Lecture 33: Describe the effect of negative feedback on amplifier parame...

Feedback in amplifiers

DI02011011: Electronics Circuit and Application (ECA)

Lecture Agenda: Parameter-by-Parameter Breakdown

- Parameter 1: Closed-Loop Gain Reduction & Desensitivity Factor
- Parameter 2: Input Impedance Transformations ($R_{in,f}$ for Series vs. Shunt Mixing)
- Parameter 3: Output Impedance Transformations ($R_{out,f}$ for Voltage vs. Current Sampling)
- Parameter 4: System Stability Enhancement & Phase Margin
- Parameter 5: Bandwidth Extension ($f_{H,f}$ and $f_{L,f}$ Derivations)
- Parameter 6: Frequency Response Flattening & Phase Linearization
- Parameter 7: Reduction of Non-Linear Harmonic Distortion ($D_f = \frac{D}{1+A\beta}$)
- Parameter 8: Internal Noise & Power Supply Hum Suppression
- Solved Problem: Full Parameter Evaluation Under Feedback
- Solved Problem: Impedance Transformations in Current-Shunt Feedback
- Comparative Impact Matrix Across 4 Feedback Topologies
- Summary & Key Engineering Takeaways

Parameter 1: Gain Reduction & Desensitivity Factor

- Closed-Loop Gain Formula: $A_f = \frac{A}{1+A\beta}$, where A is open-loop gain and β is feedback ratio.
- Gain Reduction Quantifier: Gain is reduced by the desensitivity factor $(1 + A\beta)$, equivalent to a decibel reduction $N_{dB} = 20 \log_{10}(1 + A\beta)$.
- Gain Desensitivity Function: Sensitivity $S_A^{A_f} = \frac{\partial A_f / A_f}{\partial A / A} = \frac{1}{1+A\beta}$. Open-loop gain variations caused by temperature, aging, or supply fluctuations are suppressed by $(1 + A\beta)$.
- Asymptotic Stabilization: For $A\beta \gg 1$, $A_f \approx \frac{1}{\beta}$, establishing total gain independence from active transistor parameters.

Parameter 2: Input Impedance Transformations ($R_{in,f}$)

- Series Input Connection (Voltage-Series / Current-Series): Feedback voltage V_f opposes input source V_s. Net error voltage $V_i = V_s - V_f = V_s - \beta A V_i \implies V_i(1 + A\beta) = V_s$.
- Input Current Reduction: $I_i = \frac{V_i}{R_{in}} = \frac{V_s}{R_{in}(1+A\beta)}$.
- Series Input Impedance Formula: $R_{in,f} = \frac{V_s}{I_i} = R_{in}(1 + A\beta)$. Input impedance is BOOSTED by factor $(1 + A\beta)$.
- Shunt Input Connection (Voltage-Shunt / Current-Shunt): Feedback current I_f drains source current. Total input current $I_s = I_i + I_f = I_i(1 + A\beta)$.
- Shunt Input Impedance Formula: $R_{in,f} = \frac{V_i}{I_s} = \frac{R_{in}}{1+A\beta}$. Input impedance is REDUCED by factor $(1 + A\beta)$.

Parameter 3: Output Impedance Transformations ($R_{out,f}$)

- Voltage (Shunt) Output Sampling (Voltage-Series / Voltage-Shunt): Output voltage V_o sampled. Deactivate source ($V_s = 0$) and apply test voltage V_x at output port.
- Error Voltage Induced: $V_i = -V_f = -\beta V_x$. Test current $I_x = \frac{V_x - AV_i}{R_{out}} = \frac{V_x - A(-\beta V_x)}{R_{out}} = \frac{V_x(1+A\beta)}{R_{out}}$.
- Voltage Sampling Output Impedance: $R_{out,f} = \frac{V_x}{I_x} = \frac{R_{out}}{1+A\beta}$. Output impedance is REDUCED by factor $(1 + A\beta)$ (behaves as ideal voltage source).
- Current (Series) Output Sampling (Current-Series / Current-Shunt): Output current I_o sampled.
- Current Sampling Output Impedance: $R_{out,f} = R_{out}(1 + A\beta)$. Output impedance is BOOSTED by factor $(1 + A\beta)$ (behaves as ideal current source).

Parameter 4: System Stability Enhancement

- Operating Point Drift Stabilization: Temperature changes cause DC bias point shifts ΔI_C and gain drift ΔA. Closed-loop gain drift is restricted to $\Delta A_f = \frac{\Delta A}{(1+A\beta)^2}$.
- Nyquist Criterion Criterion: Negative feedback suppresses open-loop gain magnitude at critical high frequencies where phase shift approaches -180°.
- Gain Margin (GM) Expansion: $GM = -20\log_{10}|A(j\omega_{180})\beta|$. Increasing feedback desensitivity expands gain margin, preventing runaway oscillations.
- Transient Overshoot Control: Enhances phase margin ϕ_m, reducing ringing and settling time in closed-loop step response.

Parameter 5: Bandwidth Extension Derivations

- High-Frequency Response ($f_{H,f}$): Open-loop gain $A(f) = \frac{A_0}{1+j(f/f_H)}$. Closed-loop response $A_f(f) = \frac{A(f)}{1+\beta A(f)} = \frac{A_0/(1+A_0\beta)}{1+j\frac{f}{f_H(1+A_0\beta)}}$. Upper cutoff frequency becomes $f_{H,f} = f_H(1 + A_0\beta)$.
- Low-Frequency Response ($f_{L,f}$): Open-loop gain $A(f) = \frac{A_0}{1-j(f_L/f)}$. Closed-loop lower cutoff frequency becomes $f_{L,f} = \frac{f_L}{1+A_0\beta}$.
- Total Bandwidth (BW_f): $BW_f = f_{H,f} - f_{L,f} \approx f_H(1 + A_0\beta)$. Bandwidth expands by exact desensitivity factor $(1 + A_0\beta)$!
- Gain-Bandwidth Product Invariance: $A_f \times BW_f = \left(\frac{A_0}{1+A_0\beta}\right) \times [f_H(1 + A_0\beta)] = A_0 \times f_H = f_T$.

Parameter 6: Frequency Response Flattening & Phase Linearization

- Midband Gain Flatness: Within operating passband $f_{L,f} < f < f_{H,f}$, gain fluctuations caused by reactive coupling and stray capacitances are suppressed by factor $(1 + A\beta)$.
- Phase Shift Linearization: Open-loop phase lag $\theta(f) = -\arctan(f/f_H)$ causes non-linear phase delay. Feedback reduces net phase distortion across signal frequencies.
- Ripple Suppression: Smooths out midband ripples and peakings caused by multi-stage reactive networks.
- High-Fidelity Audio Impact: Essential for audio amplifiers to ensure uniform amplification across the full human audible spectrum (20 Hz – 20 kHz).

Parameter 7: Non-Linear Harmonic Distortion Reduction (D_f)

- Distortion Mechanism: Large signal swings push transistors into non-linear transfer regions, generating harmonic distortion voltage D at the output.
- Feedback Output Equation: Output voltage with distortion: $V_o = AV_i + D$. Substituting $V_i = V_s - \beta V_o$ gives $V_o = A(V_s - \beta V_o) + D$.
- Algebraic Derivation: $V_o(1 + A\beta) = AV_s + D \implies V_o = \frac{AV_s}{1+A\beta} + \frac{D}{1+A\beta}$.
- Closed-Loop Distortion Formula: $V_o = A_f V_s + D_f$, where closed-loop distortion $D_f = \frac{D}{1+A\beta}$. Non-linear harmonic distortion is reduced by exact factor $(1 + A\beta)$!

Parameter 8: Noise Reduction & Signal-to-Noise Ratio (SNR)

- Internal Stage Noise Suppression: Power supply hum (50/100 Hz ripple) and thermal noise N generated within intermediate driver or output stages are reduced: $N_f = \frac{N}{1+A\beta}$.
- Input Stage Noise Constraint: Noise voltage N_i generated at the primary input stage (first transistor) is amplified along with signal V_s.
- Output Signal & Noise Scaling: Output signal $V_{os} = A_f V_s$; output input-noise $V_{on} = A_f N_i$.
- SNR Invariance Rule: Signal-to-Noise Ratio at output $SNR_{out} = \frac{V_{os}}{V_{on}} = \frac{A_f V_s}{A_f N_i} = \frac{V_s}{N_i} = SNR_{in}$. Negative feedback CANNOT improve input stage SNR.

Numerical Problem: Full Parameter Evaluation Under Feedback

- Given Open-Loop Parameters: $A_0 = 1000$, $R_{in} = 2$ kΩ, $R_{out} = 40$ kΩ, $f_L = 50$ Hz, $f_H = 50$ kHz, harmonic distortion $D = 10\%$, internal noise $N = 20$ mV. Feedback ratio $\beta = 0.039$ (Voltage-Series topology).
- Desensitivity Factor Calculation: $(1 + A_0\beta) = 1 + (1000 \times 0.039) = 1 + 39 = 40$ (32 dB feedback).
- Calculated Closed-Loop Parameters:
- 1. Gain: $A_f = \frac{1000}{40} = 25$ V/V.
- 2. Input Impedance: $R_{in,f} = R_{in}(1 + A_0\beta) = 2k \times 40 = 80$ kΩ.
- 3. Output Impedance: $R_{out,f} = \frac{R_{out}}{1+A_0\beta} = \frac{40k}{40} = 1$ kΩ.
- 4. Upper Cutoff Frequency: $f_{H,f} = 50 \text{ kHz} \times 40 = 2.0$ MHz.
- 5. Lower Cutoff Frequency: $f_{L,f} = \frac{50 \text{ Hz}}{40} = 1.25$ Hz.
- 6. Distortion: $D_f = \frac{10\%}{40} = 0.25\%$. 7. Internal Noise: $N_f = \frac{20 \text{ mV}}{40} = 0.5$ mV.

Numerical Problem: Impedance Transformation in Current-Shunt Feedback

- Given Circuit: Current-Shunt feedback amplifier with open-loop current gain $A_i = 400$, input impedance $R_{in} = 1.5$ kΩ, output impedance $R_{out} = 10$ kΩ, feedback factor $\beta_i = 0.09$.
- Desensitivity Factor: $(1 + A_i\beta_i) = 1 + (400 \times 0.09) = 1 + 36 = 37$.
- Input Impedance Analysis: Input connection is SHUNT $\implies R_{in,f} = \frac{R_{in}}{1+A_i\beta_i} = \frac{1500\ \Omega}{37} = 40.54\ \Omega$.
- Output Impedance Analysis: Output connection is SERIES (current sampling) $\implies R_{out,f} = R_{out}(1 + A_i\beta_i) = 10\ \text{k}\Omega \times 37 = 370\ \text{k}\Omega$.
- Engineering Function: Transforms stage into an ideal current amplifier with low R_{in} (40.54 Ω) and ultra-high R_{out} (370 kΩ).

Comparative Impact Matrix Across 4 Feedback Topologies

- Voltage-Series (Series-Shunt): Gain $A_{vf} = \frac{A_v}{1+A\beta}$; $R_{in,f} = R_{in}(1 + A\beta)$ (High); $R_{out,f} = \frac{R_{out}}{1+A\beta}$ (Low). Function: Ideal Voltage Amplifier.
- Voltage-Shunt (Shunt-Shunt): Gain $R_{mf} = \frac{R_m}{1+A\beta}$; $R_{in,f} = \frac{R_{in}}{1+A\beta}$ (Low); $R_{out,f} = \frac{R_{out}}{1+A\beta}$ (Low). Function: Ideal Transresistance Amplifier.
- Current-Series (Series-Series): Gain $G_{mf} = \frac{G_m}{1+A\beta}$; $R_{in,f} = R_{in}(1 + A\beta)$ (High); $R_{out,f} = R_{out}(1 + A\beta)$ (High). Function: Ideal Transconductance Amplifier.
- Current-Shunt (Shunt-Series): Gain $A_{if} = \frac{A_i}{1+A\beta}$; $R_{in,f} = \frac{R_{in}}{1+A\beta}$ (Low); $R_{out,f} = R_{out}(1 + A\beta)$ (High). Function: Ideal Current Amplifier.

Summary & Key Takeaways: Parameter Effects of Negative Feedback

- Gain & Desensitivity: Open-loop gain is reduced to $A_f = \frac{A}{1+A\beta}$, suppressing gain variations by factor $(1 + A\beta)$.
- Impedance Control: Series mixing boosts input impedance; shunt mixing reduces input impedance. Voltage sampling reduces output impedance; current sampling boosts output impedance.
- Bandwidth & Linearity: Bandwidth expands by $(1 + A\beta)$ $(BW_f = BW \cdot (1 + A\beta))$, while non-linear harmonic distortion drops to $D_f = \frac{D}{1+A\beta}$.
- Noise Limits: Internal stage noise and power supply hum are reduced to $N_f = \frac{N}{1+A\beta}$, but primary input stage SNR remains unchanged.