Lecture 2 – Analog Conditioning Electronics, Pt. 2
Reading…

• Horowitz and Hill
  – Finish Chapter 1, read Chapters 4&5

• Fraden
  – Interface Electronic Circuits Chapter (Chapter 4 of second edition)
Reactive Impedance

- The Capacitor
  - Adds in parallel like resistors add in series
  - Reciprocal-adds in series like resistors add in parallel

- Impedance of capacitor = $-\jmath/\omega C = -\jmath/(2\pi fC)$
  - Pass AC, block DC
    - Capacitor current: $I_c = C dV/dt$

- Impedance of inductor = $j\omega L = j(2\pi fL)$
  - Block AC, pass DC
    - Inductor Voltage: $V = L dI/dt$
Passive RC Filters

- **Passive LP Filter**: RC network: \( f_c = 1/(2\pi RC) \)
  
  \[-3\text{dB} = 0.707\]

![Image of low-pass filter](https://ocw.mit.edu/)

- **Passive HP filter**: RC network: \( f_c = 1/(2\pi RC) \)

![Image of high-pass filter](https://ocw.mit.edu/)

Figure 1.59. Frequency response of low-pass filter.

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Passive RC Filter Rolloff

Bode Plot:
Freq. Response as a log-log plot

Rolloff is 6 dB per Octave (2x)
20 dB per Decade (10x)
Passive RLC Filters

- **Resonant parallel RLC bandpass filters**
  
  \[ Z_{LC} \rightarrow \infty \quad @ \quad f_0 \]

  \[ Q = \omega_0 RC = \frac{f_0}{\Delta f_{3dB}} \]

- **Resonant series RLC notch filters**

  \[ Z_{LC} \rightarrow 0 \quad @ \quad f_0 \]

  \[ Q = \omega_0 (L/R) = \frac{f_0}{\Delta f_{3dB}} \]
Active Filters

- The Differentiator
- The Active High-Pass Filter
- Principle of Feedback Inversion
- The Integrator
- The Leaky Integrator (LP filter)
- Buffered Passive Second-Order Filter
- Sallen-Key (or VCVS) LP, HP, BP filters
- Single-OpAmp VCVS BP filter
The Differentiator

\[ V_{\text{out}} = -R_f \frac{dV_{\text{in}}}{dt} \]

\[ \frac{V_{\text{out}}}{R_f} = -C \frac{dV_{\text{in}}}{dt} \]
The First-Order Active High Pass Filter

- Low impedance drive
- Voltage gain via $R_f/R_i$
The Integrator

\[ Z_c = \frac{1}{j\omega C} \]

\[ i_c = C \frac{dV}{dT} \]

\[ i_c = -i_{in} \implies C \frac{dV_{out}}{dT} = -\frac{V_{in}}{R} \]

\[ \frac{dV_{out}}{dT} = -\frac{V_{in}}{RC} \implies V_{out} = -\frac{1}{RC} \int V_{in} \, dt \]

*Saturates at rail!!*
Integrator with Reset Switch

- Electronic switch in feedback forces output to ground when closed
  - Discharges capacitor
- Resets Integrator!
The First-Order Active Low Pass Filter

The Leaky Integrator → Low Pass Filter

- Low impedance output!!
- Voltage gain \( \beta \)
The Band-Select Filter

- Cascaded high and low pass filters
  - Always follow high-pass with low-pass (noise)
    - Low-Pass cutoff needs to be below high-pass cutoff!
  - No Q, first-order rolloffs
The State Variable Filter

- Analog Computer set up to solve a general Second-Order Differential Equation
  - Exhibits rolloff, damping, and resonance
  - Simultaneous low-pass, bandpass, high-pass, and notch outputs available
Modulars are Analog Computers?

Photo of a Compumedic Analog Computer from 1971 removed due to copyright restrictions. See: Old-Computers.com Museum.

Compumedic Analog Computer from 1971
Limitations on Filter Performance

- Multiple-OpAmp filters can attain higher Q’s than single-OpAmp filters
- Faster OpAmp's work better too
- Accumulated Phase Shifts can cause oscillation!

![Graph showing Q and frequency limits for active bandpass filters, small output swings.](http://ocw.mit.edu/fairuse)
Voltage-Controlled Filter

- Replace integrator input resistors with 2-quadrant multipliers (voltage-controlled amplifiers, or VCA’s)
  - Need to tune both VCA’s together
  - Results in a wide-range tunable filter!
    - Multiplier can be used to tune Q as well

Fig. 9-5. Voltage-controlled filter using IC four-quadrant multipliers.

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Switched-Capacitor Tunable Filters

This circuit contains four independent switches that may be used for off-on control of digital or analog signals. Signals to be controlled must be less than +5 and more than −5 volts.

+5 volts applied to pin 13 turns ON the connection between pins 1 and 2. −5 volts applied to pin 13 turns OFF the connection between pins 1 and 2. The other three switches are similarly controlled.

Input impedance to pin 13 is essentially an open circuit. The OFF resistance of pins 1 and 2 is many megohms; the ON resistance is 300 ohms. A lower-impedance, improved version is available as the 4066.

Many types of analog switches are available (e.g., ADG from Analog Devices, etc.)

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Linear has come out with a couple really nice switched cap filters that really cuts down on the design time:

LTC1564 Tunable low pass filter 10kHz to 150kHz in steps of 10kHz, 8 pole roll-off, programmable 1-16 gain, 3-10V operation.

LTC1062 parallel 5-pole tunable low pass filter. Absolutely zero DC error because the input and output are connected directly with a wire and the filter damps out the high frequencies.
Biasing

- AC Coupling
- Biasing noninverting input
- Biasing at inverting input
Diodes

• The Diode
  – I/V characteristic, ideal diode, forward drop, zeners

Drops ($V_d$):
- Si = 0.6 V
- Ge = 0.3 V
- LED = 2.4-3.5 V
- Schottky = .1-.3 V

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Basic Diode Circuits

• Limiters/Clampers
  – Passive Limiter - normal and zener
  – Precision Zener

Zener Limiters
Absolute Value Circuits

Full Wave Rectifier Circuit

Bottom $R$ is $2/3$ top $R$ in $A_1$?
Absolute Value Circuit (envelope follower)

- A1 and A2 form an absolute value detector
- C6 integrates the absolute value to give the envelope
- Note that the 748 (and its compensation cap) is long obsolete!

Image by MIT OpenCourseWare.
Peak Detector

Capacitor holds peaks!
Need reset switch to continue tracking
Pulse Stretcher

- Resistor continually (and slowly) bleeds capacitor charge
- Automatic “reset”
- Tune time constant to match signal dynamics (so peaks are always followed)
- Enables “lazy” sampling to catch transients
Voltage Multipliers, etc.

Ref: Wikipedia...

Transformer for isolation

Cascaded Villard doubler

- Diodes don’t let capacitors discharge onto source
- AC coupling lets each peak sit atop capacitor voltage
- Each AC peak increments voltage by half-wave height
- Voltage drop at given current increases rapidly (cube) with no. stages, inversely with C, freq
Sampling

- **Nyquist**: $f_{in} < f_s/2$
- **Bandlimited (demodulation) sampling**
  - $\Delta f_{in} < f_s/2$
  - Loose absolute phase information
    - Don’t know whether phase moves forward or backward
- **Quadrature sampling**
  - Bandlimited sampling at $t$ and a quarter-period later
Sampling Aids

- Aliasing for nonperiodic signals??
  - Can miss or miss-sample transient!
  - The Pulse-stretcher to the rescue!
- Sample/Holds
- Analog Multiplexers
- Programmable Gain Amplifiers (PGA’s)
- Voltage-Controlled Amplifiers (VCA’s)
The Basic Sample-Hold Circuit
• Sample-Hold grabs input signal and holds it upon receipt of a pulse edge
• Track-Hold follows the input signal when the gate is high, but holds (latches) it when the gate is low.
• Sample hold acquires quickly – can use slow ADC.
Analog Multiplexers

4-/8-Channel Analog Multiplexers

AD7501/AD7502/AD7503

FEATURES
DTL/TTL/CMOS Direct Interface
Power Dissipation: 20 µW
$R_{on} = 170 \Omega$
Standard 16-Lead DIPs and 20-Terminal Surface Mount Packages

GENERAL DESCRIPTION
The AD7501 and AD7503 are monolithic CMOS, 8-channel analog multiplexers which switch one of eight inputs to a common output, depending on the state of three binary address lines and an “enable” input. The AD7503 is identical to the AD7501 except its “enable” logic is inverted. All digital inputs are TTL/DTL and CMOS logic compatible.

The AD7502 is a monolithic CMOS dual 4-channel analog multiplexer. Depending on the state of two binary address inputs and an “enable,” it switches two output buses to two of eight inputs.

Truth Tables

**AD7501**

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Courtesy of Analog Devices. Used with permission.
Programmable Gain Amplifiers

**Digitally Controlled Programmable-Gain INSTRUMENTATION AMPLIFIER**

**FEATURES**
- **DIGITALLY PROGRAMMABLE GAINS:**
  - DECADE MODEL—PGA202
    - GAINS OF 1, 10, 100, 1000
  - BINARY MODEL—PGA203
    - GAINS OF 1, 2, 4, 8
- **LOW BIAS CURRENT:** 50pA max
- **FAST SETTLING:** 2μs to 0.01%
- **LOW NON-LINEARITY:** 0.012% max
- **HIGH CMRR:** 80dB min
- **NEW TRANSCONDUCTANCE CIRCUITRY**
- **LOW COST**

**APPLICATIONS**
- **DATA ACQUISITION SYSTEMS**
- **AUTO-RANGING CIRCUITS**
- **DYNAMIC RANGE EXPANSION**
- **REMOTE INSTRUMENTATION**
- **TEST EQUIPMENT**

**DESCRIPTION**
The PGA202 is a monolithic instrumentation amplifier with digitally controlled gains of 1, 10, 100, and 1000. The PGA203 provides gains of 1, 2, 4, and 8. Both have TTL or CMOS-compatible inputs for easy microprocessor interface. Both have FET inputs and a new transconductance circuitry that keeps the bandwidth nearly constant with gain. Gain and offsets are laser trimmed to allow use without any external components. Both amplifiers are available in ceramic or plastic packages. The ceramic package is specified over the full industrial temperature range while the plastic package covers the commercial range.

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**High-Speed Programmable Gain INSTRUMENTATION AMPLIFIER**

**FEATURES**
- **DIGITALLY PROGRAMMABLE GAINS:**
  - PGA206: G=1, 2, 4, 8V/V
  - PGA207: G=1, 2, 5, 10V/V
- **TRUE INSTRUMENTATION AMP INPUT**
- **FAST SETTLING:** 3.5μs to 0.01%
- **FET INPUT:** Ig = 100pA max
- **INPUT PROTECTION:** ±40V
- **LOW OFFSET VOLTAGE:** 1.5mV max
- **16-PIN DIP, SOL-16 SOIC PACKAGES**

**APPLICATIONS**
- **MULTIPLE-CHANNEL DATA ACQUISITION**
- **MEDICAL, PHYSIOLOGICAL AMPLIFIER**
- **PC-CONTROLLED ANALOG INPUT BOARDS**

**DESCRIPTION**
The PGA206 and PGA207 are digitally programmable gain instrumentation amplifiers that are ideally suited for data acquisition systems.

The PGA206 and PGA207’s fast settling time allows multiplexed input channels for excellent system efficiency. FET inputs eliminate Ig errors due to analog multiplexer series resistance.

Gains are selected by two CMOS/TTL-compatible address lines. Analog inputs are internally protected for overloads up to ±40V, even with the power supplies off. The PGA206 and PGA207 are laser-trimmed for low offset voltage and low drift.

The PGA206 and PGA207 are available in 16-pin plastic DIP and SOL-16 surface-mount packages. Both are specified for -40°C to +85°C operation.

Courtesy of Burr-Brown. Used with permission.
Front end of the OTA

\[ I_{ctot} = i_{c1} + i_{c2} = \beta \beta \]

OTAs have current outputs

Increasing \( +V_{IN} \) increases \( i_{c1} \), which decreases \( i_{c2} \) (for fixed \(-V_{IN}\)) since the sum of \( i_{c1} \) and \( i_{c2} \) must equal \( i_{CTOT} \)

\( i_{CTOT} \) is proportional to \( \beta \), and the voltage across the collector resistors is proportional to \( i_{CTOT} \), hence the gain of this circuit is set by \( i_{CTOT} \)

MTU ECE Diff Amp Notes
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LM13700 Datasheet
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Voltage Controlled Amplifiers

VCA output for sinusoidal input and given control voltage

\[ V_{out} = V_{in} \times V_{ctl} \text{ (or } 0 \text{ if } V_{ctl} < 0) \]
Voltage-Controlled Amplifiers (VCA)

WIDEBAND VOLTAGE CONTROLLED AMPLIFIER

**DESCRIPTION**

The VCA610 is a wideband, continuously variable, voltage-controlled gain amplifier. It provides linear dB gain control with high impedance inputs. It is designed to be used as a flexible gain-control element in a variety of electronic systems.

The VCA610 has a gain-control range of 77dB (--38.5dB to +38.5dB) providing both gain and attenuation for maximum flexibility in a small SO-8. The broad attenuation range can be used for gradual or controlled channel turn-on and turn-off for applications in which abrupt gain changes can create artifacts or other errors. In addition, the output can be disabled to provide 75dB of attenuation. Group delay variation with gain is typically less than ±2ns across a bandwidth of 1MHz to 15MHz.

The VCA610 has a noise figure of 3.5dB (with an Rs of 200Ω) including the effects of both current and voltage noise. Instantaneous output dynamic range is 70dB for gains of 0dB to +38.5dB with 1MHz noise bandwidth. The output is capable of driving 100Ω.

The high-speed, 300dB/μs, gain-control signal is a unipolar (0V to ±2V) voltage that varies the gain linearly in dB/μV over a --38.5dB to +38.5dB range.

**APPLICATIONS**

- Optical Distance Measurement
- AGC Amplifiers
- Ultrasonic
- Sonar
- Active Filters
- Log Amplifiers
- IF Circuits
- CCD Cameras

**FEATURES**

- **Wideband:** 1MHz to 15MHz
- **Gain Control:** 77dB (0dB to 38.5dB)
- **Low Noise:** 3.5dB (0Ω)
- **High Speed:** 300dB/μs

**PRODUCT DESCRIPTION**

The AD600 and AD602 dual channel, low noise variable gain amplifiers are optimized for use in ultrasound imaging systems, but are applicable to any application requiring very precise gain control, low noise and distortion, and wide bandwidth. Each independent channel provides a gain of 0dB to 40dB in the AD600 and 0dB to 30dB in the AD602. The lower gain of the AD602 results in an improved signal-to-noise ratio at the output. However, both products have the same 1.4 nV/Hz input noise spectral density. The decibel gain is directly proportional to the control voltage, is accurately calibrated, and is supply- and temperature-stable.

The gain-control interfaces are fully differential, providing an input resistance of ~15 MΩ and a scale factor of 32 dBV (that is, 31.25 mV/div) defined by an internal voltage reference. The response time of this interface is less than 1μs. Each channel also has an independent gaging facility that optionally blocks signal transmission and sets the dc output level to within a few millivolts of the output ground. The gaging control input is TTL and CMOS compatible.

The maximum gain of the AD600 is 41.07 dB, and that of the AD602 is 31.07 dB; the -3 dB bandwidth of both models is nominally 55 MHz, essentially independent of the gain. The signal-to-noise ratio (SNR) for a 1 V rms output at a 1 MHz noise bandwidth is typically 76 dB for the AD600 and 86 dB for the AD602. The amplitude response is flat within ±0.5 dB from 100 kHz to 10 MHz; over this frequency range the group delay varies by less than ±2 μs at all gain settings.

The gain-control circuit on each channel can drive 100 Ω load impedances with low distortion. For example, the peak specified output is ±2.5 V, minimum into a 500 Ω load, or ±1 V into a 100 Ω load. For a 200 Ω load in shunt with 5 pF, the total harmonic distortion for a ±1 V sinusoidal output at 10 MHz is typically ~60 dB.

The AD600J and AD602J are specified for operation from 0°C to 70°C, and are available in both 16-lead plastic DIP (N) and 16-lead SOIC (R). The AD600A and AD602A are specified for operation from -40°C to 85°C and are available in both 16-lead cerdip (Q) and 16-lead SOIC (R).

The AD600S and AD602S are specified for operation from -55°C to +125°C and are available in a 16-lead cerdip (Q) package and are MIL-STD-883 compliant. The AD600S and AD602S are also available under DESC SMD 5962-94572.
VCA Arrays

FEATURES
Four High Performance VCAs in a Single Package
0.02% THD
No External Trimming
120 dB Gain Range
0.07 dB Gain Matching (Unity Gain)
Class A or AB Operation

APPLICATIONS
Remote, Automatic, or Computer Volume Controls
Automotive Volume/Balance/Faders
Audio Mixers
Compressor/Limiters/Comandors
Noise Reduction Systems
Automatic Gain Controls
Voltage Controlled Filters
Spatial Sound Processors
Effects Processors

GENERAL DESCRIPTION
The SSM2164 contains four independent voltage controlled amplifiers (VCAs) in a single package. High performance (100 dB dynamic range, 0.02% THD) is provided at a very low cost-per- VCA, resulting in excellent value for cost sensitive gain control applications. Each VCA offers current input and output for maximum design flexibility, and a ground referenced -33 mV/2 dB control port.

All channels are closely matched to within 0.07 dB at unity gain, and 0.24 dB at 40 dB of attenuation. A 120 dB gain range is possible.

A single resistor tailors operation between full Class A and AB modes. The pinout allows upgrading of SSM2024 designs with minimal additional circuitry.

The SSM2164 will operate over a wide supply voltage range of ±4 V to ±18 V. Available in 16-pin P-DIP and SOIC packages, the device is guaranteed for operation over the extended industrial temperature range of -40°C to +85°C.

Courtesy of Analog Devices. Used with permission.
Analog Multipliers (4-Quadrant)

4 Quadrant means: Multiplying by negative values (negative voltages) inverts the output. Either input can go negative.

VCA’s are 2 Quadrant devices – the control input can’t go negative, although the signal input can.