EE 171

Feedback
(Chapter 9)

University of California, Santa Cruz
June 5, 2007
Agenda

• Negative Feedback: Why?
  – Gain stability (Section 9.1)
  – Reduction of distortion (Section 9.2)

• Frequency Dependence of Feedback
  – Gain margin and phase margin
  – Compensation

• Summary
General Feedback Circuit

- **Negative feedback**: \( x_i = x_s - \beta x_o \)
  - \( \beta \) typically less than 1
- **Output**: \( x_o = A \ (x_s - \beta x_o) \)
  - **Gain**: 
    \[
    A_f = \frac{x_o}{x_s} = \frac{A}{1 + A\beta}
    \]
  - Typically lower than open loop gain
    - No feedback: \( \beta = 0 \), \( A_f = A \) (open loop gain)
Positive Feedback

• Can be used to increase the gain
  • \( x_i = x_s + \beta x_o \)
  • \( A_f = \frac{x_o}{x_s} = \frac{A}{1 - A\beta} \)
  • Need \( A\beta < 1 \)
    • Can also occur using negative feedback (\( A < 0 \))
    • If \( A = -10, \beta = 0.0999 \) then \( A_f = -10,000 \)

• Disadvantage: poor gain stability
  • If \( A = -9.9 \) (10% decrease) then \( A_f = -901 \)
    • Possible since \( A \) depends on active device parameters (\( \beta, g_m \))
  • A better approach: use \( A\beta >> 1 \)
    • \( A_f \approx \frac{1}{\beta} \)
    • Use passive components for \( \beta \) (minimal change)
    • Want \( \beta \) to be small for large gain
    • If \( A = 10,000 \) and \( \beta = 0.01 \) then \( A_f = 99.01 \)
    • If \( A = 9000 \) (10% decrease), then \( A_f = 98.90 \)
Distortion

- Amplifiers could have poor transfer characteristics
  - Poor design
  - Loading effects
- Can result in distorted, non-symmetric output characteristics
  - If input = 1 v, output = 10 v
  - If input = −1 v, output = −5 v

Figure 9.3 Output of amplifier of Figure 9.2 for \( x_{\text{in}} = \sin(\Omega t) \).
Notice the distortion resulting from the nonlinear transfer characteristic.
Using Negative Feedback to Reduce Distortion

- An additional amplifier (pre-amp) is used to increase the open-loop gain
  - Recall: need $A\beta >> 1$
  - $A_f = \frac{10000}{1001} = 9.99$ (+ signal)
  - $A_f = \frac{5000}{501} = 9.98$ (- signal)
  - Without pre-amp, $A_f = 5$ (+) and 6.66 (-)
    - Still some distortion

\[
A_f = \frac{x_o}{x_s} = \frac{A}{1 + A\beta}
\]

\[
x_i' = 1000x_i = 1000(x_s - x_f) = 1000(x_s - 0.1x_o)
\]
Reducing Distortion

• Output signal
  • Input to the non-linear amplifier is now a pre-distorted signal

Input: $x_s(t) = \sin \omega t$

For positive signals:
$$x_o = 10x_i'$$
$$x_i' = 1000(x_s - x_i')$$
$$x_i' = \frac{1000}{1001} x_s = 0.999x_s$$

For negative signals:
$$x_o = 5x_i'$$
$$x_i' = 1000(x_s - 0.5x_i')$$
$$x_i' = \frac{1000}{501} x_s = 1.996x_s$$
An Example of a Non-Linear Amplifier

- Class-B output stage
  - Used instead of an emitter follower (0 static power dissipation)
    - Only 1 BJT on at any time
- Has a non-linear transfer characteristic
  - Need 0.6 v to turn on either transistor
  - Gain close to 1 ($V_{out} = V_{in} - V_{BE}$ diode drop)
Class-B Power Amplifier

- Cascade a differential amplifier with a Class-B output stage
  - Assume DA has a large gain \((A\beta \gg 1, A_f = 1/\beta = 1/0.1 = 10)\)
  - With switch at ‘B’, input signal to output stage is distorted
    - If feedback is done before the output stage (switch at ‘A’), there is distortion at \(V_o\)

\[ v_f = \frac{R_2}{R_1 + R_2} v_o = \beta \ v_o \]
Frequency Dependence of Gain

• In general, $A$ (open-loop gain) is not a constant
  • Depending on the frequency, you can have a 0 denominator (pole) or a zero numerator (zero)
  • Poles and zeros can be illustrated in the complex plane
    • Typically located in quadrants II and III
    • Poles with a non-zero imaginary part occur in conjugate pairs

\[ \delta = \frac{\sigma}{\omega_n} = \cos \theta \]

Conjugate pole at $s = -\sigma - j\omega$
Transient Response Based on Poles

- The location of the poles determines the transient response of the circuit
  - Negative real poles: exponential decay
- Example: RC circuit

\[ V_{in}(s) + \frac{1}{sC} \rightarrow \frac{V_{o}(s)}{-} = A_v \frac{V_{o}(s)}{V_{in}(s)} = \frac{1}{sC} \frac{1}{R + \frac{1}{sC}} = \frac{1}{1 + sRC} \]

Pole at \( s = -1 / (RC) \)

Large RC (slower decay)
Transient Response of Complex Poles

- Poles which are complex result in exponential decay with ringing
  - Example: LCR circuits from EE 70
- Typically want poles where the decay occurs faster than the ringing (blue area)
Frequency Response Based on Pole Location

- The location of poles and zeros also determines the frequency response of the circuit.
- For complex poles near the imaginary axis, the gain is large at certain frequencies.
  - Leads to undesirable ringing in the transient response (Example 9.6)
Amplifier Design

• For gain stability and distortion improvement, negative feedback is desirable
  – Need large A ($A\beta >> 1$), small B ($A_f = \text{large}$)

• Need to cascade amplifier stages to get a high open-loop gain
  – From Chapter 8, each amplifier stage contributes at least 1 pole (RC low pass filter)
Poles and Feedback

- Once feedback is used, poles which use to be along the negative real axis can shift
- Single pole: Example 9.5, Exercise 9.16 and 9.17

\[
A = \frac{v_o}{v_i} = 10^5 \frac{1}{R_P + \frac{1}{sC_P}} = 10^5 \frac{sC_P R_P + 1}{sC_P R_P + 1} = 10^5 \frac{1}{1 + \frac{s}{\omega_b}}
\]

\[
\omega_b = 2\pi f_b = \frac{1}{C_P R_P}
\]

\[
A_f = \frac{v_o}{v_i} = \frac{A}{1 + A\beta}
\]

\[
\beta = \frac{1000}{1000 + 99000} = 0.01
\]
Single Poles and Feedback

- Results in a shift in the pole along the negative real axis
  - Higher half-power frequency, but lower gain
  - Gain-bandwidth product = constant

\[ A_f = \frac{v_o}{v_i} = \frac{A}{1 + A\beta} = \frac{10^5}{1 + \frac{s}{\omega_b}} = \frac{10^5}{1 + \frac{s}{\omega_b} + 10^3} = \frac{99.9}{1 + \frac{s}{1001\omega_b}} \]
Multiple Poles and Feedback

- For an amplifier with multiple poles, the poles which used to be along the negative real axis can shift to the complex plane.
- Can cause transient response problems (Example 9.6)

\[ v_1 = \frac{1}{sC_1} \frac{1}{R_1 + \frac{1}{sC_1}} v_i \]
\[ v_2 = \frac{1}{sC_2} \frac{1}{R_2 + \frac{1}{sC_2}} v_1 \]
\[ A = \frac{v_2}{v_i} = \frac{10^4}{(1 + R_1 C_1 s)(1 + R_2 C_2 s)} \]

Open-loop gain

For \( C_1 = C_2 = 159.15 \text{ pF} \), there are two poles at \( s = -6.28 \times 10^5 \)
Multiple Poles and Feedback (2)

\[ A_f = \frac{A}{1 + A\beta} = \frac{10^4}{(1 + RC_s)^2} \]

\[ 1 + 0.1 \frac{10^4}{(1 + RC_s)^2} \]

\[ A_f = \frac{10^4}{1 + 2RC_s + R^2C^2s^2 + 10^3} \]

\[ A_f = \frac{10^4}{1001 + 3.18 \times 10^{-6}s + 2.53 \times 10^{-12}s^2} \]

Poles shift to \( s = -6.28 \times 10^5 +/\!- 1.9869 \times 10^7 \) j

(use quadratic formula)

Unstable amplifier: Im part of \( s > \) Re Part of \( s \)

(see slides 12 and 13)
Stability: Gain Margin and Phase Margin

- For stability, the open loop gain that corresponds to a $180^\circ$ phase shift needs to be $< 1$
  - If the gain is $> 1$, then the original signal (or an amplified version) will be fed back to the input ($A\beta = -1$)
  - Gain margin: how far below 0 dB (typically want at least 10 dB)
- Use feedback to lower the gain so that at $180^\circ$, it is lower than 1
  - Sets an upper limit for $\beta$ (want to be at least 1)
- Stability can also be defined based on a phase margin
  - Want phase margin $> 45$ degrees
Stability Example: Three Pole Amplifier

- Mid-band gain = 20 \log 1000 = 60 \text{ dB}
- Break frequency = 100 \text{ kHz}
- Magnitude drops at 60 dB/decade
  - Gain at 100 kHz: 60 \text{ dB}
  - Gain at 1 MHz: 0 \text{ dB}
- Phase: 0 degrees for \( f << 100 \text{ kHz} \) and 270 degrees for \( f >> 100 \text{ kHz} \)
- Stability problem: phase at 180° (before 1 MHz) is not 0 dB
  - From exact plots, you need to bring the gain down by 42 dB for stability (\( \beta = 0.008 \))
Compensation

- Add an extra pole to bring down the Bode plot
  - Low frequency, high RC
Compensation in IC Op-Amps

- $Q_1, Q_2$: differential amplifier
- $Q_3$: emitter follower
- $Q_4$: common emitter
- $Q_5, Q_6$: class-B output stage
- Open loop gain (without compensation)

Open loop gain (without compensation)
Not 0 dB or below

Use Miller Theorem to get a high $C$

- High feedback impedance in common emitter amplifier
- Don’t need a large capacitance
- Higher $R_{out}$ from differential amplifier vs. emitter follower (hook up $C$ to base of $Q_3$ not $Q_4$)
Compensation in IC Op-Amps (2)

- With compensation, the Bode plot behaves like a single pole amplifier
  - Gain-bandwidth product is constant
- Another example: CMOS IC Op-Amp from Lecture 13 (slide 17)
Summary

Required skills to pass the course:

1. Analyze circuits with open and closed loops. Calculate node voltages and currents using Kirchhoff's laws. Understand the concept of simple circuits and how they work.
2. Use BJT amplifiers and amplifiers with a single input. Understand the concept of simple circuits and how they work.
3. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
4. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
5. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
6. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
7. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
8. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
10. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
11. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
12. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
13. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
15. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
16. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
17. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
18. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
19. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
20. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
22. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.
23. Implement differential-coupled CMOS inverters. Understand the concept of simple circuits and how they work.

EE171L Analog Electronics
EE171/L Analog Electronics

24. Design and build resistor pull up and CMOS inverter circuits. Measure the transfer characteristics and determine noise margins.
25. Design and Build an analog optical transmission system using an LED, a photodiode and a loudspeaker. Optimize output stage to drive the loudspeaker and optimize signal to noise ratio.

Core topics:
1. Op amps
2. Diodes
3. Bipolar transistors
4. Transistor circuits
5. Small signal model
6. Field effect transistor
7. IC biasing and current sources
8. Differential amplifier
9. Digital logic circuits
10. Frequency response

Optional topics:
Thermal consideration and output stages

Core lab exercises:
1. Op amps
2. Diodes
3. Bipolar transistors
4. JFET transistors
5. CMOS device and logic
6. Analog optical transmission system
Where Do You Go From Here?

• Additional classes

  • EE 172 (Advanced Analog Circuits: Fall 2007)
    Analog circuit design covering the basic amplifier configurations, current mirrors, differential amplifiers, frequency response, feedback amplifiers, noise, bandgap references, one- and two-stage operational amplifier design, feedback amplifier stability, switch capacitor circuits and optionally the fundamentals of digital-to-analog and analog-to-digital converters. Emphasis throughout will be on the development of approximate and intuitive methods for understanding and designing circuits. Cannot receive credit for this course and course 221. Prerequisite(s): course 171.

  • EE 221 (Advanced Analog Integrated Circuits: Fall 2007)
    Analog integrated circuit design with emphasis on fundamentals of designing linear circuits using CMOS. Covers MOS devices and device modeling, current mirrors, op-amp design, op-amp compensation, comparators, multipliers, voltage references, sample-and-holds, noise, and an introduction to more complicated systems using these building blocks, such as phase locked loops and analog-to-digital converters. If time permits, integrated circuit layout issues and device/circuit fabrication. Students cannot receive credit for this course and course 172. Prerequisite(s): course 171 or equivalent; course 178 or equivalent recommended. Enrollment limited to 20.

  • EE 178 (Device Electronics: Spring 2008)
    This course reviews the fundamental principles, device's materials, and design and introduces the operation of several semiconductor devices. Topics include the motion of charge carriers in solids, equilibrium statistics, the electronic structure of solids, doping, the pn junction, the junction transistor, the Schottky diode, the field-effect transistor, the light-emitting diode, and the photodiode. Prerequisite(s): courses 145/L and 171/L. Enrollment restricted to School of Engineering and Division of Physical and Biological Sciences majors or permission of instructor.
Textbooks and Additional References

- “Analog Integrated Circuits”, P. Gray and R. Meyer
  - Classic text used in analog circuit design courses
- “Design of Analog CMOS Integrated Circuits”, B. Razavi
- “CMOS Analog Circuit Design”, P. Allen and D. Holberg