

## DAMPING FACTOR, OUTPUT IMPEDANCE, AND THEIR RELATIONSHIP TO OPEN LOOP GAIN, FEEDBACK, AND INTRINSIC OUTPUT IMPEDANCE.

Jed Martin

Denver CO

26DEC09

jedmartin@sohostar.com

The Damping Factor of an amplifier (in this case, an audio power amp) is expressed as a ratio:

(1)  $DF = Z_l / Z_o$  where DF is the damping factor,  $Z_l$  is the load impedance, and  $Z_o$  is the output impedance.

$Z_o$  is affected by several factors in an audio amplifier:

$A_{ol}$ , the open loop gain of the amp

$D_{fb}$ , the feedback ratio

$Z_{oa}$ , the physical output impedance of the amplifier

$Z_{ps}$ , the impedance of the power supply.

$Z_l$  is the sum total of the load impedance and the impedance of the load's interconnects.

Damping Factor is an important quantity in amplifier design, since it expresses interaction between the amplifier and its load. Speakers are essentially linear motors consisting of a coil of wire, a suspension, and a magnet. Being a linear motor, a speaker produces a back EMF when it operates, just as any other magnetic motor. The back EMF is produced by the voice coil moving through the magnetic field of the magnet gap. When the damping factor of an amp is low, the back EMF of a speaker can alter the waveform across the speaker, causing errors in speaker movement. This effect is present in rotary motors, and can be experimentally observed. If you take a small DC motor, and add a large capacitor across the terminals (the larger, the better), then apply power, the motor spins. When power is removed, the motor continues spinning (the capacitors serve to store the back EMF), and gradually slows down, until the motor has converted all of its inertia back into electricity, and then into heat. The back EMF can be measured across the motor as it spins down. If you place a short across the motor, the back EMF causes a braking effect (I once saw a very efficient motor that was difficult to turn, even with a pair of pliers, while the terminals were shorted). This braking effect is how an amplifier with a low output impedance "controls" voice coil movement. The amplifier acts as a "short" across the voice coil "motor" and shunts the back EMF, thereby keeping the voice coil from moving from the position that the amplifier has placed it.

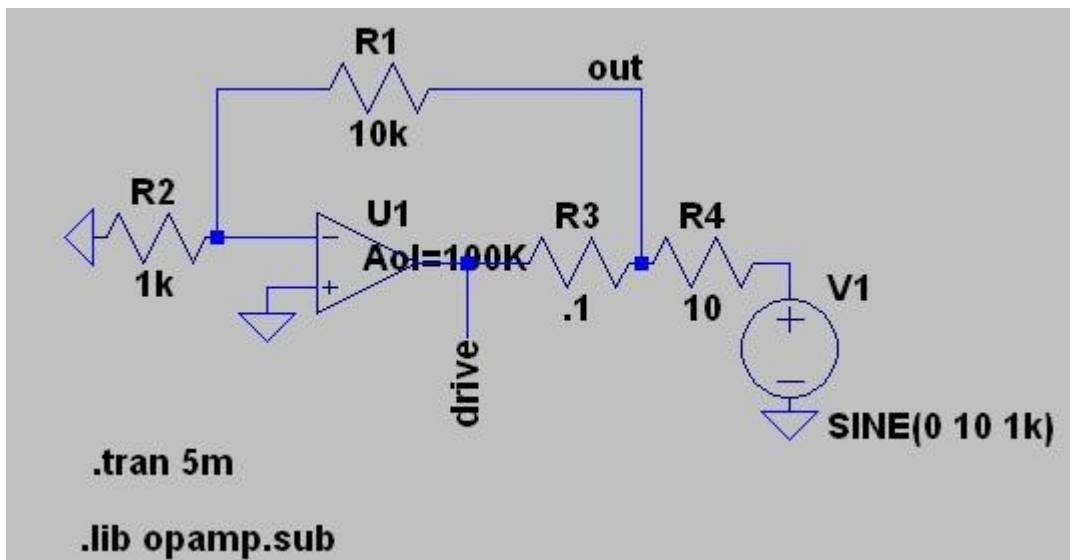
An ideal audio power amplifier is identical in characteristics to an ideal op amp. An ideal amplifier has:

- 1) infinite input impedance
- 2) zero output impedance
- 3) infinite open loop gain

However, there is no such thing as an ideal amplifier, but in the simulations used in this article, we will use one that exists in software, and add the physical limitations to the model. Most modern audio amplifiers have (analogous to the characteristics of the ideal amp):

- 1) high input impedance
- 2) very low output impedance
- 3) very high open loop gain

Also, when the circuit topology is carefully compared, it will also be seen that most modern audio amplifiers follow the same (sometimes identical) design as an op amp. Most modern amps use a differential pair for the input, which gives the amplifier two equal and opposite inputs, inverting and non-inverting. Then there is a voltage amplifier stage, along with its compensating capacitance. Last there is the output stage, usually consisting of a bias network, and a back to back complementary pair of transistors for the output, and this usually includes complementary driver transistors as well. The feedback used in the amp is derived and applied in exactly the same way as with an op amp. For our discussion on output impedance, we are going to model the following circuit (so turn on your computer, go pour another cup of coffee, and then load your SPICE software....):



**FIG 1 CIRCUIT MODEL FOR OUTPUT IMPEDANCE EXPERIMENTS**

I am using LTSpice (SWCAD3) from Linear Technology. The components and their function are:

R1 is the high side of the feedback voltage divider, and the value of this component will be changed during experiments.

R2 is the low side of the feedback voltage divider, and will remain fixed.

R3 is the intrinsic output impedance of the amplifier, and will be changed for some experiments.

R4 is the amplifier load resistor, and is scaled with the sine voltage source to give approximately 1mV output per 1mOhm of output impedance.

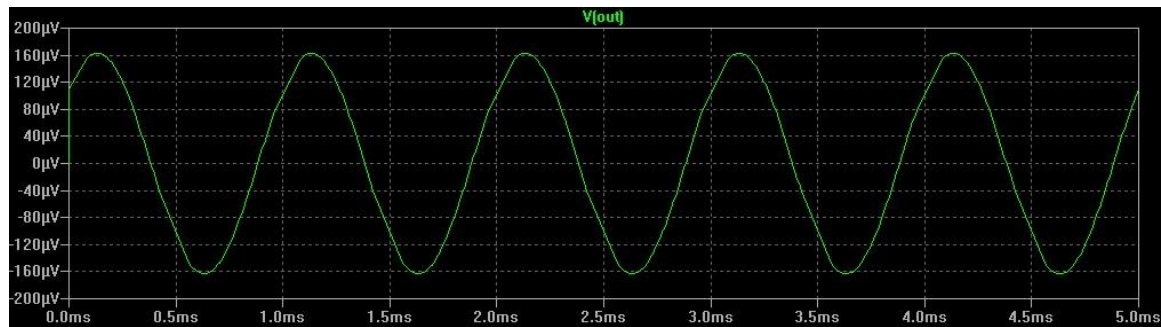
U1 is an ideal op amp provided in the SPICE library, and has a changeable Aol, which will be changed during experiments.

V1 is a sine wave generator with a zero source resistance, and is set to 10V at 1kHz. The voltage test points are V(out) and V(drive) both of which will be monitored during experiments.

R4, while not giving us exactly perfect scaling in determining output impedance, is close to the 8 Ohm impedance of most speakers, and as long as the physical output impedance is less than 1% of the load, we won't have significant errors to deal with. Most of the experiments will be with a physical output impedance of 0.01 Ohm, so the voltage read at the V(out) node will have a 1:1 relationship with the output impedance (or pretty close)

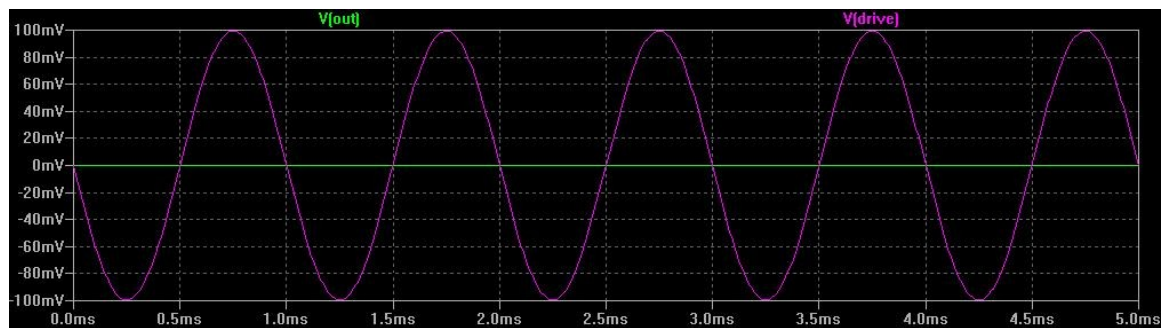
I highly recommend that you use an ideal op amp like this one that uses no power supply, etc...

So.... Just to verify everything is working, let's run the simulation as-is, monitoring V(out).....



**FIG 2 TRANSIENT SIMULATION OF CIRCUIT IN FIG 1**

The voltage comes out as just over 160uV, showing an output impedance of 160uOhms. How is that possible, when the actual physical output impedance is 0.1 Ohms? Running the simulation again, this time monitoring V(drive), we get this waveform:

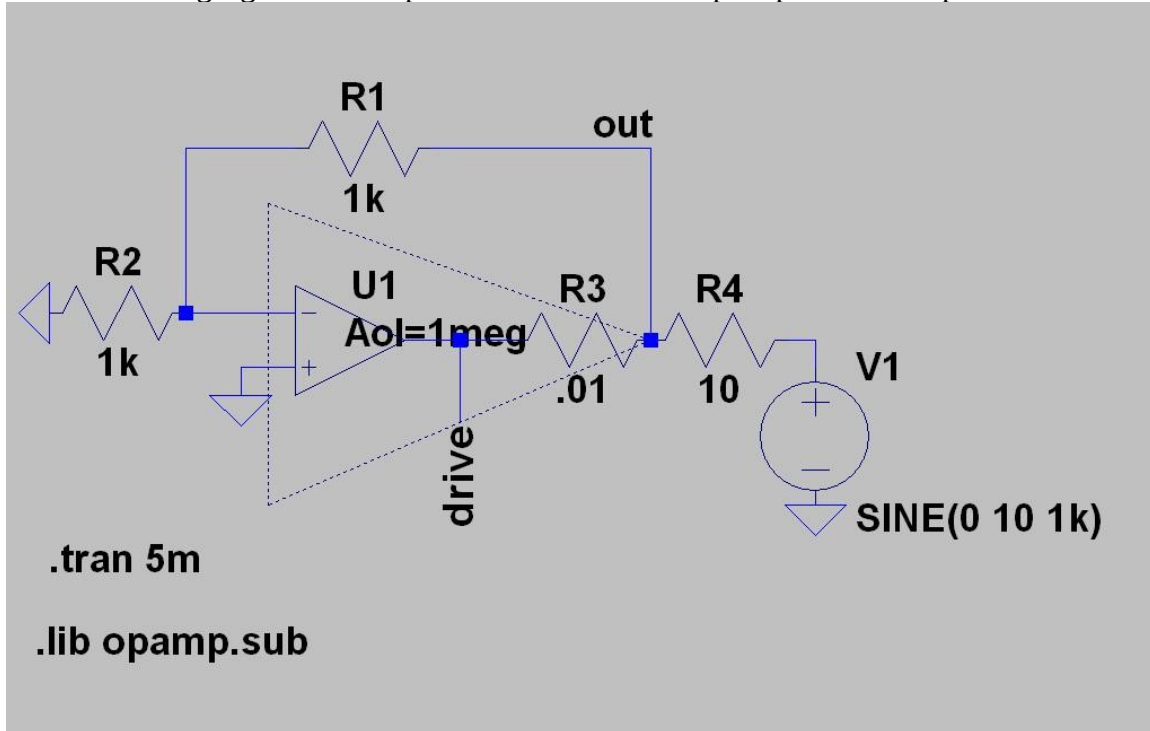


**FIG 3 SIMULATION SHOWING V(drive)**

Notice that the waveform is not only much higher in amplitude, but opposite in phase to the signal on V(out). In order to maintain as close to 0V as is practical at the point where the feedback is tapped off, the amplifier actively opposes the voltage applied to V(out) through R4. the amplifier is attempting to maintain 0V on the inverting input (remember, we have grounded the non-inverting input, where signal would be applied in normal operation of this amp).

So, exactly what does determine output impedance? Obviously, the physical output resistance only plays a small part, and it's the feedback and gain that play a large part. So, now we can run some experiments to determine the relationships between gain and feedback, and their effects on output impedance.

In the following figure the “amplifier” consists of the op amp and the output resistance.

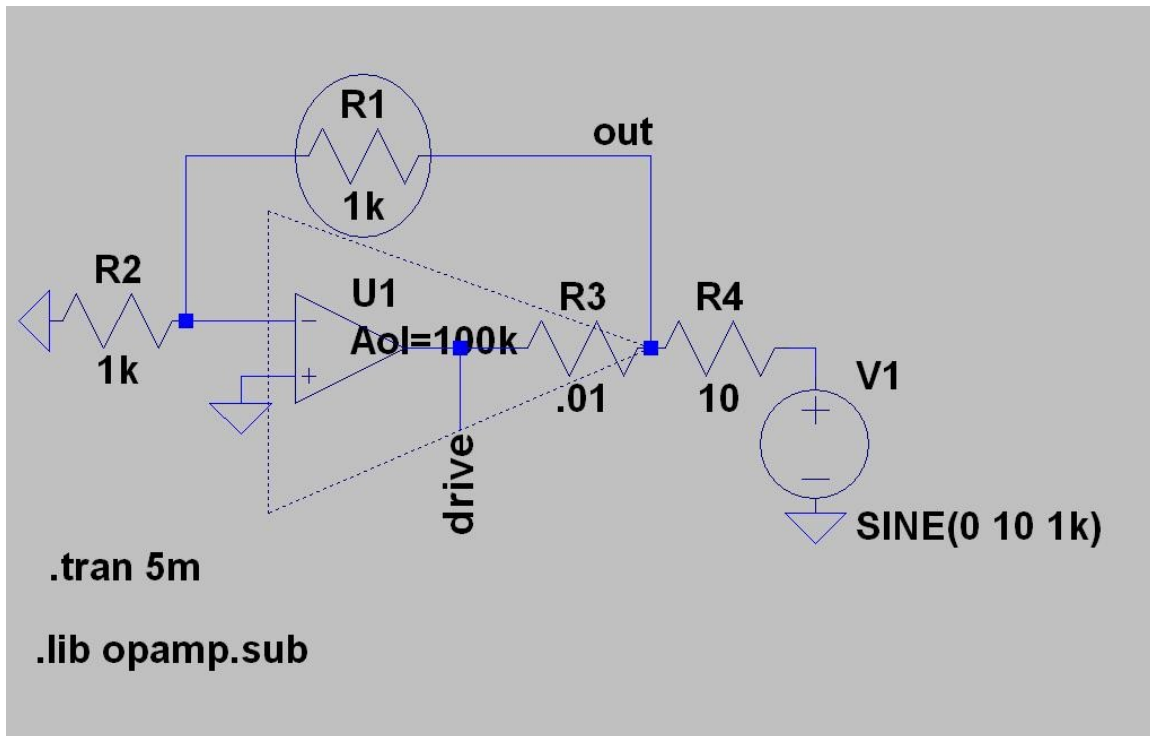


**FIG 4 AMPLIFIER AND OUTPUT RESISTANCE**

### EXPERIMENT 1. EFFECT OF FEEDBACK ON OUTPUT IMPEDANCE

First, let's change R3 to 0.01 Ohm, and change R1 to 1k.

What we will do in this experiment is run the simulation, first looking at V(out), then V(drive), step to the next value of R1, and run the simulation again. The gain formula for a noninverting amp is  $A_v = 1 + (R_1/R_2)$ . We will be stepping R1 in a “1-2-5” series, meaning that we will be going “1k, 2k, 5k, 10k, 20k” etc... from 1k to 5meg.



**FIG 5 R1 WILL BE CHANGED IN EXPERIMENT 1**

In the following chart, I will supply my experimental data, and leave space for yours.

R1	Av	Vout (peak) (my data)	Vout (peak) (your data)	Vdrive(peak) (my data)	Vdrive(peak) (your data)
1k	2	20uV		10mv	
2k	3	30uv		10mv	
5k	6	60uv		10mv	
10k	11	110uv		10mv	
20k	21	210uv		10mv	
50k	51	510uv		10mv	
100k	101	1.01mv		9mv	
200k	201	2.01mv		8mv	
500k	501	5.01mv		5mv	
1meg	1001	10mv		0mv	
2meg	2001	19.5mv		10mv (noninv)	
5meg	5001	43.5mv		34mv (noninv)	

So, in this case, (at least until we reached  $A_v=2000$ ) the output impedance is proportional to  $A_v$ . The ratio here works out to  $Z= A_v/100,000$ . Is there a concrete meaning to this

ratio? More experiments will tell us. As for the results of the last two (2meg and 5 meg), we will explore this later in the article.

## EXPERIMENT 2 EFFECT OF OPEN LOOP GAIN (Aol) ON OUTPUT IMPEDANCE.

Now, set R1 to 1k, and the Aol of U1 to 1k. In this experiment, we are going to step the Aol of U1 in a “1-2-5” series, just as we did R1 in the first experiment.

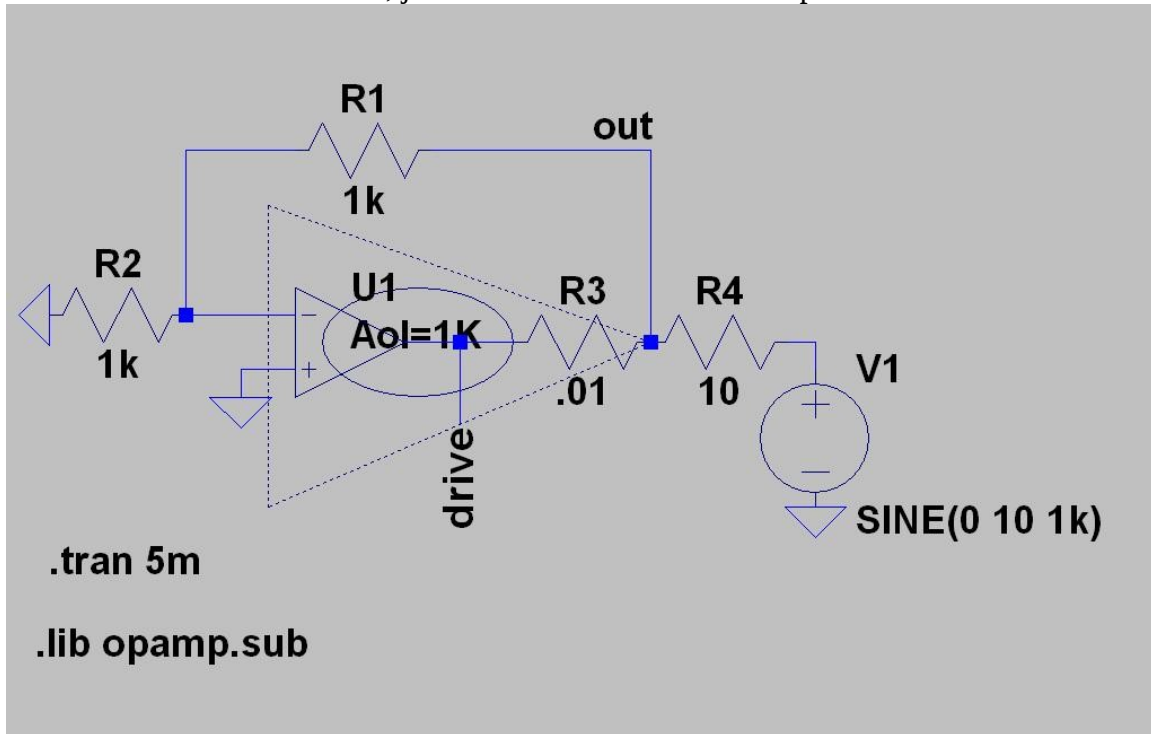


FIG 6 Aol WILL BE CHANGED IN EXPERIMENT 2

Aol	Vout (peak) (my data)	Vout (peak) (your data)	Vdrive (pk) (my data)	Vdrive (peak) (your data)
1k	2mv		8mv	
2k	1mv		9mv	
5k	400uv		9.5mv	
10k	200uv		10mv	
20k	100uv		10mv	
50k	40uv		10mv	
100k	20uv		10mv	
200k	10uv		10mv	
500k	4.5uv		10mv	
1meg	3uv		10mv	

So once again, we have a proportional relationship, this time inversely proportional. What we get for a mathematical relationship is  $Z=2/Aol$ . Again we have two somewhat “off track” results which we will explore later. If we compare the math between the two experiments we get:

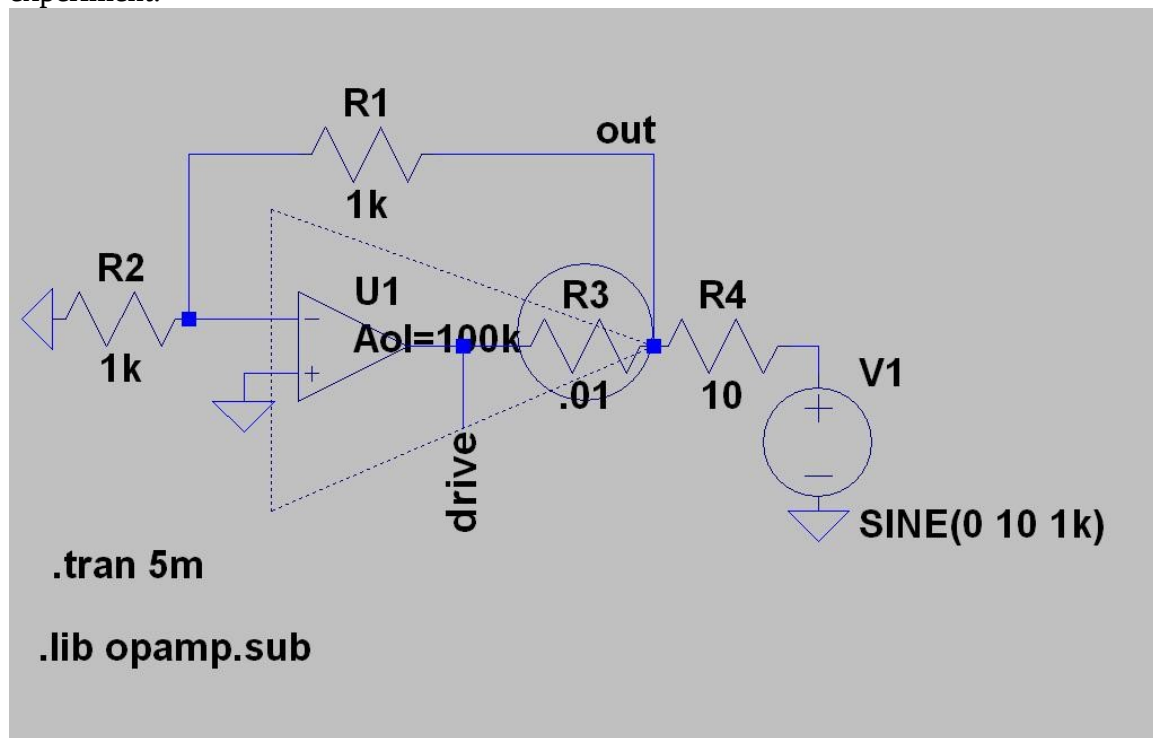
(2)  $Z=A_v/Aol$

What this means for amp design is that we can predict the output impedance and damping factor of an amplifier without guesswork.

There is, however, another factor here that we haven’t yet experimented with. And that’s the physical resistance of the output stage. In the previous two experiments, we set it at a somewhat low value and left it there. So, let’s find out just how much effect it has, since it is a real world concern.

### EXPERIMENT 3 EFFECT OF PHYSICAL OUTPUT RESISTANCE ON OUTPUT IMPEDANCE.

Set U1 Aol back to 100k, and R3 to .001 Ohms. We will be stepping R3 in this experiment.



**FIG 7 R3 WILL BE CHANGED IN EXPERIMENT 3**

R3	Vout (my data)	Vout (your data)	Vdrive (my data)	Vdrive (your data)
.001	20uv		1mv	
.002	20uv		2mv	
.005	20uv		5mv	
.01	20uv		10mv	
.02	20.75uv		20mv	

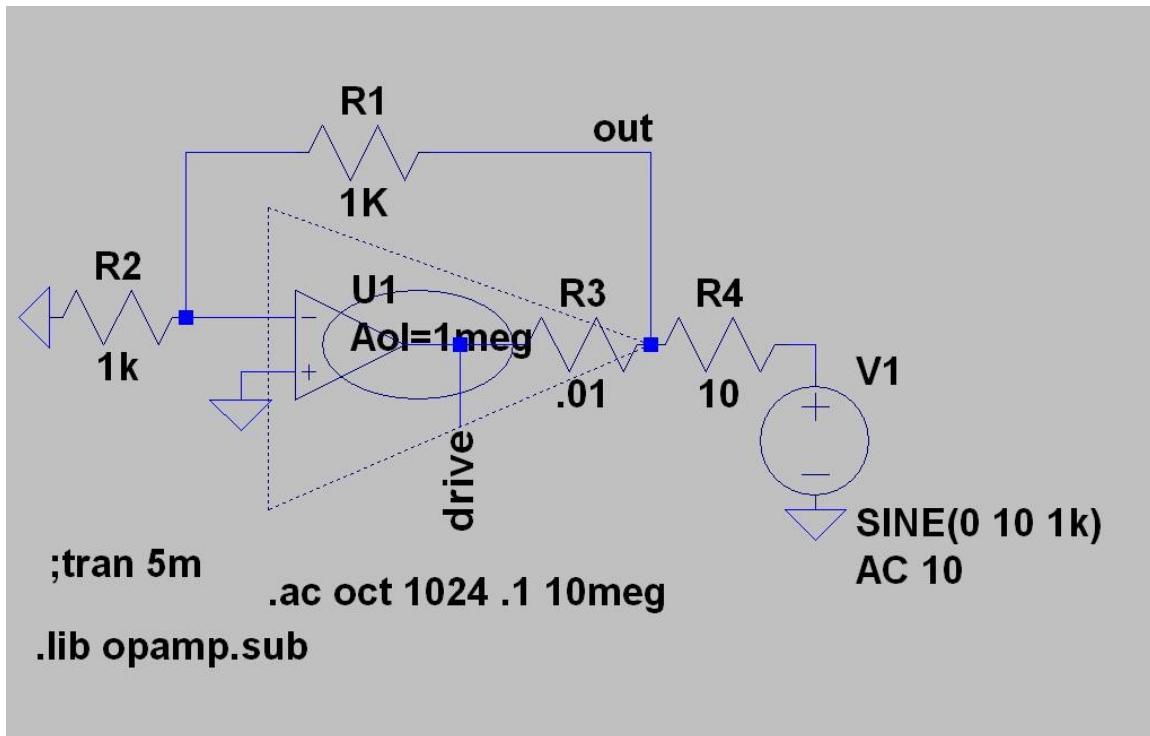
.05	23uv		50mv	
.1	30uv		.1v	
.2	45uv		.2v	
.5	100uv		.5v	
1	200uv		1v	
2	400uv		2v	
5	1mv		5v	
10	2mv		10v	
20	4mv		20v	

As we can see, the output impedance remains constant until the output resistance gets above .02 Ohms, then settles to a proportional relationship. The interesting part here is the results for V(drive). There is a direct 1:1 proportion of voltage vs resistance. The drive voltage even exceeds the applied voltage in an effort to maintain a low output impedance. Even with a 20 ohm output resistance, the amp maintains a low output impedance of .004 Ohms, which with an 8 ohm load would be a damping factor of 2000. of course, with such an extreme condition, the amp would probably misbehave with a complex load (as well as having insufficient output current to drive a 16 Ohm or lower load)

## EFFECTS OF OTHER PARAMETERS

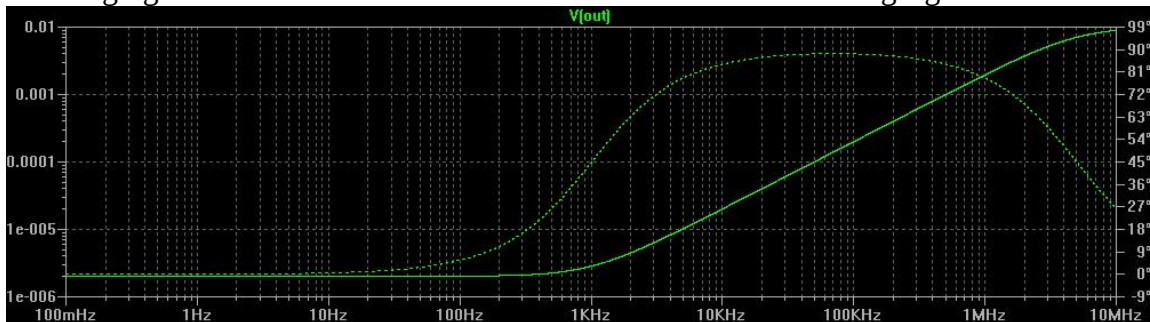
Ok, now, let's investigate where some of the deviations from the linear relationships came from. First of all, there is only one other parameter that the current SPICE model of the amp has that can be changed. That parameter is the GBW, or Gain Bandwidth Product, which put simply is the frequency at which the gain of the amp is unity. All amplifiers have this characteristic. With op amps, there is a frequency at which the open loop gain begins to fall off at a 6db/octave rate. This is usually called the dominant pole turnover frequency. Then there is a frequency at which the gain of the amp drops to 1 or unity, called the unity gain frequency, and this is numerically the same as the Gain Bandwidth Product ( $A_v * f = \text{GBW}$ ). The amplifier cannot operate outside this curve. The  $A_v$  figures we have been using in our experiments are actually DC gain figures, and so are not necessarily accurate for AC waveforms. If the GBW is exceeded, there is less gain than  $A_{ol}$  at all frequencies above the dominant pole turnover frequency, and can have an effect on our results. First, we'll reset all of our component values back to where we started in the first experiment, but we're going to change the simulation type to .AC so that we can see the output impedance vs frequency. You will notice that the .TRAN statement has been commented out and replaced with .AC OCT 1024 .1 10MEG. This sets the simulation to an AC sweep, 1024 points per octave, 0.1hz to 10 Mhz.





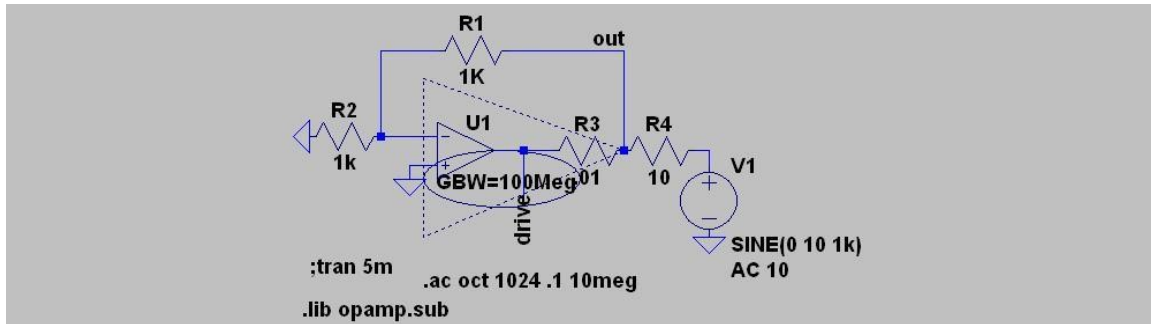
**FIGURE 8 AC SWEEP SIMULATION OF OUTPUT IMPEDANCE VS FREQUENCY**

Now run the sweep and observe the output curve. You will need to change the plot vertical scale to logarithmic, and set the manual limits of the scale, and turn off the autoranging feature. Your results should look similar to the following figure.



**FIGURE 9 OUTPUT IMPEDANCE VS FREQUENCY OF CIRCUIT IN FIGURE 8**

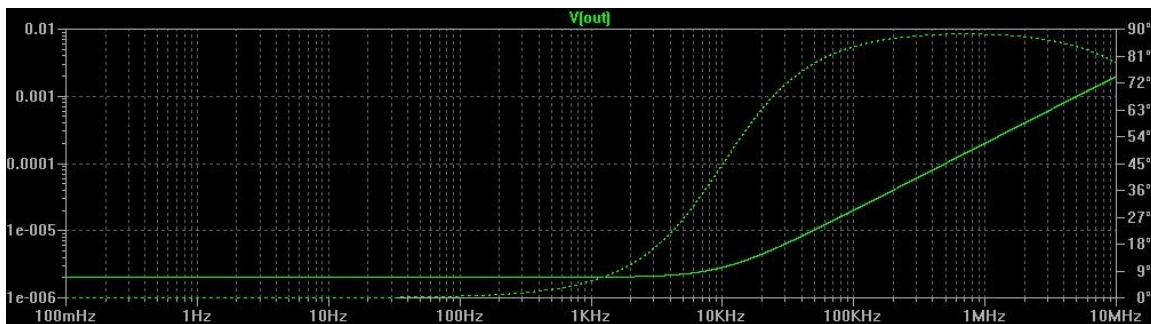
You will notice that the impedance is very low up to 1kHz, then begins to change until it is equal to R3 at 10MHz (the unity gain frequency of this amp). The reason for this is that above 1kHz, the amp is losing the ability to respond to feedback. For our next experiment we will change the GBW of the amp and plot the output impedance vs frequency curve.



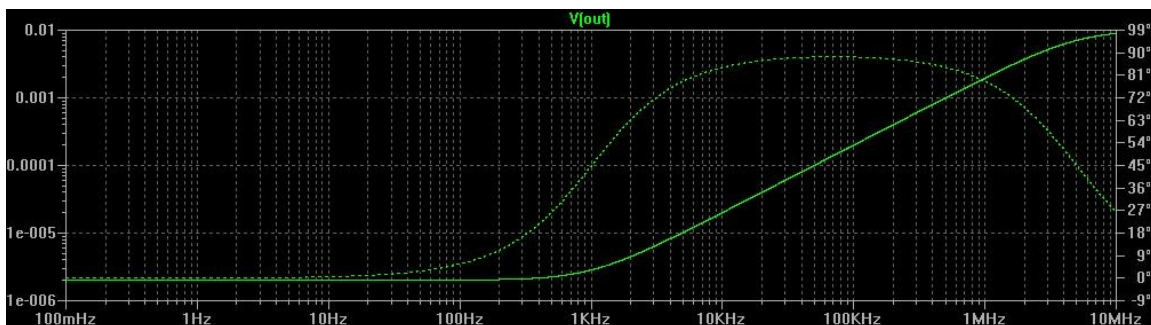
**FIG 10 EXPERIMENT 4, EFFECTS OF GBW ON OUTPUT IMPEDANCE**

#### EXPERIMENT 4 THE EFFECTS OF GBW ON OUTPUT IMPEDANCE

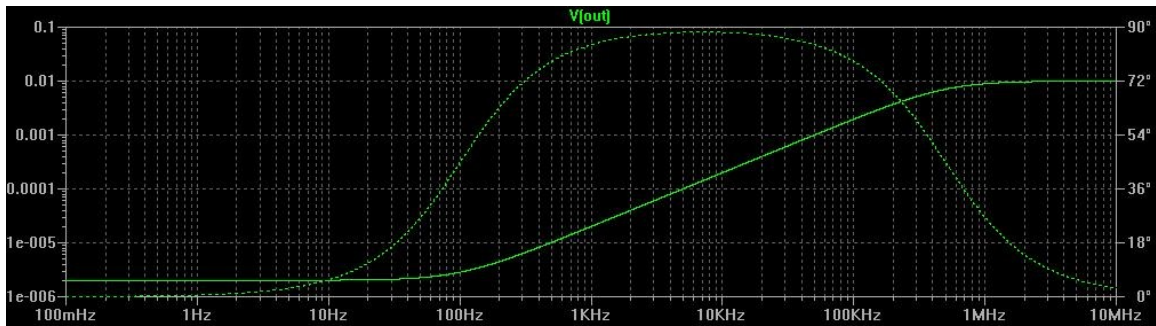
In this experiment we will be changing the GBW of the amplifier. Instead of a chart, I will include pictures of the impedance curves. We will plot the impedance curves at 100Mhz, 10Mhz, and 1Mhz. By the way, you should ignore the dotted line curve in the following figures. It is the phase angle curve which has it's scale on the right side, and we're not interested in the phase right now, except that you may have noticed in earlier experiments that the resultant waveform was a bit out of phase on the Vout graphs.



**FIG 11 GBW SET AT 100MHZ**

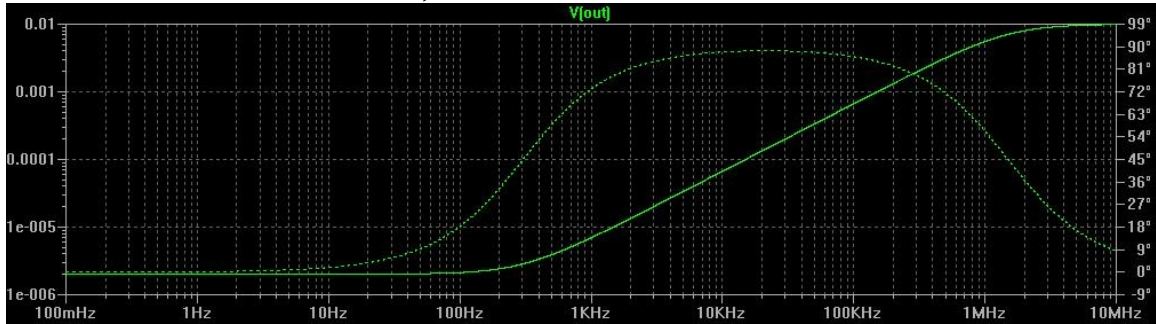


**FIG 12 GBW SET AT 10MHZ**



**FIG 13 GBW SET AT 1MHZ**

Notice how the changing GBW effected the frequency we were using for our previous experiments at 1khz. Since most audio power amps average 3Mhz GBW, we'll now run a chart with the GBW set at 3Mhz,



**FIG 14. OUTPUT IMPEDANCE VS FREQUENCY WITH GBW AT 3MHZ**

So now we have curves with various GBW products, including one that is a close approximation of the average GBW of many amplifiers on the market today. The reason that the impedance goes up after a certain point on the curve, and then (shown in the cases of 1Mhz and 3Mhz) levels off at the value of  $R_3$ , is that the amplifier's response to feedback begins to decrease at the "turnover" frequency of the amplifier's open loop response curve. The  $-3\text{db}$  point of the amplifier's response curve is found by the equation  $\text{GBW}/A_{ol}$ . The impedance levels off at the value of  $R_3$  because there is now no effect of feedback (as well as no gain in the amplifier), and the output impedance is now equal to  $R_3$ . This effect of loss of feedback above the turnover frequency is why the Damping Factor of an amplifier is usually specified both at 200hz and 20khz. This is also why the THD changes between 1khz (where most manufacturers measure it) and 20khz. Since the amp cannot respond as well to feedback as the frequency rises, all of the effects due to feedback,(distortion and output impedance, etc...) begin to get worse.

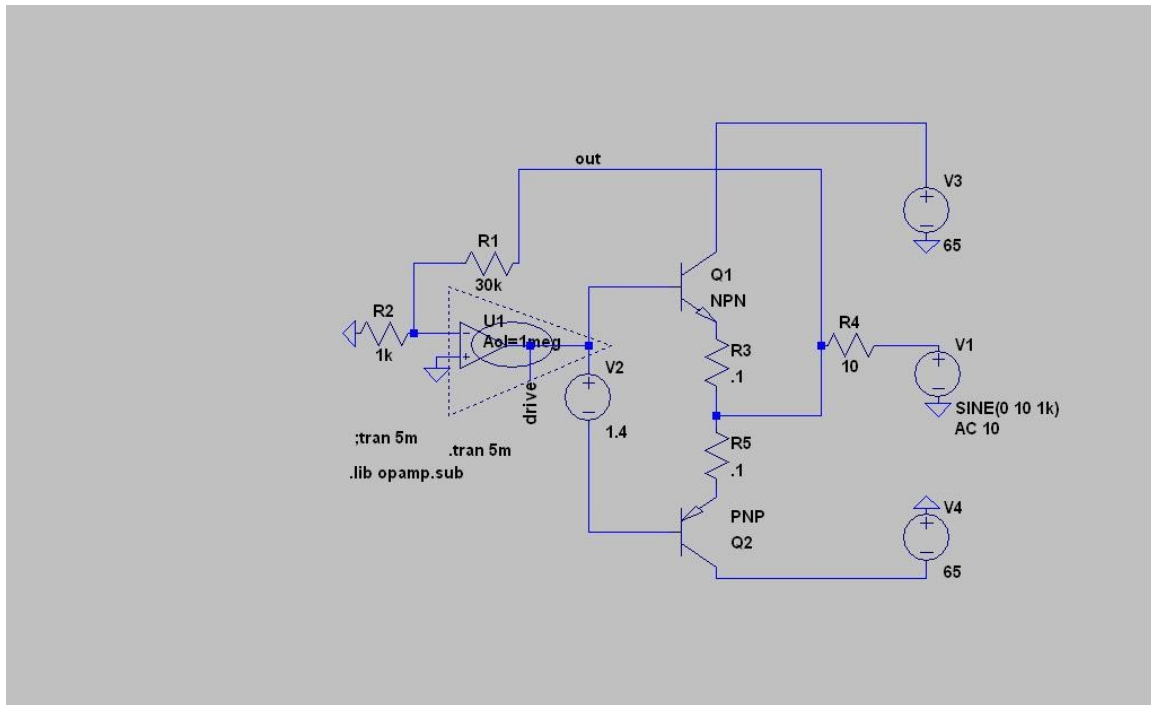
## PUTTING SOME OF THIS TOGETHER

So, we can see a picture of what effect various amplifier parameters have on the output impedance of an amplifier. So far we have done all of our experiments with an "ideal" amplifier, and stepped through various parameters to see exactly what effect they have. Some of the things we have found out are:

1. OUTPUT IMPEDANCE IS PROPORTIONAL TO THE FEEDBACK RATIO
2. OUTPUT IMPEDANCE IS INVERSELY PROPORTIONAL TO  $A_{ol}$

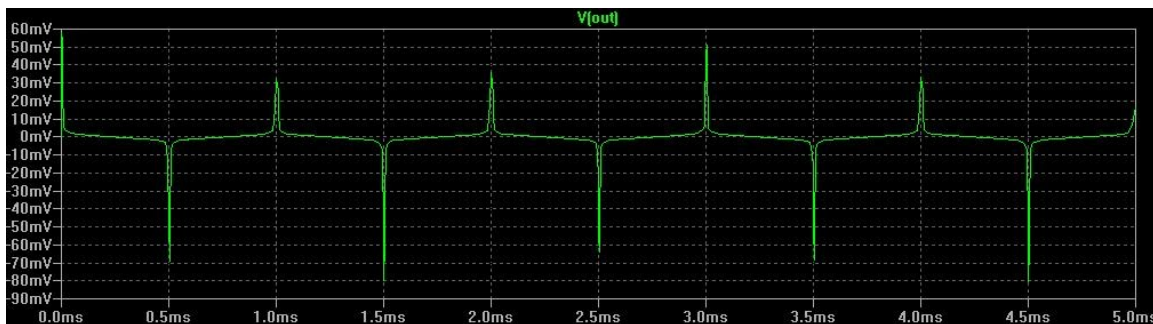
3. THERE IS A LINEAR RELATIONSHIP BETWEEN OUTPUT RESISTANCE AND OUTPUT IMPEDANCE (BUT THE OUTPUT IMPEDANCE IS MUCH SMALLER THAN THE OUTPUT RESISTANCE)
4. THE OUTPUT IMPEDANCE CHANGES WITH FREQUENCY

So we see that several things have an effect on the output impedance of even a theoretical “ideal” amplifier. Now we will add components to the amplifier that begin to mimic more closely a real world amplifier. First we are going to replace R3 with a bipolar transistor output stage, emitter resistors, and power supply. We are also going to change other things on the amplifier to match a real amplifier. Change R1 to 30Kohms, the amp Aol to 10k, and leave the GBW at 3Mhz.



**FIG 15 AMPLIFIER WITH OUTPUT STAGE ADDED IN PLACE OF R3**

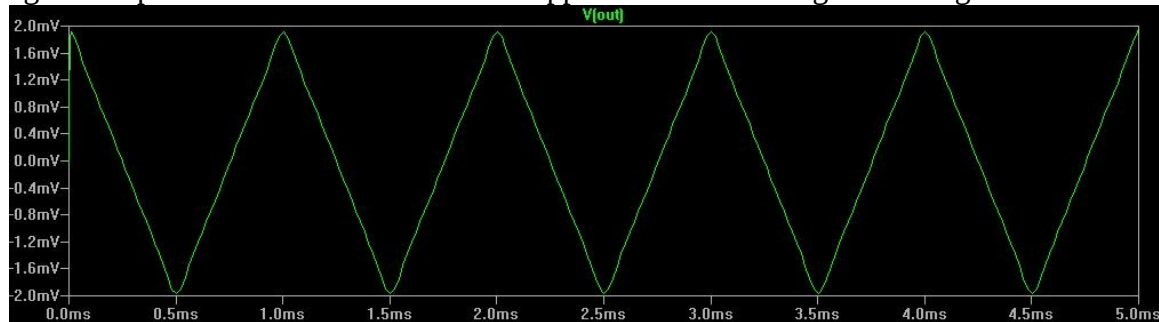
Notice that R3 has been replaced with a pair of output transistors, emitter resistors, bias voltage, and +/- power supplies. The output transistors are not biased to conduction, but are close. Let's run the simulation as-is and look at the results.



**FIG 16. WAVEFORM AT  $V_{out}$  WITH OUTPUT TRANSISTOR STAGE**

This is very interesting, since it appears that there is some kind of nonlinear effect taking place when the applied voltage crosses the zero line (which occurs at the millisecond and half millisecond marks). This is happening because the transistors are not yet biased into conduction at idle. We are actually seeing the output impedance change between two different values, one very low (about 1.8 milliohm), the other relatively high (about 80 milliohm). What would happen on a real amplifier in this condition is that there would be some crossover distortion at low signal levels.

Now begin stepping up the bias voltage at intervals of 0.1 volts and running the test again. Stop when the crossover notch disappears. The following is what I got at 1.9 volts.



**FIG 17 OUTPUT IMPEDANCE WITH BIAS SET TO 1.9V**

The output devices are biased at about 91 ma (a bit higher than most amplifiers normally run, but not outrageously high). To check the quiescent current, shut off the voltage source V1 (set it's output voltage to 0) and read the current through R3 or R5. The output impedance is remaining at 2 milliohms. This seems to be the optimum bias setting for this output stage (when I get to the physical testing, I will experiment with this as a better method of setting output stage bias). There are actually some nonlinear variations taking place in the output impedance, which account for the triangle shape of the waveform, but those variations are very small compared to the crossover notch variations that we just eliminated. You may try increasing the bias until you get a nice sine wave, as did I, but you will find that your quiescent current is very high at about an amp or more. In a real amplifier, this will require very large heat sinks and very careful attention to thermal protection, as well as accepting a loss in efficiency.

## TESTING A MODEL OF A REAL AMPLIFIER

First of all, let me thank Doug Self for giving me permission to use his Blameless Amplifier as an example in this paper.

We will be using the Blameless Amplifier design for the next experiments. Before continuing, we need some complements for transistors in the LTC Spice Standard.BJT database file. Copy the following .MODEL statements into the STANDARD.BJT file in SWCad's \lib\cmp directory:

```
.model 2N5551 PNP(Is=2.511f Xti=3 Eg=1.11 Vaf=100 Bf=213.4 Ne=1.241 Ise=2.511f
Ikf=.3495 Xtb=1.5 Br=3.24 Nc=2 Isc=0 Ikr=0 Rc=1 Cjc=4.883p
+ Mjc=.3047 Vjc=.75 Fc=.5 Cje=18.79p Mje=.3416 Vje=.75 Tr=1.212n Tf=560.1p
Itf=50m Vtf=5 Xtf=8 Rb=10 Vceo=150 Icrating=600m mfg=Fairchild)
```



Next, create the following schematic in LTSpice:

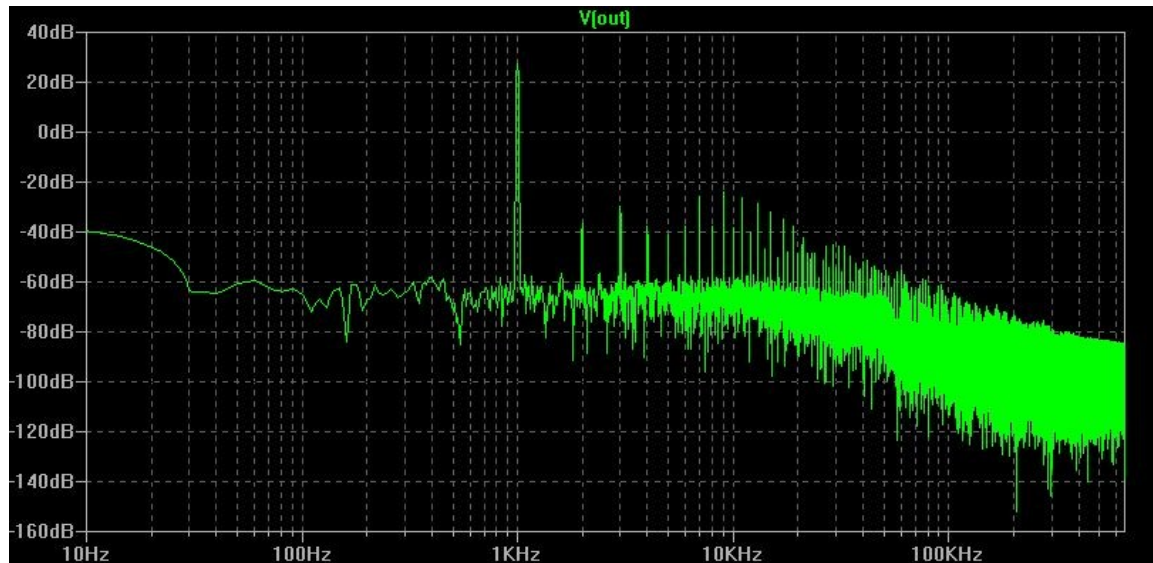


Go ahead and run the simulation as-is. You should get a waveform similar to this:



Now run a FFT analysis on the waveform using 131072 data points, 1 point data smoothing, and Blackman windowing.

Your result should resemble this:



**FIG 20 FFT ANALYSIS OF BLAMELESS AMP OUTPUT**

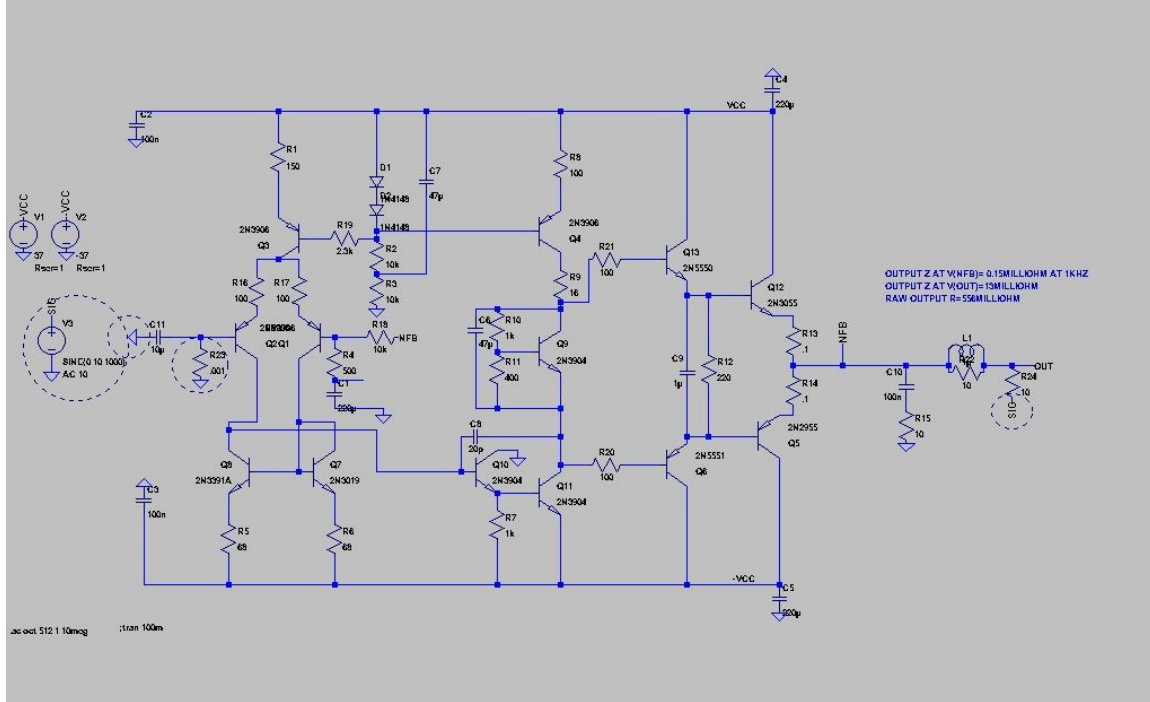
As you can see, the fundamental is at 28db, the second harmonic at about -35db and the 3<sup>rd</sup> at about -30db. This gives a distortion level of second harmonic at about -63dbc and 3<sup>rd</sup> at about -58dbc. If you compare these levels to a baseline trace FFT of the input signal (my test results were -73dbc 2<sup>nd</sup> and -58dbc 3<sup>rd</sup>) that's not too bad for a first try. Most of the additional distortion here is 2<sup>nd</sup> harmonic, which is probably from crossover notch.

Let's make some measurements on the specs of this amp now. First we will measure the open loop gain of the amp. Change R18 to 10000meg and set the input signal level to 0V.. Change the simulation time to 5mS. Add a dc voltage source at the top of C1. Run simulations until you get a somewhat stable DC voltage within +/- 10V, adjusting the dc voltage of V4. Once you get a stable voltage, set Vsig to 1uv and run a sim to get an output amplitude. Divide the output voltage by 1uv to get the open loop gain. My results were about 5,000,000. This procedure can be a time consuming process. Remember that your offset voltage source is on the inverting input, so a positive change drives the output negative. My offset voltage was .052V for a 4 volt DC offset. With a gain of about 5Meg, your results may vary a lot, and the offset voltage adjustment is very touchy. About 100 microvolts difference can take you from one rail to the other. I tried the standard method of breaking the connection between R4 and R18, but the circuit would not stabilize well enough to get a good reading.

## OUTPUT IMPEDANCE AND OUTPUT RESISTANCE OF THE BLAMELESS AMP

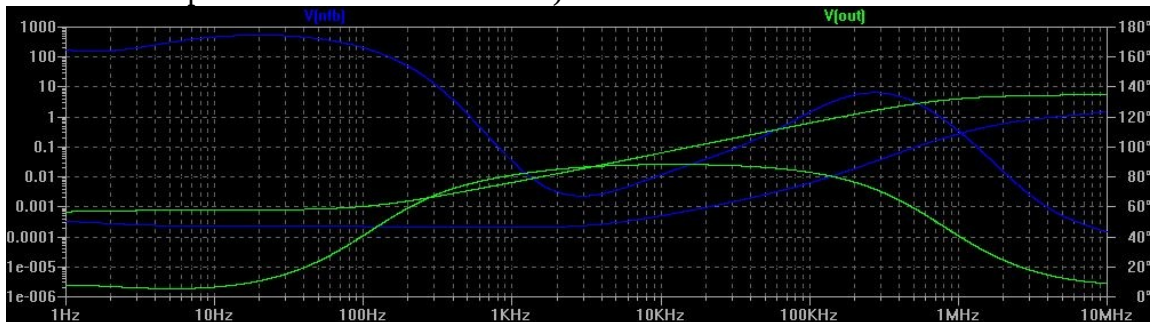
Now that we have a working model of an amplifier, let's find the output impedance and raw output resistance of the amplifier. Save a second copy of BLAMELESS.ASC as BLAMELESSOUTIMP.ASC. Then move the V(SIG) node from the input of the amp to the low side of the load resistor R24 and move the ground point to the amp input and change R23 to .001 ohms. Change the level of V(SIG) to 10V. Change the simulation command to .AC OCT 512 1 10MEG.

The schematic should look like this:



**FIG 21 BLAMELESS SCHEMATIC MODIFIED TO MEASURE OUTPUT IMPEDANCE**

Pay attention to the items circled with dotted lines. We are ready to measure the output impedance. Run the simulation. Plot both V(OUT) and V(NFB). You can see here that the output inductor L1 used to isolate speaker cable capacitance has a small but measureable effect on the output impedance. My results (and it seems to vary depending on which computer I run the simulation on) came out like this:



**FIG 22 OUTPUT IMPEDANCE PLOT OF BLAMELESS AMP**



The first time I ran this simulation on a different computer, the results came out as listed on the schematic with the output Z leveling off at 550 milliohm between 1Mhz and 10 Mhz. But here it's different with an output resistance (at V(NFB)) of a little more than an ohm. Again pay no attention to the phase curves as all they do is clutter up the display. The output impedance curves both begin at a little less than a milliohm and end at 1.2 and 5.6 ohms. The difference between them is the effect of the inductor L1. to eliminate any effects from the reactive components in the output stage, remove L1, R22, R15, and C10. replace L1 with a short. Run the simulation again and see what happens without the reactive components.

So we have the output impedance beginning at about 300 microohms, leveling off to about 200 microohms at 10hz (this is the effect of C1 in the feedback loop), and rising between 1khz and about 1Mhz to about an ohm, This is the effect of the gain bandwidth limits of the feedback. Next let's look at the output impedance at 1khz. Change the simulation command back to .TRAN 100m and run a transient simulation. Run a simulation without signal as well to measure the quiescent current of the output devices. With R11 at 450 ohms, quiescent current should be about 66mA and there should be no crossover notch. In a real amplifier R11 would be a pot so you could adjust the bias. There are a few manufacturers that use fixed bias, but they "err on the side of caution" and leave the bias with a small amount of crossover notch. This is usually only the case in Pro-Audio gear that is rarely, if ever driven at low levels where crossover notch would be audible (their full power distortion specs are usually very good with most of them measuring at 0.01%THD or better). In our Blameless amp, an idle current of 66mA while being a bit higher than most Class AB amps is not high enough to generate too much heat. A lot of technicians and manufacturers like a nice round number of 20mA (good), but many use a distortion analyzer to set bias to where the crossover notch disappears (better), but it would be interesting to see if setting the bias to where the crossover notch disappears on the impedance test setup is the same bias point as where the distortion analyzer says it is. If so, the impedance test setup would be a lot less expensive than a distortion analyzer. In the next few sections we will explore this.

## **PROPOSED TEST SETUP**

The following test setup is what we'll be using for our actual physical tests. If time permits, I can build a Blameless amp to see how well it matches our modeling data.

What will be needed here will be:

An oscilloscope preferably one capable of between 0.1 and 1 millivolt per division vertical gain. If not, a suitable op amp preamp could be added.

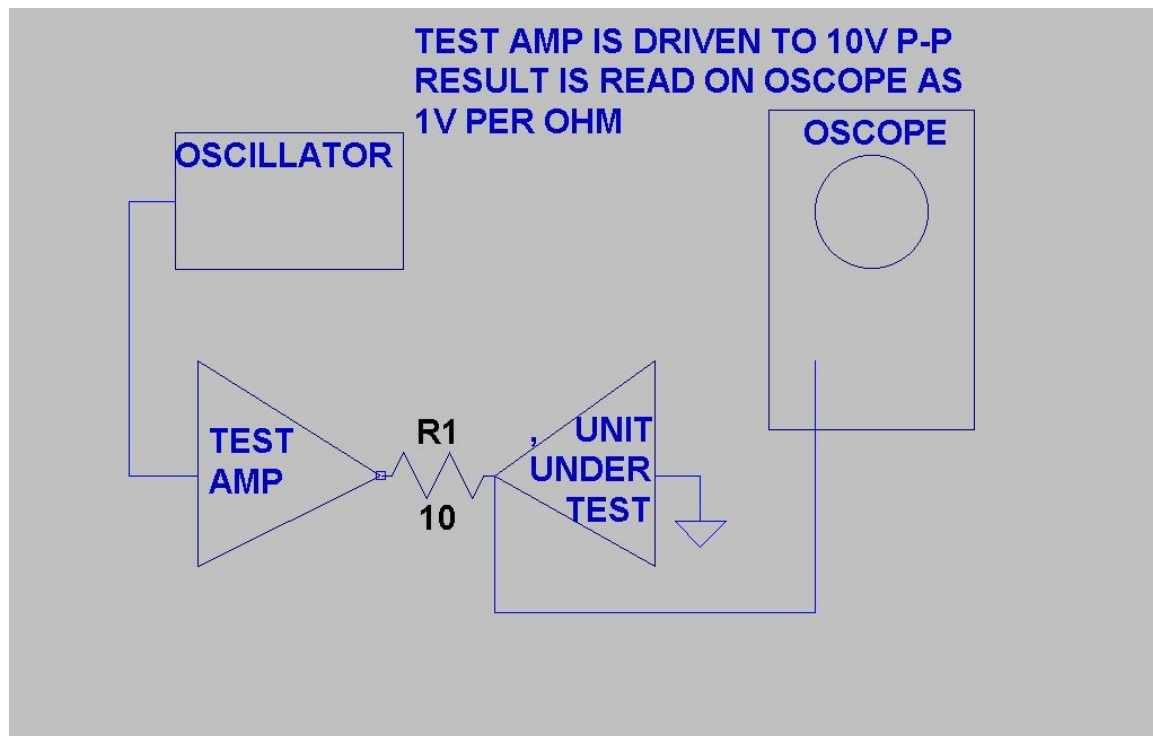
An audio sine wave oscillator or function generator capable of at least 20hz-20khz, but preferably 1hz to at least 100khz. If the function generator is sweepable, it may also be possible to produce frequency vs impedance plots as used above.

An amplifier capable of at least 20W 20hz-20khz. Preferably with a frequency response of 1hz-100khz

A 10 ohm 20W resistor, preferably noninductive

Shorting plugs for RCA or ¼" input jacks.

Here's the basic test setup:



**FIG 23 BASIC OUTPUT IMPEDANCE TEST SETUP**

As can be seen, no piece of equipment here needs to be anything special that most hobbyists, experimenters or even engineers would be hard pressed to find. If the oscscope doesn't have the required gain, a simple X10 or X100 wideband op amp circuit would easily fill the gap.

Possible sources of error in this setup:

Lead resistance between UUT and load resistor. Since we are measuring milliohms and microohms here this is definitely the most important source of error. Use very heavy gauge short wiring between the load resistor and the amp output. Attach the oscscope probe at the junction of the output emitter resistors, preferably exactly where the feedback resistor connects (may not be the same location in amps with poorly laid out pc boards). If you are trying to calculate actual damping factor, put the probe at the output terminal.

Note: most of our testing has been geared towards measuring the raw output impedance of amplifiers without the wiring and contact resistances (and in one case bypassing an inductive reactance) found in real physical amplifiers. In fact, so far this investigation has been taking place in cyberspace, and has only used one model approaching anything

realistic. Now the experiments are moving into the real world, and many things will behave much differently. In the real world, for instance, if we oversaturate a transistor, instead of getting some strange glitch in our output waveform, we actually will let the magic blue smoke out of the component.

Inductive load resistor. This will have most of its effect at the upper end of the audio spectrum. We can compensate for this by driving the test amp into the load resistor in series with a known noninductive resistance and recording the error factor at the frequency of interest, and use it to correct our test results.

Crossover notch in the test amp. We can “hot-rod” the test amp output bias to remove any crossover notch distortion, since any notch might cause errors in reading crossover notch in the UUT.

Oscope miscalibration. As long as it's not out more than about 5% it's not critical. We can again measure with a known voltage and resistance to get a correction factor.