Operational Amplifier Stability
Part 11 of 15: Modeling Complex Zo for Op Amps

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Part 11 of this series will venture into the world of complex Zo inside operational amplifiers. As single supply applications of op amps have become more predominant at the board and systems level, semiconductor manufacturers have been challenged to create unique op amp topologies to provide rail-to-rail inputs and outputs along with high open-loop gains for accuracy and low noise on an ever-dwindling signal range (ie from ±10 V down to 0 – 5 V down to 0 – 3 V). These new and unique op amp topologies produce some very interesting and unique Zo characteristics which need to be understood and modeled in order to guarantee, by design, a stable circuit when driving reactive loads. We will look at a novel approach to modeling the complex output impedance of op amps. The building of an op amp Zo Block will allow us to move the op amp Zo outside of the traditional op amp SPICE macromodel and thereby separate the Aol curve from the effects of Zo interacting with reactive loads on the output. This will allow us, in a future Part, to simplify the challenges of stabilizing op amps with complex Zo characteristics.

As with any engineering problem there is more than one possible solution. One may be tempted to construct a Zo Block from only passive components (inductors, resistors, capacitors). That solution has been researched and proven to not be so good, as undesired peaking occurs in the frequency areas of L-C resonance. A real op amp Zo will have smooth, non-resonant frequency transitions like the model in this TechNote produces. The technique for building an external Zo Block in SPICE is rather straight-forward and easy to build yielding acceptable results in the minimum amount of time.

One final prologue before we head to the Zo Block. TINA SPICE, used extensively in this TechNote series as a SPICE simulator, has a very good convergence engine. Some other SPICE simulators are not as forgiving and sometimes require either scaling down of large value reactive components or setting of specific option parameters to easily converge. Our goal in this TechNote is to divulge a quick way to measure Zo on a SPICE macromodel and show the blueprint for an external Zo Block for SPICE stability analysis. If the recommended circuits below cause other simulators to operate a bit rough then re-scaling of reactive components may be necessary.

By now we have realized, through this series, that the only thing we need to know about an op amp to solve any stability problem is the Aol curve and the Zo characteristics (see Fig. 11.1, overleaf). The Zload will be determined by system demands and we will tailor 1/Beta for stability.

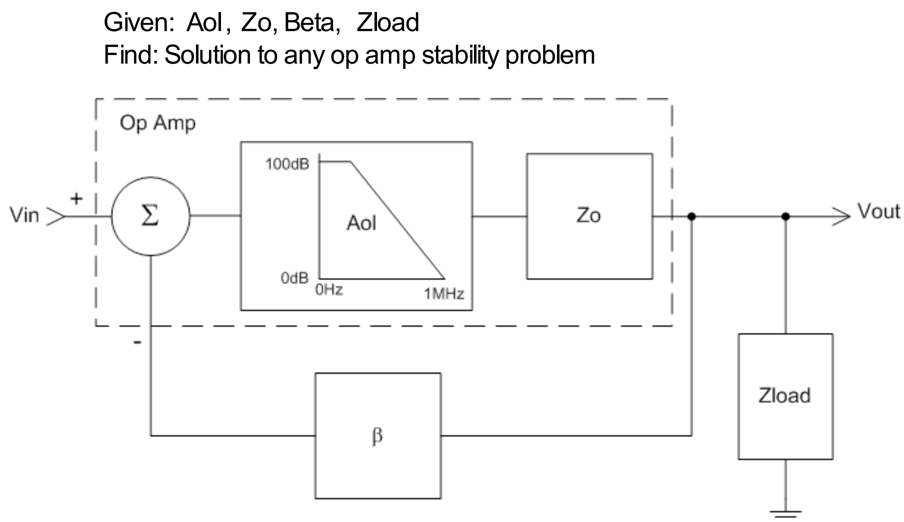


Fig. 11.1: All You Need to Solve Op Amp Stability Problems

To empower us to solve stability problems, when we use op amps with complex Zo characteristics, we will want to move the Zo characteristic of the op amp macromodel outside of the op amp (see Fig. 11.2).

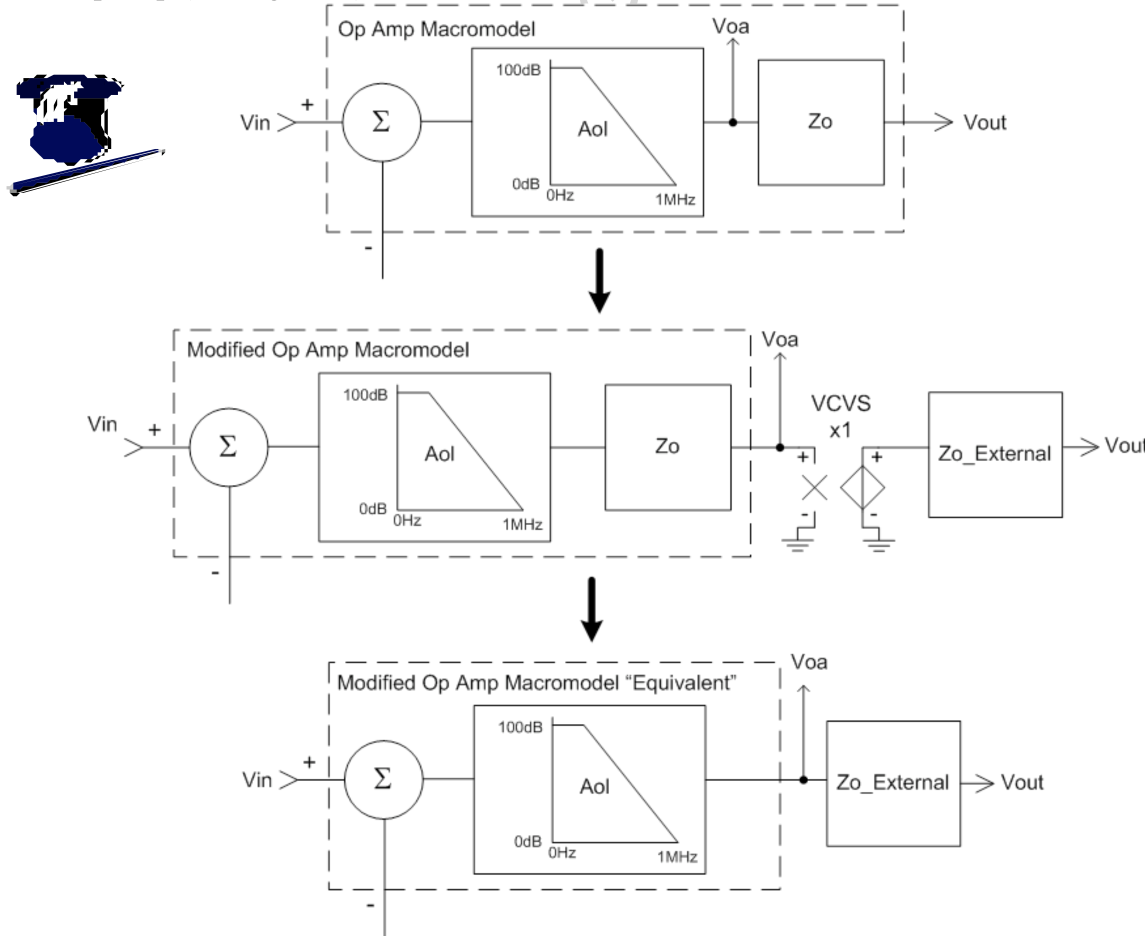


Fig. 11.2: Moving Zo Outside Op Amp Macromodel

This will be accomplished by creating a standalone Zo Block which will be isolated from the original macromodel by a voltage-controlled voltage source with a gain equal to 1. The voltage-controlled voltage source acts as an ideal isolation amplifier with a gain of 1 and retains the original macromodel Aol curve and presents no interaction between the op amp macromodel output and the external Zo Block. The final result will be an Aol curve and a Zo Block with capability of measurement between the Aol curve and Zo Block.

Recall from *Part 3 of 15: R_O and R_{OUT}* how R_O and R_{OUT} are related. R_{OUT} is R_O reduced by loop gain. Fig. 11.3 will define the op amp model used for the derivation of R_{OUT} from R_O. This simplified op amp model focuses solely on the basic dc characteristics of an op amp. A high input resistance (100 MΩ to GΩ), R_{DIFF} develops an error voltage across it, V_E, due to the voltage differences between -IN and +IN. The error voltage, V_E, is amplified by the open-loop gain factor Aol and becomes V_O. In series with V_O to the output, V_{OUT}, is R_O, the open-loop output resistance. The resultant relationship between R_{OUT} and R_O is shown above with the detailed derivation in this Part's Appendix. We will use the same terminology for complex op amp output impedances. That is, Zo is the open-loop output impedance and Zout is the closed-loop output impedance.

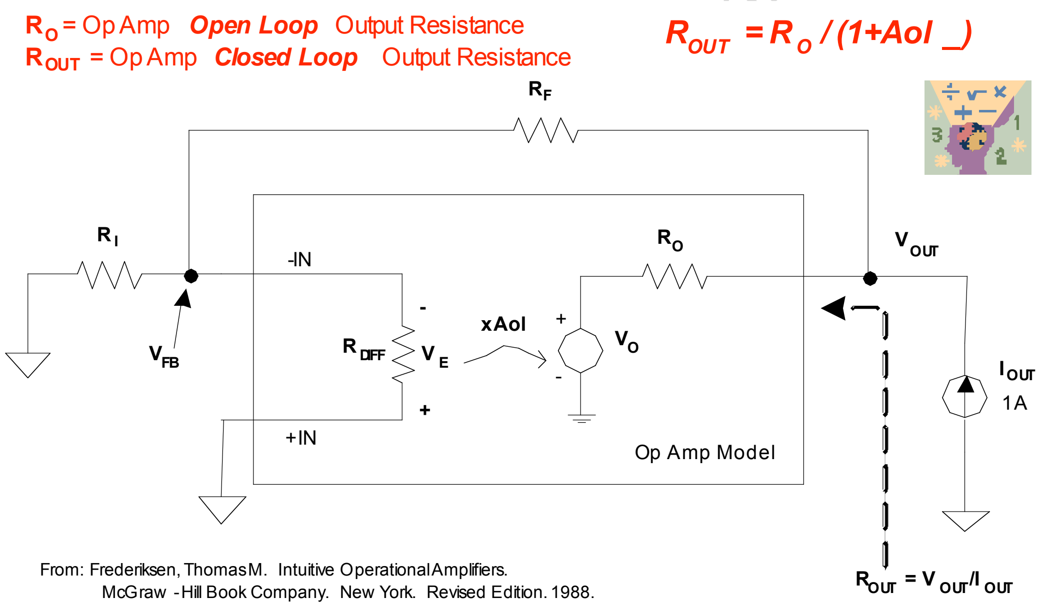


Fig. 11.3: R_O and R_{OUT}

Our op amp of choice for complex Zo analysis and external Zo Block build is a CMOS RRIO op amp with specifications as detailed in Fig 11.4. The OPA376 is a low quiescent current (950 µA) op amp optimized for single supply. operation (2.7 V to 5.5 V) with beyond rail-to-rail input (greater than 0.1 V beyond either supply) and rail-to-rail output (Vsat = 20 mV @ Iout = 254.8 µA). The OPA376 will also provide output current of 2.7 mA at a saturation voltage of 50 mV max. In addition, the OPA376 has a wide bandwidth of 5.5 MHz and a slew rate of 2 V/µs.

OPA376
Low-Noise, Low Quiescent Current, Precision Operational Amplifier

Input Specs

Offset Voltage	25uV max
Offset Drift	1uV/C
Input Voltage Range	(V-)-0.1V to (V+)+0.1V
Common-Mode Rejection Ratio	90dB typ
Input Bias Current	10pA max

Noise

Input Voltage Noise	0.8uVpp, f=0.1Hz to 10Hz
Input Voltage Noise Density	7.5nV/rt-Hz @1kHz
Input Current Noise Density	2fA/rt-Hz

Output Specs

Vsat @ Iout = 54.8uA	20mV max
Vsat @ Iout = 2.7mA	50m max
Iout Short Circuit	+30/-50mA

AC Specs

Open Loop Gain, RL = 10k	134dB typ
Open Loop Gain, RL = 2k	126dB typ
Gain Bandwidth Product	5.5 MHz
Slew Rate	2V/us
Overload Recovery Time	0.33us
Total Harmonic Distortion + Noise	0.00327%, f=1kHz
Settling Time, 0.01%	2us

Supply Specs

Specified Voltage Range	2.5V to 5.5V
Quiescent Current	950uA max
Over Temperature	1mA max

Temperature & Package

Operating Range	-40C to +125C
Package options	SC70-5, SOT23-5, SO-8

Fig. 11.4: OPA376 Op Amp for External Zo Block Build

The OPA376 data sheet contains a Zo curve (see Fig. 11.5).

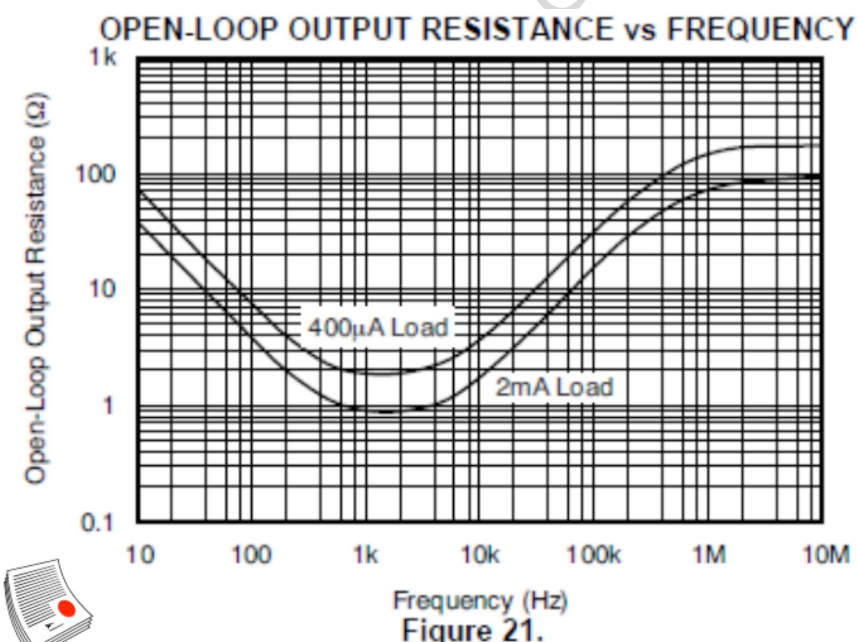


Fig. 11.5: OPA376 Op Amp Data Sheet Zo Curve

Most op amp data sheets contain only a closed-loop output resistance vs frequency curve from which it is very difficult to extract a complex Zo. (Fortunately for us some sort of 'Zo Wizard' must have had influence here to include this most valuable curve. Notice that Zo changes with dc load current (almost always lowers as dc load current increases). Since circuits we design must be stable under all operating conditions we will choose to use the rule-of-thumb worst case curve (most lightly loaded and capacitive loaded).

An important tool in our op amp stability toolbox will be a way to measure Zo on a SPICE op amp macromodel. This measurement will enable us to ensure the macromodel matches either the data sheet Zo curve or measured Zo results. With regards to measuring Zo on an op amp: do not try this at home as it is best left to trained professionals. It requires a gain-phase analyzer, custom circuits and custom software to yield 1 kHz to 10 MHz accurate measurements. Better to demand the Zo curve from your semiconductor op amp manufacturer. We can use IC simulated results if real measurements are not available. Comparing the results of a Zo measured result on a SPICE macromodel to other data sheet characteristics of the op amp can tell us if the op amp macromodel Zo is believable. The details of this comparison are beyond our immediate focus here. Our first step in measuring Zo is to measure Aol. For single supply op amps we will run all of our ac tests using dual supplies to eliminate any common mode issue on the input and to eliminate any negative input offset voltages from trying to drive the output below ground (if we used single supply) and saturating the output devices: which will not give an accurate ac result. For the Aol Test circuit in Fig. 11.6 the inductor, LT, will act as a short at dc and an open for any frequencies of interest. C1 will act as an open at dc and as a short for any frequency of interest. RL can be adjusted to check Aol at different dc load currents if desired by adjusting VL. Before we run any ac analysis we should run a dc analysis to ensure the op amp is in a linear region of operation or our ac results will not be valid. In Fig. 11.6 we see the op amp output at -25.38 µV for a dc analysis and thus we are in a linear region of operation (output is not saturated to either rail).

For most single supply op amp AC tests:
Run dual supply to
- **eliminate input common mode violations**
- **eliminate saturation of output devices with zero input times closed loop in DC Analysis (i.e. negative Vos trying to driver output less than ground)**

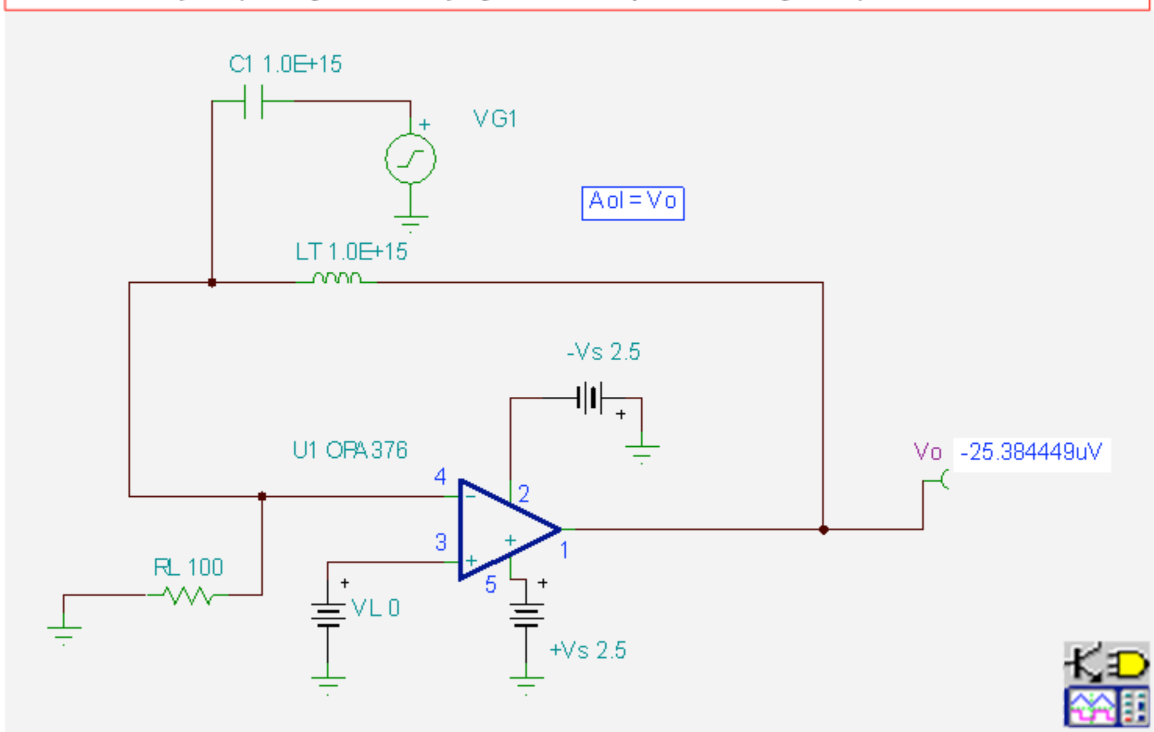


Fig. 11.6: Measuring Zo in SPICE: Step 1 – Measure Aol

TINA SPICE results of our Aol test (Fig. 11.7) show a low-frequency gain of 144.13 dB (16.0879 MV/V). Also observe a low-frequency pole in Aol at about 400 MHz.

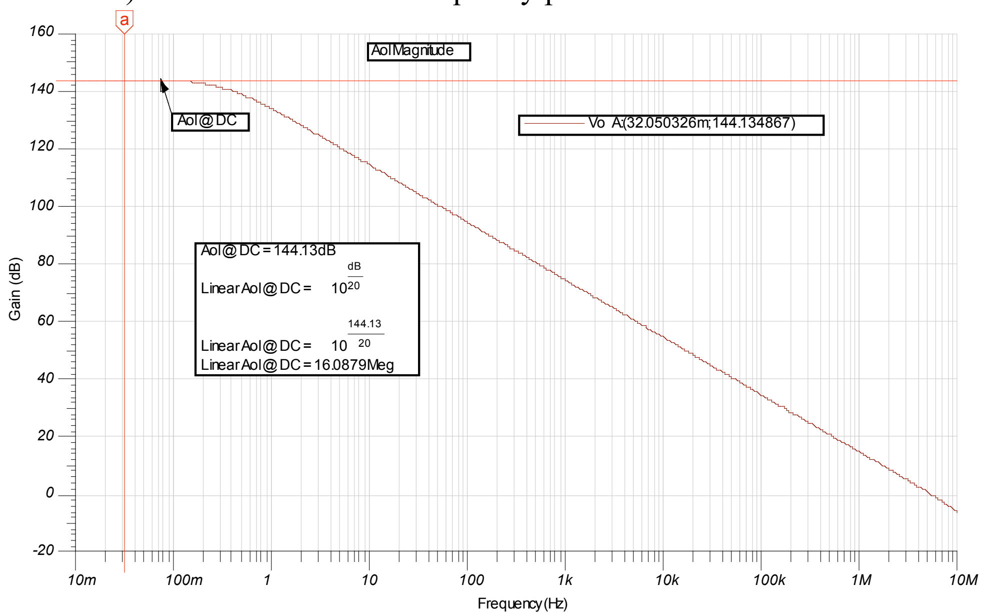


Fig. 11.7: Measuring Zo in SPICE: Step 1 – Measure Aol Results

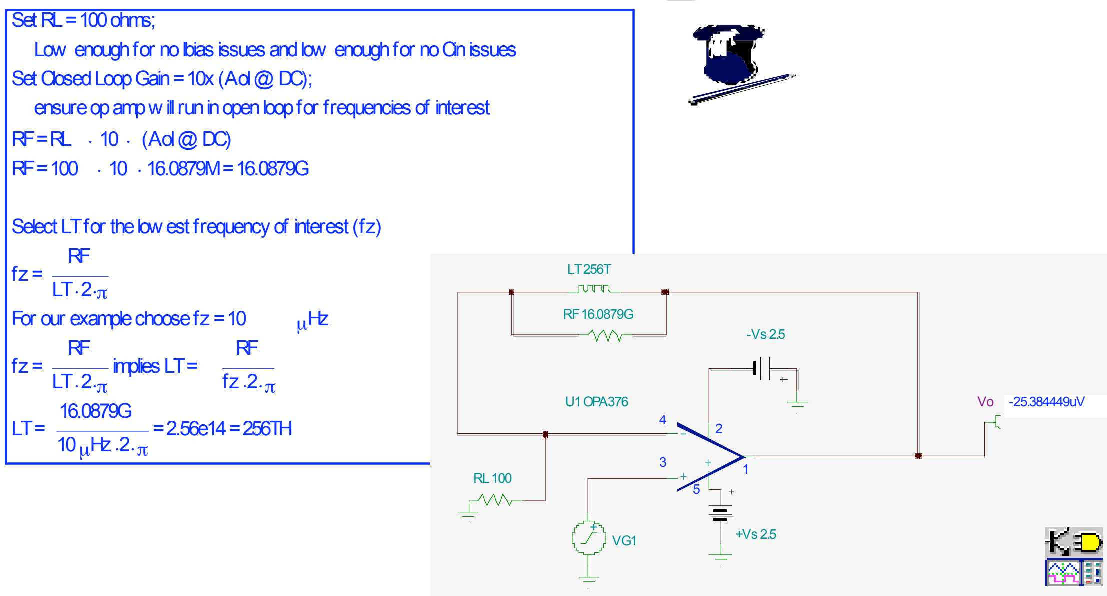


Fig. 11.8: Measuring Zo in SPICE: Step 1 – Configure Closed Loop Gain

The test circuit in Fig. 11.8 will be constructed to measure Zo once we know the Aol of the amplifier. We want to design the closed-loop gain of our Zo test circuit to be greater than the Aol of the amplifier for all frequencies of interest. Such a design will guarantee that when we test for Zo it will be Zo and not Zout. Remember that AolBeta on a dB plot is Aol(dB) – 1/Beta(dB). So if 1/Beta is larger than Aol we will have AolBeta = -?dB or a very small number. Then from:

Zout = Zo / (1+AolBeta), for AolBeta <0.1 (or -20 dB) Zout approaches Zo

Using the design criteria in Fig. 11.8 we build a Zo Test Circuit and the TINA SPICE simulation results in Fig. 11.9 show us the closed-loop gain.

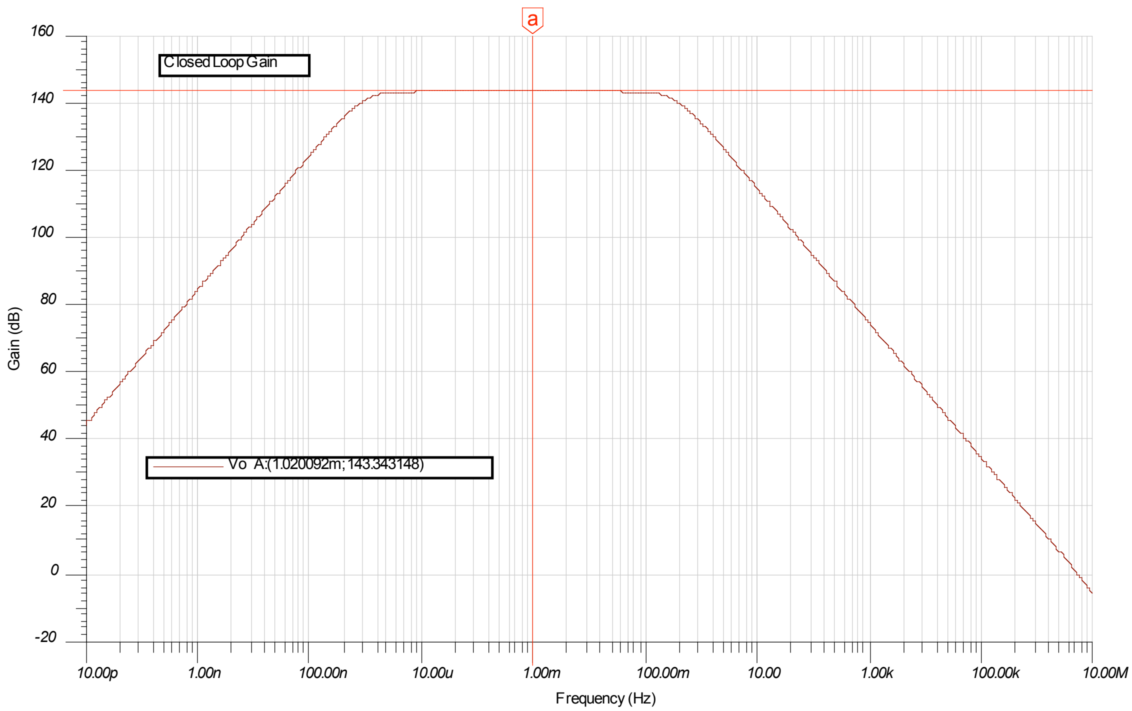


Fig. 11.9: Measuring Zo in SPICE: Step 1 – Configure Closed Loop Gain Results

To check our design procedure for the Zo test circuit we will use the circuit in Fig. 11.10 to measure 1/Beta.

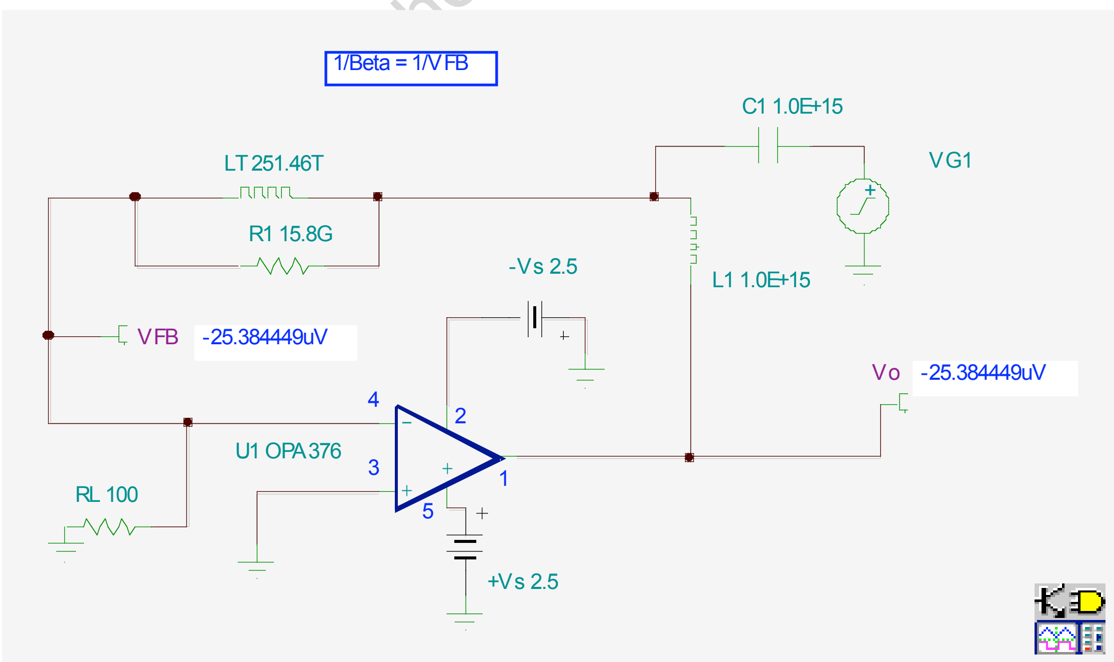


Fig. 11.10: Measuring Zo in SPICE: Step 3 – 1/Beta Test

1/Beta is seen in Fig. 11.11 to be greater than our Aol at dc by at least 20 dB.

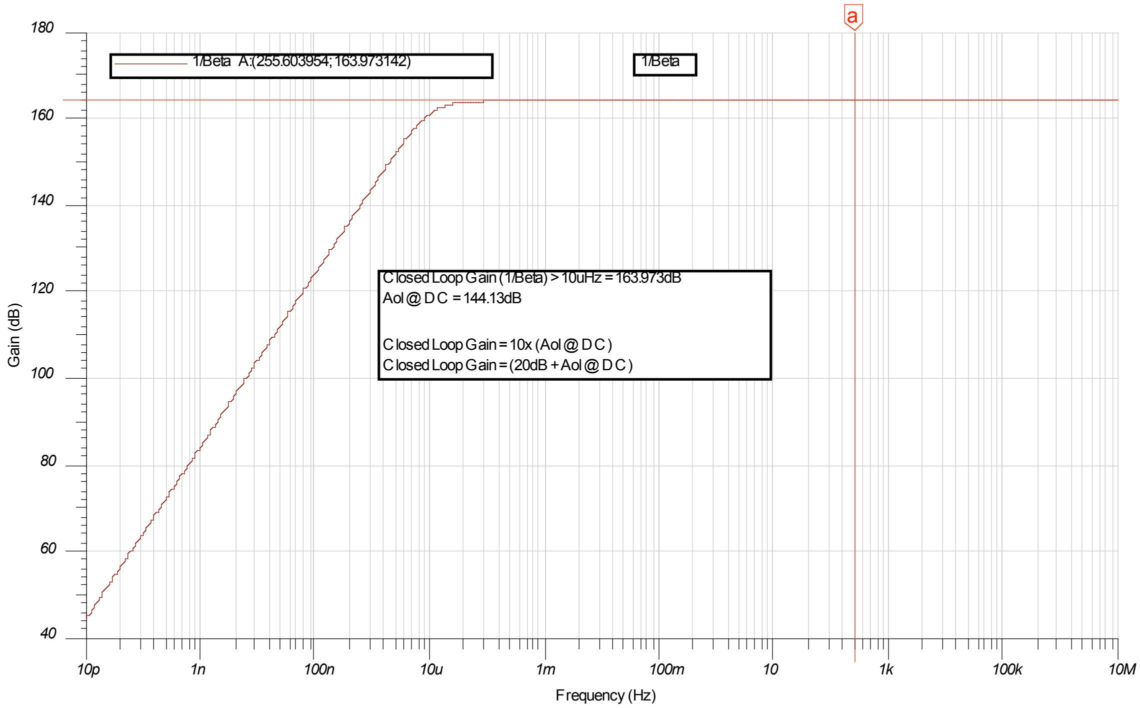


Fig. 11.11: Measuring Zo in SPICE: Step 3 – 1/Beta Test Results

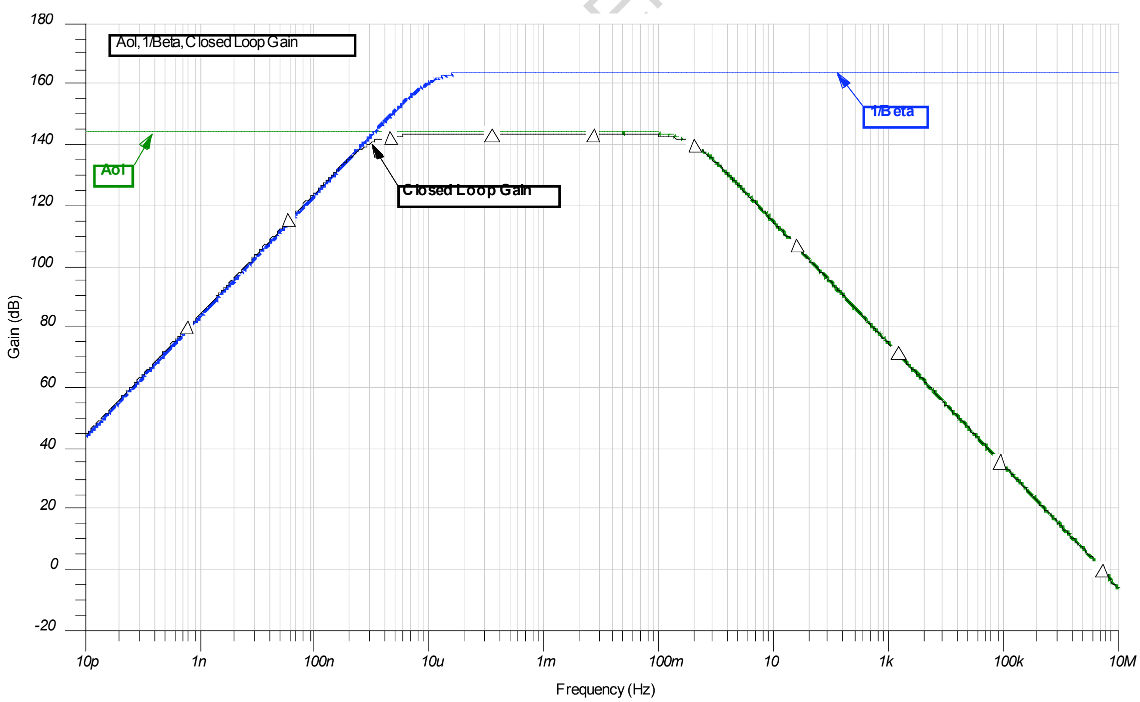


Fig. 11.12: Measuring Zo in SPICE: Step 4 – Aol, 1/Beta, Closed Loop Gain

In Fig. 11.12 the Zo test circuit responses are all on a single plot. We see the op amp Aol and our 1/Beta plot that yield the desired closed-loop gain we originally designed for. From this figure we see that any Zo measurements less than 300 nHz will not be valid since Aol Beta will approach 0 dB (or 1 V/V) and Zout will not be Zo.

Our final Zo test circuit (Fig. 11.13) will use our closed-loop gain designed in previously to force the op amp to run open loop for frequencies of interest. We will attach a current generator, IT, on the output of the op amp. The current generator will be set to 0 A at dc. This will not affect the dc operating point found by analysis since a 0 A dc current source is high impedance by definition. The current generator, IT, will be swept over frequency in an ac analysis to test for Zo impedance over frequency by dividing Vo by IT.

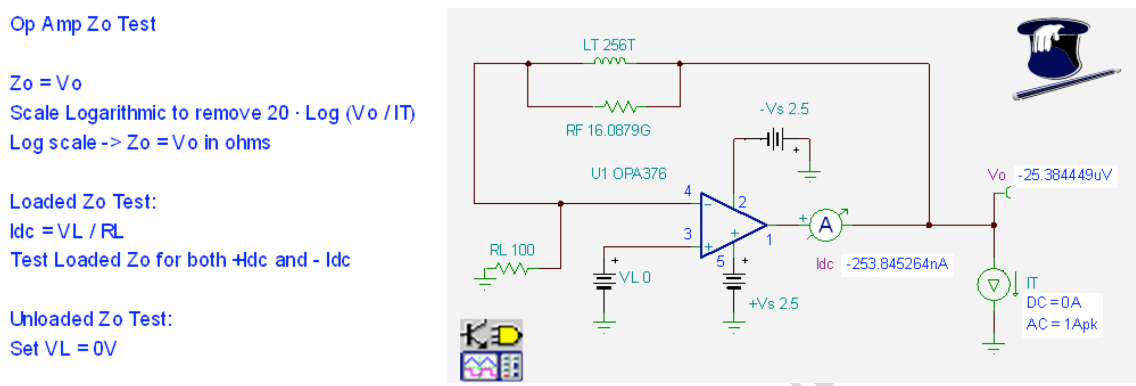


Fig. 11.13: Measuring Zo in SPICE: Step 5 – Final Zo Test Circuit

The results of measuring the OPA376 Zo are shown in Fig. 11.14. Note that we recall any frequencies below fx (about 300 nHz) we do not know Zo since AolBeta is not <-20 dB (or <0.1). The result above on the Y-axis labeled Gain(dB) is really Vo/IT in dB, or Zo.

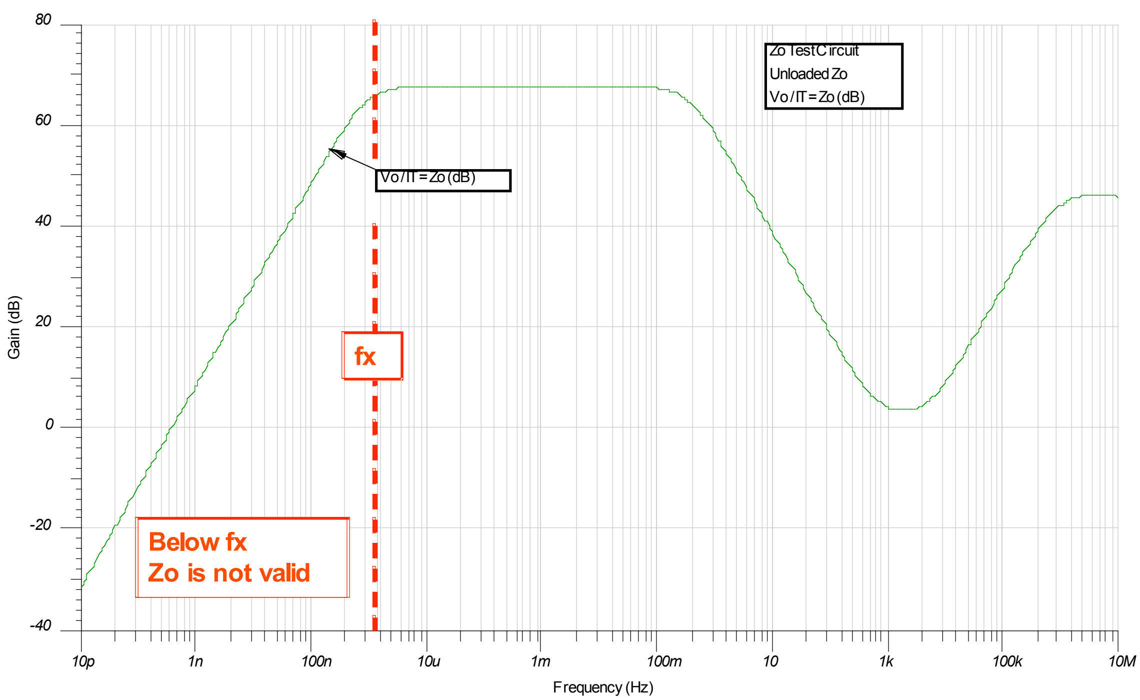


Fig. 11.14: Measuring Zo in SPICE: Step 5 – Final Zo Test Circuit Results (dB)

An easy way to convert our dB ac analysis results into Zo in ohms is simply to change the Y-axis scaling in SPICE to logarithmic which will yield Zo in ohms since the Y-axis is the result of Vo/IT over frequency. The result of our OPA376 Zo Test in Fig. 11.15 show that its Zo (starting at 300 nHz and going up in frequency) is resistive, then capacitive, then resistive, then inductive then resistive. Not looking much like a simple Ro is it?

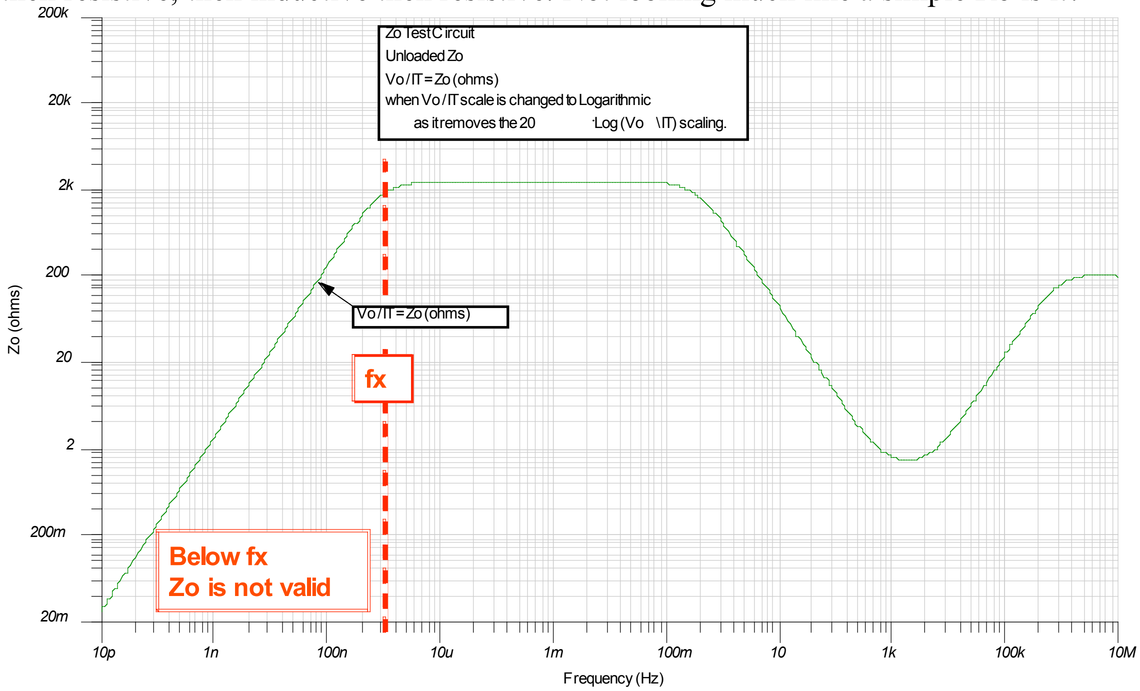


Fig. 11.15: Measuring Zo in SPICE: Step 5 – Final Zo Test Circuit Results (Ω)

For building our Zo Block we first need frequency breakpoints from our measured Zo. These breakpoints are easily measured by leaving the ac analysis test results in dB format and measuring for the 3 dB points at all frequency transitions as shown in Fig. 11.16.

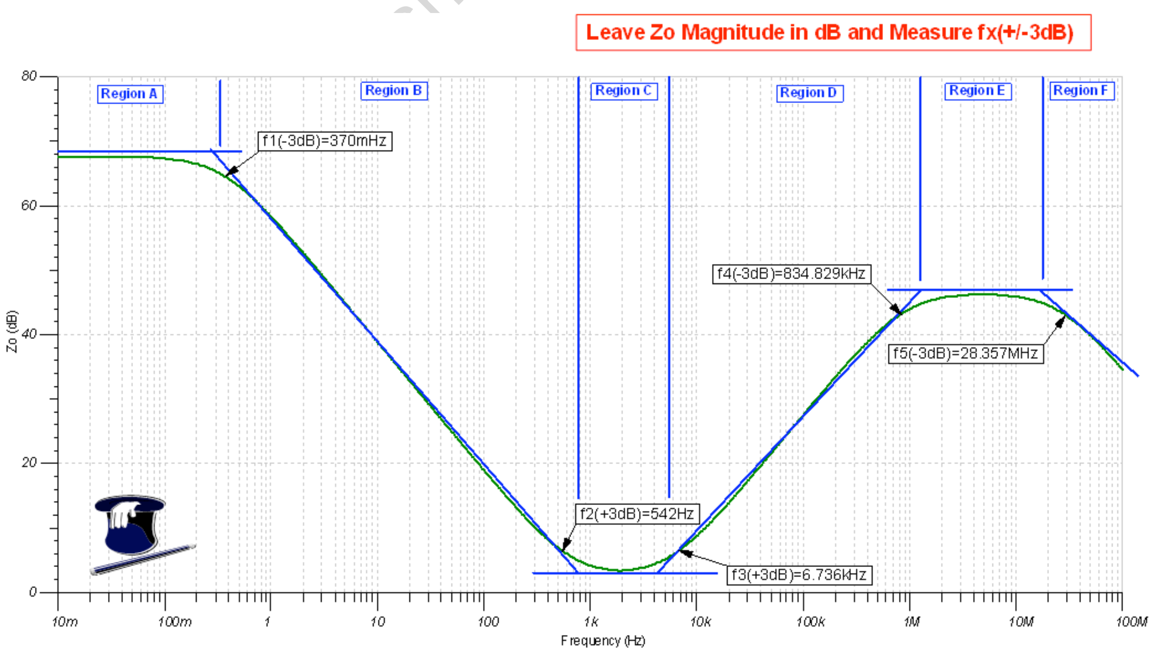


Fig. 11.16: Zo Regions and Frequency Breakpoints

Secondly, to build our Zo Block we will need magnitudes in any region where the Zo magnitude is flat. To easily get the magnitudes convert the Y-axis into logarithmic and measure each region as shown in Fig. 11.17.

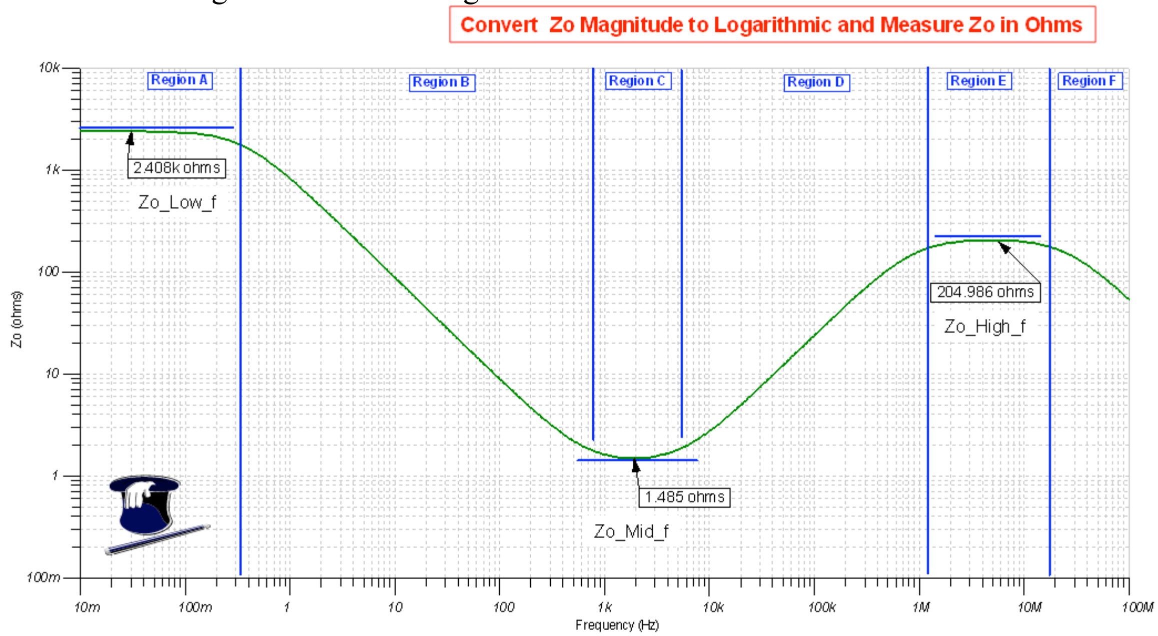


Fig. 11.17: Zo Regions and Magnitudes

The Zo Measurement Steps and results for the OPA376 are shown in Fig. 11.18. Now we are ready to proceed forward in building the external Zo Block.

Zo Measurement Steps:

1) Measure Zo in dB to get frequency breakpoints

2) Convert to ohms to get magnitudes in flat regions

3) Now ready to build Zo_External?

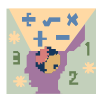
Summary of Zo Measurements			
Region	Freq Min (Hz)	Freq Max (Hz)	Zo Magnitude (ohms)
A	37m	370m	2.408k
B	370m	542	x1/10 decrease per decade frequency
C	542	6.736k	1.485
D	6.736k	834.829k	x10 increase per decade frequency
E	834.829k	28.357M	204.986
F	28.357M	28.357M	x1/10 decrease per decade frequency

Fig. 11.18: Zo Measurement Steps

There is probably more than one way to design an external Zo Block. Real inductors, capacitors, resistors in combination do not work easily since their combinations will cause peaking at resonances which do not exist in the real op amp Zo. The technique (Fig. 11.19) is simple and straight forward to use once it is understood. A fixed Rx will be used inside the closed loop of an op amp whose Aol (Aolz here) will be designed to create a closed-loop Zout looking back into the op amp with feedback around Rx. The varying shape of the op amp Aol curve will yield the varying shape of the measured Zout of the configuration which will then be used as a Zo Block. In Fig. 11.19 we are measuring the Zo Block from its output and so we will call this Zo_reverse. Since this arrangement is identical to our familiar 'Rout vs Ro Derivation' we know what Zo_reverse is as shown in Fig. 11.19. Note that if there is a ZL on the output of the Zo Block then the Zo_reverse will be Zo in parallel with this ZL. If ZL >> Zo_rev then Zo_rev = Rx/(1+Aolz).

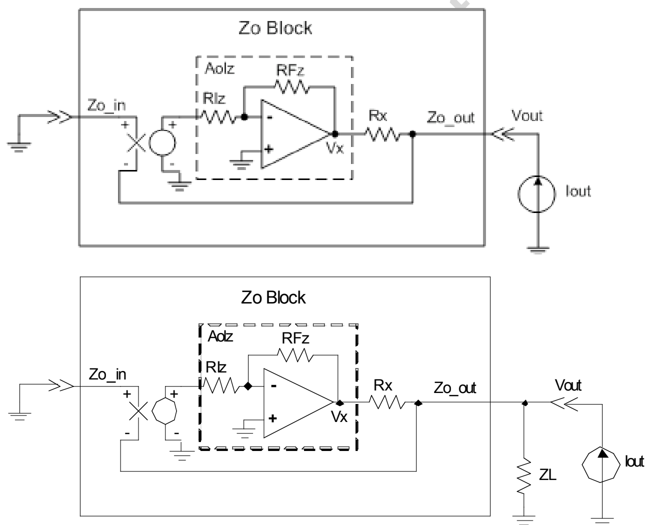
Zo_reverse without ZL

$$Zo\_rev = \frac{Rx}{1 + Aolz}$$



Zo_reverse with ZL

$$Zo\_rev\_ZL = \frac{(Zo\_rev \cdot ZL)}{Zo\_rev + ZL}$$



Note for Zo_rev_ZL :
If ZL >> Zo_rev; Then Zo_rev_ZL = ***Zo_rev = Rx/(1+Aolz)***

Fig. 11.19: Zo_reverse Equations

For the Zo Block to give accurate simulation result for stability analysis the Zo must look the same in both directions. That is Zo_forward must be the same as Zo_reverse. Zo forward is defined in Fig. 11.20 (overleaf). The derivation for Zo_forward is given in the Appendix of this article. Zo_forward is whatever Vin is put into the Zo Block divided by the current, IL, which comes out of the block as shown above. Note the effect of ZL on Zo_fwd. If ZL<<Rx then Zo_forward = Rx/Aolz.

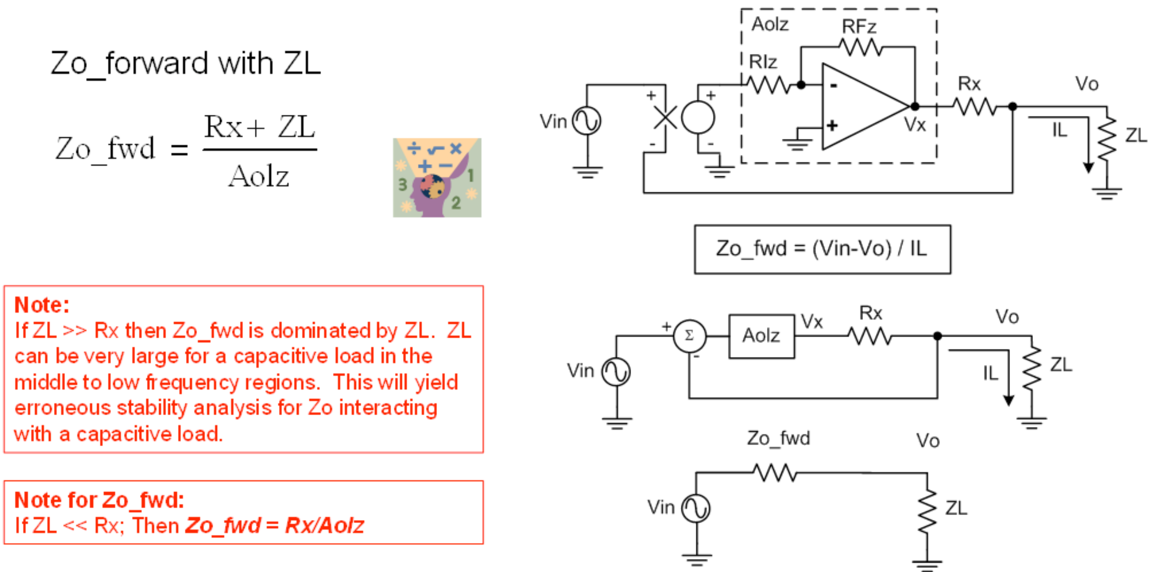


Fig. 11.20: Zo_forward Equations

The example in Fig. 11.21 shows how an improper design of the Zo Block can yield erroneous results with a capacitive load. This example places a 100 pF capacitor directly on the output of a Zo Block whose Rx = 400 kΩ. Notice that on the "Zo_forward open, 100p" curve that until ZL (Xc of the 100 pF capacitive load) becomes <½ of Rx (about 162 kΩ) that the "Desired Zo" curve is not met. Other curves are shown with varying resistive loads in parallel with the capacitive load of 100 pF. In conclusion, we see that the larger ZL is in comparison to Rx the more in error Zo_forward is from our desired Zo in this improperly designed Zo Block.

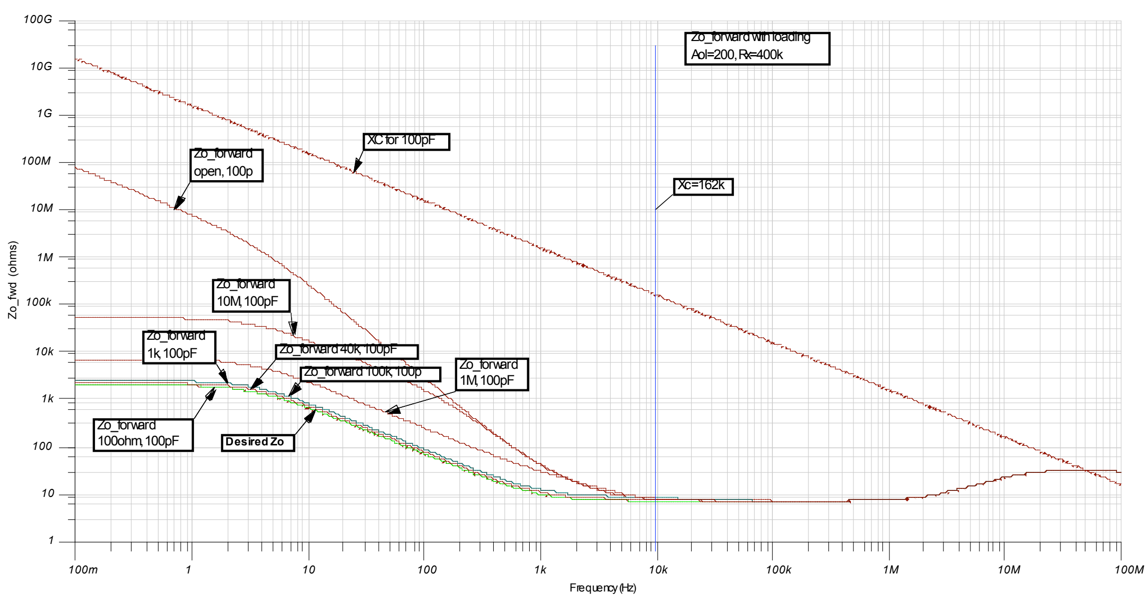


Fig. 11.21: Improper Zo Design – ZL >>Rx

Fig. 11.22 shows how to fix our problem of ZL larger than Rx creating errors in our desired Zo by adding an Rdummy inside our Zo Block to keep the 'effective ZL' at a minimum value regardless of how high in value the actual load external to the Zo Block becomes. Note also that because of the special arrangement and use of VCVS1 (gain =-1) the gain computation for Aolz is simply the respective (–ZF/ZI) * (-1) or just ZF/ZI where, ZF and ZI represent the total impedance in the feedback (ZF) or input (ZI) path of our closed-loop op amp arrangement.

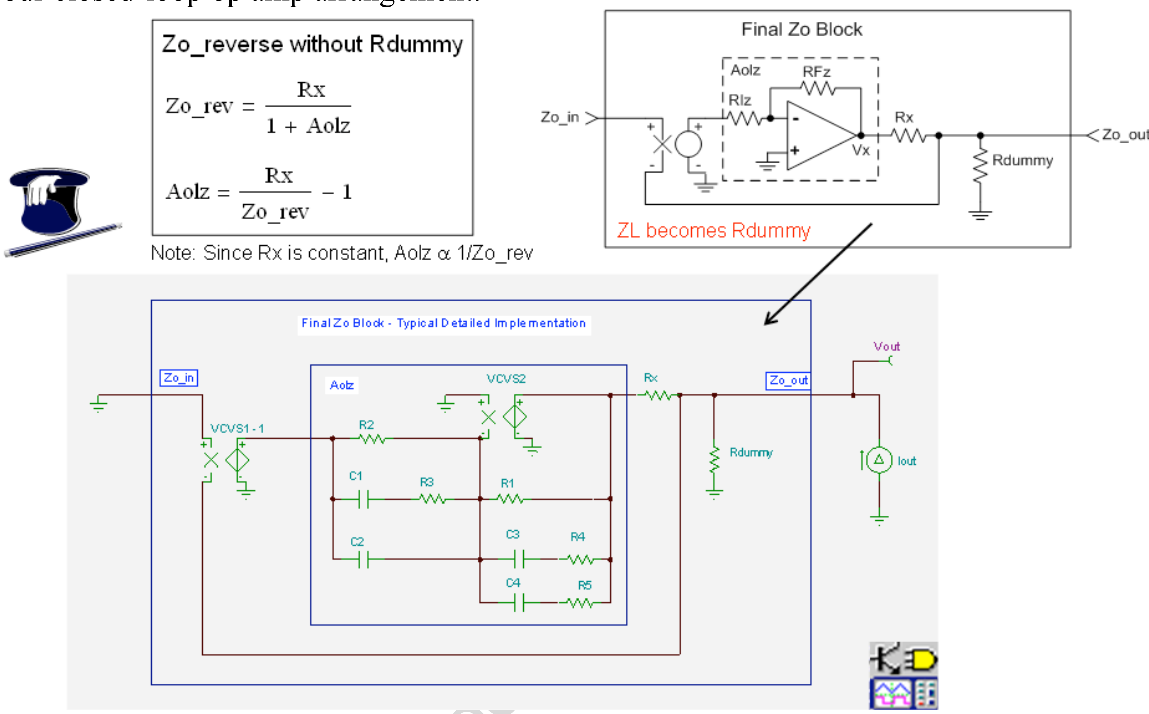


Fig. 11.22: Final Zo Block Architecture

Now let's zoom out and evaluate our design trade-offs for the Zo Block as shown in Fig. 11.23. We note that no matter how we design the Zo Block using our proposed architecture it will never have Zo_forward = Zo_reverse. However, we will see as we proceed forward that it will yield acceptable closeness between them to make this external Zo Block a powerful tool in our stability analysis toolbox. Based on many, many Zo Blocks built, with this architecture, we see in Fig. 11.23 a few design rules of thumb to optimize the Zo Block design on first pass.

Note Design Compromise:

Zo_fwd: If Rdummy << Rx; Then ***Zo_fwd = Rx/Aolz***

Zo_rev: If Rdummy >> Zo_rev; Then ***Zo_rev = Rx/(1+Aolz)***

Final Zo Block Design Guidelines:

1) Rdummy > 50* Zo_Low_f

(or 50* Highest Zo value – usually Zo_Low_f)

2) Rx > 10 * Rdummy

3) VCVS2 > 10 * (Largest Aolz Magnitude)

Fig. 11.23: Zo Block Design Guidelines

Before we begin our OPA376 Zo Block final design we consider designing a little Excel spreadsheet calculator to help speed the computation process. A ‘3 dB Frequency’ (Fig. 11.24) calculator will allow us to enter a frequency and an R value and compute the necessary C value. The “R1 or R2 from Req Parallel” calculator allows us to enter Req (parallel resistance desired) and either R1 or R2 and compute the other parallel resistor. The “Req Parallel” calculator accepts R1 and R2 and computes Req.

3dB Frequency				**Comment**
Enter	f =	3.2800E+04	Hz	f = 1/(2*pi*R*C)
	R=	1.4000E+02	ohms	
Compute	C=	3.4659E-08	Farads	C = 1 / (f*2*pi*R)
Enter	f =	8.1100E+05	Hz	
	C=	1.5900E-08	Farads	
Compute	R=	1.2342E+01	ohms	R = 1 / (f*2*pi*C)
R1 or R2 from Req Parallel				
Enter	Req=	1.2277E+02	ohms	Req = (R1*R2) / (R1+R2)
	R1=	1.0000E+03	ohms	
Compute	R2=	1.3995E+02	ohms	R2 = (Req*R1) / (R1 - Req)
Enter	Req=	1.6363E+04	ohms	Req = (R1*R2) / (R1+R2)
	R1=	2.5641E+04	ohms	
Compute	R2=	4.5221E+04	ohms	R1 = (Req*R2) / (R2 - Req)
Req Parallel				
Enter	R1=	2.0000E+03	ohms	
	R2=	2.0000E+03	ohms	
Compute	Req=	1.0000E+03	ohms	Req = (R1*R2) / (R1+R2)

Fig. 11.24: Excel Calculator Ideas For Ease of Zo Block Build

Gain RI				**Comment**
Enter	Gain =	8.0800E+05	V/V	Gain = RF / RI
	RF=	4.9734E+04	ohms	
Compute	RI=	6.1552E-02	ohms	RI = RF / Gain
Gain RF				
Enter	Gain =	4.9734E+02	V/V	Gain = RF / RI
	RI =	1.0000E+02	ohms	
Compute	RF=	4.9734E+04	ohms	RF = Gain * RI
Aolz Calculator				**Comment**
Enter	Zo_rev =	2.05E+02	ohms	
	Rx =	1.20E+06	ohms	
Compute	Aolz =	5.8531E+03	V/V	Aolz = (Rx/Zo_rev) - 1

Zo_reverse without Rdummy

$$Zo\_rev = \frac{Rx}{1 + Aolz}$$

$$Aolz = \frac{Rx}{Zo\_rev} - 1$$

Fig. 11.25: Additional Excel Calculator Ideas For Ease of Zo Block Build

Three more calculators in Excel will help speed the Zo Block building process. As shown in Fig. 11.25 the “Gain RI Calculator” allows us to enter a desired gain and RF and compute the required RI. The “Gain RF Calculator” allows us to enter a desired gain and RI and compute the required RF. The “Aolz Calculator” requires we enter the desired Zo_reverse and fixed value of Rx so it can compute the required Aolz.

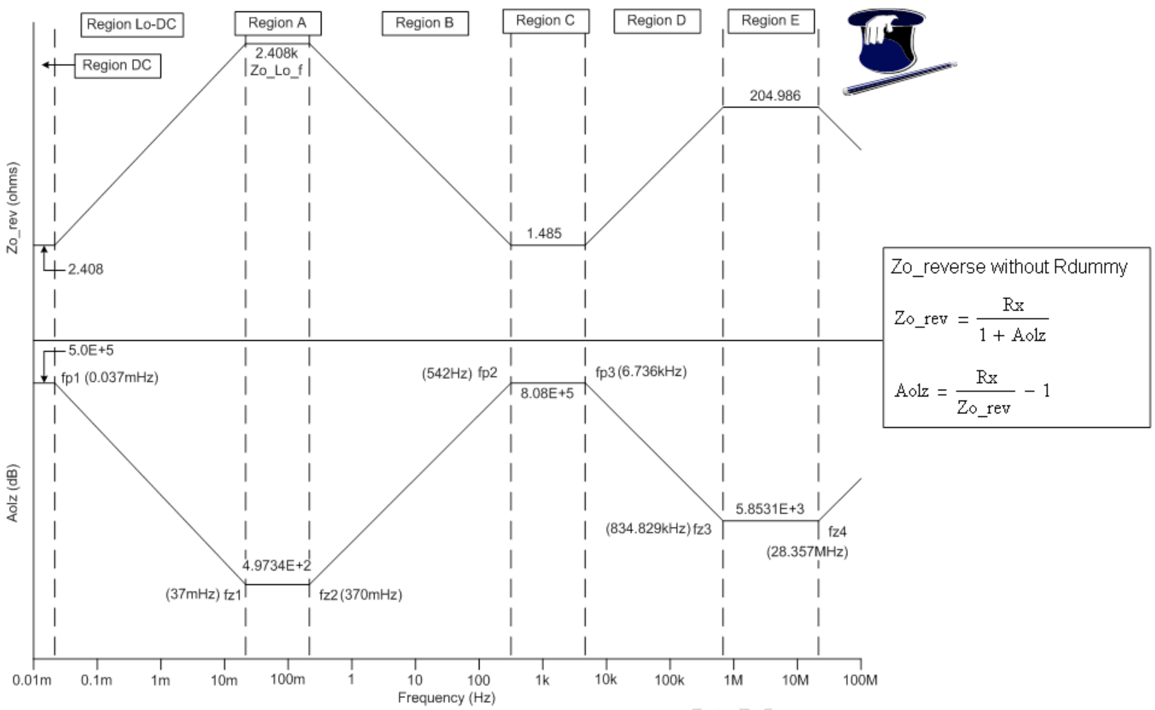


Fig. 11.26: Final OPA376 Zo Block Design

The real trick to building the Zo Block is shown in Fig. 11.26. Notice that we have added two new regions, Region Lo-DC and Region DC, to the OPA376 Zo Curve. When we go to use our Zo Block in SPICE simulations, SPICE will run a dc analysis before it runs an ac analysis. We need to make sure that the dc operating point can be found correctly without our external Zo Block adding any errors or preventing dc convergence. To guarantee this find we need a low value at dc for our Zo Block. For example, if the OPA376, in a final SPICE application circuit, needs 3 mA for the dc operating point to be correct then a Zo Block with a flat curve at dc of 2.408 kΩ would drop >6 V across our Zo Block from a 5 V single supply on the OPA376. The dc operating point would not be found. From the OPA376 we know it can drive 3 mA with only about a 10 mV drop from the 5 V rail. This is the difference between the real op amp and the original SPICE macromodel of the OPA376, and our External Zo Block. Our External Zo Block does not model the dc or large signal Zo behavior of the op amp. The focus of our Zo Block is for ac stability analysis. There are other, more complicated ways, to add a dc and large signal Zo operation of an external Zo Block, but they are not required for our end goal and are beyond the focus here. In Fig. 11.26 we see our desired Zo curve over frequency.

Remember that the relationship between Zo_reverse and Aolz is a reciprocal one for a fixed Rx. So once we know the desired Zo_reverse the necessary Aolz, for a fixed Rx, is simply the inverse shape of it. Shown in Fig. 11.26 are the measured frequency points and desired magnitudes from the OPA376 Zo testing in the Zo_reverse curve. The Aolz curve gets its frequency points from the Zo_reverse curve and its magnitudes from the magnitude values in the Zo_reverse curve, Rx, and using the Aolz calculator.

To achieve the desired Aolz for a fixed Rx we will need the circuit arrangement in Fig. 11.27. Now we are ready to compute values for this circuit: from our design guidelines in Fig. 11.23 we choose Rx = 1.2 MΩ, Rdummy = 120 kΩ, and VCVS2 = 5 M.

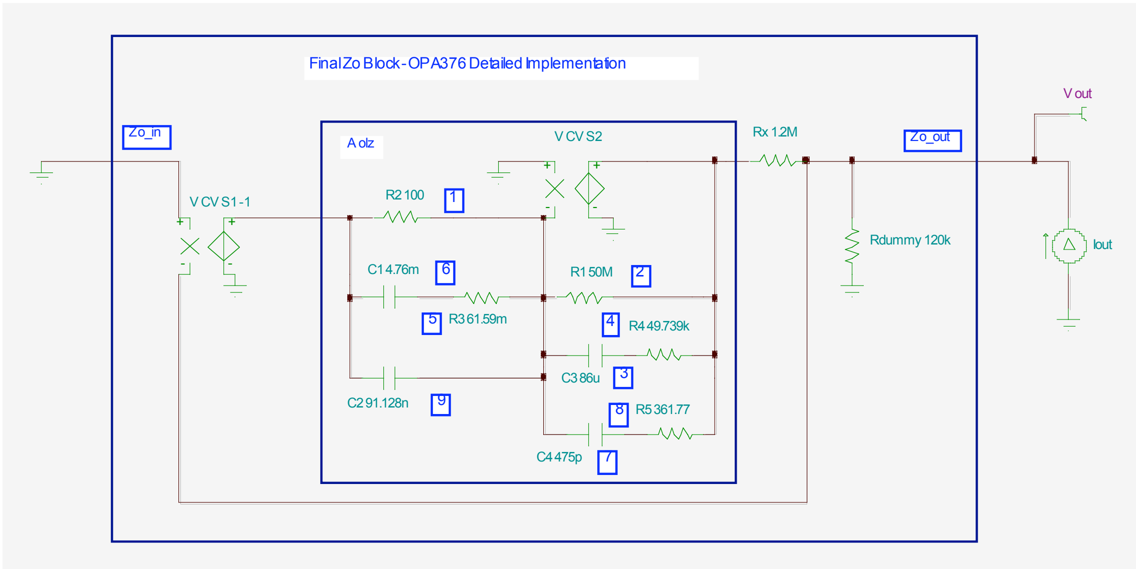


Fig. 11.27: Final OPA376 Zo Block Design – Zo_reverse Test

Figs. 11.26 and 11.27 should be referred to as we walk through our OPA376 Zo Block design using the table in Fig. 11.28. We will start from Region DC and work our way from low frequency to high frequency in the design process. Refer to Fig. 11.26. There are Pole Eq and Zero Eq equations which are estimates as to the respective pole and zero locations. These estimates will use the dominant components which set the pole or zero and will turn out to be accurate enough for our external Zo Block. If one is concerned about exact accuracy you can derive and use more exact equations for the pole/zero locations. Remember to use our Excel calculators to simplify the choosing of values for R and/or C to design the respective Aolz. You will notice in the table in Fig. 11.28 that we do not compute every pole and zero since the ones we do not compute will occur as a result of the ±20 dB/decade slopes in the Aolz curve along with its flat regions. Step 1 is to set a starting point by assigning R2 = 100 Ω to keep R1 reasonable. Step 2 is in Region DC where gain is set by R1/R2 and we need Aolz = 5.0e+5 which yields R1 = 50 MΩ for R2 = 100 Ω. Step 3 is at the start of the Region Lo-DC where we need fp1 = 0.037 mHz, which is predominantly set by R1 and C3. C3 is chosen to yield fp1 given R1. Step 4 uses Region A where we need Aolz = 4.9734e+2. This gain is set by (R1//R4)/R2. We already know R1 and R2 so we solve for R4. Step 5 jumps ahead to Region C where gain is set by (R1//R4) / (R2//R3). Since we know R1, R2, and R4 we can solve for R3 to get Aolz = 8.08e + 5. Step 6 computes the pole fp2 in Region B by computing C1 based on R3 which we now know. Step 7 computes fp3 at the beginning of Region D. fp3 is determined by (R1//R4) and C4. Since we know R1 and R4, C4 is computed to yield fp3. Step 8 computes Aolz = 5.8531e + 3 by [R5//(R1//R4)]/[R2//R3]. Since we already have R1, R2, R3, and R4 we can compute R5. Finally Step 9 will give us fz4 by (R2//R3) and C2. Since we know R2 and R3 we will compute for C2. The external Zo Block for OPA376 is now completely built and ready for testing

Zo Final Build Data											
Region	Freq Min	Freq Max	Zo Magnitude	Aolz	Aolz Eq	Pole	Pole Eq	Zero	Zero Eq	Solve	Step
	(Hz)	(Hz)	(ohms)	(V/V)		(Hz)	(estimate)	(Hz)	(estimate)	R2=100 Ω	1
DC	DC	0.037m	2.408	5.0000E+05	R1/R2					R1=50M Ω	2
Lo-DC	0.037m	37m	x10increase per decade frequency	-20db slope		0.037m	fp1= 1/(2*pi*R1*C3)			C3=86uF	3
A	37m	370m	2.408k	4.9734E+02	Z14/R2					R4=49.739k Ω	4
C	542	6.736k	1.485	8.0800E+05	Z14//Z23					R3=61.59m Ω	5
B	370m	542	x1/10decrease per decade frequency	+20db slope		542	fp2= 1/(2*pi*R3*C1)			C1=4.76mF	6
D	6.736k	834.829k	x10increase per decade frequency	-20db slope		6.736k	fp3= 1/(2*pi*Z14*C4)	834.829k		C4=475pF	7
E	834.829k	28.357M	204.986	5.8531E+03	(R5//Z14)/Z23					R5=361.77 Ω	8
F	28.357M	28.357M	x1/10decrease per decade frequency	+20db slope				28.357M	fz4= 1/(2*pi*Z23*C2)	C2=91.128nF	9
Rdummy=120kohm, Rx=1.2Mohm, R2=1kohm, Z14=R1//R4, Z23=R2//R3											

Fig. 11.28: Final OPA376 Zo Block Design – Equations

The final build of our OPA376 Zo Block is tested for Zo_reverse and the results shown in Fig. 11.29 where we leave the results in dB and measure the frequency 3 dB points.

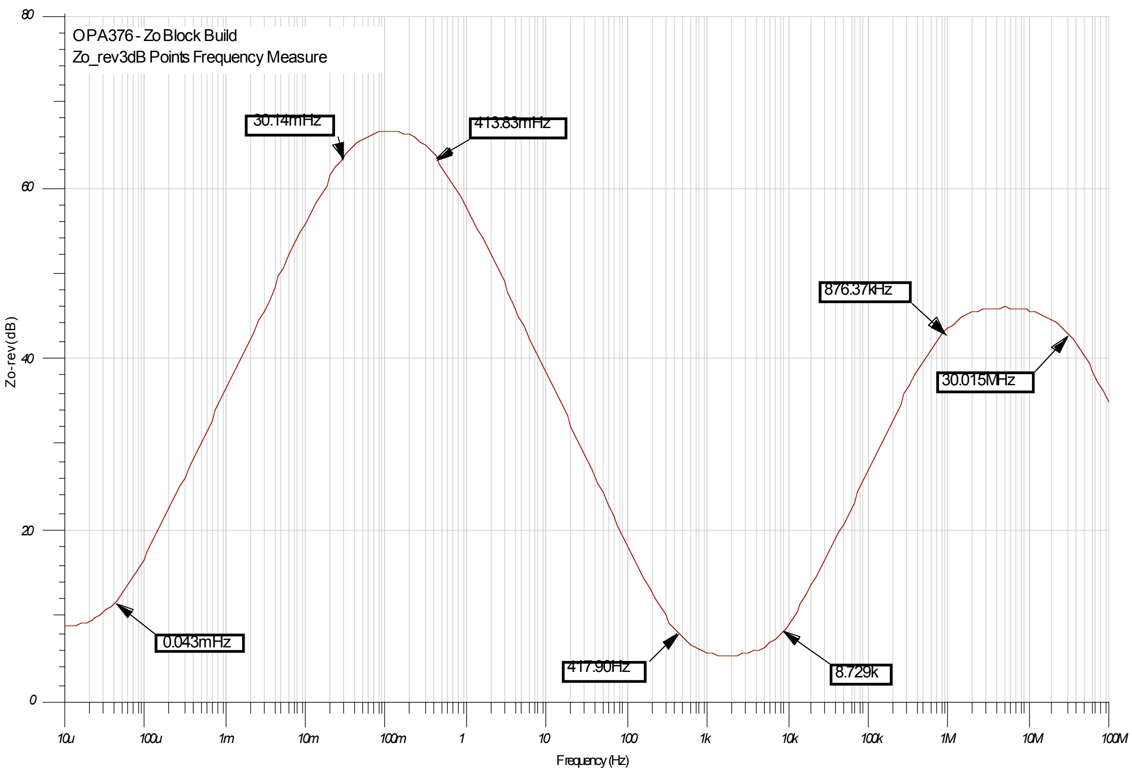


Fig. 11.29: Final OPA376 Zo Block Design – Zo_reverse Curve (dB)

In Fig. 11.30 (overleaf) our final build of our OPA376 Zo Block is tested for Zo_reverse and the magnitude results on the Y-axis are converted to logarithmic so we can read Zo_reverse magnitude directly in ohms.

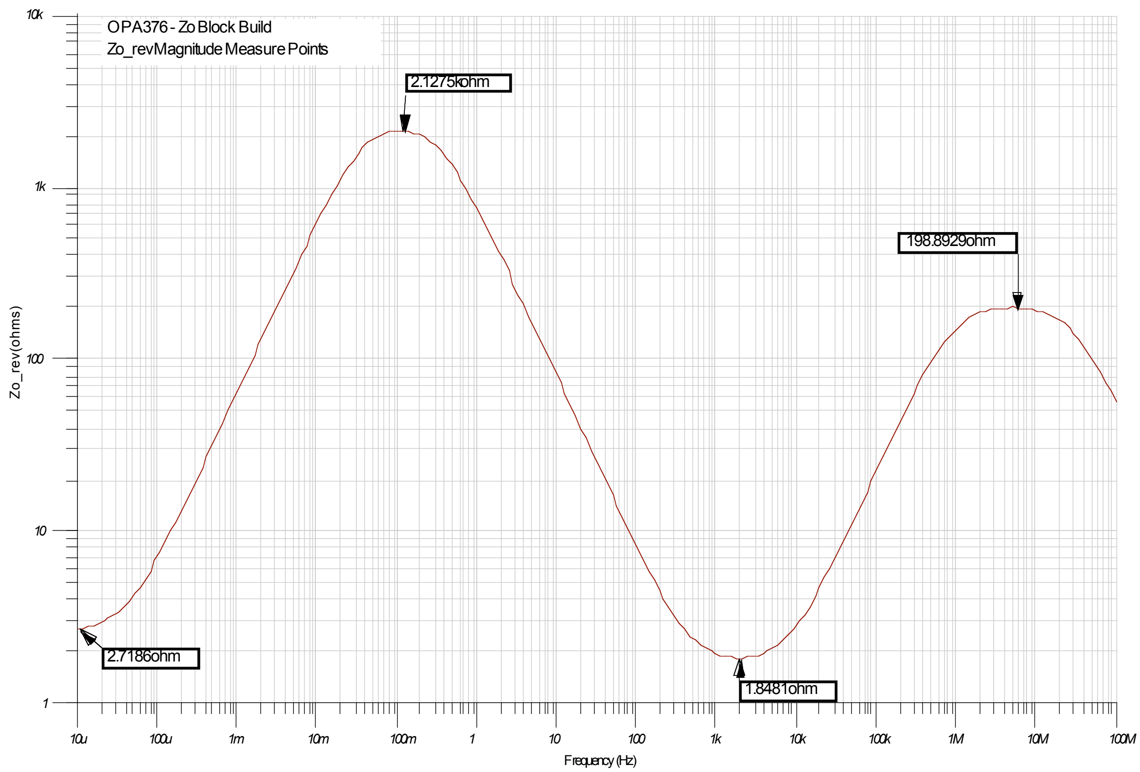


Fig. 11.30: Final OPA376 Zo Block Design – Zo_reverse Curve (Ω)

Zo_rev Parameter	Design Frequency (Hz)	Final Frequency (Hz)	Design Magnitude (ohms)	Final Magnitude (ohms)
Region DC			2.408	2.7186
fp1	0.037m	0.043m		
fz1	37m	30.14m		
Region A			2.408k	2.1275k
fz2	370m	413.83m		
fp2	542	417.90		
Region C			1.485	1.8481
fp3	6.736k	8.729k		
fz3	834.829k	876.37k		
Region E			204.986	198.8929
fz4	28.357M	30.015M		

Fig. 11.31: Final OPA376 Zo Block Design – Build vs Design Goal

In Fig. 11.31 we compile the results of Zo_reverse to compare both frequency break points and magnitude flat regions of the final OPA376 Zo Block build and the original design goal for each respective data point. Our final frequency breakpoints are going to be bounded by +20 dB/decade or -20 dB/decade slopes with intercepts at the flat magnitude portions of the Zo_reverse curve. As we compare design frequency points versus final frequency points we see 10% - 20% variance from desired versus final frequency points. In the magnitude comparison we see 3% - 24% variance from desired versus final magnitude points. This is an acceptable result without spending any more design time on the Zo Block. Real silicon typically has capacitors that vary ±20% over process and temperature along with resistors that vary ±30% over process and temperature. So yes, Zo, will vary from part to part but with our stability techniques in place using decade rules-of-thumb we will have good design margin.

Our Final Zo Block for the OPA376 will now be tested for Zo_forward using the test circuit in Fig. 11.32 in TINA SPICE.

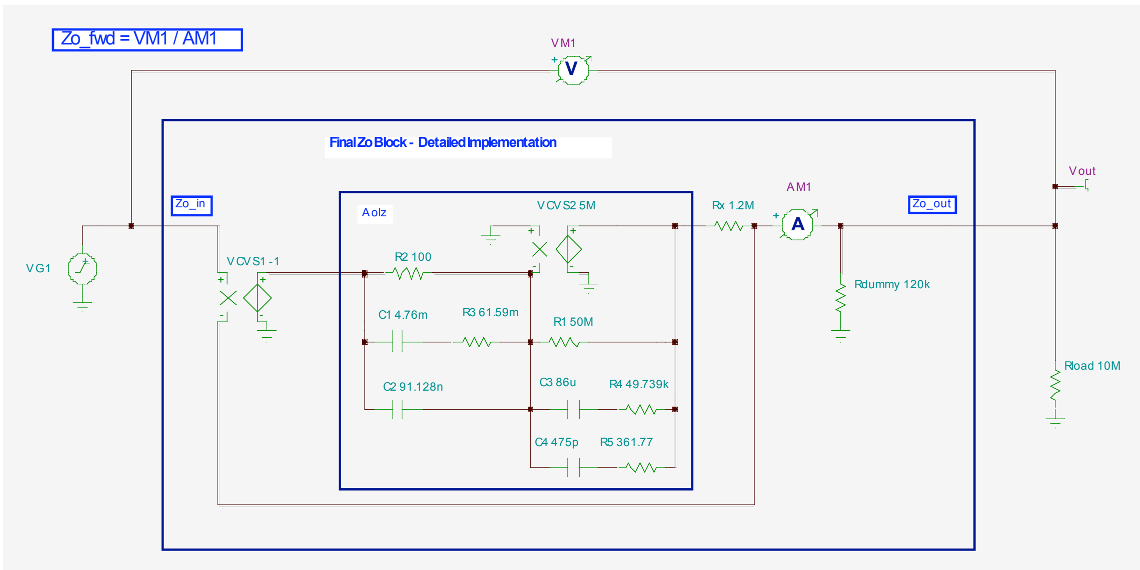


Fig. 11.32: Final OPA376 Zo Block Design – Zo_forward Test

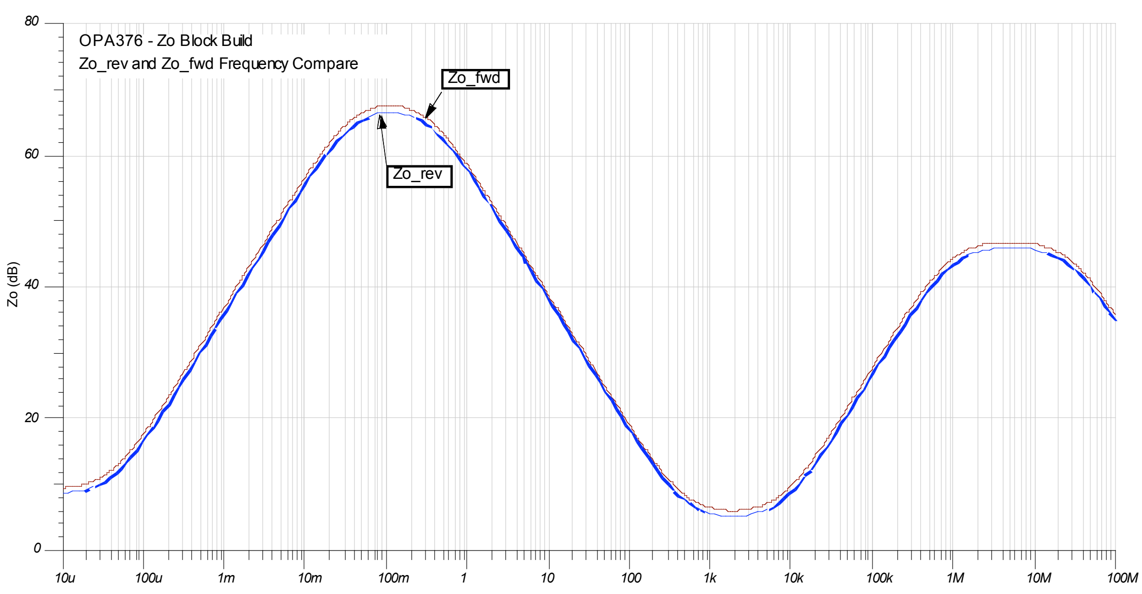


Fig. 11.33: Final Zo Block Design – Zo_forward/_reverse Frequency Compare

TINA SPICE results of our testing Zo_forward vs. Zo_reverse are shown in Fig. 11.33. We see Zo_forward versus Zo_reverse does have some minor discrepancies as we would expect since the equations for Zo_forward versus Zo_reverse have a small difference. Recall (Fig. 11.23) Zo_forward = Rx/Aolz and Zo_reverse = Rx/(1+Aolz). The frequency differences are so small they are not of any concern. Fig. 11.34 shows the results of our testing Zo_forward versus Zo_reverse with the Y-axis set to logarithmic scale so we can compare the magnitude differences directly in ohms. Magnitude comparison shows Zo_reverse and Zo_forward within 12% at all flat magnitude portions of the curve. Again, no major concerns here.

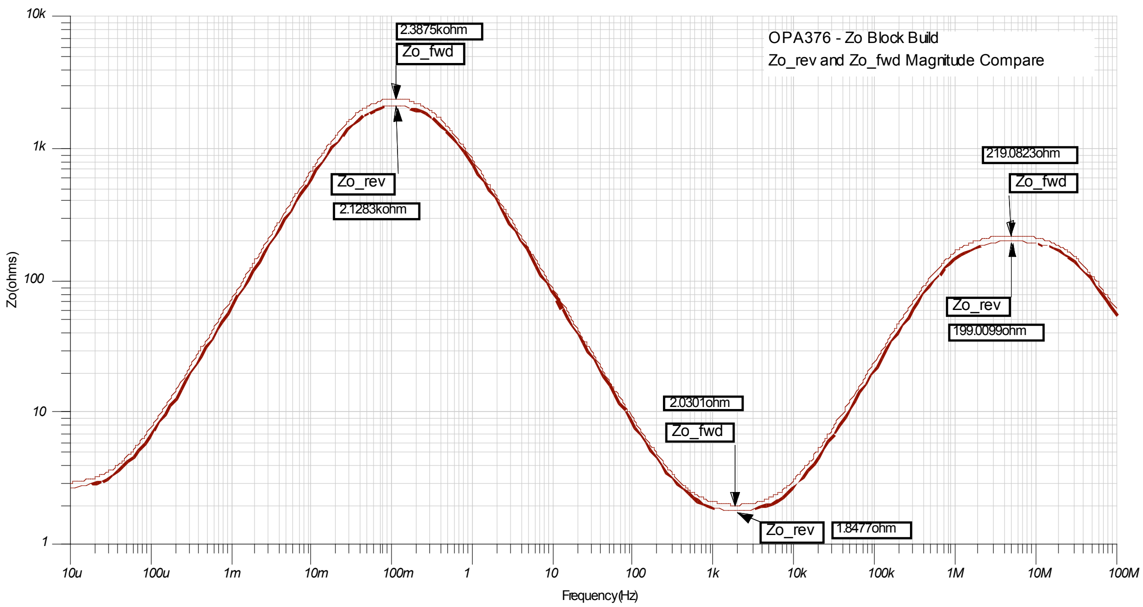


Fig. 11.34: Final Zo Block Design – Zo_forward/_reverse Magnitude Compare

In Fig. 11.35 we add a side note on building external Zo blocks. Sometimes the Zo_Lo_f value is not available from the data sheet as the curve may still be rising at the rate of 20 dB/decade as it approaches lower frequencies. Sometimes the op amp electrical characteristics table will contain two different test conditions for the open-loop gain or Aol specification (Fig. 11.35). Based on these measurements one can compute the Zo_Lo_f value. The detailed derivation of this equation is included in the Appendix.

Typical Electrical Characteristics Table Excerpt		
Parameter	**Condition**	**Typical**
Open Loop Gain	Vs = 5V, RL = 10k	134dB
	Vs = 5V, RL = 2k	126dB

$$Ro = \frac{RL2 - \left(\frac{Aol1}{Aol2}\cdot\frac{RL2}{RL1}\right)\cdot RL1}{\left(\frac{Aol1}{Aol2}\cdot\frac{RL2}{RL1}\right) - 1}$$

Parameter	**Aol**	**Aol**	**RLx**
	(dB)	(V/V)	(ohms)
Aol1	134	5.01E+06	RL1=10k
Aol2	126	2.00E+06	RL2=2k

Aol1/Aol2	RL2/RL1
2.5	5

$$Ro := \frac{2000 - (2.5\cdot 0.2)\cdot 10000}{(2.5\cdot 0.2) - 1}$$

$$Ro = 6 \times 10^{3}$$

Fig. 11.35: Zo_Lo_f Calculation From Datasheet Aol Tests

One final trick for our external Zo Block is shown in Fig. 11.36. When the external Zo Block is used in an op amp SPICE circuit it is advisable to bound the possible voltages coming out of the external Zo Block to slightly above or below (typically ±0.7V) the positive and negative supplies used on the respective op amp for which the external Zo Block was created. This helps prevent convergence issues in SPICE especially since VCVS2 (Fig. 11.36) can potentially produce very large voltages. D1 and D2 are diode clamps to keep the output of the external Zo Block within a reasonable range close to the positive and negative supplies used for the simulated application circuit. Vp_clmp and Vm_clmp dc sources (Fig. 11.36) can be adjusted to move Vout clamp points as close as desired to the supplies used on the op amp for which the external Zo Block was created.

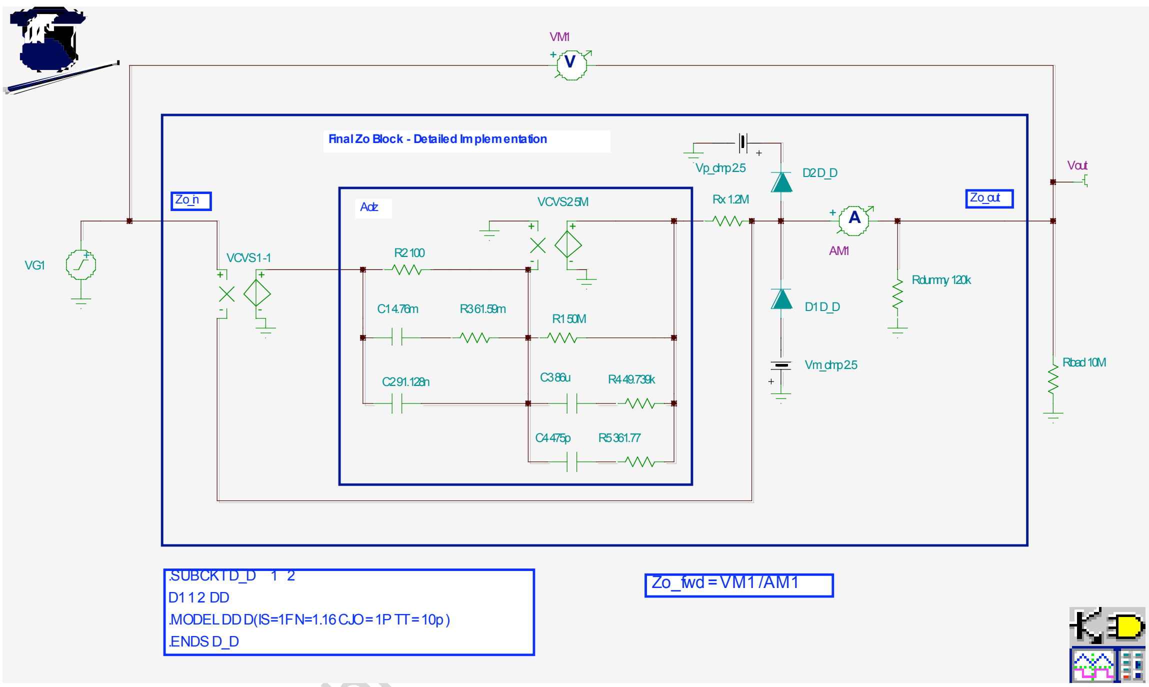


Fig. 11.36: Final Zo Block With Added Diode Clamps For SPICE Convergence

A transient TINA SPICE simulation of our final Zo Block with Added Clamp Diodes is show in Fig. 11.37 (overleaf) and illustrates the point that Vout is clamped within ±1.1 V of the ±2.5 V supplies (Vm_clmp and Vp_clmp) used to set the clamp levels. Vm_clmp and Vp_clmp may be adjusted as desired to raise or lower these clamping levels.

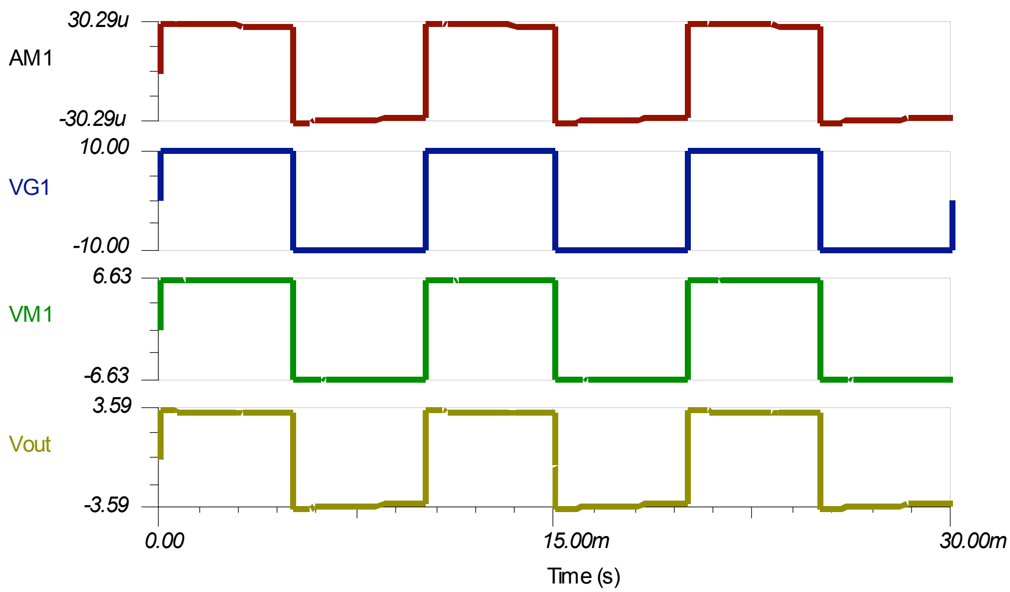
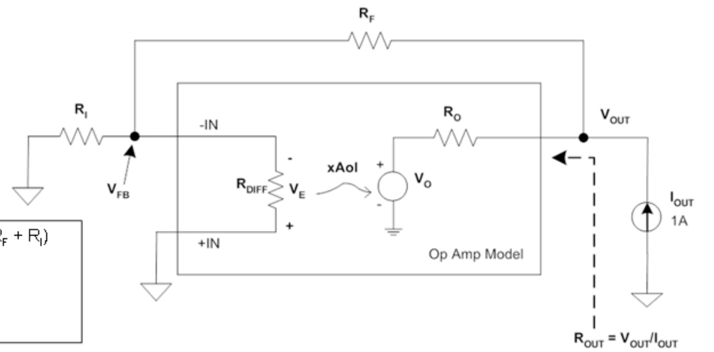


Fig. 11.37: Final Zo Block With Added Diode Clamps For SPICE Convergence Test

APPENDIX: DETAILED DERIVATIONS

R_O and R_{OUT} Derivation



1) $\beta = V_{FB} / V_{OUT} = [V_{OUT} (R_I / \{R_F + R_I\})]/V_{OUT} = R_I / (R_F + R_I)$

2) $R_{OUT} = V_{OUT} / I_{OUT}$

3) $V_O = -V_E\,Aol$

4) $V_E = V_{OUT} [R_I / (R_F + R_I)]$

5) $V_{OUT} = V_O + I_{OUT}R_O$

6) $V_{OUT} = -V_E Aol + I_{OUT}R_O$ *Substitute 3) into 5) for V_O*

7) $V_{OUT} = -V_{OUT} [R_I/(R_F + R_I)] Aol + I_{OUT}R_O$ *Substitute 4) into 6) for V_E*

8) $V_{OUT} + V_{OUT} [R_I/(R_F + R_I)] Aol = I_{OUT}R_O$ *Rearrange 7) to get V_{OUT} terms on left*

9) $V_{OUT} = I_{OUT}R_O / \{1+[R_I Aol/(R_F+R_I)]\}$ *Divide in 8) to get V_{OUT} on left*

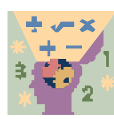
10) $R_{OUT} = V_{OUT}/I_{OUT} =[I_{OUT}R_O / \{1+[R_I Aol / (R_F+R_I)]\}] / I_{OUT}$

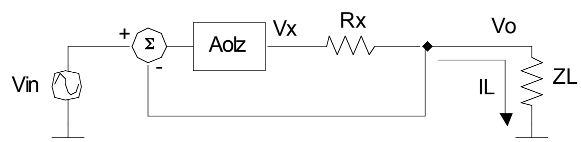
Divide both sides of 9) by I_{OUT} to get R_{OUT} [from 2)] on left

11) $R_{OUT} = R_O / (1+Aol\beta)$ *Substitute 1) into 10)*

From: Frederiksen, Thomas M. Intuitive Operational Amplifiers. McGraw-Hill Book Company. New York. Revised Edition. 1988.

Zo_forward Derivation





Zo_Forward Derivation

Eq1: $Vx = (Vin - Vo) \cdot Aolz$

Eq2: $Vo = \dfrac{Vx \cdot ZL}{Rx + ZL}$

Eq3: $IL = \dfrac{Vo}{ZL}$

Eq4: $Zo\_fwd = \dfrac{Vin - Vo}{IL}$

Zo_forward Derivation (cont.)

Solve for Zo_fwd
Substitute Eq3 into Eq4

Eq7: $Zo\_fwd = \dfrac{Vin - Vo}{\left(\dfrac{Vo}{ZL}\right)}$

Solve for Zo_fwd
Substitute Eq6 into Eq7

$$Zo\_fwd = \frac{\left[Vin - \dfrac{\left(Vin \cdot \dfrac{ZL}{Rx + ZL}\right)}{\dfrac{1}{Aolz} + \dfrac{ZL}{Rx + ZL}}\right]}{\dfrac{\left[\dfrac{\left(Vin \cdot \dfrac{ZL}{Rx+ZL}\right)}{\dfrac{1}{Aolz} + \dfrac{ZL}{Rx+ZL}}\right]}{ZL}}$$

Divide numerator and denominator by Vin

$$Zo\_fwd = \frac{\left[1 - \dfrac{\left(\dfrac{ZL}{Rx + ZL}\right)}{\dfrac{1}{Aolz} + \dfrac{ZL}{Rx + ZL}}\right]}{\left[\dfrac{\left(\dfrac{ZL}{Rx + ZL}\right)}{\dfrac{1}{Aolz} + \dfrac{ZL}{Rx + ZL}}\right] \cdot \dfrac{1}{ZL}}$$

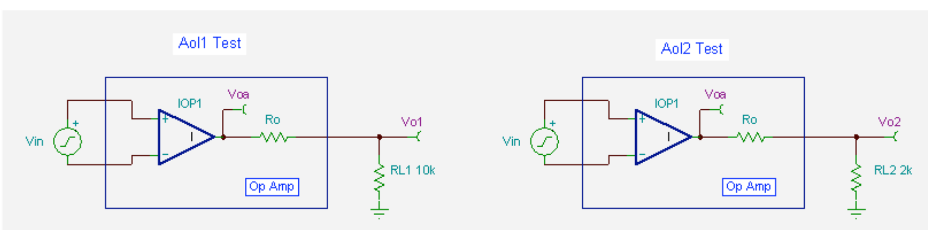
Multiply numerator and denominator by:
[1/Aolz + ZL/(Rx+ZL)]

$$Zo\_fwd = \frac{\dfrac{1}{Aolz} + \dfrac{ZL}{Rx + ZL} - \left(\dfrac{ZL}{Rx + ZL}\right)}{\left(\dfrac{ZL}{Rx + ZL}\right) \cdot \dfrac{1}{ZL}}$$

$$Zo\_fwd = \frac{\dfrac{1}{Aolz}}{\left(\dfrac{1}{Rx + ZL}\right)}$$

Eq8: $Zo\_fwd = \dfrac{Rx + ZL}{Aolz}$

Zo_Lo_f Calculation from Aol Tests Derivation



Eq1.1: $Vo1 = \dfrac{Voa \, RL1}{Ro + RL1}$

Eq 2.1: $Aol1 = \dfrac{Vo1}{Vin}$

Eq 3.1: $Voa = Vo1 \cdot \dfrac{Ro + RL1}{RL1}$ From Eq 1.1

Eq 4.1: $Vo1 = Aol1 \cdot Vin$ From Eq 2.1

Eq 5.1: $Voa = (Aol1 \cdot Vin) \cdot \dfrac{Ro + RL1}{RL1}$ Substitute EQ 4.1 into EQ 3.1

Eq 6.1: $\dfrac{Voa}{Vin} = Aol1 \cdot \dfrac{Ro + RL1}{RL1}$ Divide by Vin

Eq 1.2: $Vo2 = \dfrac{Voa \, RL2}{Ro + RL2}$

Eq 2.2: $Aol2 = \dfrac{Vo2}{Vin}$

Eq 3.2: $Voa = Vo2 \cdot \dfrac{Ro + RL2}{RL2}$ From Eq 1.2

Eq 4.2: $Vo2 = Aol2 \cdot Vin$ From Eq 2.2

Eq 5.2: $Voa = (Aol2 \cdot Vin) \cdot \dfrac{Ro + RL2}{RL2}$ Substitute EQ 4.2 into EQ 3

Eq 6.2: $\dfrac{Voa}{Vin} = Aol2 \cdot \dfrac{Ro + RL2}{RL2}$ Divide by Vin

Zo_Lo_f Calculation from Aol Tests Derivation (cont.)

Set EQ 6.1 = EQ 6.2

EQ 7: $$Aol1 \cdot \frac{Ro + RL1}{RL1} = Aol2 \cdot \frac{Ro + RL2}{RL2}$$

$$\frac{Aol1}{Aol2} = \frac{Ro + RL2}{RL2} \frac{RL1}{Ro + RL1}$$

EQ 8: $$\frac{Aol1}{Aol2} \cdot \frac{RL2}{RL1} = \frac{Ro + RL2}{Ro + RL1}$$

EQ 9: $$X = \frac{Aol1}{Aol2} \cdot \frac{RL2}{RL1}$$

Eq 10: $$X = \frac{Ro + RL2}{Ro + RL1}$$ Substitute Eq 9 inot Eq 8

Eq 11: $$Ro = \frac{RL2 - X \cdot RL1}{X - 1}$$ Solve Eq 10 for Ro

Eq 12: $$Ro = \frac{RL2 - \left(\frac{Aol1}{Aol2} \cdot \frac{RL2}{RL1}\right) \cdot RL1}{\left(\frac{Aol1}{Aol2} \cdot \frac{RL2}{RL1}\right) - 1}$$ Substitute Eq 9 into Eq 11

Acknowledgements

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For his being the first IC Design Engineer to work cooperatively with the author on Zo at the IC simulation level and measure without argument, question, or protest, Zo on his op amp: Stephen Sanchez, Manager Design Engineering Apex Precision Power, a division of Cirrus Logic, Inc.

For their easy to use SPICE Simulator: DesignSoft, TINA SPICE link at http://www.tina.com/

About the Author

After earning a BSEE from the University of Arizona, in 1981, Tim Green has worked as an analog and mixed signal board/system level design engineer for over 30 years, including brushless motor control, aircraft jet engine control, missile systems, power op amps, data acquisition systems, CCD cameras, and analog/mixed signal semiconductors. Tim's recent experience is focused on power audio for the automotive market. He is currently a Senior Staff Systems Engineer for Audio Power Products located in Tucson, Arizona at Apex Precision Power, a division of Cirrus Logic, Inc. Tim may be reached at tim.green@cirrus.com