Application Note

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SOME TIPS ON STABILIZING OPERATIONAL AMPLIFIERS (1

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 the "gain vs. frequency" and "phase vs. frequency" open loop performance. If the phase response exhibits -180 degrees 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 response is less than -180 degrees and there is no sustained oscillation, there will be overshoot and possibility of bursts of oscillation triggered from external noise sources, if the phase response is not "sufficiently less" than -180 degrees for all frequencies where the gain is above unity. This "sufficiently less" term is more properly called "phase margin". If the phase response is -135 degrees, then the phase margin is 45 degrees (the amount "less than -180 degrees"). 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 degrees or more, the amplifier is quite stable. The 45 degree 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 independant of frequency which represents more degrees at higher frequencies. An amplifier with 45 degrees phase margin at the frequency of unity gain open loop is said to be "unity gain stable". Some amplifier types can be compensated for unity gain stability optionally at some sacrifice in slew rate. If stability is considered to be of high priority, the tradeoff must be made. "Unity gain stability" means stable operation at the lowest closed loop gains where stability is usually worst.

1) Deane Jensen,"Some tips on stabilizing operational amplifiers", Recording Engineer/Producer, Vol.9, No.3, pp 42-53, June 1978

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 the "Miller compensation capacitor" to create a zero in the response at the frequency of unity gain open loop. This adds up to 45 degrees to the phase margin at the frequency of unity gain open loop. A Miller compensated amplifier without the zero will most probably exhibit less than 45 degrees phase margin at the frequency of unity gain open loop and therefore it may not be "unity gain stable".

EXCESS PHASE

There is always some delay in the amplifier which is independant of frequency and will therefore exhibit an excess phase component which appears as an increasing number of degrees with increasing frequency. This delay is a critical term relating the frequency of unity gain open loop 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 degrees. If the frequency-independant delay represents -45 degrees equivalent phase response at the frequency of unity gain open loop, the total is -135 degrees or 45 degrees phase margin. The number of degrees of "excess phase" created by the frequency independant delay is dependant upon both the delay time and the frequency of unity gain open loop. Only 12.5 nanoseconds excess delay limits a 10 MHz amplifier with a single pole compensated response to 45 degrees phase margin. Given the excess delay time (T), the maximum possible unity gain frequency (Ft) for 45 degrees phase margin can be calculated: Ft = 1/8T.

FEEDBACK COMPENSATION

So far, the characteristics mentioned relate to the internal amplifier circuitry. And the analysis of the phase response reveals only its 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 applications. Amplifiers, which are not unity gain stable, require analysis beyond this text and are usually confined to fixed gain configurations; as the required compensation must be changed for various closed loop gains.

Recall that the phase margin of interest for analyzing stability includes the effect of the feedback circuit phase response or related delay. Another viewpoint which suggests the need for frequency dependant compensation in the feedback circuit is revealed by the "Bode Plot" of the open and closed loop responses. The graph shown is a simplified plot showing the open loop gain of a typical operational amplifier with a gain bandwidth of 10 MHz (some amplifiers are lower which means the plot must be moved to the left). Amplifiers differ also in the exact shape of the open loop response. Also for simplification, the "closed loop" plots shown here are actually the inverted feedback function which do not include the affect of the limited open loop gain. Generally the open loop gain diminishes similar to the 6 dB/octave slope as shown, which describes some real limitations to the amount of gain which can be realized as a function of frequency. Note that a 10 MHz amplifier can exhibit 40 dB of closed loop gain only up to 100 kHz.

This is called the frequency of intercept, where the uncompensated inverted feedback function (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 for the frequency range above intercept if a simple resistive voltage divider is used in the feedback circuit. A capacitor Cf connected across the series feedback resistor Rf 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 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 the frequency of intercept divided by the square root of 2. Higher values will improve stability and reduce overshoot with reduced bandwidth.

Then converting to the time constant form by:

$$Tc = 1/(2*PI*F)$$

The capacitor can be calculated by:

$$Cf = Tc/Rf$$

The calculation should be used to determine an initial value, but observation of the small signal overshoot should be used to finalize the compensation. 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 Rshunt. The series feedback resistor Rf and the compensation capacitor Cf 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, Rshunt 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 isolate any capacitance associated with the wiring to the potentiometer from causing a delay in the feedback signal which would reduce phase margin.

If the series feedback resistor Rf 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 considered 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 allowable gain-bandwidth which can be realized safely even though the initial calculation is made for the maximum 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 triggered from external noise sources. For stability, it would seem well worth while to arrange some gain in the amplifier and add a voltage divider (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 (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. It does not affect all sensitivity to RF or external noise sources, so transient analysis, usually a good indicator for evaluating stability, may be optimistically misleading.

SOURCE IMPEDANCE EFFECTS (See Fig. 1.11 on Page 7)

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 operational amplifier is highly dependant upon and inversely related to the source impedance. This means that a lower source impedance increases the gain-bandwidth of the first stage. 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 reduce below zero and the first stage will 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. Of course, this may affect noise. This problem is prevalent in amplifiers lacking emitter resistors in the differential input pair. The emitter resistors limit the gain bandwidth similar to, but not exactly the same as, the series input resistor.

The preceeding paragraph refered 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 input capacitance. The resulting reduction in phase margin affects stability. This is more prevalent in amplifiers where the inverting (feedback) input is an emitter rather than a base of a transistor.

The 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 a phase lag or delay of the signal at the output node of the amplifier. The feedback signal is derived from the same output node, so the feedback signal also suffers the delay caused by the capacitive load. As the capacitance is increased, the delay increases and eventually the 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 resistance is too high compared to the output source impedance required by 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 ohm 1 watt Allen-Bradley resistor. The inductance of the winding is about 40 uH creating a impedance pole at 155 kHz. So above 155 kHz, the isolator is like a 39 ohm resistor; but below 155 kHz, the impedance decreases to about 0.2 ohms at DC.

A smaller isolater can be made by threading a piece of buss wire through a "ferrite" bead. This method can only be used with limited current levels, because the "ferrite" magnetic material will saturate and cause distortion at some maximum current. Of course, the current is proportional to level (voltage) 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. When the "ferrite" bead is used, an additional series resistor as small as 10 ohms very significantly improves the isolator. However, if the load is a Steel core output transformer, the 10 ohm resistor should not be used as the source impedance will affect distortion.

Some amplifiers have an internal series current limiting resistor in the output circuit in addition to the emitter resistors. This means the output impedance is high and therefore a capacitive load will cause more delay than with an amplifier without the additional internal resistor. This type of amplifier may not be suitable to drive a capacitive load, perhaps not even a length of cable without a relatively high value of isolation resistance. Since the feedback circuit also loads the output stage, the capacitor Cf required for "Phase lead compensation" may create a phase lag at the output node.

POWER SUPPLY DECOUPLING

Each amplifier must have a pair of low loss (low inductance) capacitors connected from each power supply terminal 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 three circuit nodes. One small type of monolithic 0.1 uF capacitor is Centralab (USCC) #CY20C104P.

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 and "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

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 the 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. Even a few ohms seriously alters the flatness of the very high frequency response. Therefore an input buffer amplifier is required and most all realizations in use today incorporate this required buffer. Note that the two amplifier outputs are anti-phase and are connected together through the two series capacitors C1 & C4. This condition results in peaking response due to the reduced phase margin caused by the phase lag created by the capacitive load. A second problem is a pseudo slew rate limitation (I/C) determined by the maximum output current capability of the amplifier and the capacitances.

The modified topology requires two resistors R6 & R7 which isolate the effects of the capacitive loading and one 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. The two resistors R6 & R7 must be closely matched because their effects upon the very high frequency response are complimentary. The absolute value of R6 & R7 is set to one tenth the value of R2 to minimize the error which the stability modification introduces to the response function. A ratio greater than 10 will create less error. Noise and amplifier loading considerations should be used to scale the overall impedances used. The capacitor C8 avoids intercept by introducing phase lead compensation. The inverted feedback function of the "textbook" topology is 2 (6 dB) at all frequencies well above Fc of the function, so the intercept frequency was the gain-bandwidth divided by 2.

REFERENCES:

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Operational Amplifiers, Theory and Practice:
Roberge: Wiley, 1975

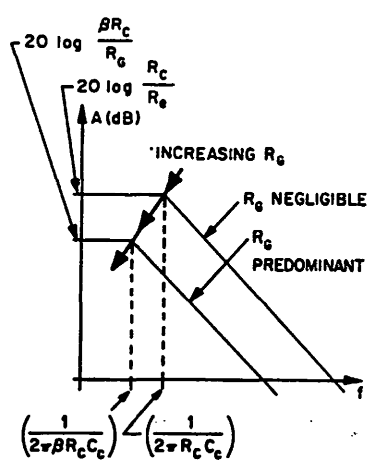


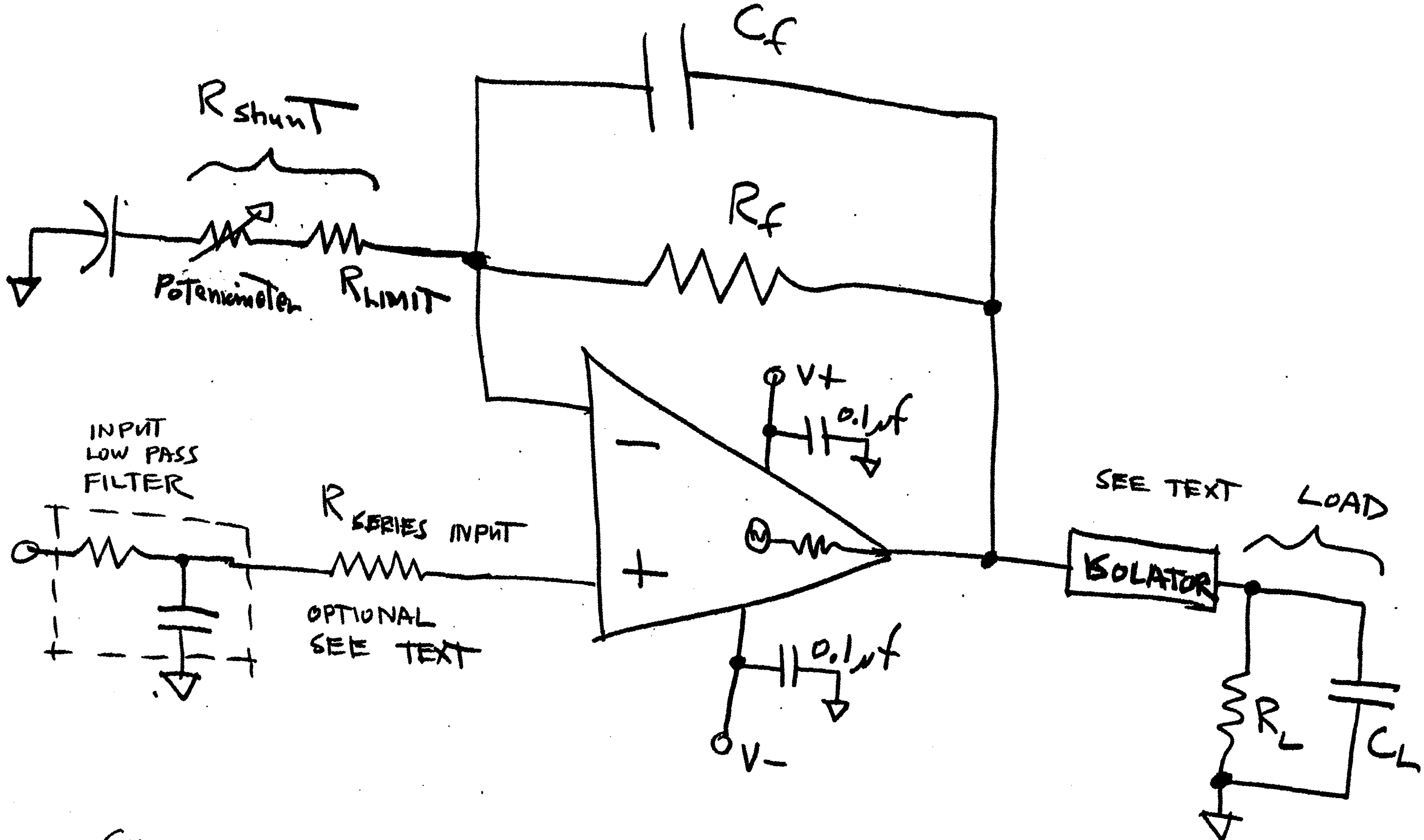
Fig. 1.11 Differential-stage Bode plot showing the effect of source resistance on response.

Note the heavy dependence upon source impedance of both the dc gain

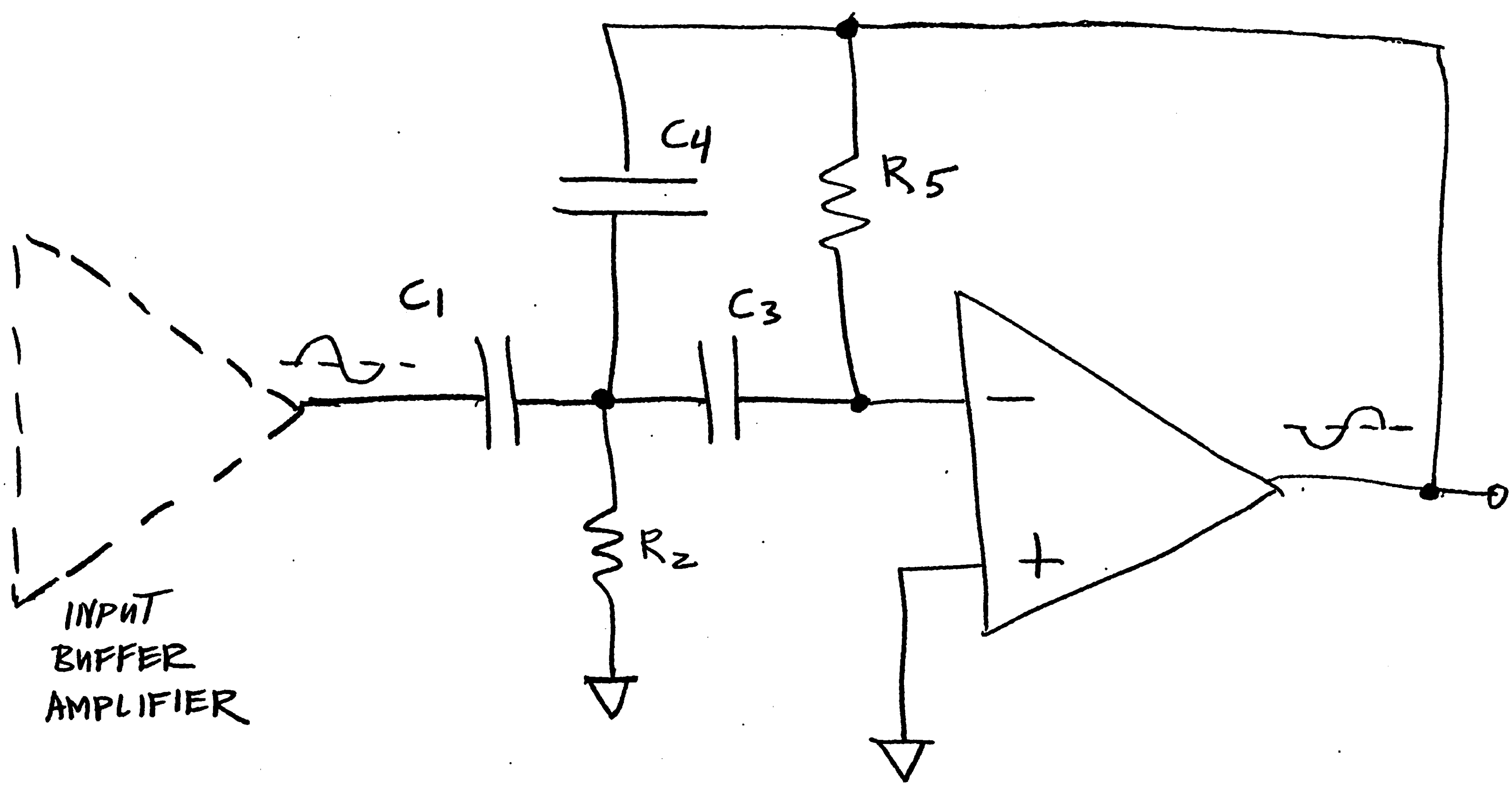
$$A_O \doteq \frac{-R_C}{R_e + R_G/\beta}$$

and of the pole frequency

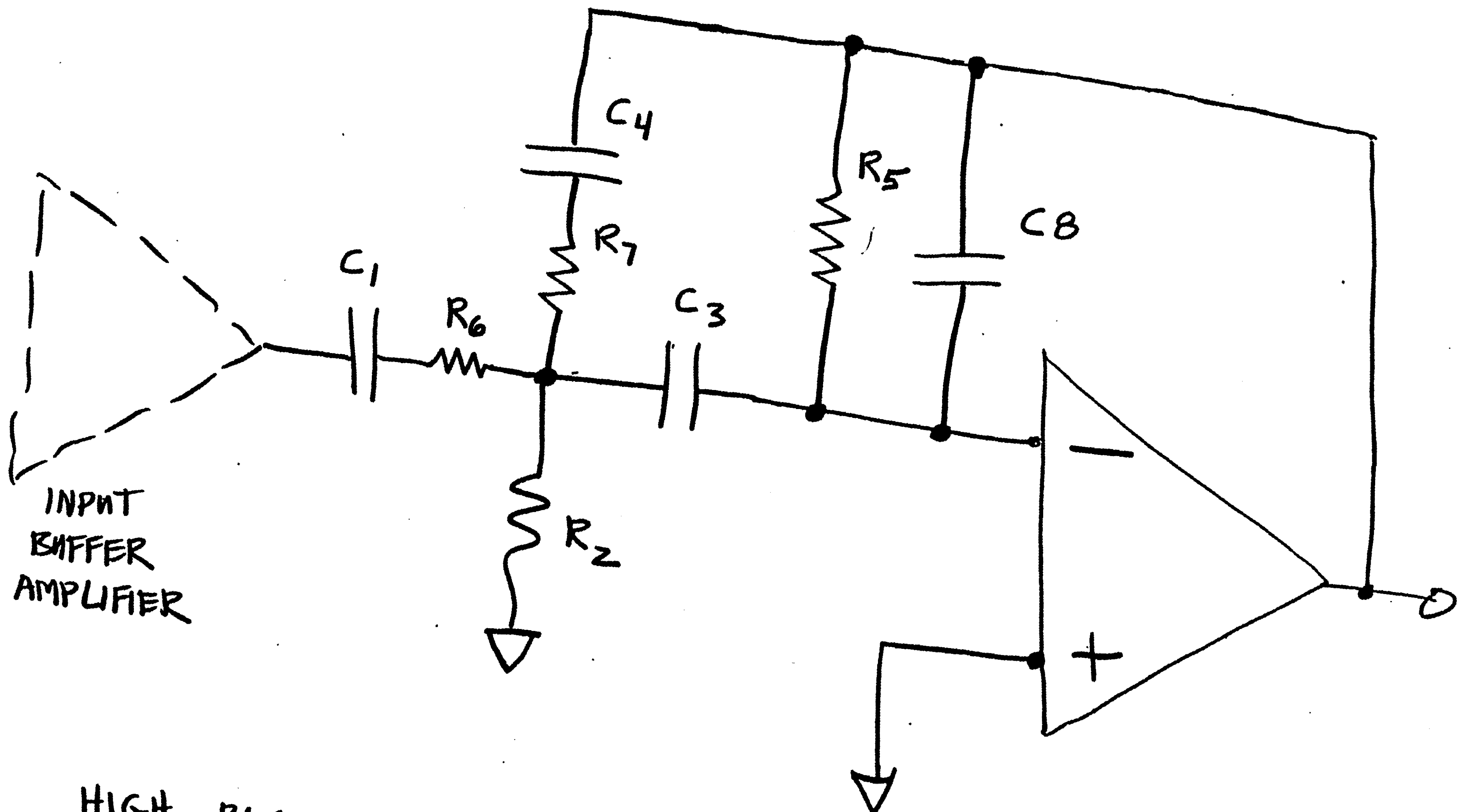
$$f_p \doteq \frac{1}{2\pi R_C C_c} \frac{R_e + R_G/\beta}{R_e + R_G}$$



SIMPLIFIED SCHEMATIC SHOWING COMPONENTS FOR STABILITY



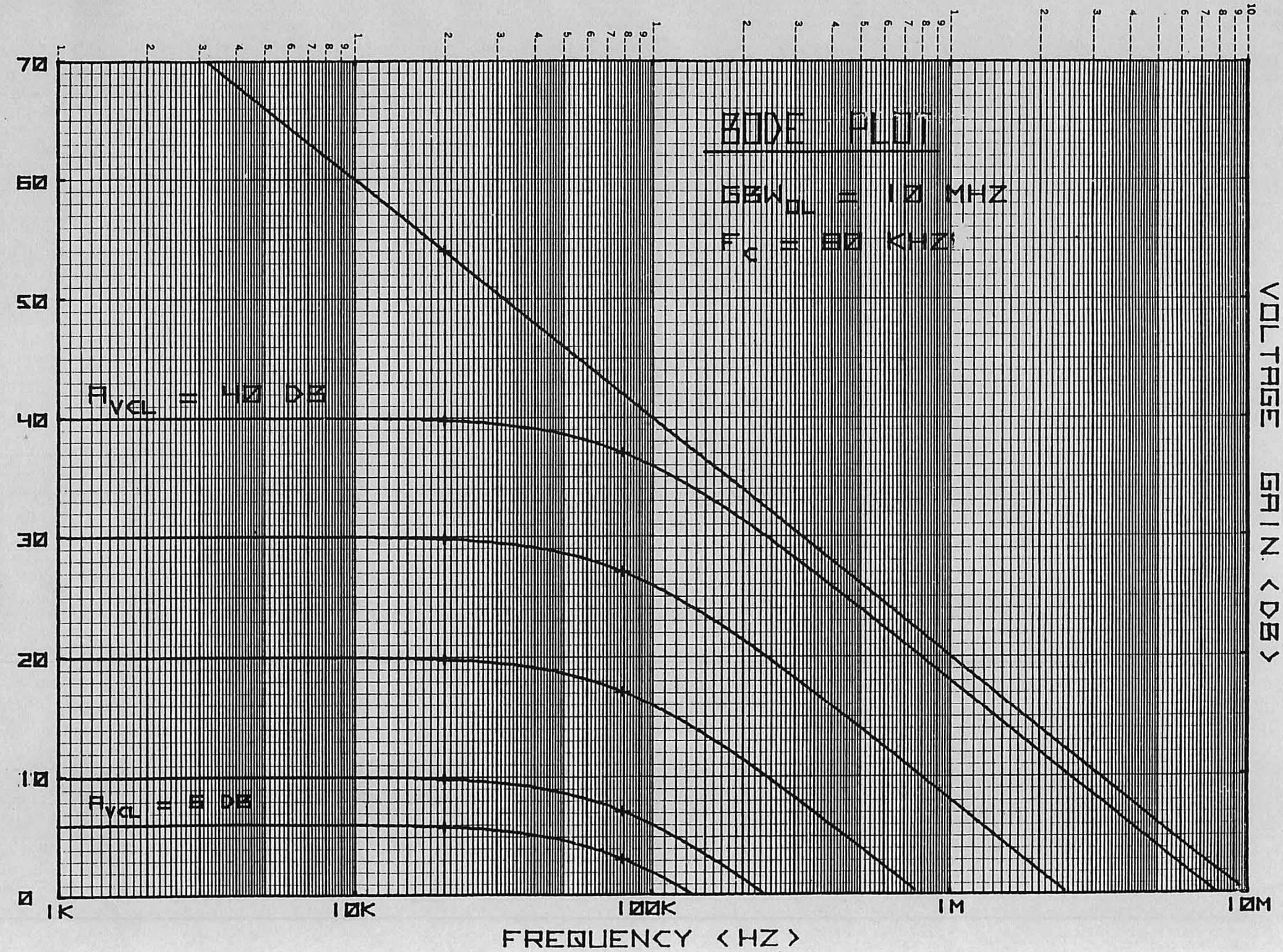
TEXTBOOK MODEL FOR INVERTING HIGH PASS FILTER



HIGH PASS FILTER MODEL MODIFIED FOR STABILITY

$R_6 = R_7 = R_2/10$

$C_8 = 0.1 ns / R_7$


BODE PLOT
GBW$_{OL}$ = 10 MHZ
F$_C$ = 80 KHZ
A$_{VCL}$ = 40 DB
A$_{VCL}$ = 6 DB
70
60
50
40
30
20
10
0
1K
10K
100K
1M
10M
FREQUENCY (HZ)
VOLTAGE GAIN (DB)