Lecture 34: List the advantages and disadvantages of negative feedback

Feedback in amplifiers

DI02011011: Electronics Circuit and Application (ECA)

Lecture Agenda: Benefits vs. Drawbacks Analysis

- Advantage 1: Gain Stabilization & Thermal/Parameter Immunity
- Advantage 2: Non-Linear Harmonic Distortion Suppression
- Advantage 3: Bandwidth Extension & Passband Flattening
- Advantage 4: Custom Input and Output Impedance Tailoring
- Advantage 5: Internal Noise & Power Supply Ripple Attenuation
- Disadvantage 1: Severe Loss of Overall Voltage Gain
- Disadvantage 2: High-Frequency Phase Shift & Oscillation Risks
- Disadvantage 3: Required Frequency Compensation & Slew Rate Limits
- Disadvantage 4: Inability to Improve Primary Input Stage SNR
- Solved Engineering Problem: Gain Loss vs. Distortion Improvement
- Comparative Summary Table: Advantages vs. Disadvantages
- Summary & Design Recommendations

Advantage 1: Gain Stabilization & Parameter Immunity

- Parameter Instability Problem: Open-loop transistor gain A fluctuates widely due to manufacturing beta spread ($\pm 50\%$), ambient temperature changes, and supply voltage noise.
- Desensitivity Mechanism: Closed-loop gain formula $A_f = \frac{A}{1+A\beta}$ yields fractional variation $\frac{dA_f}{A_f} = \frac{1}{1+A\beta}\frac{dA}{A}$.
- Quantitative Example: For desensitivity factor $(1 + A\beta) = 1000$, a 50% drop in open-loop gain causes only $\frac{50\%}{1000} = 0.05\%$ variation in closed-loop gain.
- IC Manufacturing Impact: Enables mass production of precision analog ICs (op-amps, instrumentation amplifiers) with matched gain without costly manual laser trimming.

Advantage 2: Non-Linear Distortion Reduction

- Transistor Non-Linearity: BJT exponential transfer characteristic ($I_C = I_S e^{V_{BE}/V_T}$) generates non-linear harmonic distortion (D_2, D_3) at large signal amplitudes.
- Distortion Attenuation Equation: Closed-loop harmonic distortion $D_f = \frac{D}{1+A\beta}$, where D is open-loop distortion.
- Quantitative Impact: A feedback factor of 100 (40 dB) reduces Total Harmonic Distortion (THD) from 5.0% down to 0.05%.
- Hi-Fi Audio Relevance: Essential in audio power amplifiers to eliminate push-pull crossover distortion and deliver clean, un-distorted audio signals.

Advantage 3: Bandwidth Extension & Response Flatness

- Frequency Extension: Upper 3-dB cutoff frequency extended to $f_{Hf} = f_H(1 + A_0\beta)$; lower cutoff reduced to $f_{Lf} = \frac{f_L}{1+A_0\beta}$.
- Bandwidth Expansion: Overall bandwidth $BW_f \approx f_H(1 + A_0\beta)$ expands proportionally to feedback factor.
- Gain-Bandwidth Trade-off Flexibility: Engineers can select precise gain-bandwidth combinations while maintaining constant product $A_{0f} \cdot f_{Hf} = f_T$.
- Passband Flattening: Suppresses gain peaking and midband ripples, establishing uniform frequency response across operating bands.

Advantage 4: Custom Input & Output Impedance Tailoring

- Input Impedance Boosting: Voltage-series feedback increases input resistance $R_{in,f} = R_{in}(1 + A\beta)$ into megaohms ($M\Omega$), preventing source loading.
- Output Impedance Minimization: Voltage-series feedback drops output resistance $R_{out,f} = \frac{R_{out}}{1+A\beta}$ to fractional ohms (Ω), creating ideal voltage drivers.
- Current Amplifier Customization: Current-shunt feedback drops R_{in} and boosts R_{out}, forming ideal current buffers.
- Versatile Buffer Design: Allows transformation of standard transistor stages into specialized voltage, current, transresistance, or transconductance amplifiers.

Advantage 5: Internal Noise & Power Supply Hum Suppression

- Internal Noise Mechanism: Thermal noise, shot noise, and 50/100 Hz power supply hum generated in intermediate or output power stages are attenuated by feedback.
- Attenuation Formula: Closed-loop internal stage noise $N_f = \frac{N}{1+A\beta}$.
- Power Supply Rejection Ratio (PSRR): High feedback desensitivity significantly improves op-amp PSRR.
- Operation from Unregulated Supplies: Allows high-power amplifiers to operate from simple unregulated DC power supplies without inducing audible 50 Hz/100 Hz hum.

Disadvantage 1: Severe Loss of Overall Voltage Gain

- Gain Reduction Penalty: Closed-loop gain $A_f = \frac{A}{1+A\beta}$ is reduced by factor $(1 + A\beta)$ compared to open-loop gain A.
- High Gain Loss: Achieving 40 dB of feedback desensitivity reduces voltage gain by 40 dB (100-fold drop).
- Multi-Stage Hardware Overhead: To maintain high closed-loop gain with feedback, designers must cascade multiple gain stages (Q_1, Q_2, Q_3).
- Power & Area Penalty: Increases total transistor count, silicon area, power dissipation, and component cost.

Disadvantage 2: High-Frequency Instability & Oscillation

- Phase Shift Accumulation: Parasitic device capacitances (C_π, C_μ, C_{load}) create high-frequency poles, accumulating phase lag $\theta(f)$.
- Barkhausen Criterion Risk: At frequency f_{180} where phase shift reaches $-180°$, negative feedback turns into POSITIVE feedback.
- Self-Oscillation Condition: If loop gain magnitude $|A(jf_{180})\beta| \geq 1.0$, the amplifier becomes unstable and oscillates spontaneously.
- Transient Ringing: Low phase margin ($\phi_m < 45°$) causes step-response overshoot and severe transient ringing.

Disadvantage 3: Required Frequency Compensation & Slew Rate Limits

- Compensation Overhead: To guarantee phase margin $\phi_m \geq 60^\circ$, internal compensation networks (Miller capacitor C_c) must be added.
- Slew Rate Degradation: Dominant pole compensation capacitor C_c limits maximum rate of output voltage change: $SR = \frac{I_{tail}}{C_c}$.
- Large-Signal Bandwidth Restriction: High-frequency large-amplitude signals suffer from slew-rate induced distortion.
- Design Complexity: Requires extensive AC stability simulation (Bode plots, Nyquist diagrams, corner analysis), increasing engineering design time.

Disadvantage 4: Inability to Improve Primary Input Stage SNR

- Input Noise Origin: Thermal noise, shot noise, and flicker noise generated at the primary input transistor (Q_1) appear directly in series with source V_s.
- Scaling Behavior: Output signal $V_{os} = A_f V_s$; output input-stage noise $V_{on} = A_f N_i$.
- SNR Invariance: Signal-to-Noise Ratio at output $SNR_{out} = \frac{A_f V_s}{A_f N_i} = \frac{V_s}{N_i} = SNR_{in}$. Negative feedback CANNOT improve input stage SNR.
- LNA Design Restriction: Low-Noise Amplifiers (LNAs) in wireless receivers cannot rely on feedback for noise figure improvement; discrete low-noise components are mandatory.

Engineering Example: Quantifying Gain Loss vs. Distortion Improvement

- Design Requirement: An audio power amplifier requires total harmonic distortion $THD \leq 0.05\%$. Open-loop amplifier has voltage gain $A = 2000$ and open-loop $THD = 4.0\%$.
- Step 1 - Determine Required Desensitivity Factor: $1 + A\beta = \frac{THD_{open}}{THD_{closed}} = \frac{4.0\%}{0.05\%} = 80$ (38.06 dB feedback).
- Step 2 - Calculate Required Feedback Factor (β): $\beta = \frac{80-1}{2000} = \frac{79}{2000} = 0.0395$ (3.95%).
- Step 3 - Calculate Resulting Closed-Loop Gain (A_f): $A_f = \frac{2000}{80} = 25$ V/V (27.96 dB).
- Trade-Off Assessment: Voltage gain drops by 38.06 dB (from 2000 to 25) to achieve an 80-fold reduction in harmonic distortion!

Comparative Analysis: Advantages vs. Disadvantages Summary Matrix

- Gain Stability: + Fractional variation reduced by $(1 + A\beta)$ — - Severe gain reduction $(A_f = \frac{A}{1+A\beta})$
- Bandwidth: + Extended to $f_{Hf} = f_H(1 + A\beta)$ — - Slew rate limited by compensation $(SR = \frac{I}{C_c})$
- Distortion: + Harmonic distortion reduced $(D_f = \frac{D}{1+A\beta})$ — - No improvement in primary input SNR
- Impedance: + Flexible R_{in} boost and R_{out} reduction — - Risk of high-frequency self-oscillation
- Noise: + Internal stage noise and hum suppressed — - Increased circuit complexity and stage count

Summary & Strategic Engineering Design Rules

- Essential Benefits: Negative feedback provides indispensable gain stabilization, non-linear distortion suppression, bandwidth extension, and impedance tailoring.
- Engineering Costs: The price paid includes severe voltage gain loss, risk of high-frequency self-oscillation, slew-rate degradation, and multi-stage complexity.
- Design Rule 1: Always verify Phase Margin $\phi_m \geq 60^\circ$ using Bode plots to prevent instability.
- Design Rule 2: Use Miller dominant pole compensation to secure stability while minimizing slew rate degradation.