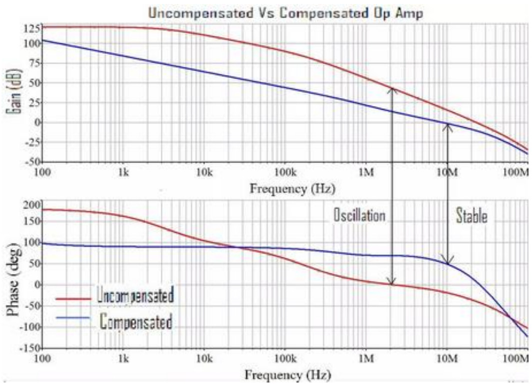
Op Amps in Audio

Introduction

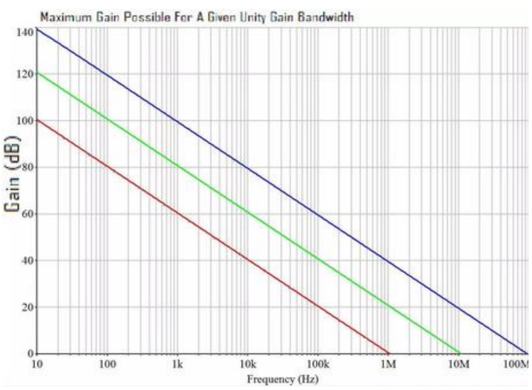
When choosing an audio grade op amp, some opt for high loop gain devices as it is well known that high loop gain makes for more precise amplifiers lower THD specifications. Others decry the use of high gain devices, claiming the high gain has audible affects. Others want high speed in the form of fast slew rates and wide bandwidths following the old adage that "faster is better."

There is a thing that ties gain, slew rate and bandwidth together, and that thing is the op amp's compensation. Op amps always operate with an amount of external feedback where some of the output signal is fed back into the input. If we start looking at op amp circuits, we can see how this is being done with feedback resistor Rf. The gain of which is determined by R_f/R_{in}. The purpose of the feedback is to set a closed loop gain and to provide the op amp with a way of "watching its own output" so that its output can be tightly held to a mirror image of the input signal multiplied by the closed loop gain. To describe feedback action is that it is used to hold the op amps output to a mirror image of input signal, multiplied by the closed loop gain. Exactly how tightly it holds it to it is determined by the op amps **open** loop gain.

The thing we must be leery of when using feedback, is the phase delay (phase shift, or time lag) that op amps have. It can't hold its output to a copy of its input if there is a time lag between the two. Unfortunately, all op amps will have some phase lag associated with them, and it is caused by the small parasitic capacitances associated with the transistors that the device is fabricated from. There are several of these stray capacitances, and they will stack up quickly causing a rapid phase shift of many degrees to occur at the transition frequency of the internal transistors inside the op amp. If the phase lag in the op amp is severe enough, it will oscillate as the delayed feedback signal causes the op amp to chase its own tail, resulting in an oscillation.



In order to prevent this condition and maintain stability, the op amp must not have more than a half cycle or 180º of phase shift at the point where its loop gain has fallen to 0dB. This condition is called Nyquist stability criteria, and frequency compensation is employed to ensure it. Compensation works by employing a single dominant pole in the device that hits first, and will come long before the phase delays that come from internal parasitic capacitances have any affect. This single pole will systematically reduce the gain, and push the gain below zero before the subsequent poles come into play, and stability will be maintained. It ensures that there will not be a phase shift of more than 180º while the op amp still has open loop gain. The compensated amplifier plotted in blue only has about 130º of phase shift at the point when the gain falls to zero. This amplifier will be stable, and can be said to have 50º of phase margin. (Phase margin is the amount of phase left over out of the 180º that is necessary for stability when the gain crosses 0 dB).



You can see that the compensated graph in blue has a very orderly slope of 6 dB/octave, and a phase shift of around 90º over most of the frequency range. This is the characteristic of a single pole roll off. It is created by a single capacitor purposefully placed inside of the device to roll off and reduce the gain to zero before the poles from the parasitic capacitors internal to the op amp come into play.

Since unity gain stable op amps use single pole compensation and therefore have a 6 dB/octave gain roll off, it is possible to plot the maximum theoretical gain that could ever exist at any frequency, knowing only the bandwidth. An example of this appears left. Three hypothetical amplifiers are presented with a unity gain bandwidths of 1, 10, and 100MHz. This plot shows the maximum theoretical gain that any of them can have at any frequency. Keep in mind, this plot is for a **maximum** possible loop gain. A given device may well have less gain in the low frequency region (10 – 100 Hz) where loop gain typically tops out.

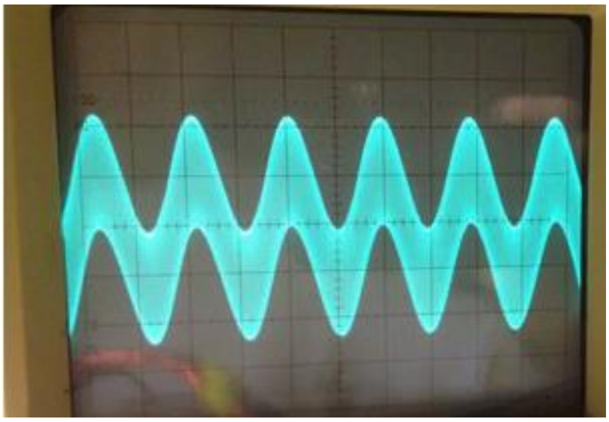
The point here is to illustrate how unity gain bandwidth sets an inherent cap on how much gain is possible given a single pole compensation scheme. For example it is impossible to find a 10 MHz single pole compensated op amp with 80 dB of gain at 10KHz. The nature of the compensation scheme would limit said amplifier to around 60dB of loop gain at that frequency. Keep in mind too, that when an op amp data sheet specifies the loop gain, they are specifying a **maximum**, which usually occurs at ~100 Hz or less. The fact that the gain drops at 6 dB per octave is assumed to be known by the reader, and often goes unmentioned by the author of the device datasheet. The point is that a 10 MHz op amp with a specified gain of 100 dB in the datasheet will still only have 80 dB of gain at 1 kHz, 60 dB at 10 kHz, and so on, whether the datasheet spells this out or not.

So why don't we just select the highest bandwidth device possible knowing that we are also maximizing closed loop gain in the audio band at the same time? Well, because high bandwidth devices are *finicky creatures*. By causal inspection, it would stand to reason that we don't need a 100 MHz op amp to amplify audio signals in the 10's or even 100's of kHz region. Granted it's nice to pick up the loop gain that is inseparably linked to the bandwidth, but the high bandwidth itself isn't needed, and in fact becomes problematic the higher it gets.

If you read the datasheets of high bandwidth devices, you will begin to notice all sorts of extra things and special precautions that one must start paying attention to in order to successfully use them in your circuits without oscillating. For example, they usually require extra power supply bypass capacitors on their power pins. Some manufacturers recommend an array of them, comprised of tantalums, ceramics, and a small NPO for high frequency decoupling. None of these high speed devices are recommended for use in DIP sockets, as the inductance of the socket is enough to upset the delicate balance that must be maintained to ensure stability. Most of these high bandwidth devices specify a maximum value of feedback resistor R_f that can be used, and its typically less than 1 kΩ. This is because the feedback resistor will form an extra pole (and add extra phase shift) with the input capacitance of the device. The parasitics of the board layout must also be taken into account. A few tenths of a pf of stray capacitance on the input pins are enough to send a 100 MHz op amp into a tizzy. And if you plan on driving *anything* that even remotely resembles a capacitive load, forget it. In short, do not drop high bandwidth devices into audio circuits with DIP sockets well.

When the bold do attempt to put such a device in their system, more often than not the device will have a low level oscillation in the MHz region, yet still play audio signals. It will just sound like crap due to the oscillation.

Here we can see an audio signal, with a bunch of high frequency "fuzz" (the oscillation) riding on top of it. This is why high gain devices receive minimal praise in some audio circles. It's not the gain at all, but rather the high bandwidth and associated temper mental nature of such a device. These devices will often oscillate in the MHz region when used with DIP sockets, feedback resistors of a few kΩ, leaded bypass capacitors, and PCB's without ground planes. The oscillation from the high bandwidth is what causes the terrible sound. It doesn't have anything to do with the gain, <u>it's the bandwidth to blame</u>, not the gain.



Its not the slew rate, either: Fast slew rate devices are a favorite among audiophiles as well, and fast slew rates are usually associated with wide bandwidth devices. There is an equation that can be used to calculate the slew rate requirement of a device if we know the maximum frequency and the peak amplitude of the signal that the device must amplify. This equation is:

Required Slew Rate (in V/µs) $= 2\pi f\ V_{pk}.10^{-6}$

Division by 1 million to get an answer in V/µs. Slew rates are typically specified in volts per microsecond.

So let's bang out some math, and see what we get. Most op amps in line level circuits process signal amplitudes of a few volts peak. Typically, these op amps are supplied from something like ± 15 V, so it's impossible for them to process signals much beyond 12 volts peak anyway, due to the limitation of the power supply rails. The upper limit of audio frequencies is widely considered to be around 20 kHz, but let's be obnoxious with this too, and call it 160 kHz. So how much slew rate is required of an op amp to reproduce a **12 V_{pk}** signal at **160 kHz**? Turns out, its **12 V/µs**. Pretty slow, right? If we get more

reasonable, and calculate a slew rate requirement for **10 V_{pk}** at **50KHz**, we only need a paltry **3 V/µs** slew rate device to accomplish this.
Under mathematical inspection, it would appear that excessive slew rates, just like excessive band-widths, are not needed for audio signal amplification. The reason that so many audiophiles choose these devices and think they sound good is due to the associated loop gain of such devices, as it has been demonstrated that the high speeds and large bandwidths aren't really buying them anything. What they are getting that they like, is the higher loop gain in the audio band. It seems like we are stuck, Right? If you want high loop gain, you will only get it with high bandwidths and slew rates, and we will just have to deal with the cantankerous nature of such devices. If you like low gain and high speeds, you're doubly screwed. Can we have it all? Can we get radically high loop gains with reasonable bandwidths? Well, just put two of them with lower closed loop gain after each other!

By the way: Douglas Self states that **30 dB** loop gain at **20 kHz** is more than enough!

Which op amp to choose, depends on total other items which are not simply measurable, if ever. For LF-applications the OPA134 has proven to be an excellent op amp for 20 dB closed loop gain.

NE5534: Number of channels (#) 1,
Total supply voltage Max ±15 V,
GBW 10 MHz,
Slew rate (Typ) 13 V/us,
Rail-to-rail No,
Vos (offset voltage @ 25 C) (Max) (mV) 4,
Iq per channel (Typ) 4 mA,
Vn at 1 kHz (Typ) (nV/rtHz) 4,
Features Decompensated,
THD + N @ 1 kHz (Typ) (%) 0.002,
Output current (Typ) (mA) 38,
Architecture Bipolar CMRR 100 dB,
Input bias current 1500000 pA.

LT1122: Tested with Fixed Feedback Capacitor,
Slew Rate 60V/µs Min,
Gain-Bandwidth Product 14MHz,
Power Bandwidth (20V_{P-P}) 1.2 MHz,
Unity-Gain Stable; Phase Margin 60°,
Input Offset Voltage 600µV Max.

OPA627: Number of channels (#), 1
Total supply voltage (Max) 36,
Vos (offset voltage @ 25 C) (Max) (mV) 0.1,
GBW (Typ) (MHz) 16,
Features Burr-Brown™ Audio Slew rate (Typ) (V/us) 55,
Rail-to-rail No,
Offset drift (Typ) (uV/C) 0.4,
Iq per channel (Typ) (mA) 7,
Vn at 1 kHz (Typ) (nV/rtHz) 5.2,
CMRR (Typ) (dB) 110,
Input bias current (Max) (pA) 5,
Output current (Typ) (mA) 45,
Architecture FET,
THD + N @ 1 kHz (Typ) (%) 0.00003

AD811: High speed
140 MHz bandwidth (3 dB, G = +1)
120 MHz bandwidth (3 dB, G = +2)
35 MHz bandwidth (0.1 dB, G = + 2)
2500 V/µs slew rate
25 ns settling time to 0.1% (for a 2 V step)
65 ns settling time to 0.01% (for a 10 V step)

Excellent dc precision
3 mV max input offfset voltage
Low distortion: THD = -74 dB @ 10 MHz
Excellent video performance (R_L = 150 Ω)
0.01% differential gain, 0.01° differential phase
Voltage noise of 1.9 nV/√Hz
Flexible Operation
Specified for ±5 V and ±15 V operation
±2.3 V output swing into a 75 Ω Load
(V_S = ±5 V)

AD844: Wide bandwidth
60 MHz at gain of −1
33 MHz at gain of −10
Slew rate: 2000 V/µs
20 MHz full power bandwidth, 20 V p-p, R_L = 500 Ω
Fast settling: 100 ns to 0.1% (10 V step)
Differential gain error: 0.03% at 4.4 MHz
Differential phase error: 0.16° at 4.4 MHz
Low offset voltage: 150 µV maximum (B Grade)
Low quiescent current: 6.5 mA

OPA1655: Total supply voltage (Min) (+5V=5, +/-5V=10) 4.5
Total supply voltage (Max) (+5V=5, +/-5V=10) 36
GBW (Typ) (MHz) 53
Slew rate (Typ) (V/us) 24
Rail-to-rail Out
Vos (offset voltage @ 25 C) (Max) (mV) 1
Iq per channel (Typ) (mA) 3.9
Vn at 1 kHz (Typ) (nV/rtHz) 4.3
Features Burr-Brown™ Audio,
Premium Sound THD + N @ 1 kHz (Typ) (%) 0.000029
Rating Catalog Operating temperature range (C) -40 to 125
Output current (Typ) (mA) 100
Product type Premier Architecture CMOS
CMRR (Typ) (dB) 120

OPA1677: Total supply voltage (Min) (+5V=5, +/-5V=10) 4.5
Total supply voltage (Max) (+5V=5, +/-5V=10) 36
GBW (Typ) (MHz) 16
Slew rate (Typ) (V/us) 9
Rail-to-rail Out Vos (offset voltage @ 25 C) (Max) (mV) 2
Iq per channel (Typ) (mA) 2
Vn at 1 kHz (Typ) (nV/rtHz) 4.5
THD + N @ 1 kHz (Typ) (%) 0.0001
Output current (Typ) (mA) 50
Architecture CMOS CMRR (Typ) (dB) 110