Op-Amp Stability Spice Model

Based on Bench Measurements

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Abstract

In this application note we will show how to take open loop gain measurements and output impedance measurements. And how these measurements can be used to verify manufacturers' models, or to create your own op amp stability model. A good stability model lets you assess performance under various loads, enables feedback optimization and the use of more advanced compensation schemes (higher order compensation, composite feedback loops/amplifiers).

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Brief introduction

Negative feedback is one of the greatest engineering concepts ever devised and the importance cannot be overstated. Negative feedback can reduce your output impedance, increase input impedance, improve PSSR, reduce noise, and much more. The effects are dependent on the amount of open loop gain available. The open loop gain is one of the most important graphs in the datasheet. Unfortunately, the open loop gain is not always plotted. Shockingly enough, sometimes the open loop gain is not stated at all.

If a DC open loop gain and gain bandwidth (GBW) is stated, you can guesstimate the dominant pole in the open loop gain. After the dominant pole, the benefits of negative feedback are (usually) reduced at a rate of 6 db/octave, respectively 20 db/decade. Luckily, in some datasheets, the open loop gain is plotted. But in order to fully model the stability, the open loop output impedance is needed. This information is usually not stated in the datasheet at all. Most vendors provide SPICE models for their parts. As with information in the datasheet, quality varies wildly. Some are excellent, some are good, some are not. As with all SPICE models, their accuracy needs to be checked before they can be considered trustworthy.

In this application note we will show how to take open loop gain measurements and input & output impedance measurements. And how these measurements can be used to verify manufacturers' models, or to create your own op amp stability model. A good stability model lets you assess performance under various loads, enables feedback optimization and the use of a more advanced compensation schemes (higher order compensation, composite feedback loops/amplifiers). A good understanding of Op-Amp basics and basics of feedback theory is assumed.

Op-Amp and Gains

Modern operational amplifiers can have a very high open loop gain. For example, the OPA2134, a popular audio op-amp, has 120dB of open loop gain. That's a gain of 1 000 000 times. In other words, if we were to put 1uV on the input of the idealized amplifier without feedback in place, you'd get 1V on the output of the amplifier. Theoretically. The input noise will force the output towards one of the power rails. Ideally, we would like to have infinite gain, spanning across infinite bandwidth. So, the infinite benefits of negative feedback would cover all frequencies.

Unfortunately, in our real world, we are plagued by phase shifts and bound by stability requirements. In order to fulfill the stability requirements, the gain needs to be reduced, before the accumulated phase shifts can turn negative feedback into positive. This is facilitated usually by a dominant pole (somewhere around 3Hz in the picture below) compensation. After the dominant pole, the loop gain is gradually reduced (usually at a rate of 6db/oct). This is how the open loop gain plot looks like for the OPA2134[1]

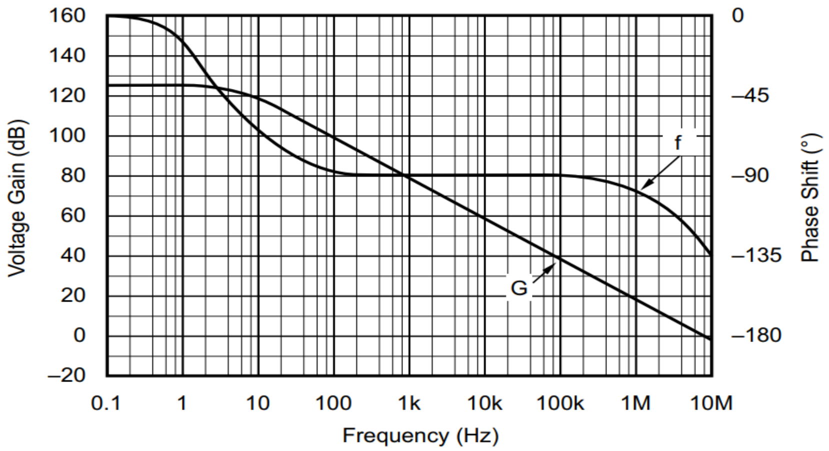


Figure 1 Open loop gain of OPA2134, courtesy of the part datasheet

The open loop gain is all the gain that is available from the amplifier. Design usually requires a certain amount of signal gain - ie. how many times you need to amplify the input signal. This signal gain is also called closed-loop gain. The reminder of op-amp open loop gain, that is unused for signal amplification, is used by the feedback loop and is usually described as loop gain. As the discussion above is rather abstract, let's illustrate the point with an example. If you have an op-amp with 120dB of open loop gain, and in your circuit, you require gain of 10X (20dB). 20dB of gain will be used to amplify the signal, the remaining 100dB will be used by the feedback to improve performance of the amplifier. If we need just a signal gain of 1X(0dB), then the remaining 120dB will be available as loop gain. The latter amplifier will be 20dB more linear, since the loop gain is 20dB higher. In other words, the higher the signal gain, the less the loop gain and therefore also less benefits of negative feedback.

As you can see, high signal gains can have dire consequences on the loop gain. For this reason, in some cases, it might be beneficial to split a high gain stage in two stages with less gain. While total gain will be the same, the linearity would be much improved.
To summarize, we have several gains:

[1] "OPAx134 SoundPlus™ High Performance Audio Operational ...." http://www.ti.com/lit/gpn/opa2134

- Open loop gain - the gain without feedback, describes all the gain, the amplifier can provide
- Signal gain or closed-loop gain - the amount of gain an incoming signal is amplified with
- Loop gain - gain of the feedback loop, quantifies impact of the feedback loop on the amplifier and dictates amplifier’s stability

It is important to realize that the amount of loop gain at a given frequency dictates how big the benefit of negative feedback will be. Provided that everything else is the same, an amplifier with 20dB more of loop gain will have an order of magnitude lower harmonic distortion. Since loop gain changes with frequency, it is not only the question of DC/maximum value of loop gain, but also of the position of the dominant pole compensation.

As you go up in frequency, the available open loop gain decreases (because of the dominant pole compensation). If open loop gain decreases, but signal gain stays the same, the loop gain must decrease as well. With decreasing loop gain, the effects of negative feedback are also decreased. The loop gain and effect of negative feedback will keep decreasing until there is no more loop gain and thus no more negative feedback.

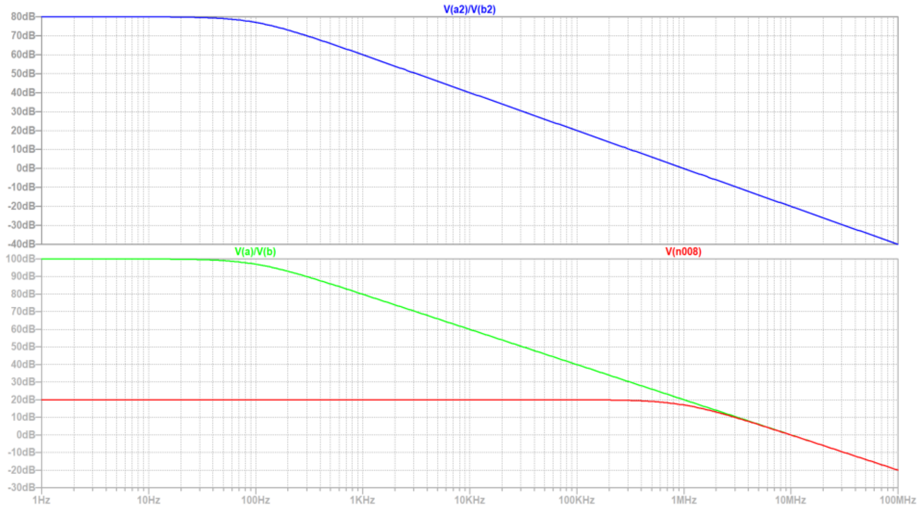


Figure 2 Op amp Gains
Green - Open loop gain
Red - Signal gain/closed loop gain
Blue - Loop gain

Keep in mind that the underlying concepts of feedback are the same, no matter whether your application is a high-speed op amp, offline SMPS, high end audio amplifier, or slow temperature regulator.

In our brief introduction, we have made some simplifications and disregarded some aspects (amplifier configuration, noise gain). Luckily, it’s an interesting topic and there is an abundance of quality literature available, to name just a few:

- MT-033TUTORIAL, Analog Devices
- Op Amps for Everyone,
  - Texas Instruments, Ron Mancini, SLOD006B
- Operational Amplifiers 2nd Edition
  - Jiri Dostal, ISBN 9781483292366
- Designing Control Loops for Linear and Switching Power Supplies: A Tutorial Guide
  - C.Basso, ISBN 978-1608075577

Measurements

A Note on Signal Levels

Before we start to discuss different variants on how to measure the open loop gain, it's important to note that all the measurements that we will be talking about today are small signal measurements (as we are building a small signal model). That means that all measurements need to be "small signal measurements". The amplitude of the signal should be small enough, so there is no large signal limiting (no current limiting, no slew rate limiting etc). How small is small enough? It depends. In general, the test is performed at various signal levels, and the level of test signal is being reduced as long as the shape of the transfer function is changing (see Fig. 3 around 1MHz). Once there is no effect of signal level on the shape of the transfer function, this is our small signal response. As with every measurement, knowing what is the expected outcome is of paramount importance - how else should one know whether the result is reasonable?

In general, it's recommended to perform the measurement with a test signal as small as possible, while attaining clear results. You can use shaping on input signal amplitude to improve your measurement fidelity - increase signal in areas where the measurement is noisy (within reason). To illustrate the issue, please look at the signal gain of our test amplifier, at various levels of input signal. For some measurements, the needed signal levels might be surprisingly low.

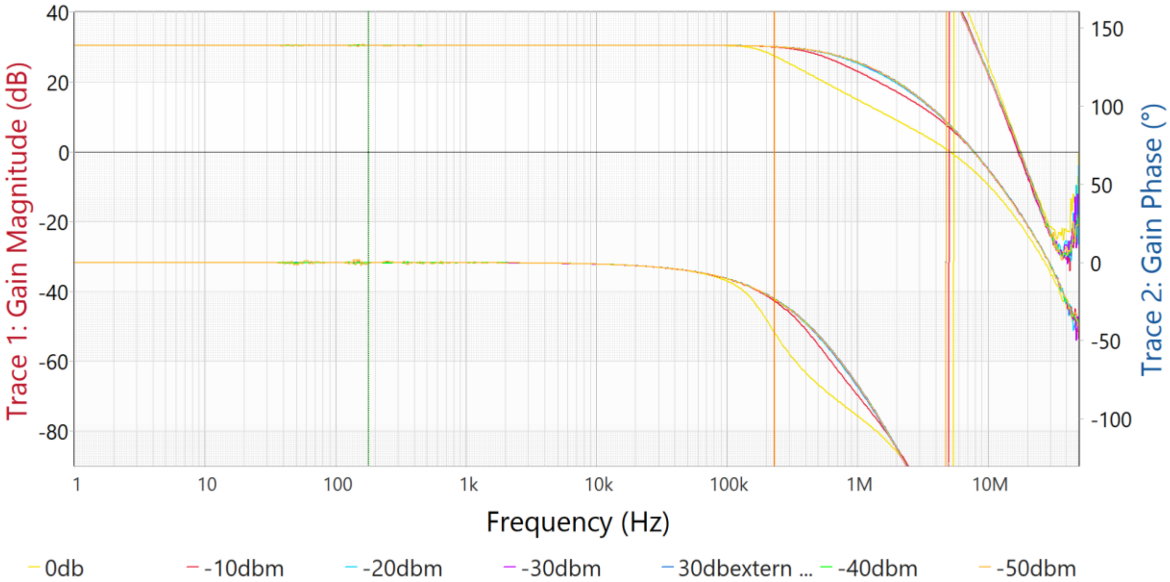


Figure 3 Effect of input signal amplitude on signal gain measurement

Open Loop Gain (OLG) Measurements

Indirect

With the indirect OLG measurement, the OLG is assessed by means of measuring the loop gain and signal gain. If your opamp is unity-gain stable, the most convenient configuration is a unity gain amplifier. As the closed-loop gain is one, all of the open loop gain is used as the loop gain. In this case, loop gain measurement/stability measurement is equal to our OLG measurement. In a loop gain measurement, disturbances are injected into the feedback loop via an injection transformer. By observing the reaction of the feedback system on the injected disturbances, we can assess the loop characteristics. A detailed description how to perform loop gain measurements can be found at [2]
If the amplifier is not unity-gain stable, two measurements are needed - a closed loop/signal gain measurement, and a loop gain measurement. As our test amplifier is not unity gain stable, this is what we will do. Before we proceed further, let's take a brief look at our test amplifier schematics:

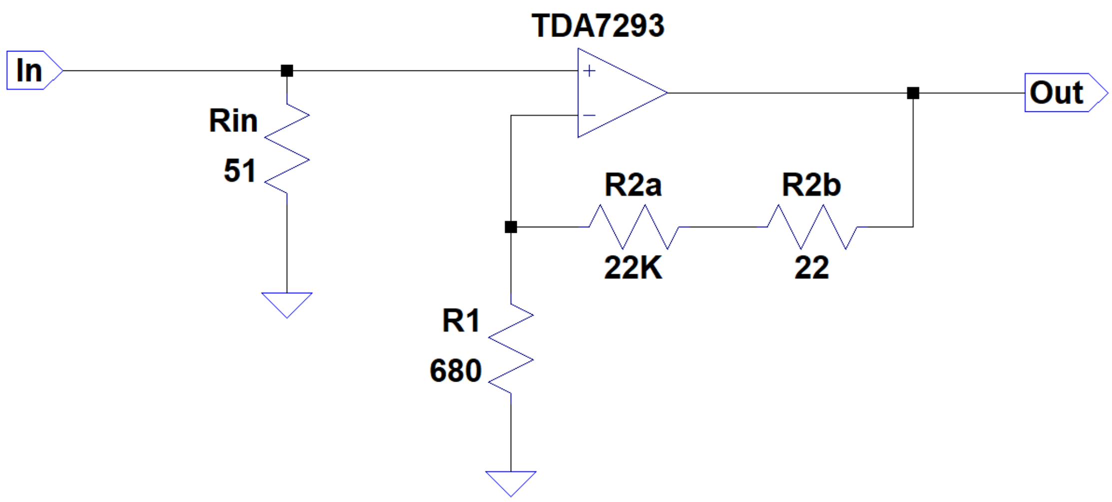
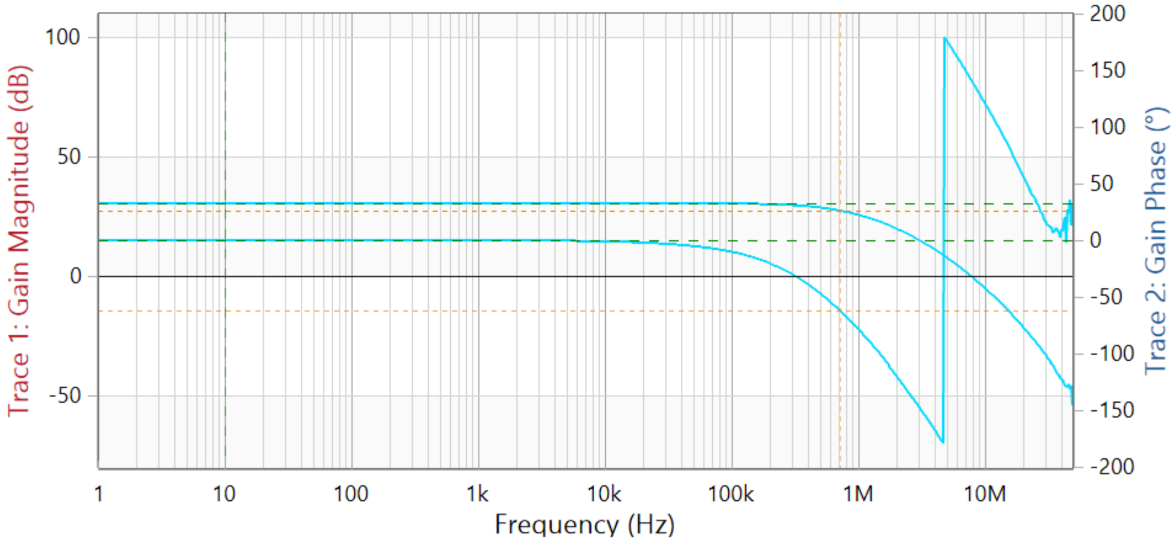


Figure 4 Amplifier Schematics

[2] "DC/DC Converter Stability Measurement - OMICRON Lab." https://www.omicron-lab.com/fileadmin/assets/Bode_100/ApplicationNotes/DC_DC_Stability/App_Note_DC_DC_Stability_V3_3.pdf.

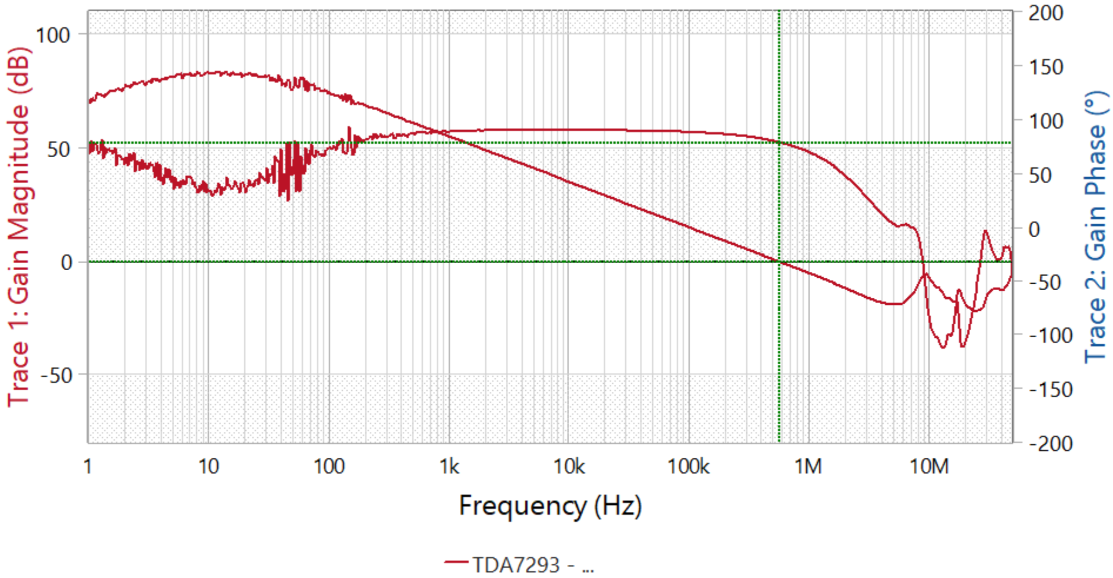
The first measurement that we will perform is a signal gain measurement:



	Frequency	TDA7293 - ...	TDA7293 - ...
Cursor 1	10 Hz	30,429 dB	-1,809 m°
Cursor 2	719,647 kHz	27,429 dB	-61,695 °
Delta C2-C1	719,637 kHz	-3 dB	-61,693 °

Figure 5 Amplifier signal gain/closed loop gain

Performing the loop gain measurement with injection across R2b gives following results:



	Frequency	TDA7293 - ...	TDA7293 - ...
Cursor 1	562,036 kHz	0 dB	78,788 °
Cursor 2			
Delta C2-C1			

Figure 6 Loop gain measurement

Let’s try to put the two measurements together - adjusting the loop gain measurement by the amount of signal gain, and plotting loop gain and signal gain into one plot, we will get:

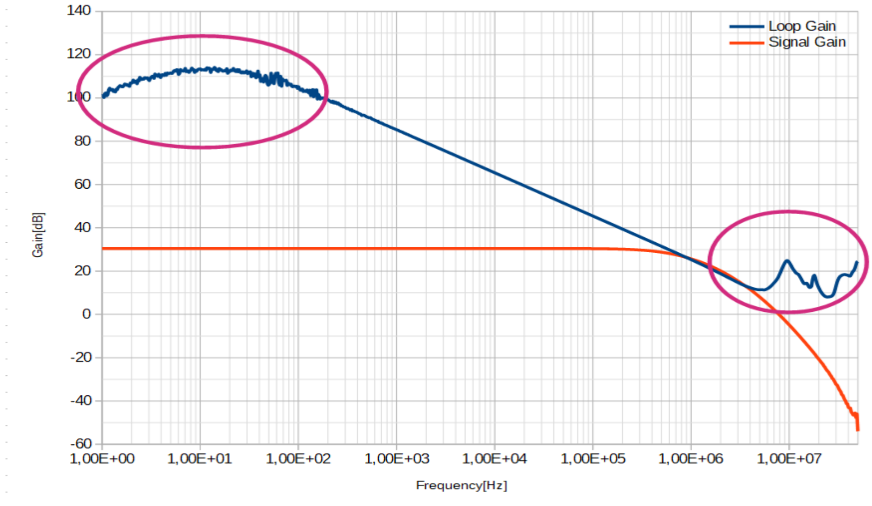


Figure 7 Loop gain and signal gain measurement

In the plot we can see two highlighted regions. Why are they of interest? Because they are not what was expected. Let's start with the low frequency part. There is no obvious reason why the gain should be reduced in a low frequency region, we would expect a flat gain, up to a dominant pole. As both inputs are on the same side of the injection transformer, the bandwidth limit of the injection transformer should only affect the test signal amplitude, not the measured transfer function. Yet the injection transformer is the only thing in the test setup that can create something with such a constant time. If anyone knows what the source of this hump is, the author would be very interested to hear the explanation. The other, perhaps more important issue in the LF region, is the amount of the open loop gain. From the TDA7293 datasheet the typical open loop gain is stated as 80dB
Even if we disregard the mild resonance, we still have measured much more gain than advertised in the datasheet. Also, our measurement in the high frequency part of the spectrum does not match.
Let’s move our attention to the HF region. Here we can see a severe resonance. The transfer function of Injection transformer can shed some light on the HF resonances:

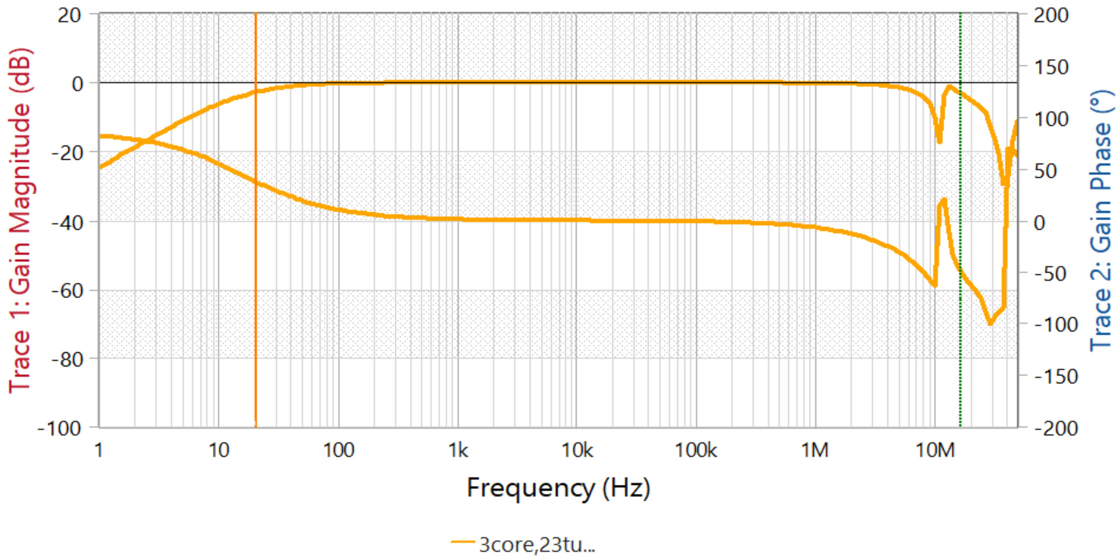


Figure 8 DIY Injection transformer transfer function

The homemade transformer was built with heavy emphasis on LF performance. Unfortunately, this resulted in reduced HF extensions. The resonance that we see in HF seems to be related to our injection transformer. In other words, our DIY transformer bandwidth is not good enough for our measurements. In order to verify our hypothesis that the transformer is to blame, one more measurement was done. The circuit was modified by adding one more resistor (RNG):

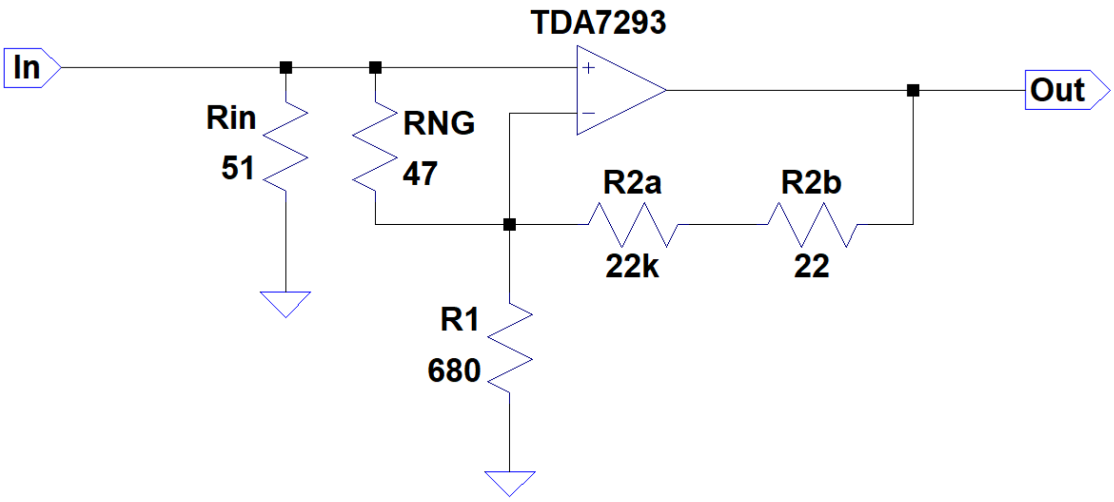


Figure 9 Modified amplifier circuit

We have introduced a new resistor - RNG. By adding this resistor, we have increased our noise gain, which in turn reduced our loop gain (and all the benefits of NFB - for example distortion[3]), without modifying our signal gain.

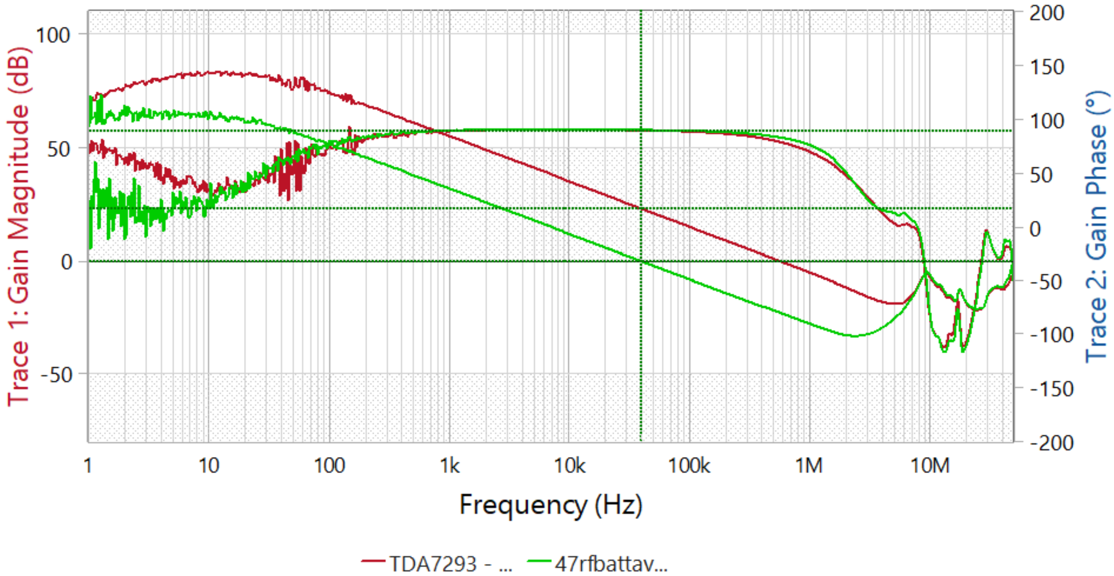


Figure 10 Loop gain of modified circuit

We can clearly see the reduced loop gain, yet in the HF region the traces are almost identical. This is an indication that what we are seeing is the effect of our test setup, and is not really related to the loop gain that we have modified by adding RNG. If the resonances

[3] "LME49720 - Texas Instruments." http://www.ti.com/lit/gpn/lme49720, p. 24

were part of the loop gain, we would expect them to be affected by the addition of RNG. The mysterious hump in low frequency disappeared, we still have the issue of the amount of the LF gain…

Before we move to another technique, I'd like to highlight that although we are measuring the loop gain, the loop gain is part of the whole circuit. As such, other aspects have an effect on the opamp performance and loop measurements. To illustrate this, let's have one more open loop measurement comparison:

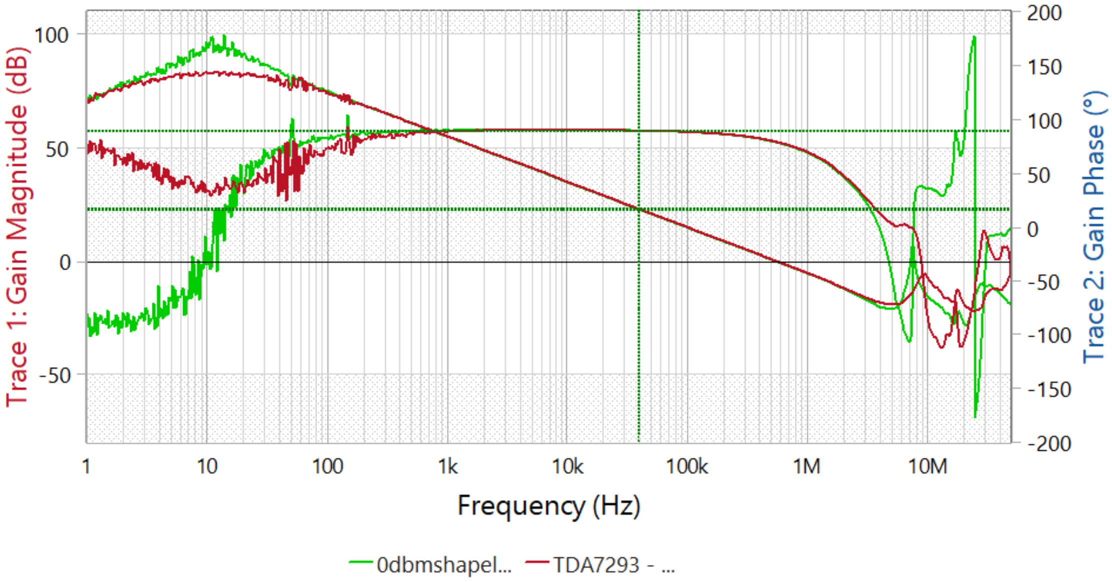


Figure 11 Effects of decoupling on loop gain

The red trace is the original open loop measurement. The green trace is the same amplifier configuration, only with reduced supply decoupling. 10000µf capacitors were removed, only 330µF and 100nF remained. We can notice that the LF resonance is now more pronounced, as are the HF resonances.

Although we were not successful in measuring the open loop gain with the indirect method, the loop gain measurement with an injection transformer is very valuable on its own, to assess stability of the feedback loop, if parameters of the injection transformer are good enough with regards to the bandwidth of the measured feedback loop. This technique is widely used to assess stability of slower feedback loops, such as SMPS and linear regulators.

Direct Open Loop Gain Measurements

Compared to a feedback loop of a voltage regulator, the more general op amp circuit has one big benefit - the input of the opamp is usually accessible for direct signal excitation. In that case no injection transformer is needed. There are several ways to measure the loop gain directly, depending on your op amp configuration. The most convenient one is the inverting configuration. The convenience lies in the virtual ground - the input difference voltage can be measured directly against ground. This is of great benefit as a single ended probe can be used:

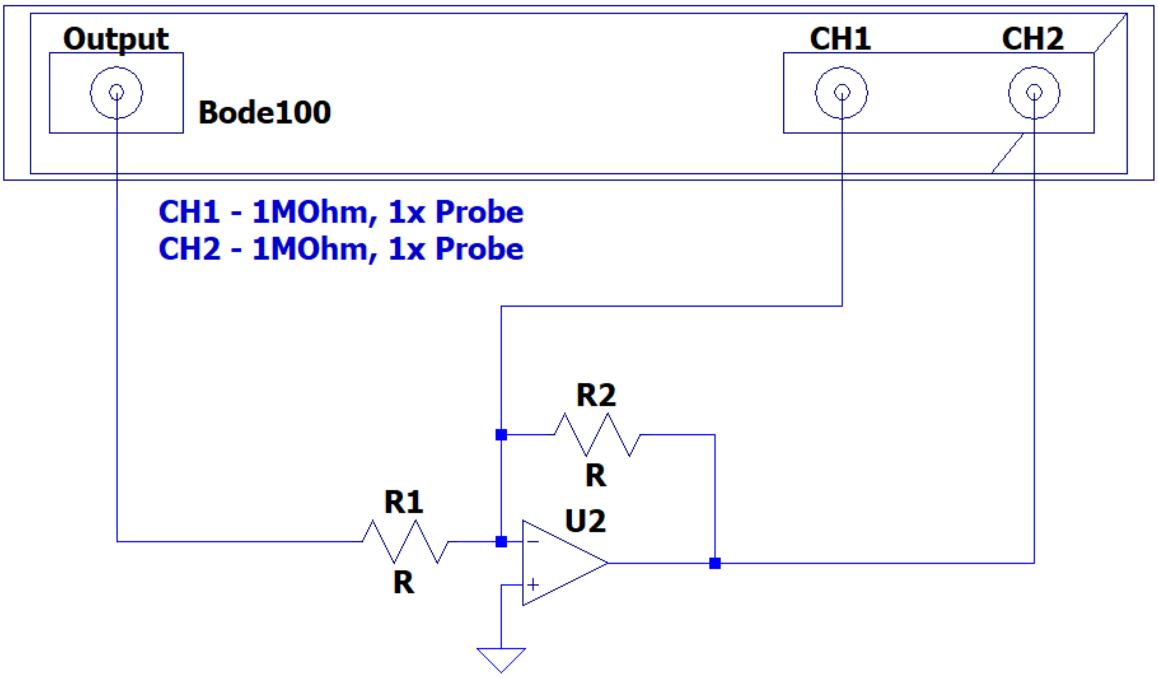


Figure 12 Loop Gain measurement of inverting amplifier

More details about measurements of the inverting configuration can be found in the corresponding OMICRON Lab appnote[4]. Unfortunately, our amplifier is in non-inverting configuration and a differential probe is needed to extract the input voltage. Unfortunately, the more affordable differential probes are aimed at high voltage measurements with attenuation in the range of 10x-1000x. As the voltage between the inputs of the op amp is very low, no further attenuation is desirable. 1x differential probes exist but are aimed at high-speed work and usually carry proprietary oscilloscope connections (and hefty price tags). A DIY differential probe (originally constructed for low impedance measurements) with 20 dB of gain was used for the measurements. An alternative to a DIY approach could be a used Tektronix P6046 probe. As the dynamic range of these measurements is very large, shaping of the generator output signal is recommended.

[4] "Operational Amplifier - OMICRON Lab." https://www.omicron-lab.com/fileadmin/assets/Bode_100/ApplicationNotes/Op-Amp_Analysis/2018-01-18_Appnote_open_loop_gain_V1.1.pdf.

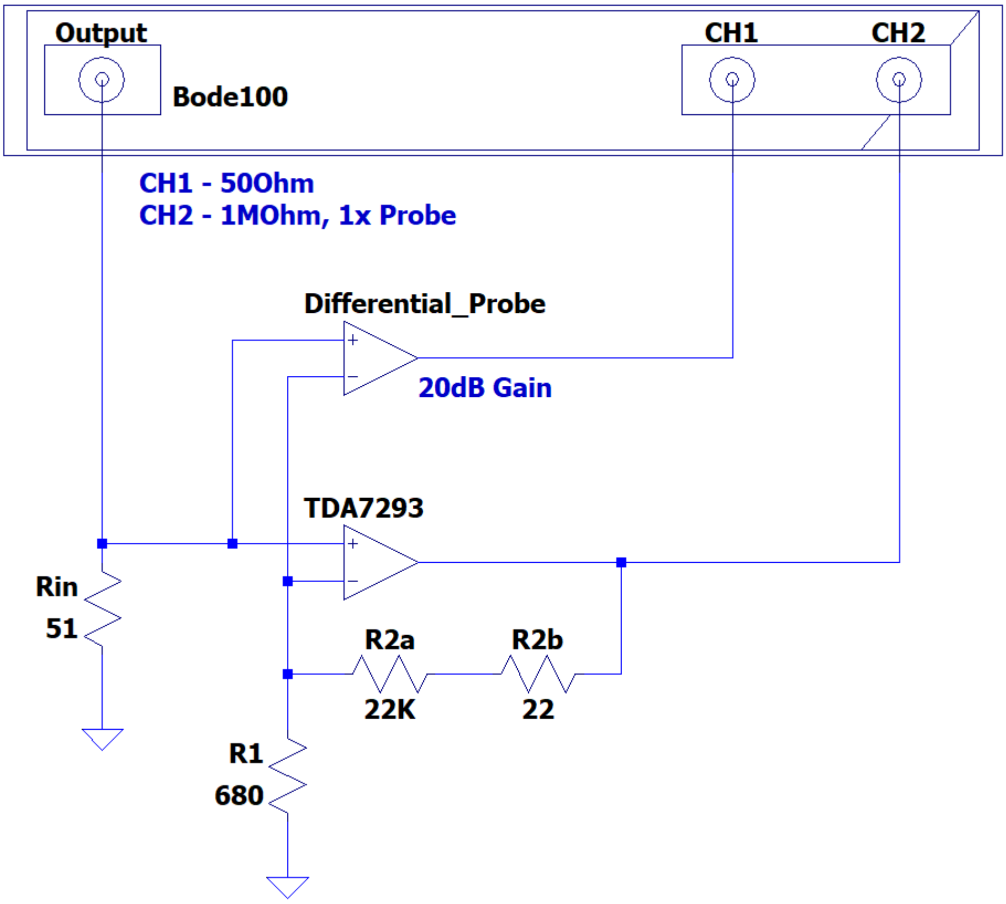


Figure 13 Differential connection of our amplifier

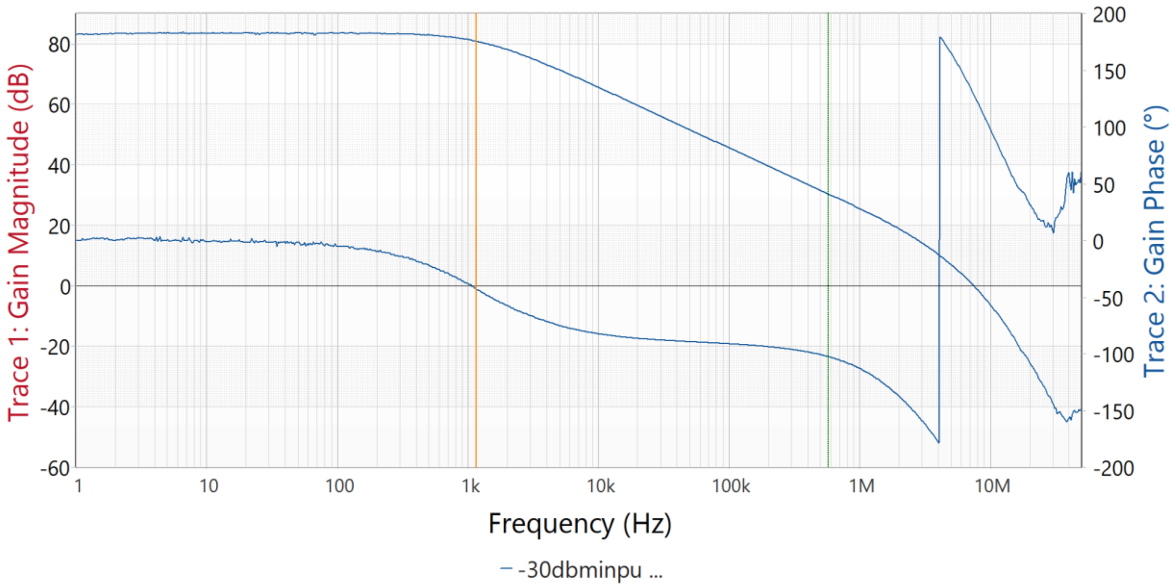


Figure 14 Open loop gain measurements with differential probe

Now if we plot open loop gain together with signal gain:

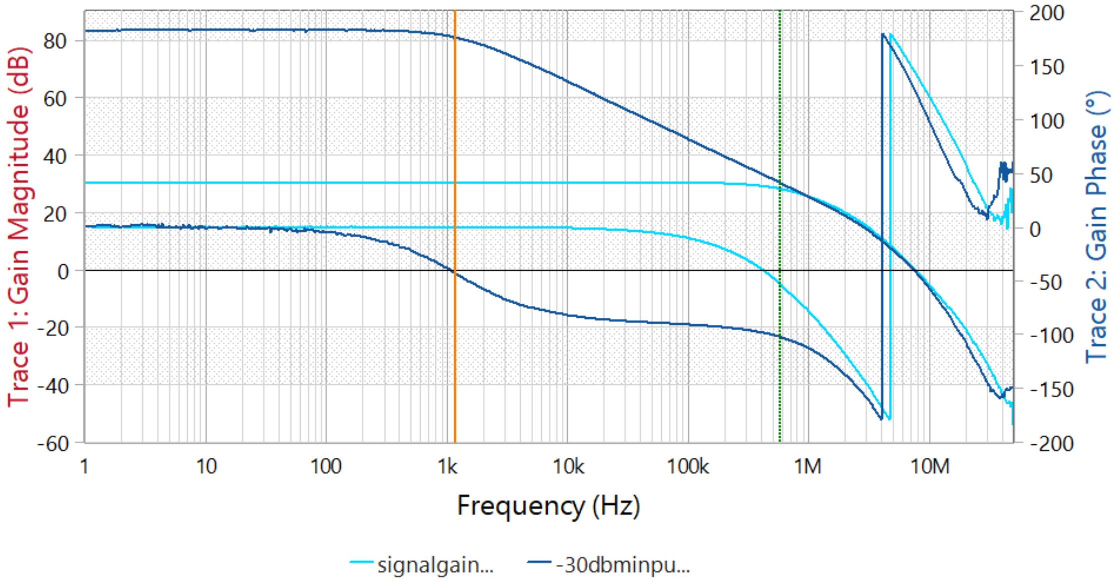


Figure 15 Open loop gain and signal gain

The open loop gain corresponds well with datasheet value, also there is a reasonable agreement with signal gain measurement.

Observations

- Keep the limits of your DIY tools/jigs in mind and verify their performance
- Power Supply bypassing does influence loop gain
- Indirect open loop measurements might be feasible with wide bandwidth injection transformer/solid state injector. Might be practical for unity gain stable op amps, or in cases where input of opamp is not accessible to the designer.
- For regular opamp, the inverting configuration is the most convenient one

Output Impedance Measurements

Unfortunately, in most of the amplifiers the input of the output stage is not directly accessible to the designer. And as such it can't be measured on its own. By default, the output stage is included in the feedback loop and if you probe the output of the amplifier, you will measure closed loop output impedance. Can't we measure the closed loop output impedance and calculate the open loop output impedance (provided that we know the amount of loop gain)? Theoretically we could, but this approach has several drawbacks, as the output impedance is reduced by the available loop gain. This makes the output impedance very, very small. Which in turn makes the measurements rather challenging. As the output of an amplifier is usually connected by a PCB trace (not a power plane/ground plane pair), both the PCB layout (output trace geometry + feedback take off point) and probe position has a severe effect on the measured value. In the author's opinion, due to all difficulties stated above, it's not a very practical approach. Yes, it was tried…

For our measurement of open-loop output impedance we need feedback just at DC, to maintain the operation point of the amplifier, and ideally no feedback at AC, so the output impedance is not affected by the feedback. Heavy filtering of the feedback path is needed. For simulation purposes, feedback filtering with 1TH inductor and 1TF capacitor works very well[5]. Unfortunately, the values are a bit impractical for breadboarding. For practical measurements, a simple RC filter is enough. A similar approach was used in[6], to measure op amp loop gain. Using a 2 stage RC filter is possible, but compensation is a bit more involved. Using a properly chosen single stage RC filter is the easiest way.
There are several points we need to keep in mind:

- we need to filter out all the gain before we reach the frequency band of our interest - that is a lot of filtering.
- Closing the feedback loop very low does not dispense us from stability requirements.

For those reasons, it is beneficial to measure open loop gain before we measure the output impedance, as we will have all the required inputs for correct filter design. As op amps are wildly different and chances are high that using an ad hoc random RC filter might not work, a proper design procedure is highly recommended. To ensure stability, we would like the crossover point to be at highest, one decade below the dominant compensation pole. By choosing the crossover point in this way, we maintain a -1 slope at crossover frequency, and the effects of the dominant pole are negligible. Pushing the crossover frequency too low might create its own set of problems. As settling times are rather long, the amplifier is not properly biased before the feedback loop settles. In the case of TDA7293 we have observed phase reversal of the output (and inability to settle to final value) with too low crossover frequency. A possible solution to the latch up issue could be a slow ramp up of power supplies, or a tunable/switchable filter that could decrease its crossover frequency. In our case we have simply increased the crossover frequency of the filter, the downside is that the effect of feedback can now be observed in the low frequency part of our measurement. As the low frequency region is very far away from the feedback crossover region, this will have no effect on our model.

[5] "Modeling the output impedance of an op amp for stability ...." http://www.ti.com/lit/slyt677.
[6] "Operational Amplifier Measurements with Bode100." https://www.omicron-lab.com/fileadmin/assets/Bode_100/ApplicationNotes/Op-Amp_Analysis/App_Note_Op-AMP_FH_Regensburg_V1.2.pdf.

Another point to keep in mind is that using excessive values for R in the RC filter might, depending on the magnitude of input bias current, lead to big offsets/shifts in operating points. Before connecting the amplifier to the network analyzer, please check that output is settled to 0V, and that the amplifier is stable.

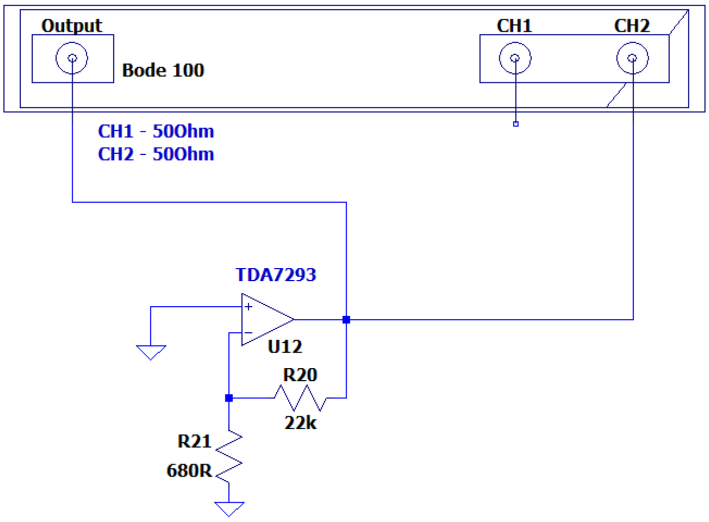


Figure 16 Closed Loop output impedance measurements

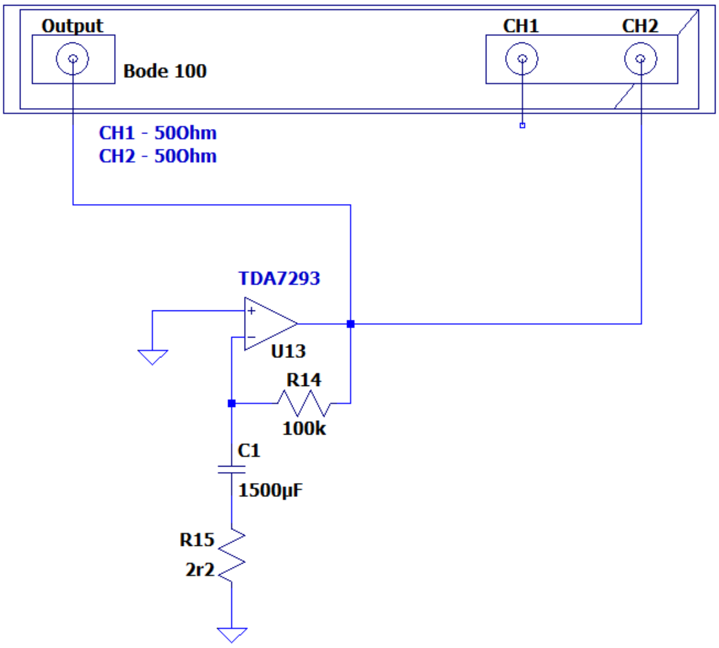


Figure 17 Output impedance measurement with filtered feedback

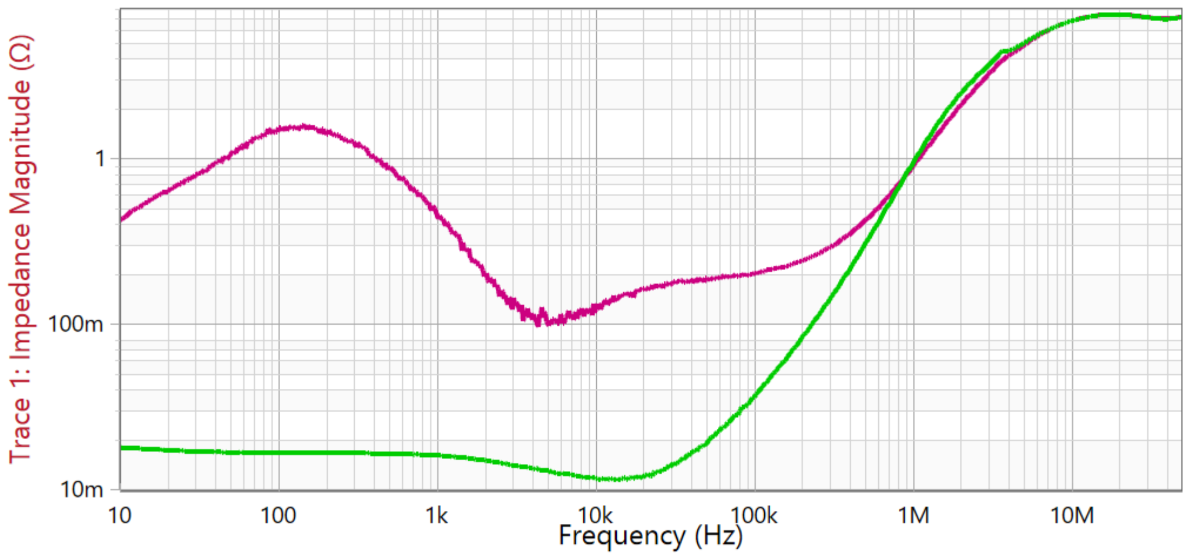


Figure 18 Output impedance

Green - with regular feedback
Magenta - RC filtered feedback

Please note that closed loop output impedance and open loop output impedance are equal at the frequency where the amplifier runs out of gain, i.e., all of available gain is used for signal amplification. This agrees with our signal gain and open loop gain measurements in Fig.15. The decrease in open loop output impedance is probably caused by insufficient filtering of feedback path, i.e. There is still some feedback left to reduce output impedance.

To verify our measurement, a simple model was constructed. This allows us to compare closed loop output impedance measurement with simulate one - i.e., open loop impedance + effect of the feedback.

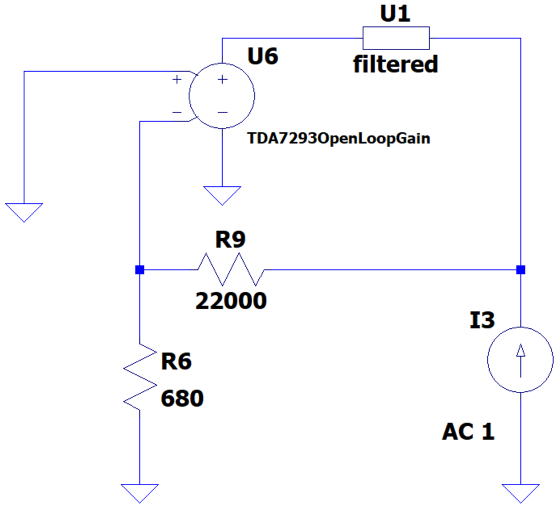


Figure 19 Closed loop output impedance simulation

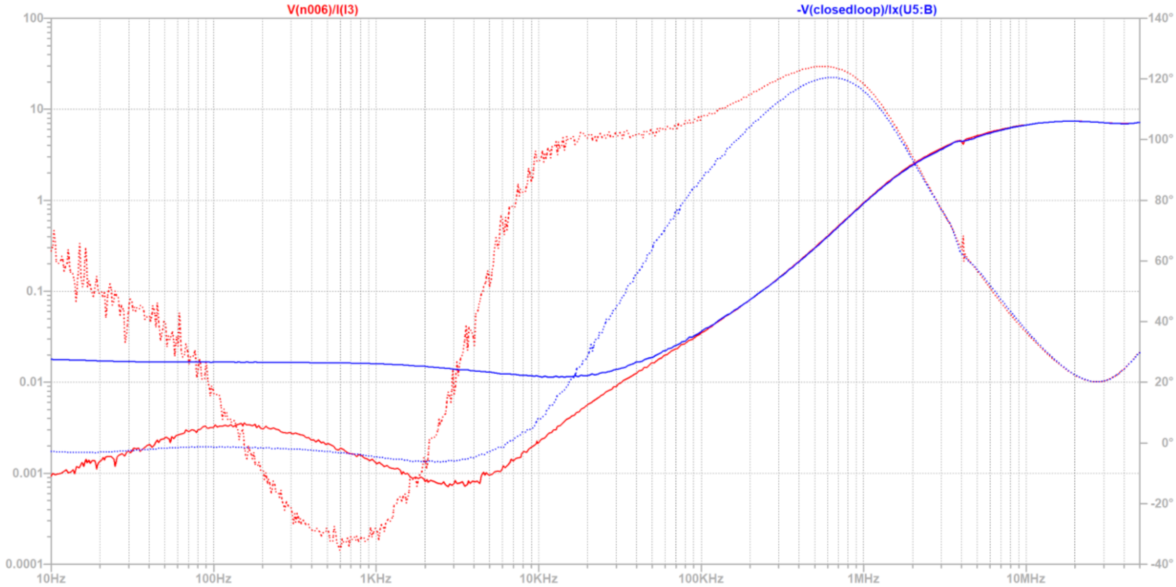


Figure 20 Output impedance comparison

Blue - closed loop output impedance measurement
Red - simulated closed loop output impedance

Apart from the discrepancies below 10 kHz, the results are in a good agreement. The low frequency discrepancies are caused by:

- high roll off of RC feedback filter
- Differential preamp was not used - effects of braid error (ground-loop) can be observed.
- Output impedance was not measured directly at IC pins

For best results, a design of dedicated test PCB with proper 4-wire/shunt-through test connection directly to the DUT output pin is highly recommended. Our test board was not designed with this measurement in mind, as such the output impedance measurement includes PCB traces. Depending on your amplifier open loop output impedance, shunt through measurement might not be the most suitable one, as the low frequency output impedance can be outside of the measurement window for shunt through. As our amplifier is an audio power amplifier, the open loop output impedance is very low. For a small opamp, output impedance can be easily in hundreds of ohms. In the case of hundreds ohm range, the shunt-through measurement with external resistance would be a suitable way to shift the measurement window up to fit the output impedance. Compared to one port impedance, shunt-through is easy to calibrate with only DUT/amplifier removal from the circuit. One port impedance measurement would require full OSM (open-short-match/load) calibration.

Input impedance

To have a correct stability model of an opamp, all of the phase shifts that occur in the feedback loop need to be accounted for. Phase shifts resulting from the internal op amp structure are incorporated in our open loop measurements. Phase shifts that arise from the interaction between opamp and load are correctly modeled with the help of the output impedance measurement. The final phase shift that occurs before the feedback loop is closed is the result of the interaction between our feedback network and input impedance of the op-amp.

The input impedance is consisting of two parts[7]. Differential - Impedance seen across the inputs, and common-mode - impedance to ground/power.

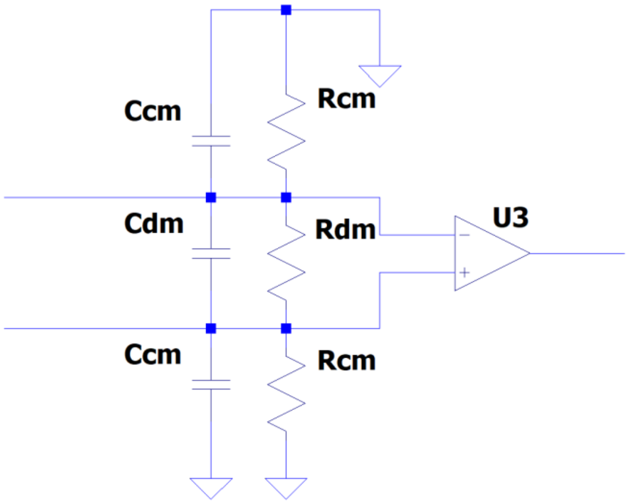


Figure 21 Input Impedances

In some cases, the resistive part can be negligible. For really slow amplifiers and low impedance feedback networks, we might be able to disregard input impedance as a whole, as the effect would be negligible. For medium and high-speed op amps, the effects of input capacitance can't be neglected, as they can have serious impact on stability[8]. If we are lucky, the input impedance is stated in the datasheet.
If values are not available, or we'd like to verify the datasheet figure, measurement is in order. Before proceeding to measurement of input impedance, it's important to realize that the PCB parasitics might be comparable to the values we are trying to measure. Parasitic capacitance of PCB needs to be minimized or calibrated out. Unless you are interested in models that include PCB layout/parasitics.

[7] "Input Capacitance—common-mode?...differential?… - TI E2E." 15 led. 2013, https://e2e.ti.com/blogs_/archives/b/thesignal/archive/2013/01/15/input-capacitance-common-mode-differential-huh.
[8] "The impact of input capacitance on op-amp stability"

Common mode Input impedance

The measurements of common mode part are rather straightforward[9]. Contrary to the AN 5086, the author does not recommend performing calibration without the opamp. Instead, a calibration at the splitter output is recommended. Instead of an active probe, a simple buffer with OPA659 was used.

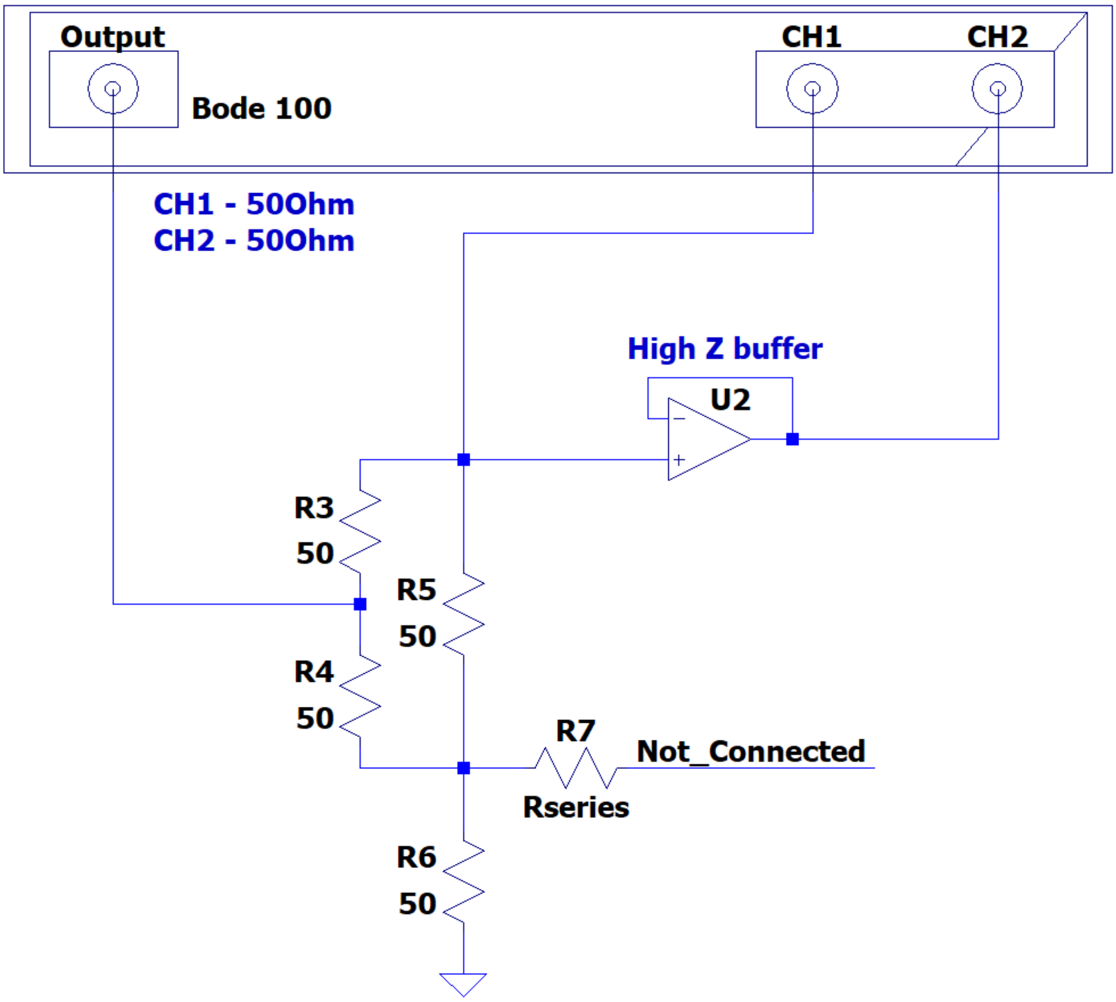


Figure 22 Calibration connection

[9] "Measure the Input Capacitance of an Op Amp"

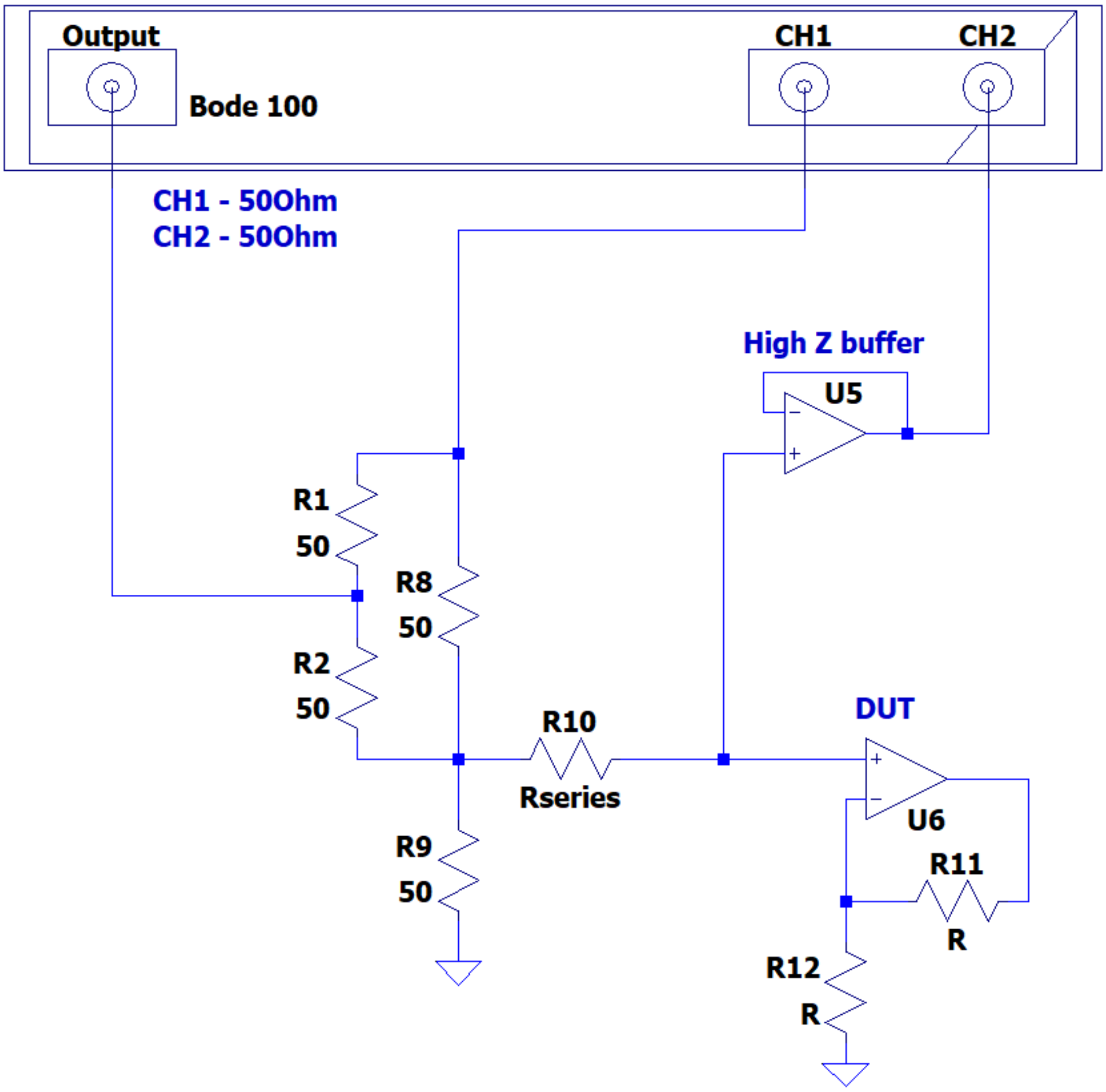


Figure 23 DUT connection

If the effect of test jig is not calibrated out, the transfer function starts to roll off at frequency defined by Rseries (provided that Rseries >> splitter resistance) and test jig parasitic. If we connect the test jig to the DUT, the roll off frequency is shifted downwards by the amount of extra capacity that we have added by connecting the DUT. By comparing the roll-off frequency change it is easy to evaluate the DUT capacitance. If we were to calibrate the jig parasitics out, the calibration routine would apply an upwards slope to compensate for the jig roll-off. If the DUT capacitance is small compared to the jig parasitics, the measured trace flattens out rather soon. Evaluating the DUT capacitance is then not as straightforward as from the shifting roll-off frequency.

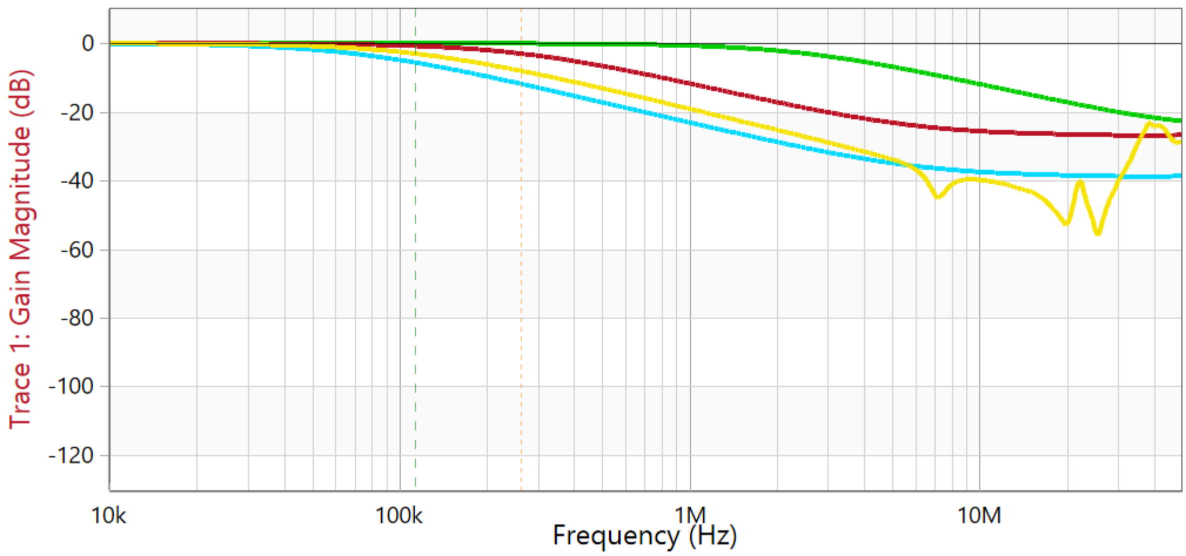


Figure 24 Input capacitance measurement

Green - test jig with10kOhm resistor
Red - test jig with 100kOhm resistor
Blue - 18pf Capacitor as DUT
Yellow - OPA2134 in place of DUT

Rseries [Ohm]	Roll-off Frequency [Hz]	Measured Total Capacitance [F]	Note
9960	2.52E+06	6.33E-12	No DUT
99380	2.63E+05	6.10E-12	No DUT
99380	6.93E+04	2.31E-11	18pF
99380	1.13E+05	1.42E-11	OPA2134

Two values of Rseries were used for a sanity check of the test setup. Both values gave the same value for jig parasitics - ca. 6pF. To further verify the test setup, an external 18pf capacitor was soldered in place of the DUT - with measured value in our test setup of 17pF. Also, the OPA2134 was measured in place of the DUT, with a measured value of 8pf input capacitance. This is quite a bit higher than the datasheet value of 5pF but given that the IC was in the socket and the whole setup was constructed dead bug style, it is not an unreasonable result.

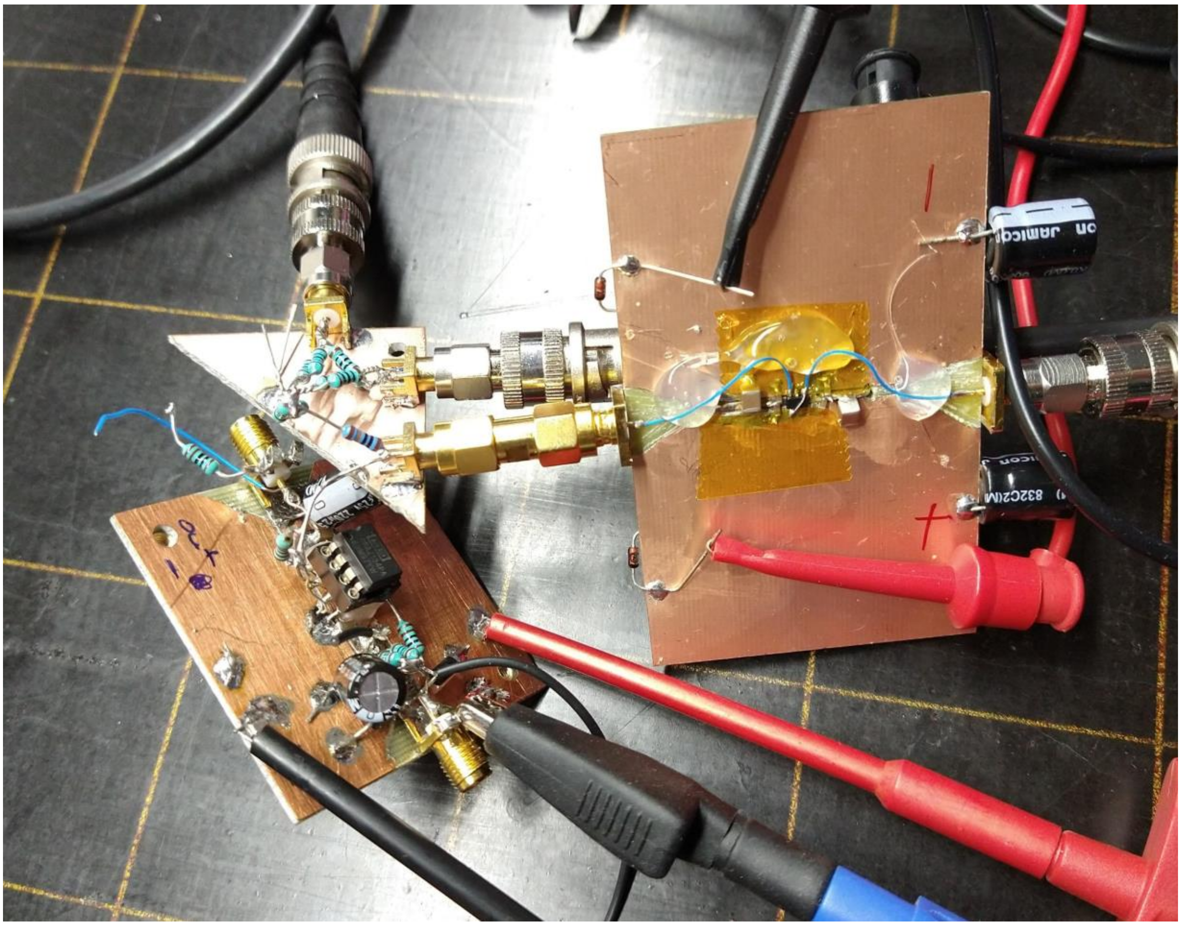


Figure 25 Input capacitance measurement setup

Right - high Z buffer
Left - signal splitter
Bottom - DUT (OPA2134)

As with the output impedance measurement, a dedicated test board could provide much better performance and repeatability. As the connection between the splitter, DUT and high impedance buffer was physically rather large, the jig capacitance was rather high. Tight PCB layout, with a buffer located very close to the DUT pins and with removed ground plane under the measurement node would provide lower capacitance of the test setup. The measurement of TDA7293 gave an input capacitance value of 8.2pF.

Another option how to evaluate input capacitance is the amount of attenuation in the upper frequency region. The attenuation is defined by the parasitic capacitance across the series resistor and the capacitance to ground - be it just test fixture capacitance or test fixture+DUT. This capacitive divider will define high frequency attenuation. This approach can be beneficial in cases when the -3dB roll-off is not very clear.

Differential mode Input impedance

What happens with the effects of the differential mode capacitance and the other part common mode capacitance? The other side of differential mode capacitance is driven by feedback to a very same voltage (voltage across the inputs is equal). As the voltage is greatly reduced, the current flowing through is as well reduced. Thus, the feedback is making the input impedance to be much bigger than without feedback. This enlarged impedance is in series with the other leg of the common mode input impedance, thus rendering the effect of the other leg of common mode input impedance negligible. In other words, the current passage is blocked by an extremely big differential mode impedance. The same effect that nicely isolated the differential mode impedance also makes it very hard to measure it. Luckily a novel measurement technique was recently published by Analog Devices[10]. Unfortunately, a virtual summing ground test jig was not ready in time of publication, and as such our model will not have measured the value of Cdm. Source and test connection is provided to readers for reference.

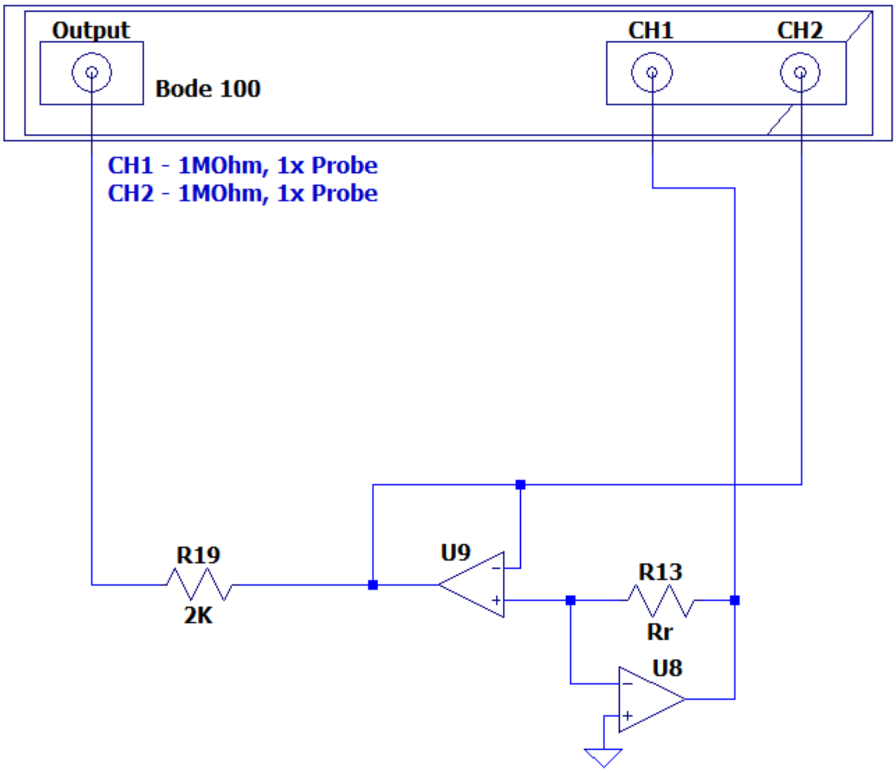


Figure 26 Test jig from Analog Dialogue - Volume 53

[10] "A Direct Method of Measuring Op Amp Input Differential ...." https://www.analog.com/media/en/analog-dialogue/volume-53/number-4/a-direct-method-of-measuring-op-amp-input-differential-capacitance.pdf.

SPICE Model

Now that we have the required data, we can do two things:

- Use the raw data for simulation
- Make an analytical model that would fit our measured data

Simulation with a model that would fit our measured data would be more useful, as we could use such a model for tolerance analysis. How would the performance of our circuit change with 50% change of open loop gain? Or with change in the dominant pole placement, or parasitic poles? Although the basic model is not complex, for simplicity's sake let's use raw data for simulation. Depending on your simulation program, you might be able to load your data directly. For example, QUCS[11] can import touchstone files directly. Unfortunately, one of the most popular SPICE software, LTSpice, does not provide this feature via the GUI. Luckily there is support for frequency data import in spice syntax itself, by using a B source (voltage-controlled voltage source).

```
.subckt MeasOLG 1 2 3 4
* (Freq, mag, deg)
B1 1 2  V=V(3,4) DB FREQ=
+ (1.000, 70.582, 78.118)
+ (1.022, 70.749, 68.043)
+ (1.045, 69.807, 76.558)
+ (1.069, 71.627, 80.570)
+ (3718.753, 43.617, 89.866)
+ (3802.078, 43.412, 89.706)
+ (3887.271, 43.223, 89.634)
.
.
.
.
+ (42815795.436, -12.038, -18.407)
+ (43775158.708, -11.072, -17.915)
+ (44756018.203, -10.508, -18.884)
+ (45758855.581, -9.994, -18.381)
+ (46784163.297, -8.979, -17.648)
+ (47832444.837, -7.648, -21.195)
+ (48904214.970, -6.249, -29.183)
+ (50000000.000, -5.976, -43.476)
.ends MeasOLG
```

Figure 27 Tabulated B source subcircuit

Output impedance can be imported in a similar fashion, but in this case as voltage controlled current source. Luckily for LTSpice users a very handy utility bode2spice[12] exist. This utility takes the CSV output from Bode 100 and will create a desired spice entity. It can export both, measured transfer functions, as well as impedance data.

[11] "Qucs project: Quite Universal Circuit ...." http://qucs.sourceforge.net/.
[12] "ladmanj/bode2spice: bode2spice creates LTSpice ... - GitHub." https://github.com/ladmanj/bode2spice.

On a side note, the import of frequency and impedance data into LTSpice is extremely useful. It enables the engineer to mix real world measurements with simulation to speed up the design process and aid debugging. An example of use would be a measurement of the plant transfer function for power supply (biased to operation point), and compensator design in LTSpice.
Now we have the required datasets for our spice “model”. The model itself is rather simple, gain is represented by our open loop gain measurement, and our impedance measurement is in series with the gain block. The final step is the addition of input capacitance. To complete the circuit, feedback resistors are added.

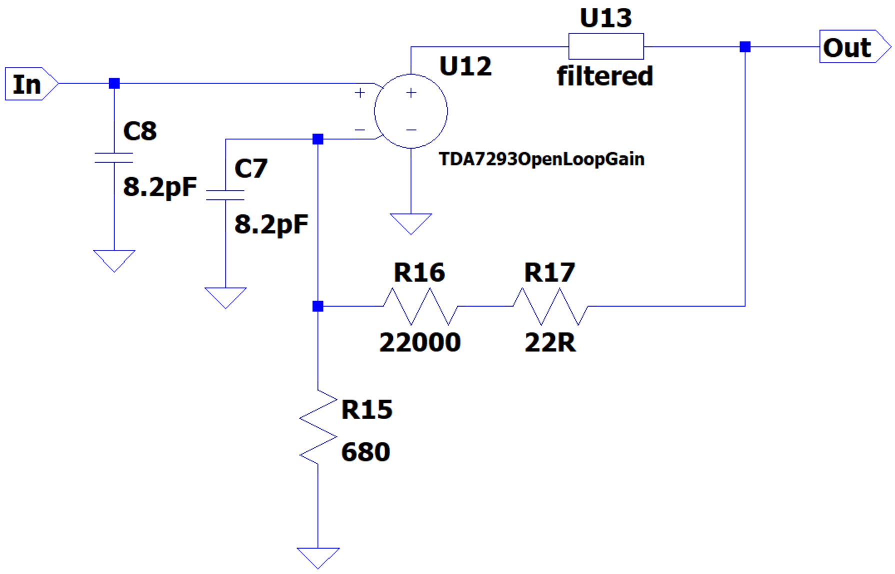


Figure 28 The amplifier model, with inclusion of feedback resistors

If needed, the simple model can be expanded, to simulate other aspects of the opamp[13] [14] , or measured data can be used to create an analytical model, which would further expand simulation possibilities.

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[13] "Build an Op Amp SPICE Model from Its Datasheet – Part 1 ...." https://masteringelectronicsdesign.com/buildi-an-op-amp-spice-model-from-its-datasheet/.
[14] "Opamp Models - eCircuit Center." http://www.ecircuitcenter.com/OpModels/OpampModels.htm.

As the model is rather simple, it is easy to demonstrate what is the effect of particular aspect of the model on the loop gain of the amplifier.

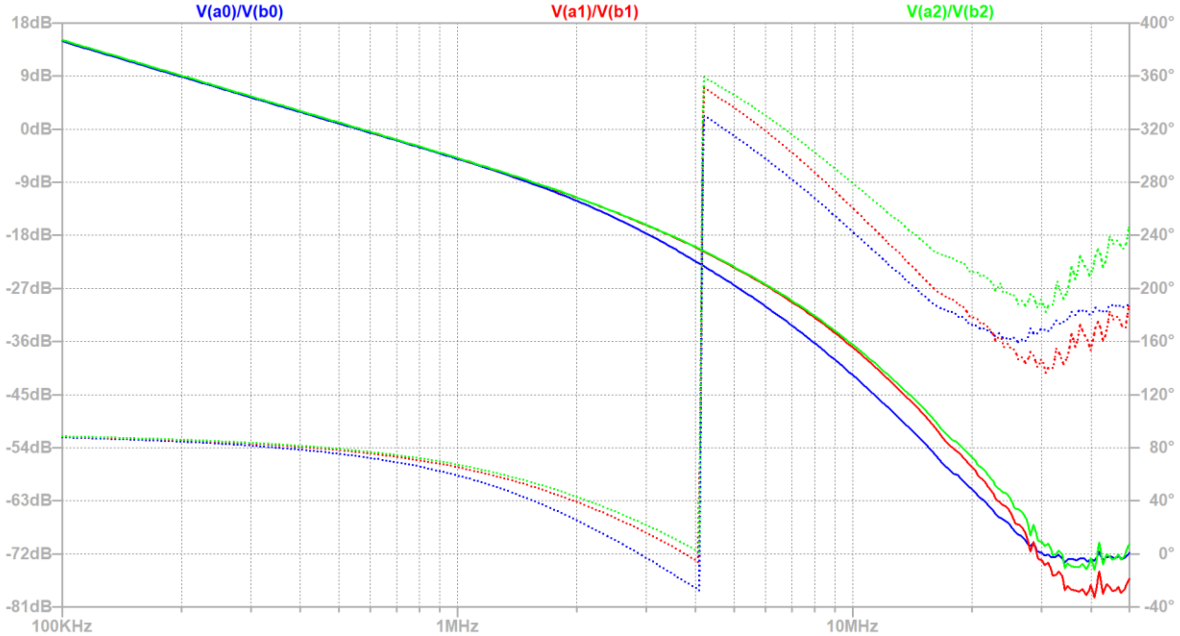

Figure 29 Effect of model on loop gain with 8 Ohm load

Green - only OLG simulated
Red - OLG, input capacitance
Blue - OLG, input capacitance, Output impedance

While modeling the input capacitance might be optional for slow opamps, modeling the output impedance aspect of the model is not. Without the output impedance, the model is unable to show the effect of load on the amplifier loop gain stability.

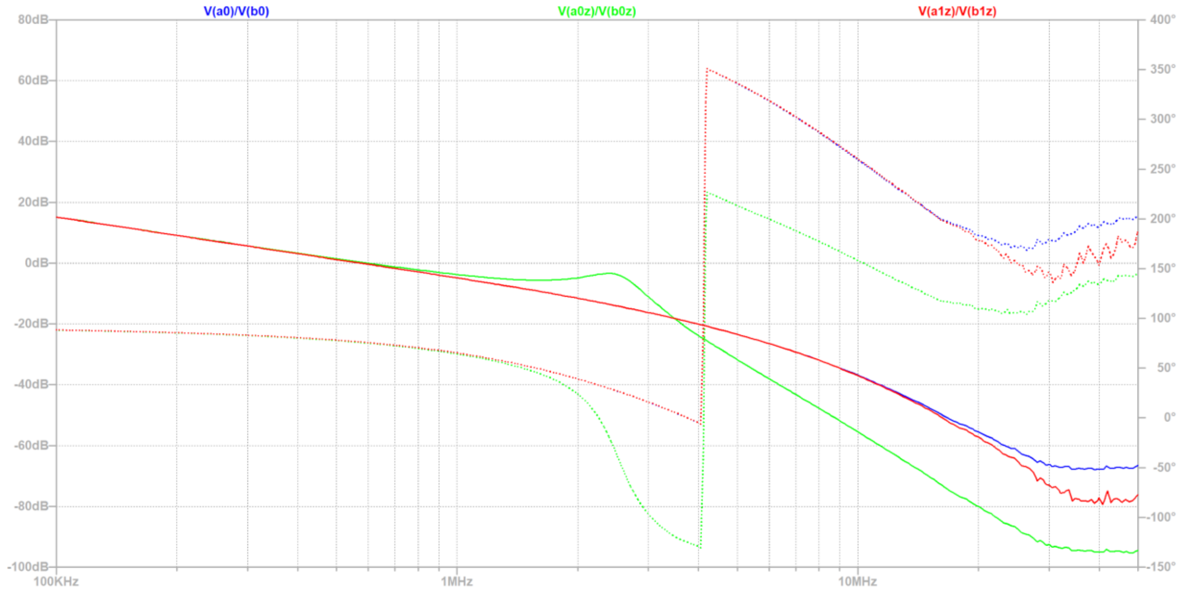

Figure 30 Effects of load capacitance on loop gain

Blue - complete model without capacitive loading
Green - complete model with 22nF load
Red - mode without output impedance modeled and with 22nF load

Summary

Creating a simple measurement-based op-amp spice model is in the end a rather straightforward affair. At minimum two measurements - open loop gain and open loop output impedance are needed. For reasonably fast op amps, a measurement of the input impedance is needed for improved model fidelity. For open loop gain measurements, the inverting configuration is beneficial. If a non-inverting configuration is used, a differential probe is needed. For open loop output impedance measurements, a feedback path is needed to stabilize the operating point of the amplifier. This feedback needs to be rolled off low enough, not to impair our measurement, and needs to keep the amplifier stable. To complete our model, the input impedance needs to be measured. Ways to measure input impedance were presented.

As with all measurements, care is needed with a proper level of test signal and possible loading of amplifiers with test probes/cables needs to be assessed. As the dynamic range might be rather extreme, a careful optimization of test setup with regards to attenuators, probes and amplifiers is required. 1x probes and preamplifiers are recommended. A FRA/VNA with wide frequency bandwidth, high dynamic range and separate signal generator output, like Bode 100, is an invaluable tool.

Measured data were imported into Spice as tabulated B source (transfer function for loop gain and impedance profile for output impedance) and a simple stability model was created. With a simple stability model, the assessment of various compensation techniques and creation of composite amplifiers with superior performance is possible. The model only covers small signal AC behavior. As always, bench testing of large signal behavior of the circuit is needed to verify soundness of the design.

Most of the measurements were done as ad hoc dead bug prototypes. Although this approach was convenient, as it allowed quick modification and good test accessibility, repeatability and reliability of the measurement suffered. Test measurements are demanding as they are, no need to complicate them further. Once the test plan is clear, designing a dedicated test board is highly recommended, as it provides superior repeatability and fidelity. As most of the measurements require calibration, two boards would be optimal - one without DUT for calibration, the other for DUT measurements.

Although we have landed a bit short of a complete mode this time, as differential capacitance is missing and mode verification are still missing, the author hopes that presented pages have piqued reader's interest in the interesting world of analog electronics, op amp modeling and VNA measurements. Comments and feedback are welcomed and encouraged.

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