Lecture 29: Types of feedback

Feedback in amplifiers

DI02011011: Electronics Circuit and Application (ECA)

Lecture Agenda & Outline

- 1. Topological Taxonomy: Classification by Output Sampling (Voltage/Current) and Input Mixing (Series/Shunt)
- 2. Voltage-Series (Series-Shunt) Feedback: BJT Two-Stage Feedback Pair Schematics and Op-Amp Non-Inverting Stage
- 3. Current-Series (Series-Series) Feedback: Single-Stage CE/CS Unbypassed Emitter/Source Resistor Stage
- 4. Voltage-Shunt (Shunt-Shunt) Feedback: BJT Collector-to-Base Feedback Resistor and Op-Amp Inverting Amplifier
- 5. Current-Shunt (Shunt-Series) Feedback: Two-Stage BJT Current Amplifier Circuit Configuration
- 6. Step-by-Step Worked Engineering Examples and Comprehensive Topological Comparison Matrix

Formal Taxonomy of the Four Feedback Topologies

- Classification Basis: Feedback circuits are classified according to the physical quantity sampled at the output node (Voltage or Current) and the physical quantity summed at the input node (Series Voltage or Shunt Current).
- 1. Voltage-Series (Series-Shunt): Output Voltage V_o sampled in parallel; Feedback Voltage V_f summed in series with input source V_s.
- 2. Current-Series (Series-Series): Output Current I_o sampled in series; Feedback Voltage V_f summed in series with input source V_s.
- 3. Voltage-Shunt (Shunt-Shunt): Output Voltage V_o sampled in parallel; Feedback Current I_f summed in parallel (shunt) with input source I_s.
- 4. Current-Shunt (Shunt-Series): Output Current I_o sampled in series; Feedback Current I_f summed in parallel (shunt) with input source I_s.
- Source & Load Characterization: Series input requires voltage source (low R_s); Shunt input requires current source (high R_s). Voltage output drives high load R_L; Current output drives low load R_L.

Voltage-Series (Series-Shunt) Topology & Impedance Effects

- Circuit Mechanics: Voltage sampler measures output voltage V_o across load R_L; Feedback network presents attenuation beta_v = V_f / V_o; Series summer subtracts feedback voltage V_f from input voltage V_s.
- Ideal Amplifier Equivalent: Acts as an ideal Voltage Amplifier (Voltage-Controlled Voltage Source, VCVS).
- Transfer Gain Metric: Closed-loop voltage gain A_vf = V_o / V_s = A_v / (1 + A_v * beta_v).
- Asymptotic Limit: When open-loop loop gain A_v * beta_v ¿¿ 1, closed-loop gain A_vf approx 1 / beta_v.
- Input Impedance Transformation: Series input mixing boosts input resistance: R_inf = R_in *(1 + A_v* beta_v). Prevents loading on high-impedance voltage sources.
- Output Impedance Transformation: Voltage output sampling lowers output resistance: R_of = R_o / (1 + A_v * beta_v). Delivers stiff, load-independent output voltage.

Discrete BJT Voltage-Series Feedback Pair Circuit Analysis

- Circuit Configuration: Two-stage cascaded Common-Emitter (CE) BJT amplifier. Feedback resistor R_F is connected from Stage 2 emitter node to Stage 1 emitter node.
- AC Signal Flow: Output voltage V_o at Stage 2 collector causes AC current through R_F into Stage 1 emitter resistor R_E1, producing feedback voltage V_f = V_o * [R_E1 / (R_E1 + R_F)] across R_E1.
- Input Summer Operation: Input voltage V_s is applied to Stage 1 base. Base-emitter signal voltage is V_be1 = V_s - V_f (Series Voltage Summing).
- Feedback Ratio Formulation: beta_v = V_f / V_o = R_E1 / (R_E1 + R_F).
- Loading Resistances Incorporation: r_11 = R_E1 —— R_F added in series with Stage 1 emitter; r_22 = R_E1 + R_F added in parallel with Stage 2 collector load.
- Closed-Loop Voltage Gain: A_vf = V_o / V_s approx (R_E1 + R_F) / R_E1 = 1 + R_F / R_E1.

Current-Series (Series-Series) Topology & Transconductance

- Circuit Mechanics: Current sampler senses output current I_o flowing through load R_L; Feedback network generates feedback voltage V_f = beta_z * I_o; Series summer subtracts V_f from input V_s.
- Ideal Amplifier Equivalent: Acts as an ideal Transconductance Amplifier (Voltage-Controlled Current Source, VCCS).
- Transfer Gain Metric: Open-loop transconductance A_m = I_o / V_i (Siemens); Feedback factor beta_z = V_f / I_o (Ohms). Loop gain T = A_m * beta_z.
- Closed-Loop Transconductance: A_mf = I_o / V_s = A_m / (1 + A_m *beta_z). Closed-loop voltage gain A_vf = V_o / V_s = -A_mf* R_L.
- Input Impedance Transformation: Series input mixing boosts input resistance: R_inf = R_in *(1 + A_m* beta_z).
- Output Impedance Transformation: Current output sampling boosts output resistance: R_of = R_o *(1 + A_m* beta_z). Delivers stiff, load-independent output current.

Discrete Current-Series Circuit: Unbypassed Emitter/Source Resistor

- Single-Stage CE Circuit Configuration: BJT Common-Emitter amplifier with emitter resistor R_E left UNBYPASSED (no parallel bypass capacitor C_E).
- AC Signal Mechanics: Collector current I_c approx I_e flows through unbypassed resistor R_E, generating feedback voltage V_f = I_o * R_E directly in series with base input voltage V_s.
- Feedback Impedance Value: beta_z = V_f / I_o = R_E (Ohms).
- Loaded Transconductance (A_m): For basic CE transistor without feedback, A_m = g_m. Loop gain T = g_m * R_E.
- Closed-Loop Transconductance: A_mf = g_m / (1 + g_m * R_E).
- Closed-Loop Voltage Gain Derivation: A_vf = -A_mf *R_C = -[g_m / (1 + g_m* R_E)] *R_C. If *g_m* R_E ¿¿ 1, then A_vf approx -R_C / R_E!
- FET Source Follower Variant: CS MOSFET with unbypassed source resistor R_S yields feedback factor beta_z = R_S and A_vf approx -R_D / R_S.

Voltage-Shunt (Shunt-Shunt) Topology & Transresistance

- Circuit Mechanics: Voltage sampler measures output voltage V_o across load R_L; Feedback network generates feedback current I_f = beta_g * V_o; Shunt summer subtracts I_f from input current source I_s.
- Ideal Amplifier Equivalent: Acts as an ideal Transresistance Amplifier (Current-Controlled Voltage Source, CCVS).
- Transfer Gain Metric: Open-loop transresistance A_r = V_o / I_i (Ohms); Feedback factor beta_g = I_f / V_o (Siemens). Loop gain T = A_r * beta_g.
- Closed-Loop Transresistance: A_rf = V_o / I_s = A_r / (1 + A_r * beta_g). Closed-loop voltage gain from source V_s (via R_s): A_vf = V_o / V_s = -A_rf / R_s.
- Input Impedance Transformation: Shunt input mixing lowers input resistance: R_inf = R_in / (1 + A_r * beta_g). Creates virtual ground at input node.
- Output Impedance Transformation: Voltage output sampling lowers output resistance: R_of = R_o / (1 + A_r * beta_g).

Discrete Voltage-Shunt Circuit: Collector-to-Base Feedback Resistor

- Circuit Configuration: Single-stage Common-Emitter BJT amplifier with a feedback resistor R_F connected directly between collector (output node) and base (input node).
- AC Signal Mechanics: Output voltage V_o at collector drives AC feedback current I_f = (V_o - V_b) / R_F approx V_o / R_F into base input node, subtracting from signal current I_s.
- Feedback Admittance Value: beta_g = I_f / V_o = -1 / R_F (Siemens).
- Loaded Open-Loop Transresistance (A_r): A_r = V_o / I_i = -g_m *(R_C —— r_pi —— R_F)* r_pi.
- Closed-Loop Transresistance Asymptote: When loop gain —A_r * beta_g— ¿¿ 1, closed-loop transresistance A_rf = V_o / I_s approx 1 / beta_g = -R_F!
- Closed-Loop Voltage Gain (from Voltage Source V_s with R_s): A_vf = V_o / V_s = (V_o / I_s) / R_s = -R_F / R_s.
- Miller Effect Perspective: Resistor R_F appears at input as equivalent parallel resistance R_in,M = R_F / (1 + —A_v—), explaining the drastic drop in R_inf.

Current-Shunt (Shunt-Series) Topology & Current Amplification

- Circuit Mechanics: Current sampler senses output current I_o flowing through load; Feedback network generates feedback current $I_f = beta_i * I_o$; Shunt summer subtracts I_f from input current I_s.
- Ideal Amplifier Equivalent: Acts as an ideal Current Amplifier (Current-Controlled Current Source, CCCS).
- Transfer Gain Metric: Open-loop current gain $A_i = I_o / I_i$ (dimensionless); Feedback factor $beta_i = I_f / I_o$ (dimensionless). Loop gain $T = A_i * beta_i$.
- Closed-Loop Current Gain: $A_if = I_o / I_s = A_i / (1 + A_i * beta_i)$. Asymptote for large loop gain: A_if approx $1 / beta_i$.
- Input Impedance Transformation: Shunt input mixing lowers input resistance: $R_inf = R_in / (1 + A_i * beta_i)$. Ideal for low-impedance current inputs.
- Output Impedance Transformation: Current output sampling boosts output resistance: $R_of = R_o$ $(1 + A_i$ $beta_i)$. Ideal for driving low-impedance current loads.

Discrete BJT Current-Shunt Circuit: Two-Stage Current Pair

- Circuit Configuration: Two-stage BJT amplifier. Feedback resistor R_F is connected from Stage 2 emitter to Stage 1 base input node. Emitter resistor R_{E2} is unbypassed.
- AC Signal Flow: Stage 2 AC emitter current I_{e2} approx I_o flows through R_{E2}, generating AC voltage $V_{e2} = I_o * R_{E2}$. This drives feedback current $I_f = V_{e2} / R_F$ into Stage 1 base node.
- Feedback Ratio Formulation: $beta_i = I_f / I_o = [I_o * R_{E2} / (R_{E2} + R_F)] / I_o = R_{E2} / (R_{E2} + R_F)$.
- Closed-Loop Current Gain Asymptote: $A_{if} = I_o / I_s$ approx $1 / beta_i = (R_{E2} + R_F) / R_{E2} = 1 + R_F / R_{E2}$.
- Application in Photodiode Preamps: Used to amplify low-level photocurrents from sensors while maintaining low input impedance to prevent RC speed degradation.

Comprehensive Op-Amp Non-Inverting Voltage-Series Analysis

- Circuit Configuration: Op-amp with input signal V_s applied to non-inverting (+) terminal. Feedback voltage divider (R_1, R_2) connected from output V_o to inverting (-) terminal.
- Step 1 (Topology Identification): Output voltage V_o is sampled; feedback voltage V_f = V_o * [R_1 / (R_1 + R_2)] is subtracted at differential input (V_+ - V_-) =¿ Voltage-Series Feedback.
- Step 2 (Feedback Factor beta_v): beta_v = V_f / V_o = R_1 / (R_1 + R_2).
- Step 3 (Open-Loop Parameters): Ideal op-amp has open-loop voltage gain A_OL = 10^5 (100 dB), differential input resistance R_in = 2 M-Ohm, output resistance R_o = 75 Ohm.
- Step 4 (Closed-Loop Gain A_vf): Given R_1 = 1 k-Ohm, R_2 = 9 k-Ohm =¿ beta_v = 1k / (1k + 9k) = 0.1.
- Loop Gain T = A_OL *beta_v = 10^5* 0.1 = 10,000 (80 dB).
- A_vf = A_OL / (1 + T) = 10^5 / 10,001 = 9.999 (exact 1 / beta_v = 10!).
- Step 5 (Transformed Impedances): Closed-loop input resistance R_inf = 2 M-Ohm * (1 + 10,000) = 20.002 Giga-Ohms!
- Closed-loop output resistance R_of = 75 Ohm / (1 + 10,000) = 0.0075 Ohms (7.5 milli-Ohms)!

Comprehensive Op-Amp Inverting Voltage-Shunt Analysis

- Circuit Configuration: Op-amp with non-inverting (+) terminal grounded. Input source V_s connected through R_1 to inverting (-) terminal. Feedback resistor R_F connected from output V_o to (-) terminal.
- Step 1 (Topology Identification): Output voltage V_o sampled; feedback current I_f = (V_o - V_-) / R_F summed in parallel with input current I_in = (V_s - V_-) / R_1 at inverting node =¿ Voltage-Shunt Feedback.
- Step 2 (Virtual Ground Concept): High loop gain forces differential voltage (V_+ - V_-) -¿ 0. Since V_+ = 0V, inverting terminal V_- is held at Virtual Ground (0V).
- Step 3 (Nodal Current Equilibrium): Summing AC currents at inverting node: I_in + I_f = 0 =¿ (V_s - 0) / R_1 + (V_o - 0) / R_F = 0.
- Step 4 (Closed-Loop Voltage Gain Derivation): V_o / R_F = -V_s / R_1 =¿ A_vf = V_o / V_s = -R_F / R_1.
- Step 5 (Closed-Loop Input Impedance): Looking into input terminal past R_1: Resistance at inverting node R_in,node = R_in / (1 + A_OL * beta_g) approx 0 Ohm. Therefore, total input resistance seen by source is R_inf = R_1 + 0 = R_1.

Summary & Topological Comparison Matrix

- Comprehensive Feedback Comparison Matrix:
- 1. Voltage-Series: Samples V_o, Sums V_f Series — A_vf approx 1 / beta_v — R_inf = R_in(1+T) [HIGH] — R_of = R_o/(1+T) [LOW]. Circuit: Op-Amp Non-Inverting, BJT 2-stage voltage pair.
- 2. Current-Series: Samples I_o, Sums V_f Series — A_mf approx 1 / beta_z — R_inf = R_in(1+T) [HIGH] — R_of = R_o(1+T) [HIGH]. Circuit: Unbypassed R_E / R_S stage.
- 3. Voltage-Shunt: Samples V_o, Sums I_f Shunt — A_rf approx 1 / beta_g — R_inf = R_in/(1+T) [LOW] — R_of = R_o/(1+T) [LOW]. Circuit: Op-Amp Inverting, Collector-Base R_F.
- 4. Current-Shunt: Samples I_o, Sums I_f Shunt — A_if approx 1 / beta_i — R_inf = R_in/(1+T) [LOW] — R_of = R_o(1+T) [HIGH]. Circuit: BJT 2-stage current pair.
- Design Rule: Select Voltage sampling to deliver stable voltage; Current sampling for stable current. Select Series mixing for high input impedance; Shunt mixing for low input impedance.