ECE 327: *Electronic Devices and Circuits Laboratory I*

Notes for Lab 7 (Output Filtering/Project Integration Lab)

1. Output filtering

   - Remove higher harmonics from PWM demodulator's pulse-amplitude-modulated output to recover "smooth" reconstruction of input
   - Butterworth low-pass filter
     - Butterworth filter has *maximally* flat passband response (like a boring "graphic equalizer")
       - Slow roll-off, but hard "knee" at -3 dB breakpoint corner frequency
         - Can get faster roll-off with higher order
       - In reality, component variations place ripples in passband
         - Other filters have ripples *by design*, but give steep roll-off at low order
     - Group delay/Phase delay
       - "Shape" of a wave is the result of summing a "group" of sinusoids
       - Can make a square wave look triangular by changing relative phase of harmonics
       - "Linear-phase" response leads to shape integrity
         - Every frequency sees **same time delay**
         - Result: "Group" appears to be delayed
         - Constant "group delay" of envelope = constant "phase delay" of harmonics
         - True linear phase possible with DSP (ECE 600)
       - "Nonlinear-phase" leads to "phase distortion" (i.e., group shape changes)
         - Crossover in speakers (e.g., tweeter and woofer off by 180°); church acoustics; etc.
         - *Some* acoustic phase distortion *expected* (position effects) or *not noticeable* to *ear*
         - Phase distortion demodulates to amplitude distortion for FM, PM, PWM, etc.
       - Butterworth have fairly constant group delay far below corner frequency
         - Frequencies near corner have frequency-dependent delay (compare with Bessel)
         - In lab, 10 kHz test signal has residual modulation harmonics that add out of phase
         - Not a concern in this *for-human-ear* application
   - Implementation: Sallen-and-Key Filter (SKF) topology
     - How to get a hard Butterworth knee?
       - Begin with cascade of two *RC* voltage dividers
         - Second divider loads first divider; response is degraded
       - Add buffer between dividers so that first-order transfer functions multiply
         - High frequency response looks good, but knee is *softer* ($p^2 < p$ when $0 < p < 1$)
       - Use an *RLC* filter
         - Inductors suck
       - Use an *active* filter to get sharpness of *RLC* without an *actual* L
     - SKF bootstraps cascaded filter output
       - (i) Start with two cascaded *RC* filters PLUS output buffer
       - (ii) Reconnect first filter ground to buffer output
       - (iii) Sharper response means Butterworth implementation is now possible

2. Speaker driver

- 0.25 W output means 2 V peak (procedure document explains why; also explains RMS)
  - At full-scale, we're already at 3 V peak (i.e., no amplification *necessary*)
  - Add voltage gain of 2
    - Will *overdrive* full-scale signals
    - Will ensure audible output for small signals
  - Use LSA circuit with gain of 2 and a pole for additional smoothing
- Need current amplifier to drive 8 Ω speaker load
  - ⋆ Despite its looks, circuit is SIMPLE when broken into its parts

(i) Begin with Class-B push–pull amplifier

(ii) To remove *crossover distortion*, add biasing diodes for Class-AB operation

(iii) To reduce push–pull base current, implement transistors as *Sziklai pairs*
  - Sziklai pairs are like *Darlington pairs*
  - *Darlington pair* has two transistors of the *same* type with *shared collectors*
    - Use one transistor to "control" the base of another transistor
    - Acts like "big" transistor with β^2 current gain
    - Has twice the base–emitter drop
  - *Sziklai pair* uses two transistors of *different* types
    - Again, like "big" transistor (of "master" type) with β^2 gain
    - Normal base–emitter drop (i.e., not doubled)

(iv) Replace biasing diodes with "Rubber diode"/"Rubber Zener"
  - Shifts output offset
  - Allows tuning to ensure no class-B crossover distortion

(v) Add emitter–follower to drive biasing circuit
  - Stiff biasing circuit requires high current
  - Also reduces input-output offset

(vi) Add emitter resistors to reduce thermal runaway

(vii) Wrap amplifier in negative voltage feedback
  - Removes any output offset
  - Improves linearity
  - Can use separate feedback circuit or build current amplifier into voltage amplifier

(viii) Finally, capacitively couple speaker to output
  - Output has $5\,V_{DC}$ offset that should *not* be placed across speaker
  - Dual rails would have allowed a direct connection
    - Output offset would have been $0\,V_{DC}$
    - Negative rail can be produced by DC-to-DC switcher
    - *Input* capacitor on both LSAs could be removed too

3. Parts in the lab
   - NO CALCULATIONS are required. Component values are given (with explanations).
     - To help ensure component availability, different sets of components are given.
   - Use low-leakage BiMOS (MOS input, BJT gain, CMOS push–pull output) CA3160 operational amplifier for BUFFER.
     - If CA3160 is not available, use CA3130 with 45–100 pF (e.g., 68 pF) from pin 1 to pin 8 (for feedback stability compensation).
   - Use LM741 or LF351 operational amplifiers for filtering.
   - DO NOT install speaker without SEEING ME FIRST.
     - A large electrolytic capacitor is required for AC coupling amplifier output (5 V average) to speaker (0 V average).
4. Laboratory experience
   - Make use of **bypass capacitors** at *supply pins* to reduce output noise.
   - When taking plots, save as CSV or BMP
     - Saving as BMP prevents extra work, but make sure scope plots show all required information
       - Intervals between horizontal and vertical divisions should be clear
       - In most cases, channel grounds should be shown
       - Channels should be labeled in report (e.g., "top waveform is input")
     - If saving as CSV, be sure to...
       - Label axes and show units
       - Identify waveforms (e.g., "input" and "output")
   - See pin-out handout
   - **Follow lab *book* procedures**
     - Handout gives detailed instructions.
       - Procedure pages have been marked in TOC with (∗).
       - Additional pages given for explanation.
       - Bonus credit is available if time permits.
     - DO NOT use class-AB amplifier components from book!
       - Use design given in supplementary text.
     - If you finish, restore components TO THE CABINET!
       - Do **NOT** place them in the metal tin at your table!
5. Laboratory reports
   - Answer all questions and provide all plots from lab procedures in lab text
   - Include ALL PLOTS from procedure (even if they aren't mentioned in book)
     - USE the plots in your discussion
   - Consider answering some of the questions from the procedure
   - As usual, **LAB REPORT** due a week after lab **COMPLETION**