

Book Review

Op Amp Applications

Reviewed by Charles Hansen



Op Amp Applications, edited by Walt Jung, Analog Devices, Inc., July 2002, ISBN 0-916550-26-5, 960 pp., \$40 plus S&H

This eight-chapter, 960-page soft cover book was produced for the Analog Devices 2002 Amplifier Seminar North American and European tours. It is now available through ADI's distributors (Arrow, Avnet, Future, and others). You can obtain further ordering information at 1-800-262-5643 or at www.analog.com/seminar. The order code is OP-AMP-APPLIC-BOOK.

The book was edited by Walt Jung, and compiled with the input from many other ADI engineers: James Bryant, Joe Buxton, Wes Freeman, Paul Hendriks, Walt Kester, Charles Kitchin, Scott Wurcer, and Hank Zumbahlen. It is loaded with application examples, and gives performance tables and selection charts for the ADI op amps recommended for many applications.

The purely "audio" portion of this book, while substantial, is really only a small portion of the total. But the breadth of detail, amplifier types, and the application content should interest even those who only dabble in audio electronics.

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HISTORY

Chapter H is an extensive history of the technology that led to the development of the op amp. It's a fascinating path from the two-element Fleming diode that evolved from Edison's filament electric lamp (1904), to Lee De Forest's "audion" triode (1906), which provided the means for amplification, to Harold Black's 1934 Bell Systems Journal "Stabilized Feedback Amplifiers" paper that led to the first phase of vacuum tube op amp development in the early 1940s. The term "operational amplifier" actually came after World War II, in 1947.

Technology marched forward at a rapid pace after the war. Vacuum tube op amps evolved from the early amplifiers. Analog computing was developed further, often using more accurate chopper-stabilized amplifiers, and the first true vacuum tube op amp products; many based on the Bell Labs M9 amplifier, and then the first commercial op amp, the PHILBRICK K2-W.

With the invention of the germanium transistor in 1947, and later the much improved silicon variety, solid-state versions of the op amp came into being. The first devices were discrete modular transistor designs, then hybrid packages. Jack Kilby and Robert Noyce independently invented the integrated circuit, and Bob Widlar designed the first monolithic op amp, the Fairchild μ A702.

The history continues from Widlar's famous μ A709 to the modern low-noise, high-performance, high-speed op amps we see today. I don't want to diminish the technical content but, to me, this chapter alone is worth the price of the book.

CONTENT BREAKDOWN

Chapter 1 is entitled Op Amp Basics. It starts with

the ideal op amp and generalized feedback circuits: the non-inverting amp and follower, the inverting amp, and the differential amp. Next, it looks at non-ideal static errors and common-mode dynamics. Power supplies play an important part in op amp design, so both single and dual supply issues are discussed. Finally, there is a device selection matrix, showing the decision drivers that can influence the priorities when selecting an op amp (*Table 1*).

The next topic is the topologies of voltage feedback (VFB) and current feedback (CFB) op amps, with an interesting example of CFB using vacuum tubes. The structure of the monolithic op amp starts with single-supply issues. Input stages are well covered: bipolar inputs and bias compensation, super-beta, and JFET. A discussion of rail-to-rail input requirements, and input overdrive/overvoltage (OV) protection follows.

Output stages include NPN, NMOS, complementary-bipolar (CB), "almost rail-to-rail" bipolar junction transistor (BJT), and CMOS. The important practical considerations of open-loop impedance, output surge protection, and the offset voltage trim processes typify the depth of coverage that is found in this book. Finally, there is a look at the op amp process technologies developed by ADI.

One look at the data sheets from various manufacturers shows that a detailed discussion of op amp specifications is absolutely necessary for the poor design engineer, since the significance of any

TABLE 1

FUNCTION	PERFORMANCE	PACKAGE	MARKET
Single, Dual, Quad	Precision	Type	Cost
Single or Dual Supply	Speed	Size	Availability
Supply Voltage	Distortion, Noise	Footprint	
	Low Bias Current		
	Power Dissipation		

spec parameter is highly dependent on the final application. The parameters covered in this section include:

Input offset voltage V_{OS}
 Offset adjustment (internal and external)
 Drift and aging
 Input bias current I_B
 Bias current cancellation and total error calculation
 Input impedance for VFB and CFB
 Noise and signal gain
 Open-loop gain and its non-linearity
 Frequency response
 Slew rate
 Full-power bandwidth (FPBW)
 Settling time
 VFB gain-bandwidth product (GBW)
 CFB optimum feedback resistance
 Bandwidth flatness
 Input noise current (i_n) and voltage (e_n)
 Source impedance and noise
 Frequency characteristics of noise (1/f, popcorn, rms noise over bandwidth)
 Total noise calculations
 Noise effect of resistance and reactance elements
 Distortion, total harmonic distortion (THD), and THD+noise (THD+N)
 Common-mode rejection ratio (CMRR) and power supply rejection ratio (PSRR)
 Power supply decoupling
 Power supply voltage and power dissipation (Pdiss)

The next section delves into precision op amps: a definition of their characteristics, an error budget analysis, chopper stabilization, and noise considerations.

From here, the book moves to high-speed op amps: VFB bandwidth and slew rate calculations, the folded cascode topology, and the ADI current-on-demand and quad core g_m topology. The CFB is also covered, with the effects of feedback caps, and noise comparisons between VFB and CFB circuits.

KINDS OF AMPS

Chapter 2 covers Specialty Amplifiers, starting with instrument amps (in amps). The authors present the definition of the in amp, difference amps, and the 2-op amp and 3-op amp configurations. Next come the details, such as single-supply considerations, error

sources, noise sources, bridge amplifier error budgets, performance tables, and a discussion of input OV protection. Finally, there is a generous selection of applications.

Programmable gain amplifiers (PGA) are next, with design issues, the effects of gain switch R_{on} , differential input PGAs, and some application examples. For applications where galvanic isolation is important, such as the medical electronics field, the next section on isolation amps is a must. There is a discussion of the various methods for analog isolation (transformer, optical, capacitive coupled) and digital isolation (transformer, optical).

Chapter 3 explains how to use op amps with data converters. The introduction talks about data sampling techniques, applications, and trends. An op amp selection criteria table is included. The first section presents analog-digital converter (ADC) and digital-analog converter (DAC) specs. The pertinent topics are transfer functions and DC errors, quantization noise, ADC input-referred noise, calculation of output noise compared with ADC input-referred noise, converter dynamic performance; signal-noise and distortion ratio (SINAD), signal-noise ratio (SNR), and effective number of bits (ENOB); analog BW, aliasing, harmonic distortion, worst harmonics, THD and THD+N, spurious-free dynamic range (SFDR), and two-tone intermodulation distortion (IMD).

Next is a section on driving ADC inputs, with the key op amp specs and requirements. There is a discussion of high-resolution sigma-delta ($\Sigma\Delta$) measurement ADCs, multiplexed (MUX) data acquisition systems, single-supply ADCs with scaled inputs, buffered input and buffered differential ADCs, switched-capacitor CMOS ADCs, single-ended (SE) ADC drive circuits, DC coupled gain setting and level shifting, and differential input ADCs. Finally, there is the important topic of input overload/OV considerations.

Every DAC or ADC needs a conversion reference, so reference stability is an important topic. This section covers ADC/DAC reference input drivers and successive-approximation (SAR) ADC references. The final section in this chapter involves DAC outputs. The general considerations are presented first,

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followed by differential to SE conversion techniques, SE current-to-voltage (I-V) conversion, differential I-V conversion, and low pass (LP) filters for audio DACs.

Chapter 4 covers sensor signal conditioning. The introduction encompasses sensor characteristics, output formats, and the process control loop. Treatment of the bridge circuit involves amplification and linearization of bridge outputs, driving remote bridge circuits, minimizing system offset, and AC and DC excitation. Next come strain, force, pressure, and flow measurements and their signal conditioning. High-impedance sensors include photodiodes, charge outputs sensors (piezo, accelerometers, hydrophones), pH monitors, and chemical and smoke detectors. Finally, we find the temperature sensors: linearizing techniques, thermocouple cold junction compensation, platinum RTDs, thermistors, and semiconductor sensors.

FILTERS

Chapter 5 presents analog filter circuits. The introduction covers the idealized filter response, the transfer function, and key filter parameters. Next we delve into the S-plane, pole-zero response, f_0 , and Q. Applicable filter types are low pass (LP), high pass (HP), band-pass (BP), band reject (BR) or notch, and all-pass (AP). The third section covers phase response, time domain response, and impulse and step response.

Section 4 includes the standard responses: Butterworth, Chebyshev, Bessel, linear phase, transitional, Gaussian, all-pole, elliptical, maximally-flat delay, and inverse Chebyshev. There are 11 pages of response curves and 11 design tables for the various filters. Next up are frequency transformations: LP-HP, LP-BP, LP-BR, and LP-AP.

Section 6 contains real filter realizations: single pole (SP) passive RC and SP active, passive LC, the integrator, general impedance converter, active inductor, frequency-dependent negative resistor (FDNR), Sallen-Key (S-K) or voltage-controlled voltage source (VCVS) LP, HP, and BP; multi-feedback (MFB) LP, HP, BP; the state variable filter, the biquadratic (biquad), the dual-amp bandpass (DABP), the twin-T notch, the Bainter notch, the Boctor

notch, the 1-BP notch, and the first- and second-order AP. There are 19 pages of design equations for all of these filters.

Section 7 covers practical problems in filter implementation, beginning with passive components (R, L, and C). There are capacitor and resistor parameter comparison charts, and a discussion of the limits of op amps; gain variations with frequency, GBW requirements, and input and output impedance. Next, the book looks at distortion from input capacitance modulation in FET op amps, and Q enhancement. The final section has a number of filter design examples. Of interest to audio types are the fifth-order anti-aliasing filters (passive LC, S-K, MFB, state variable, and FDNR), and the seventh-order CD DAC reconstruction filters (passive LC, FDNR).

Chapter 6, which is the longest chapter in the book at 210 pages, presents signal amplifiers. The first section covers audio amplifiers. First are the microphone preamps; single and differential input solid-state, electret mike amps, and transformer-coupled mike amps. The RIAA phono preamp is presented next, with the RIAA idealized response. The two RIAA equalization (EQ) networks, "N1" and "N2," are shown with a discussion on the sensitivity to device tolerances, parasitic capacitance, and resistor and capacitor parameters. The phono preamp topologies presented in this section are the active feedback preamp (AC and DC coupled), and the passive EQ preamp.

The book covers line stages next. Line receivers are shown in balanced, SE, and transformer-coupled configurations. The line drivers that the authors present are balanced, SE, current-boosted composite amps, inverter-follower differential drivers, cross-coupled, transformer output and mixed-feedback transformer output types. The topic for Section 2 is buffer amplifiers, and driving capacitive loads and the types of compensation required to do so.

APPLICATIONS

The third section details video amps. The intro covers video signals and specifications for NTSC and PAL. Video amp design considerations look at BW, signal transmission, and line termination. Video line driver and distribution

amplifier driver topologies include the inverter-follower, cross-coupled differential amp, and the fully integrated differential amp.

Video line receiver topologies include the four-resistor differential receiver and the active FB differential receiver. Some design examples are the cable-tap (through-loop) amp, high-speed clamping amp, high-speed video multiplexing, and single-supply video amps. Communications amplifiers come next, with noise and distortion specs, automatic gain control (AGC), voltage-controlled amplifiers (VCA), and two application examples: a CATV upstream driver and an xDSL upstream driver.

Section 5 presents miscellaneous amplifier ideas and applications: a high-efficiency video line driver, wide-band noise generator, precision rectifiers, parallel amps for low noise, a pulse generator, clamp amps, a sync inserter, and a negative resistance buffer.

The final section of this chapter discusses the composite amplifier; the two-op amp composite, a chopper-stabilized amp, voltage-boosted rail-rail output, and gain-boosted input composite amps. The final amplifier is a Walt Jung-designed "Nostalgia" vacuum tube input/output composite amp with a discrete transistor folded-cascode, cascade current-mirror in between the input and output tube stages.

HARDWARE

Chapter 7 is a very practical presentation of Hardware and Housekeeping Techniques. Section 1 begins with passive components and their comparison charts again. The parameters of capacitors include dielectric absorption (DA), parasitic elements, dissipation factor (DF), tolerance, temperature variations, and other effects. Resistor topics include temperature coefficient (TC), parasitic elements, thermoelectric effects, voltage sensitivity, aging, excess noise, and a discussion on the use of trimpots. Stray and mutual inductance, ringing, parasitic elements, and quality factor (Q) are discussed, plus, inductors finally get covered in-depth.

Section 2 covers the otherwise obscure printed circuit (PC) board design issues; conductor resistance, kelvin feedback, return currents, ground

noise/loops, grounding (star, analog, digital), ground planes, skin effect, ground isolation, static PC board effects, leakage, and the use of input guard tracks on PC boards.

Section 3 covers the all-important topic of op amp power supplies (PS). The authors investigate fixed and adjustable linear IC regulators, low-dropout regulators; charge-pump voltage converters, inverters, and doublers; and linear post-regulators for switching power supplies. Next comes PS noise reduction and filtering. Pertinent topics include filter caps, inductors, ferrites, resistors, post-regulators, bypass and decoupling caps; grounding and component separation consideration, and PC board layout.

Section 4 looks at op amp input protection: OV, common-mode limitations, clamp protection, clamp diode leakage, CMOS channel protection, high common-mode input instrument amps, and inverting amplifier protection. Then the section covers the output phase reversal problem, and input differential protection and series resistance. The last topic in this section is electrostatic dis-

charge (ESD) protection and testing. Section 5 investigates thermal considerations. The intro looks at thermal basics and follows with the concept of thermal resistance (θ) as it pertains to cooling and heatsinking.

Section 6 covers electromagnetic interference (EMI) and radio frequency interference (RFI) mechanisms. It looks at EMI/RFI noise sources, coupling paths, passive filters, shielding, cables and their shields, and ground loop contributions. Then it covers RFI rectification sensitivity in emitter-coupled and source-coupled op amp input stages. There is a discussion of reducing this sensitivity in op amp and instrument amp inputs. The section also looks at output stage EMI/RFI protection, PC board design, logic level protection, and gets into microstrip and transmission line termination.

Section 7 wraps up the book with Simulation, Breadboarding and Prototyping. The first topic is analog circuit simulation with SPICE and IC SPICE models, and macro models vs. micro models. ADI's ADSPICE op amp macro models are discussed in depth: input and

gain/pole stages, frequency-shaping stages, output stages, model transient response, and noise models. The book considers CFB amplifier models and ways to deal with PC board parasitics.

Under breadboarding and prototyping, the book examines the "deadbug" and solder-mount breadboard methods, and milled prototype PC boards. There is a discussion of sockets, DIP and SOIC packages, and evaluation op amp boards (general purpose and dedicated). This section on real-world hardware issues is invaluable. No book is complete without a thorough index, and this one covers 45 pages, indexing both key words and ADI device numbers.

CONCLUSION

I found this to be a fascinating and technically valuable book. It has been thoroughly researched, fully footnoted with lots of references, and is written in an interesting and engaging style. *Op Amp Applications* is a must-have for anyone interested in the history of technology and/or the practical application of op amps over the proverbial range of "DC to daylight." ❖

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