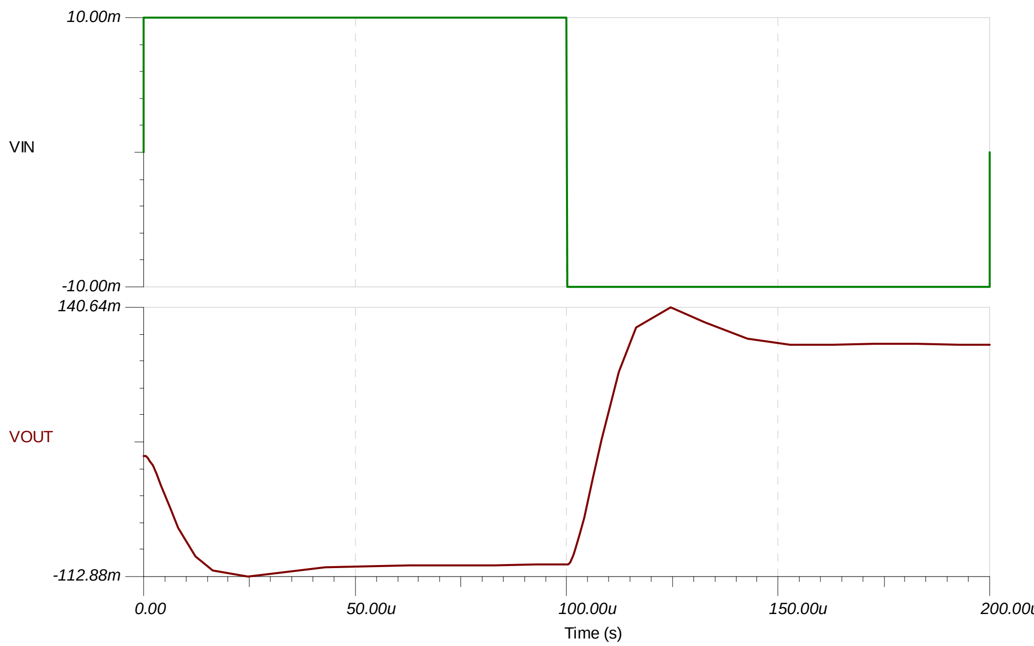


Fig. 6.39: Tina SPICE: Noise Gain V_{OUT}/V_{IN} Transient Analysis

Review

Three (R_{ISO}, high-gain & CF, noise gain) of the "six ways to leave your capacitive load stable" have been covered in this Part. For each technique we were able to analyze, synthesize, and simulate a stable circuit for an op amp driving a capacitive load. Part 7 covers noise gain & CF and output pin compensation techniques. And Part 8 presents the sixth technique, R_{ISO} with dual feedback.

The Burr-Brown Products group of Texas Instruments has made available a free version of Tina SPICE. It contains almost all of Burr-Brown and Texas Instruments op amp models and will run up to two op amp models in one circuit. Tina-TI SPICE is available at: http://www.ti.com/tina-ti

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About The Author

After earning a BSEE from the University of Arizona, Tim Green has worked as an analog and mixed-signal board/system level design engineer for over 23 years, including brushless motor control, aircraft jet engine control, missile systems, power op amps, data acquisition systems, and CCD cameras. Tim's recent experience includes analog & mixed-signal semiconductor strategic marketing. He is currently a Strategic Development Engineer at Burr-Brown, a division of Texas Instruments, in Tucson, AZ and focuses on instrumentation amplifiers and digitally-programmable analog conditioning ICs. He can be contacted at green_tim@ti.com