Chapter 13S

Analog Review Notes, Fall 2013

Contents

13S Analog Review Notes, Fall 2013
13S.1 Jargon Notes Included ................................................. 1
13S.2 Analog ........................................................................... 2
  13S.2.1 Passive ................................................................. 2
  13S.2.2 Discrete Transistor ...................................................... 2
  13S.2.3 Op Amp .................................................................. 3
  13S.2.4 A Common Theme: Impedances ................................. 4
13S.3 Jargon: Passive, Discrete Transistors, Op Amps ................. 5
  13S.3.1 Jargon: Passive Devices ............................................. 5
  13S.3.2 Jargon: Discrete Transistors (bipolar) ......................... 5
  13S.3.3 Jargon: Op Amps ...................................................... 6

13S.1 Jargon Notes Included

We’ve appended, to these review notes, collections of jargon that may jog your memory concerning the many circuits that have raced past you since the start of the course.

---

1Revisions: add jargon, per fall 11 model, whose source is lost (oct 13); beginning with May 2010 notes, add notes re impedances (3/11).
13S.2 Analog

13S.2.1 Passive

13S.2.1.1 RC

- time-domain: look again at pulse input exercises, for various RC values (HW 3, fall 2010)
- frequency domain: this is more usual. Design a filter to keep specified frequency range; how much does it attenuate noise at $f_{\text{noise}}$? Impedance of RF filter: use $R$ (worst case value of $Z$, in or out)

13S.2.1.2 Diode Circuits

- power supplies, of course: “split” is a favorite, and a little hard to remember (ground center of Xformer tap)
- clamp (don’t forget the current-limiting resistor)
- rectifier: full-wave in power supplies—but not possible in ordinary rectifier circuits, like AM demodulator

13S.2.1.3 RLC

This is the most sensitive frequency-dependent circuit we’ve met. Useful as simple radio tuner—and we used it as first stage of simple FM demodulator

13S.2.2 Discrete Transistor

Once we know about op amps, transistors are reduced, for the most part, to serving as muscular helpers for brainy op amp circuits. For example...

- high-current push-pull (op gives low output impedance and beats X-over at modest frequencies)
- current sources (higher current than op amp can provide, and nicer configuration, allowing one to tie load to V+ or ground or V-)

Important case for discrete transistor on its own: power switch:

- bipolar: need base resistor to limit current; note base current may be substantial (about $I_C/10$ not $I_C/\beta$)...
- …therefore you may prefer power MOSFET, which takes negligible drive current
- and note that switch configuration puts full control voltage across $V_{BE}$
- follower configuration (using emitter or source resistor), which wastes much of control voltage across the transistor, and puts less than full supply voltage across the load (inefficient)
- for inductive load, include shunt diode to prevent damaging voltage spike on turn-off

---

1. Well, not quite all across $V_{BE}$: a base resistor must be included, to limit base current; only about 0.6V is applied to the base, as you know.
13S.2.3 Op Amp

This is the core of the analog part of the course (as you have noticed).

- amplifiers: inverting and non-
  - non-inverting good for highest input impedance
  - inverting good for its virtual ground, useful in many circuits:
    * summing circuit (currents sum cleanly; input resistors convert input voltages to currents)
    * very-low $R_{in}$ at virtual ground is ideal for current source transducers, like photodiode and some temperature sensors
    * integrator and differentiator use virtual ground to improve on passive versions

- single-supply amplifiers require attention to biasing, an issue that doesn’t arise in the usual split-supply op amp circuit
  - recall trick of C to ground in single-supply non-inverting amp: cuts DC gain to unity. That’s good for biasing that remains fixed despite gain variation

- integrator
  - circuit is sensitive to op amp imperfections ($I_{bias}$ and $V_{offset}$), so provides a good setting for measuring these effects
  - prevent drift to saturation:
    * feedback resistor is simple, but compromises integration
    * manual reset switch: across feedback cap not output-to-ground
    * electronic reset best done with analog switch—because simpler transistor switch cannot work for both output polarities

- differentiator
  Less satisfactory than integrator because marginally-stable in its simplest form (see below, under stability)

- rectifier, peak-detector: op amp hides the diode drop

- op amp stability questions
  - the theme is always ‘does something in the feedback loop cause a lag that turns negative feedback positive?’
  - capacitive loading or (equivalently--)lowpass in loop are the usual hazards
    * plain capacitive load can cause marginal stability or even sustained oscillation (long BNC)
    * …simple remedy: series resistor; fancy remedy: same, but with ‘split feedback paths:’ high-frequency path bypasses the nasty phase-lagging thing
  - PID is an extreme case, where something very slow is put in loop. Remedy: limit gain, undo a lagging shift by inserting derivative of error; integral drives long-term error down, even at modest overall gain
  - (Similar:) discrete-transistor stability questions are similar but subtler: again, positive feedback. Remedy: cut high-frequency gain by boosting negative (Miller-) feedback with base resistor

- Positive Feedback: Useful
  - Schmitt trigger: positive feedback can stabilize an otherwise-indecisive circuit: usually done with comparator, but can be done with a logic gate that includes hysteresis
  - Oscillators:
    * square wave: ’555 IC oscillator
Analog Review Notes

- sinusoid: Wien bridge self-adjusting gain avoids clipping, avoids dying away
- VCO: can be made from integrator and comparator, letting comparator switch polarity of input to integrator; a less-perfect one can be made from ’555 (as in group audio project)

- voltage regulators:
  - home-made: reference + op amp + pass transistor. Needs stabilizing, because heavy capacitive load is normal. Current limit is standard, too.
  - 3-terminal adjustable: ’317 (more likely as exam question than 3-terminal fixed!)

13S.2.4 A Common Theme: Impedances

This is an issue we have worried about from day 1, when we met the Thevenin model, so let’s recall some wisdom on this topic.

\[ R_{\text{in}}, R_{\text{out}} \text{ for resistive circuits: } R_{\text{Thevenin}} \text{ describes the impedance of the output of a resistive circuit (not the input). When you know the circuit’s innards, by far the fastest way to find } R_{\text{Thevenin}} \text{ is to calculate the parallel resistances of all paths seen from the output.} \]

Though Thevenin is limited to resistive circuits, we generalize its method: \( Z_{\text{out}} \) is all paths seen in parallel (for example, finding the output impedance at a transistor’s collector—see current source note, below.

Dynamic Resistance: \( R_{\text{dynamic}} \): and we use \( R_{\text{dynamic}} \equiv \Delta V/\Delta I \) to calculate the local slope and thus “dynamic resistance” of devices that are not Ohmic

\[ RC \text{ filters: } \] this was one of our first encounters with Horowitz and Hill’s labor-saving use of worst-case values rather than a general answer. For an \( RC \) filter, worst case \( Z_{\text{in}} \) and \( Z_{\text{out}} \) is just \( R \), wonderfully enough.

Discrete transistors: Input Impedance: \( Z_{\text{in}} \): the input to all our discrete-transistor circuits have fed the transistor’s base, and there we get the benefit of the transistor’s current amplification: \( Z_{\text{in}} = \beta \times \{ \text{what’s connected to the emitter} \} \). In the emitter follower, the result often was as simple as \( \beta \times R_E \). In a high-gain common-emitter amplifier it can be more complicated, because a bypassing capacitor parallel to \( R_E \) makes \( r_e \) important so that at signal frequencies \( Z_{\text{in}} \) can be as low as \( \beta \times r_e \).

Output Impedance: \( Z_{\text{out}} \): Here, we must distinguish two cases—radically different, depending on whether the terminal we consider is emitter (as in the follower) or collector (as in current source or common-emitter amp).

The follower shows low \( R_{\text{out}} \) (at the emitter): \( \beta \) provides a “lens” (rose-colored) that improves \( R_{\text{out}} \), reducing what’s on the far side of the transistor by the factor \( \beta \) just as this lens improves \( R_{\text{in}} \) by that factor.

The current source, in radical contrast, provides very large \( R_{\text{out}} \) (at the collector). This is a general truth about any current source, since the nearly-constant current implies a \( \Delta I \) close to zero, as voltage is varied, producing a \( \Delta V/\Delta I \equiv R_{\text{dynamic}} \) that ideally is infinite, and in fact is large (perhaps 100k @1mA)

Since a common-emitter amplifier takes its output at the collector, \( R_{\text{out}} \) for the amp is dominated by \( R_C \), the collector resistor—normally much smaller than the transistor collectors \( R_{\text{dynamic}} \).

Op Amp Circuits: Input Impedance: \( R_{\text{in}} \) can be astronomical, when the input goes directly to the op amp (or comparator-) input. A Golden Rule makes this evident (and feedback boosts differential \( R_{\text{in}} \), if you ever care about this refinement as usually we do not).
• But $R_{in}$ is not huge in the inverting configuration; here it is only $R_1$, the path to virtual ground. If you omit $R_1$, as in an I-to-V converter, then $R_{in}$ becomes very small (ideally zero, and in fact equal to $\{\text{the feedback resistance}\}/(1 + A)$).

**Output Impedance:** $R_{out}$ is low for all op amp amplifiers (and the follower), thanks to feedback, which leads the op amp to oppose strongly any attempt by a load to alter $V_{out}$. (An op amp current source, like all others, of course shows the opposite virtue: very high $R_{out}$).

**Comparator:** an odd case: Because the output stage of a comparator is a switch rather than the push-pull follower of an op amp, the comparator shows an output impedance that switches between two values:

- with output switch ON: $R_{out}$ is low (determined by the saturated switch to ground or $V_-$);
- with output switch OFF: $R_{out}$ is higher (determined by the value of the pullup resistor). This is also the effective $R_{out}$ while output voltage is in transition toward its low value: until the transistor saturates, it looks like a current sink, so $R_{pullup}$ dominates.

### 13S.3 Jargon: Passive, Discrete Transistors, Op Amps

#### 13S.3.1 Jargon: Passive Devices

- **choke** (noun): inductor
- **droop** fall of voltage as effect of loading (loading implies drawing of current)
- **primary** input winding of transformer
- **Q** “Quality Factor” describes the sharpness of the peak of a frequency-selective $RLC$ circuit. $= f_{resonance}/3db-width$ or, equivalently, can be defined as time for resonant oscillation to decay: $= \text{number-of-cycles for energy to decay to } 1/e \text{ of its peak value}$
- **ripple** variation of voltage resulting from partial discharge of power-supply filter capacitor between re-chargings by transformer
- **risetime** time for waveform to rise from 10% of final value to 90%
- **rms** “root mean of squares”. Used to describe power delivered by time-varying waveform. For sine, $V_{rms} = V_{peak}/\sqrt{2}$. This is the DC voltage that would deliver the same power as the time-varying waveform.
- **secondary** output winding of transformer
- **stiff** of a voltage source: means it “droops” little under load
- $V_{peak} =$ “amplitude.” E.g., in $v(t) = Asin\omega t$, “$A$” is peak voltage (see AoE 1.3.1)
- $V_{peak-to-peak}$ or $V_{p-p}$ another way to characterize the size of a waveform; much less common than $V_{peak}$.

#### 13S.3.2 Jargon: Discrete Transistors (bipolar)

- **biasing** (see, for example, AoE 2.2.4) : setting quiescent conditions (see below) so that circuit elements work properly. To bias means, literally, to push off-center. We do that in transistor circuits to allow building with a single supply. The term is more general, as you know. (Compare Ch. 1, sec. 1.30, where a diode is biased into conduction.)
- **bootstrap** (see, for example, AoE 2.4.3): In general, any of several seemingly-impossible circuit tricks (source of term: “pull oneself up by the bootstraps:” impossible in life, possible in electronics!!). In this chapter refers to the trick of making the impedance of a bias divider appear very large, so as to improve the circuit’s input impedance. Also collector bootstrap. See sec. 2.17.
Analog Review Notes

bypassed (-emitter resistor) (see, for example, AoE 2.3.4.1): In common-emitter amp, a capacitor put in parallel with $R_E$ is said to bypass the resistor because it allows AC current an easy path, bypassing the larger impedance of the resistor. Used to achieve high gain while keeping $R_E$ large enough for good stability.

cascode (applied in Wilson Mirror: AoE 2.3.5.2): circuit that uses one transistor to buffer or isolate another from voltage variation, so as to improve performance of the protected transistor. Used in cascode amplifier to beat Miller effect, in current source to beat Early effect.

clipping (illustrated in AoE 2.2.2.4): Flattening of output waveform caused by hitting a limit on output swing. Example: single-supply follower will clip at ground and at the positive supply.

compliance (AoE 2.2.5.4): Well defined in text: “The output voltage range over which a current source behaves well....”

Early effect (See, for example, AoE 2.3.5.1): variation of $I_C$ with $V_{CE}$ at a given value of $V_{BE}$ or $I_C$. Thus it describes transistors’s departure from true current-source behavior.

emitter degeneration (AoE 2.3.3): Placing of resistor between emitter and ground (or other negative supply) in common-emitter amp. It is done so as to stabilize the circuit with variation in temperature. (Source of term: gain is reduced or “degenerated.” General circuit performance is much improved, however!)

impedance “looking” in a direction: impedance at a point considering only the circuit elements lying in one direction or another. Example: at transistor’s base impedance looking back one “sees” bias divider and $R_{source}$; looking into base one “sees” only $\beta \times R_E$.

Miller effect (AoE 2.4.4.2): exaggeration of actual capacitance between output and input of an inverting amplifier, tending to make a small capacitance behave like a much larger capacitance to ground: $I + \text{Gain}$ times as large as actual C.

quiescent (-current, -voltage) (AoE 2.2.4): condition prevailing when no input signal is applied. So, describes DC conditions in an amplifier designed to amplify AC signals. Example: $V_{out-quiescent}$ should be midway between $V_{CC}$ and ground in a single-supply follower, so as to allow maximum output amplitude (or “swing”) without clipping.

split supplies (See AoE 2.2.4.2): Power supplies of both polarities, negative as well as positive. Used in contrast to “single supply.”

transconductance (AoE 2.2.8): Well defined in AoE. Briefly, $\Delta I_{out}/\Delta V_{in}$.

Wilson mirror improved form of current mirror in which a third transistor protects the sensitive output transistor against effects of variation in voltage across the load (third transistor in cascode connection, incidentally). (AoE 2.3.5.2)

13S.3.3 Jargon: Op Amps

bias current ($I_{bias}$): average of input currents flowing at op amp’s two inputs (inverting, non-inverting)

frequency compensation deliberate rolling-off of op amp gain as frequency rises: used to assure stability of feedback circuits despite dangerously-large phase shifts that occur at high frequencies

hysteresis as applied to Schmitt trigger comparator circuits: the voltage difference between upper and lower thresholds

offset current difference between input currents flowing at op amp’s two inputs (inverting, non-inverting)

offset voltage ($V_{offset}$ or $V_{OS}$): op amp’s input stage mismatch voltage: the voltage that one would need to apply, between the inputs, in order to bring the op amp output to zero (op amp running without feedback, “open-loop”)
open loop  circuit wired without feedback

gain-bandwidth product \((f_T)\): a constant describing gain and frequency-response of an op amp; it equals the frequency where op amp open-loop gain has fallen to unity

rail-to-rail  said of inputs and outputs of an op amp. “Rail” is jargon for “power supply.” Some devices show rail-to-rail input range, some show close to this output range; some show both capabilities

saturation  condition in which op amp output voltage has reached one of the two \((\pm)\) output voltage limits, usually within about 1.5V of the two supplies, but much nearer in rail-to-rail-output devices

Schmitt trigger  comparator circuit that includes positive feedback

single-supply op amp  device that accepts inputs close to (and sometimes below) its negative supply, which normally is ground. Device also can drive its output close to the negative supply (ground)

slew rate  maximum rate \((dV/dt)\) at which op amp output voltage can change (assumes substantial voltage difference between op amp input terminals)

summing junction  inverting terminal of op amp, when op amp is wired in inverting configuration: inverting terminal then sums currents. That is, \(I_{\text{feedback}}\) is algebraic sum of all currents input to the summing junction

transresistance amplifier  current to voltage converter:

virtual ground  inverting terminal \((-)\) of op amp, when non-inverting terminal is grounded. Feedback tries to hold \((-)\) at 0V (hence “virtual ground”), and current sent to that terminal does not disappear into “ground,” but instead flows through the feedback path (hence the ground is only “virtual”)