SOME TIPS ON STABILIZING OPERATIONAL AMPLIFIERS
by Deane Jensen

MERITS OF STABILITY

For the scope of this text, stable operation of a feedback amplifier describes a condition which exhibits no oscillations, no overshoot, and no peak in the closed loop response. Of course, equalizer and filter circuits can have overshoot and peaks without instability; these will be discussed after the general case of the wideband "flat" gain block. Stable operation also results in relative freedom from RF sensitivity and the type of clicks and pops which are actually bursts of oscillation triggered by an external transient noise source. Good stability and low overshoot will result only if the feedback circuit response determines a reasonable amount of feedback at all frequencies of open loop gain. Often that means up to 10 MHz. Low overshoot and ringing means freedom from transient distortion caused by oscillations trailing each steep slope of the waveform.

"UNITY GAIN STABILITY"

Amplifiers differ in their ability to be stable even if the external circuitry is optimum. To evaluate the stability potential for a particular amplifier type, graphic data is required for both "gain vs frequency" and "phase vs frequency" of the open loop amplifier. If the phase response exhibits $-180°$ at a frequency where the gain is above unity, the negative feedback will become positive feedback and the amplifier will actually sustain an oscillation. Even if the phase lag is less than $-180°$ and there is no sustained oscillation, there will be overshoot and the possibility of oscillation bursts triggered by external noise sources, if the phase response is not "sufficiently less" than $-180°$ for all frequencies where the gain is above unity. The "sufficiently less" term is more properly called **phase margin**. If the phase response is $-135°$, then the phase margin is $45°$ (the amount "less than" $-180°$). Actually, the phase margin of interest to evaluate stability potential must also include the phase response of the *feedback circuit*. When this combined phase margin is $45°$ or more, the amplifier is quite stable. The $45°$ number is a "rule of thumb" value and greater phase margin will yield even better stability and less overshoot.

Often, but not always, the *lowest* phase margin is at the *highest* frequency which has gain above unity; because there is always some delay independent of frequency which represents more degrees at higher frequencies. An amplifier with $45°$ phase margin at the higher frequency of unity open loop gain is said to be "unity gain stable". Optionally, most amplifier types can be compensated for unity gain stability at some sacrifice in slew rate or high frequency noise. If stability is considered to be of high priority, the tradeoff must be made. Unity gain stable means stable operation at the lowest closed loop gain where stability is usually worst.

MILLER COMPENSATION ZERO

If the amplifier is the Miller compensated type with a capacitor from collector to base of the second stage, a resistor is sometimes used in series with this capacitor to create a zero in the response near the frequency of unity gain open loop. This adds up to $45°$ to the phase margin at the frequency of unity gain open loop. A Miller compensated amplifier without a compensating zero in its circuit will most probably exhibit less than $45°$ phase margin at the frequency of unity open loop gain and therefore may not be unity gain stable.
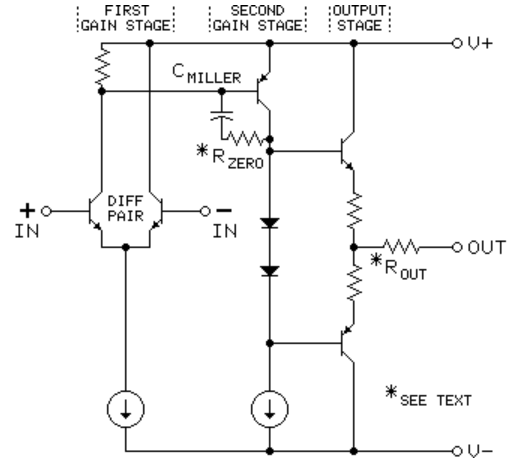

Simplified "Miller compensated" op-amp

EXCESS PHASE

There is always some time delay in the amplifier which is independent of frequency and will therefore exhibit an "excess phase" component which appears as a phase lag which increases with increasing frequency. This delay is a critical term relating the frequency of unity open loop gain to phase margin. Usually the amplifier response is close to a single pole or 6 dB/octave which creates a phase response near unity gain of $-90°$. If the frequency-independent delay represents $-45°$ equivalent phase at the frequency of unity open loop gain, the total is $-135°$ or $45°$ of phase margin. The number of degrees of excess phase created by the frequency independent delay is dependent upon both the delay time and the frequency of unity open loop gain. Only 12.5 ns of excess delay limits a 10 MHz amplifier with single pole compensation to $45°$ phase margin. Given the excess delay time T, the maximum possible unity gain frequency or F_t for $45°$ phase margin can be calculated as $F_t = 1/8T$.
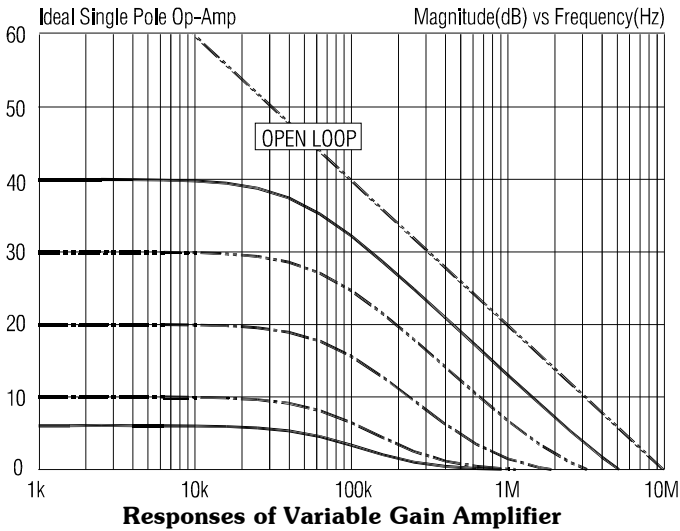
FEEDBACK COMPENSATION

So far, the characteristics mentioned relate to the internal amplifier circuitry. An analysis of open loop gain and phase data reveals only the potential to realize a stable gain block. For the scope of this text, only amplifiers which are unity gain stable will be considered acceptable for general purpose applications. Amplifiers that are not unity gain stable require analysis beyond the scope of this text and are usually confined to fixed gain configurations because the required compensation must be changed for various closed loop gains.

Recall that the phase margin of interest for analyzing stability includes not only the open loop gain and phase but the effects of the feedback circuit phase response and related delay. Another viewpoint which suggests the need for frequency dependent compensation in the feedback circuit is revealed by a "Bode Plot" of open and closed loop magnitude responses.
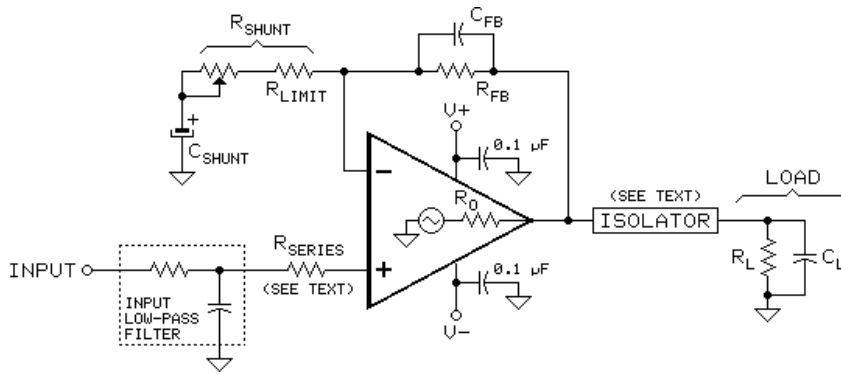
Schematic of variable gain amplifier showing components required for stability

The graph below shows the open loop gain of a typical operational amplifier with a gain bandwidth of 10 MHz. For amplifiers with lower or higher gain bandwidth, the plot is simply moved to the left or right. Amplifiers differ also in the exact shape of the open loop response. Generally the open loop gain diminishes similar to the 6 dB/octave slope shown, which describes some real limitations to the amount of gain which can be realized as a function of frequency. For example, note that an amplifier with gain bandwidth of 10 MHz can exhibit 40 dB of closed loop gain only up to 100 kHz.

Responses of Variable Gain Amplifier

In this example, 100 kHz is called the "intercept" frequency, since it is where the uncompensated inverted feedback function or 1/B intersects the open loop gain plot. Since the amount of feedback at any frequency is approximately the difference between these plots, there would be no feedback in the frequency range above intercept if a simple resistive voltage divider is used in the feedback circuit. Capacitor C_{FB} connected across the series feedback resistor R_{FB} can be used to ensure a finite amount of feedback for the entire frequency range of open loop gain greater than unity. The pole frequency created in the closed loop response must be lower than the frequency of intercept by the same ratio as the feedback voltage ratio chosen for the frequency range above intercept. If 3 dB is considered initially, the inverted feedback function pole must be at 0.707 times the frequency of intercept. Once the frequency F of the pole is determined, it can be converted to the form of an RC time constant: $RC = 1 / 6.28F$ and $C_{FB} = RC / R_{FB}$.

This calculation should be used to determine an initial value, but observation of the small signal overshoot should be used to finalize the compensation. Higher values will improve stability and reduce overshoot but reduce closed loop bandwidth. This type of compensation is called "feedback-zero compensation" or "phase lead compensation" since it creates a zero in the feedback circuit which advances the phase of the feedback signal.

VARIABLE GAIN CONTROL
The family of closed loop response curves (inverted feedback functions) in the "Bode Plot" shows a variable gain amplifier controlled by adjustment of the feedback shunt resistor R_{SHUNT}. The series feedback resistor R_{FB} and the compensation capacitor C_{FB} are fixed. This method yields close to "constant bandwidth" over the range of gain adjustment. The calculation of the compensation capacitor value must be made for the *maximum* closed loop gain. Usually R_{SHUNT} is realized with a potentiometer in series with a fixed resistor which sets the limit for maximum closed loop gain. If the fixed resistor is connected directly to the inverting input of the amplifier, it will help prevent the wiring capacitance associated with the potentiometer from causing a delay in the feedback signal which would reduce phase margin.

If the series feedback resistor R_{FB} is adjusted to control gain, the bandwidth increases as the gain is reduced. Generally, this method may exhibit more overshoot at low gain, and would be used only if the bandwidth determined by the above calculations is not sufficient at lower gain. Since the gain-bandwidth of this method is maximum at low closed loop gains, the transient response must be observed at the lowest gain setting to determine the maximum gain-bandwidth which can be realized safely even though the initial calculation is made for the maximum closed loop gain.

UNITY CLOSED LOOP GAIN
Even with a stable amplifier, unity closed loop gain operation results in the highest overshoot, sensitivity to RF pick-up, and possibility of bursts of oscillation. For stability, it would seem well worth while to arrange some gain in the amplifier and add a voltage divider, or "pad", in the circuit to re-establish the overall gain of 1. Of course, this may increase the noise to an unacceptable level. Short of limiting the minimum closed loop gain to something on the order of 2, or 6 dB, with some phase lead compensation, the merits of using a feedback circuit with a resistor paralleled by a capacitor (rather than a direct connection) should be evaluated in the laboratory for the specific amplifier type.

INPUT LOW PASS FILTER

A low pass filter at the input to the amplifier can be used to limit the bandwidth to avoid overshoot and desensitize the effects of stray positive feedback paths. This is done in addition to all other procedures, not in lieu of any necessary stabilizing precaution. It only affects the resulting response of the signal at the input of the amplifier. Transient analysis (small signal square wave response, for example), usually a good indicator for evaluating stability, may become optimistically misleading with the filter in place.

SOURCE IMPEDANCE EFFECTS

Of course, with high source impedances, the possibility of some positive feedback via stray capacitances suggests serious consideration of the input low pass filter. But at low source impedances, including "summing amplifiers" where the non-inverting input is grounded, an *internal* problem may occur. The gain-bandwidth of the first stage of the amplifier, usually a bipolar transistor differential pair, is highly dependent upon the source impedance. A lower source impedance increases the gain-bandwidth of the first stage.
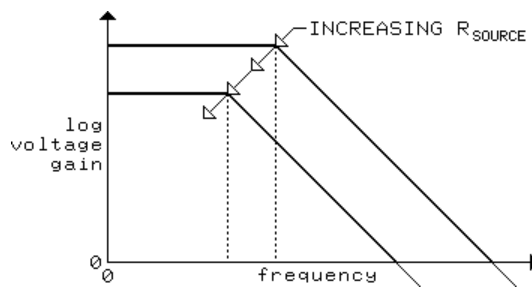
Effect of source impedance on differential pair

Consider the first stage as an amplifier which has in its feedback path the delays of the other stages as well as the feedback circuit of the complete operational amplifier. As the source impedance decreases, the first stage gain-bandwidth increases, and its phase margin decreases. In some amplifiers, the phase margin of the first stage can actually reduce to below zero and oscillate. If this amplifier type must be used with low source impedances, a resistor will be required in series with the input to limit the net minimum source impedance. Again, this may increase thermal noise. This problem is prevalent in amplifiers lacking emitter resistors in the differential input pair. The emitter resistors limit the gain bandwidth in a way similar to, but not exactly the same as, the series input resistor.

The preceding paragraph refers to the impedance at the non-inverting input. The impedance of the feedback circuit has another limitation regarding stability. If the feedback network impedance is high, additional phase lag or delay could occur as a result of the amplifier input capacitance. The resulting reduction in phase margin affects stability. This is especially prevalent in amplifiers where the inverting (feedback) input is the emitter rather than the base of a transistor.

LOAD ISOLATION

The open loop output impedance of an amplifier is not zero, but rather some finite amount which may actually increase with frequency. This means that a capacitive load, even a length of cable, will cause phase lag or delay of a signal from the output node of the amplifier. The feedback signal also suffers the delay caused by the capacitive load. As the capacitance is increased, the delay increases

and eventually the loop's phase margin will be reduced to the point of causing the amplifier to oscillate.

One remedy is a series resistor added between the output node and the load. *The feedback must still be derived **directly** from the output node.* The value of resistance required to isolate the effect of the load capacitance will depend upon the specific amplifier type, the load capacitance, and the closed loop gain. This value is best determined by observing the small signal transient response.

If the required value of this resistor makes the output impedance too high for the application, an inductive series element can be used. An inductance exhibits low impedance at low frequencies where the low source impedance is usually required for the application. But the inductance yields increasing impedance with frequency which further isolates the capacitive load. An excellent load isolator can be made with 40 turns of #30 magnet wire wound around a 39 Ω, 1 watt carbon composition resistor. The inductance of the winding is about 4 μH creating an impedance pole at about 1.5 MHz. Above 1.5 MHz, the isolator is like a 39 Ω resistor; but below 1.5 MHz, the impedance decreases to about 0.3 Ω at DC.

A smaller isolator can be made by threading a piece of bare wire through a "ferrite" bead. Attention must be paid to the current levels involved, because the "ferrite" material will magnetically saturate and cause distortion at some maximum current. Of course, this current is proportional output voltage level and inversely proportional to the load impedance. Many different "ferrite" compounds exist, including some nickel compounds which exhibit low distortion over a wide range of levels. An additional series resistor, as small as 10 Ω, very significantly improves the isolator. However, since the output impedance is now increased, it may be too high for certain loads, such as steel core output transformers, where it will significantly increase distortion.

Some amplifiers, such as the TL070 and TL080 series IC op-amps, have an internal series current limiting resistor in the output circuit in addition to the emitter resistors. This makes the output impedance rather high and, therefore, capacitive loads will cause increased delay and reduced phase margin. This type of amplifier may not be suitable to drive even relatively small capacitive loads, perhaps even a length of cable without a relatively high value of "isolator" resistance. Since the feedback circuit also loads the output stage, the capacitor C_{FB} required for "phase lead compensation" may create a phase lag at the output node.

POWER SUPPLY DECOUPLING

Each amplifier must have a low impedance (low inductance) capacitor connected from each of its power supply terminals to the common point (ground) which is the reference for the load and the non-inverting input. This ensures a low impedance at high frequencies between these circuit nodes. Small monolithic ceramic 0.1 μF capacitors with short leads are usually very effective.

ACTIVE EQUALIZERS

The inverted feedback function of an active equalizer must be analyzed to ensure sufficient loop gain at all frequencies. It is possible that the equalization function may describe a condition where the inverted feedback function exceeds the open loop gain at high frequencies. Computer modeling is suggested to verify loop gain and phase margin as a function of frequency. Equalizers with switchable functions must be analyzed to reveal these functions for each switch position as well as "in-between-positions" to avoid clicks caused by momentary instabilities. Additional components to control

stability for these "in-between-positions" can be considered after the response functions are revealed. The additional circuitry required can then be verified by computer modeling and observation of the small signal transient response.

ACTIVE FILTERS
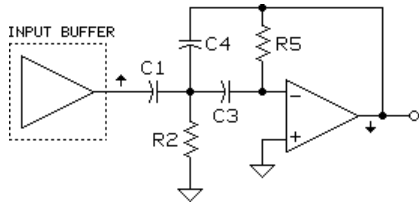
"Textbook" inverting hi-pass filter

Similar analysis is required for active filter circuits. A proper dose of skepticism applied to published topologies may improve stability. Computer-aided analysis of the active filter topologies published in popular texts has revealed that, while the authors have accurately synthesized the described functions, they have *not* analyzed the resulting amplifier stability. Many of the popular topologies use unity closed loop gain configurations which are non-optimum for sensitivity to external noise sources. Many others, including a popular "inverting high pass filter" shown in the schematic, require individual analysis and modification for stability. Others have been proven to be "impossible to stabilize" without significant error in the function.

The schematic for the "textbook inverting high pass" shows a topology which requires a voltage source (zero source impedance) at the input node to realize the function. A source impedance of even a few ohms seriously alters the flatness of the very high frequency response. Therefore, an input buffer amplifier is required and almost all realizations in use today incorporate this buffer. Note that the two amplifier outputs are anti-phase and are connected together through the two series capacitors C1 and C4. This condition results in a peaking response due to the reduced phase margin caused by the capacitive load. A possible secondary problem is slew rate limitation determined by the maximum output current capability of the amplifiers and capacitances C1 and C4.

$$R6 = R7 = \frac{R2}{10} \qquad C8 = \frac{100 \text{ ns}}{R7}$$
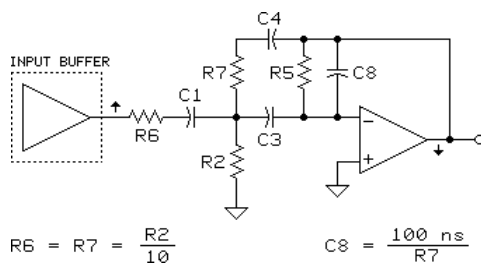
Hi-pass filter modified for stability

The modified topology requires resistors R6 and R7, which isolate the effects of the capacitive loading, and capacitor C8, which is the phase lead compensation to avoid intercept. The value for the isolation resistors is chosen to desensitize the capacitive loading based on the peaking response and/or the slew rate limiting depending upon the amplifier characteristics. Resistors R6 and R7 must be closely matched because their effects upon the very high frequency response are complimentary. The absolute value of R6

and R7 is set to about 10% of R2 to minimize the error which the stability modification introduces to the response function. Values less than 10% will create less error. Noise and amplifier loading considerations should be used to scale the overall impedances used. Capacitor C8 avoids intercept by introducing phase lead compensation. The inverted feedback function of the "textbook" topology is 2, or 6 dB, at all frequencies well above F_C of the function, so the intercept frequency was the gain-bandwidth divided by 2.

REFERENCES:

"Operational Amplifiers, Design and Applications", Burr-Brown/ Tobey, Graeme, Huelsman, McGraw-Hill, 1971.

"Operational Amplifiers, Theory and Practice", Roberge, Wiley, 1975.

This article was originally written by Deane E. Jensen and was published in the June, 1978 issue of Recording Engineer/Producer. The text was edited and additional graphics were generated by Bill Whitlock in August 1995.