INTRODUCTION TO CMOS OP-AMPS AND COMPARATORS

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ROUBIK GREGORIAN

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To my wife, Agnes
And our children, Aris and Talin

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PREFACE

Operational amplifiers (op-amps) and comparators are two of the most intricate, and in many ways the most important, building blocks of an analog circuit. These components are used in such devices as switched-capacitor filters, analog-to-digital (A/D) and digital-to-analog (D/A) converters, amplifiers, modulators, rectifiers, peak detectors, and so on. The performance of op-amps and comparators usually limits the high-frequency application and dynamic range of the overall circuit. Without a thorough understanding of the operation and basic limitation of these components, the circuit designer cannot determine or even predict the actual response of the overall system. Hence this book gives a fairly detailed explanation of the overall configurations and performance limitations of op-amps and comparators exclusively in CMOS technology. While the scaling properties of the very large scale integration (VLSI) processes have resulted in denser and higher-performance digital circuits, they have also changed the design techniques used for CMOS analog circuits. Therefore, the main purpose of these discussions is to illustrate the most important principles underlying the specific circuits and design procedures. Nevertheless, the treatment is detailed enough to enable the reader to design high-performance CMOS op-amps and comparators suitable for most analog circuit applications.

The main emphasis of this book is on physical operation and design process. It has been written as a unified text dealing with the analysis and design of CMOS op-amps and comparators. It is intended for classroom adoption to be used as a senior or graduate-level text in the electrical engineering curriculum of universities and also as training and reference material for industrial circuit designers. To increase the usefulness of the book as a text for classroom teaching, numerous problems are included at the end of each chapter; these problems may be used for homework assignments. To enhance its value as a design reference, tables and numerical design examples are included to clarify the step-by-step processes involved. The first two chapters provide a concise, basic-level, and (I hope) clear description of analog MOS integrated circuits and the necessary background in semiconductor device physics. The remainder of the book is devoted to the design of CMOS op-amps and comparators and to the practical problems encountered and their solutions. The book also includes two introductory chapters on the applications of op-amps and comparators in A/D and D/A converters. For a more detailed discussion on the important subject of data converters, readers are referred to the *Principles of Data Conversion System Design* by Behzad Rezavi, and *Delta-Sigma Data Converters: Theory, Design and Simulation* by Steven R. Norsworthy, Richard Schreier, and Gabor C. Temes.

This book is based in part on a previous book I coauthored with Gabor C. Temes, titled *Analog MOS Integrated Circuits for Signal Processing.* The original material has been augmented by the latest developments in the area of analog MOS integrated circuits, in particular op-amps and comparators. Most of the material and concepts originated from the publications cited at the end of each chapter as well as from many practicing engineers who worked with me over the years.

Since the original book evolved from a set of lecture notes written for short courses, the organization of the material was therefore influenced by the need to make the presentation suitable for audiences of widely varying backgrounds. Hence I tried to make the book reasonably self-contained, and the presentation is at the simplest level afforded by the topics discussed. Only a limited amount of preparation was assumed on the part of the reader: mathematics on the junior level, and one or two introductory-level courses in electronics and semiconductor physics are the minimum requirements.

The book contains eight chapters. Chapter 1 provides a basic introduction to digital and analog signal processing, followed by several representative examples of circuits and systems utilizing CMOS op-amps and comparators. This material can be covered in one lecture (two-hour lectures are assumed here and throughout the preface).

In Chapter 2 the physics of MOS devices is described briefly and linearized models of MOSFETs, as well as MOS capacitors and switches are discussed. The technology used to fabricate CMOS devices is also discussed briefly. Once again, depending on the background of the audience, two or three lectures should suffice to cover the content of this chapter.

Chapter 3 covers some of the basic subcircuits commonly utilized in analog MOS integrated circuits. These subcircuits are typically combined to synthesize a more complex circuit function. Complete coverage of all topics of this chapter requires about three lectures.

In Chapter 4 circuit design techniques for realizing CMOS operational amplifiers are discussed. The most common circuit configurations, as well as their design and limitations, are included. Full coverage of all topics in this chapter requires about four lectures.

In Chapter 5 the principles of CMOS comparator design are discussed. First the single-ended auto-zeroing comparator is examined, followed by simple and multistage differential comparators, regenerative comparators, and fully differential comparators. Two lectures should be sufficient for complete coverage of this chapter.

Chapters 6 and 7, which cover CMOS digital-to-analog and analog-to-digital converters, serve as practical application examples of op-amps and comparators. The fundamentals and performance metrics of the data converters are presented first, followed by a discussion of popular architectures of Nyquist-rate converters. Digital-to-analog converters are divided into voltage, charge, and current scaling types. Analog-to-digital converters include high-speed flash, medium-speed successive-approximation, and low-speed serial converters. Complete coverage of all topics may require three to four lectures.

In Chapter 8 the design principles presented in Chapter 4 and 5 are employed to work out several design examples to acquaint the reader with the problems and trade-offs involved in op-amp and comparator designs. Practical considerations such as dc biasing, systematic offset voltage, and power supply noise are discussed in some detail. All topics in this chapter can be covered in three lectures; if the detailed discussion in Sections 8.2 and 8.3 is condensed, the material can be presented in two lectures.

Thus, depending on the depth of the presentation, full coverage of all material in the book may require as many as 20 two-hour lectures or as few as 16.

I am grateful to many people who have helped me directly or indirectly in the elaborate and sometimes overwhelming task of publishing this book. In particular, I would like to thank my colleagues Drs. S. C. Fan, B. Fotouhi, B. Ghaderi, and G. C. Temes, who read and criticized versions of the manuscript. Their comments have been most helpful and are greatly appreciated. Most of the difficult typing task was done by Ms. W. Irwin and D. Baker. I am grateful for their excellent and painstaking help. Last, but not least, I would like to express my gratitude to my family for graciously suffering neglect during the writing of this book. Without their understanding and support this work would not have been possible.

ROUBIK GREGORIAN
Saratoga, California
January 1999

CHAPTER 1

INTRODUCTION

Operational amplifiers (op-amps) and comparators are two of the most important building blocks for analog signal processing. Op-amps and a few passive components can be used to realize such important functions as summing and inverting amplifiers, integrators, and buffers. The combination of these functions and comparators can result in many complex functions, such as high-order filters, signal amplifiers, analog-to-digital (A/D) and digital-to-analog (D/A) converters, input and output signal buffers, and many more. Making the op-amp and comparator faster has always been one of the goals of analog designers. In this chapter the basic concept of digital and analog signal processing is introduced. Then a third category of signal processing, the sampled-data analog technique, which is in between the two main classifications, is described. Finally, a few representative examples are given of circuits and systems utilizing CMOS op-amps and comparators, to illustrate the great potential of these components as part of an MOS-LSI chip.

1.1 CLASSIFICATION OF SIGNAL PROCESSING TECHNIQUES [1–4]

Electrical signal processors are usually divided into two categories: analog and digital systems. An *analog system* carries signals in the form of voltages, currents, charges, and so on, which are *continuous* functions of the *continuous*-time variable. Some typical examples of analog signal processors are audio amplifiers, passive- or active-*RC* filters, and so on. By contrast, in a *digital system* each signal is represented by a sequence of numbers. Since these numbers can contain only a finite number of digits (typically, coded in the form of binary digits, or bits) they can only take on discrete values. Also, these numbers are the sampled values of the signal, taken at discrete time instances. Thus both the dependent and independent variables of a digital signal are discrete. Since the processing of the digital bits is usually performed synchronously, a timing or clock circuit is an important part of the digital system. The timing provides one or more clock signals, each containing accurately timed pulses that operate or synchronize the operation of the components of the system. Typical examples of digital systems are a general-purpose digital computer or a special-purpose digital signal processor dedicated to (say) calculating the Fourier transform of a signal via the fast Fourier transform (FFT), or a digital filter used in speech analysis, and so on.

By contrast, analog signal processing circuits utilize op-amps, comparators, resistors, capacitors, and switches to perform such functions as filters, amplifiers, rectifiers, and many more. To understand the basic concepts of the most commonly used configurations of an analog circuit, consider the simple analog transfer function

$$\frac{V_{\text{out}}\,(s)}{V_{\text{in}}(s)} = \frac{b}{s^2 + as + b}. \tag{1.1}$$

It is easy to verify that the *RLC* circuit shown in Fig. 1.1*a* can realize this function (Problem 1.1). Although this circuit is easy to design, build, and test, the presence of the inductor in the circuit makes its fabrication in integrated form impractical. In fact, for low-frequency applications, this circuit may well require a very large valued, and hence bulky, inductor and capacitor. To overcome this problem, the designer may decide to realize the desired transfer function using an active-*RC* circuit. It can readily be shown that the circuit in Fig. 1.1*b*, which utilizes three *operational amplifiers*, is capable of providing the transfer function specified in Eq. (1.1). This circuit needs no inductors and may be realized with small discrete components for a wide variety of specifications (Problem 1.2). It turns out, however, that while integration of this circuit on a bipolar chip is, in principle, feasible (since the amplifiers, resistors, and capacitors needed can all be integrated), there are some major practical obstacles to integration. These include the very large chip area needed by the *RC* components, as well as the stringent accuracy and stability requirements for these elements. These requirements cannot readily be satisfied by integrated components, since neither the fabricated values nor the temperature-induced variations of the resistive and capacitive elements track each other. The resulting pole–zero variations are too large for most applications.

Prior to mid-1970s, analog circuits such as the one shown in Fig. 1.1 were implemented using integrated bipolar op-amps and discrete passive components. In the 1970s two developments made it possible to fully integrate analog circuits in metal-oxide semiconductor (MOS) technology. The first development was the emergence of a technique called switched-capacitor (SC) circuits [6], which is an effective strategy for solving both the area and the matching problems by replacing each resistor in the circuit by the combination of a capacitor and a few switches. Consider the branches shown in Fig. 1.2. Here, the four switches S_1, S_2, S_3, and S_4 open and close periodically, at a rate which is much faster than that of the variations of the terminal voltage v_A and v_B. Switches S_1 and S_4 operate synchronously with each other but in opposite phase with S_2 and S_3. Thus when S_2 and S_3 are closed, S_1 and

S_4 are open, and vice versa. Now when S_2 and S_3 close, C is discharged. When S_2 and S_3 open, S_1 and S_4 close, and C is recharged to the voltage $v_C \; 4 \; v_A \; 1 \; v_B$. This causes a charge $q \; 4 \; C(v_A \; 1 \; v_B)$ to flow through the branch of Fig. 1.2. Next, C is again discharged by S_2 and S_3, and so on. If this cycle is repeated every T seconds (where T is the *switching period or clock period*), the average current through the branch is then

$$i_{\text{av}} \; 4 \; \frac{q}{T} \; 4 \; \frac{C}{T}\,(v_A \; 1 \; v_B). \tag{1.2}$$

Thus i_{av} is *proportional* to the branch voltage $v_A \; 1 \; v_B$. Similarly, for a branch containing a resistor R, the branch current is $i \; 4 \; (1/R)(v_A \; 1 \; v_B)$. Thus the average current flowing in these two branches are the same if the relation $R \; 4 \; T/C$ holds. Physically, the switches transform the capacitor C, a nondissipative memoried element, into a dissipative memoryless (i.e., resistive) one.

It is plausible therefore that the branch of Fig. 1.2 can be used to replace all resistors in the circuit of Fig. 1.1*b*. The resulting stage [3] is shown in Fig. 1.3. In this circuit, switches that belong to different ''resistors'' but perform identical tasks have been combined. Furthermore, the second operational amplifier (op-amp) in Fig. 1.1*b*, which acted merely as a phase inverter, has been eliminated. This was possible since by simply changing the phasing of two of the switches associated with capacitor C_3, the required phase inversion could be accomplished without an op-amp.

As Fig. 1.3 illustrates, the transformed circuit contains only capacitors, switches, and op-amps. A major advantage of this new arrangement is that now all time constants, previously determined by the poorly controlled RC products, will be given by expressions of the form $(T/C_1)C_2 \; 4 \; T(C_2/C_1)$. Here the clock period T is usually determined by a quartz-crystal-controlled clock circuit and hence is very accurate and stable. The other factor of the time constant is C_2/C_1, that is, the ratio of two on-chip MOS capacitances. Using some simple rules in the layout of these elements, it is possible to obtain an accuracy and stability on the order of 0.1% for this ratio. The resulting overall accuracy is at least 100 times better than what can be achieved with an on-chip resistor and capacitor for the RC time constant.

A dramatic improvement is also achievable for the area required by the passive elements. To achieve a time constant in the audio-frequency range (say 10 krad/s), even with a large (10-pF) capacitor, a resistance of 10-MV is required. Such a resistor will occupy an area of about 10^6 mm^2, which is prohibitively large; it is nearly 10% of the area of an average chip. By contrast, for a typical clock period of 10 ms, the capacitance of the switched capacitor realizing a 10-MV resistor is $C \; 4 \; T/R \; 4 \; 10^{25}/10^7 \; 4 \; 10^{112}$ F 4 1 pF. The area required realizing this capacitance is about 2500 mm^2, only 0.25% of that needed by the resistor that it replaces.

The second development that made the realization of the fully integrated analog MOS circuits possible was the design of the MOS op-amp. Perhaps the most generally useful analog circuit function is that of the operational amplifier. Prior to about 1977, there existed a clear separation of the bipolar and MOS technologies, according to the function required [1,5]. MOS technology, with its superior device density, was used mostly for digital logic and memory applications, while all required analog functions (such as amplification, filtering, and data conversion) were performed using bipolar integrated circuits, such as bipolar op-amps. Since that time, however, rapid progress made in MOS fabrication techniques made it possible to manufacture much more complex and flexible chips. In addition, new developments occurred in communication technology (such as digital telephony, data transmission via telephone lines, adaptive communication channels, etc.) which required analog and digital signal processing circuitry in the same functional blocks. The analog functions most often needed are filtering (for antialiasing, smoothing, band separation, etc.), amplification, sample-and-hold operations, voltage comparison, and the generation as well as precise scaling of voltages and currents for data conversion. The separation of these analog functions from the digital ones merely because of the different fabrication technologies used is undesirable, since it increases both the packaging costs and the space requirements and also, due to the additional interconnections required, degrades the performance. Hence there was strong motivation to develop novel MOS circuits, which can perform these analog functions and which can also share the area on the same chip with the digital circuitry.

Compared with bipolar technology, MOS technology has both advantages and disadvantages. MOS device has extremely high impedance at its input (gate) terminal, which enables it to sense the voltage across a capacitor without discharging it. Also, there is no inherent offset voltage across the MOS device when it is used as a charge switch. Furthermore, high-quality capacitors can be fabricated reliably on an MOS chip. These features make the realization of such circuits as precision sample-and-hold stages feasible on an MOS chip [1]. This is usually not possible in bipolar technology.

On the negative side, the transconductance of MOS transistors is inherently lower than that of bipolar transistors. A typical transconductance value for a moderate-sized MOS device is around 2.5 mA/V; for a bipolar transistor, it may be about 50 times larger. This leads to a higher offset voltage for an MOS amplifier than for a bipolar amplifier. (At the same time, however, the input capacitance of the MOS transistor is typically much smaller than that of a bipolar transistor.) Also, the noise generated in an MOS device is much higher, especially at low frequencies, than in a bipolar transistor. The conclusion is that the behavior of an amplifier realized on an MOS chip tends to be inferior to an equivalent bipolar realization in terms of offset voltage, noise, and dynamic range. However, it can have much higher input impedance than that of its bipolar counterpart.

As a result of these properties, the largest use of the MOS op-amp is expected to be as part of an MOS-LSI (large-scale integration) chip. Here the design of the op-amp can take advantage of the important performance specifications that are needed. The loading of the op-amp is often very light and usually only a small-valued capacitor has to be driven by these op-amps. Switched-capacitor circuits fall especially into this category, where element-value accuracy is important but the signal frequency is not too high and the dynamic range required is not excessive.

Voice- and audio-frequency filtering and data conversion are in this category and represent the bulk of the past applications.

In addition to frequency-selective switched-capacitor filtering introduced in Fig. 1.3, which has been the most common application of MOS op-amps, there are many other functions for which op-amps and comparators can be used. These include analog-to-digital (A/D) and digital-to-analog (D/A) data conversion, programmable-gain amplification for AGC and other applications, peak-detection, rectification, zero-crossing detection, and so on. They have also been used extensively in large mixed-signal analog/digital systems such as voice codecs, high-speed data communication moderns, audio codecs, and speech processors. This range will expand continuously as the quality (bandwidth, dynamic range, power consumption, etc.) of the components, especially op-amps and comparators, improves.

1.2. EXAMPLES OF APPLICATIONS OF OP-AMPS AND COMPARATORS IN ANALOG MOS CIRCUITS

In this section, a few selected examples of practical analog MOS circuits are given where CMOS op-amps and comparators are used extensively. Of course, the reader should not expect to understand the details of these systems at this stage. However, the diagrams may give an idea of the potentials of these components in analog signal processing.

As mentioned earlier, one of the most important applications of CMOS op-amps is in switched-capacitor filters. Figure 1.4*a* shows the circuit diagram of a seventh-order switched-capacitor filter. Its measured frequency response is shown in Fig. 1.4*b*. The measured *passband* variation for the device is less than 0.06 dB. This represents a superior performance, which could not have been achieved without extensive trimming using any other filter technology.

An obvious application of a CMOS op-amp is the realization of charge-mode digital-to-analog converters (DAC). It can be obtained by combining a programmable capacitor array and an offset-free switched-capacitor gain stage. An example of an N-bit charge-mode DAC is shown in Fig. 1.5, where V_{ref} is a temperature-stabilized constant reference voltage. The output of the DAC is the product of the reference voltage and the binary-coded digital signal ($b_1, b_2, b_3, \ldots, b_N$). In Chapter 6 the design of such circuits is discussed in some detail.

Modulators, rectifiers, and peak detectors [6] belong to an important class of nonlinear circuits, which can be implemented with a combination of op-amps and comparators. In an amplitude modulator the amplitude of a signal $x(t)$ (usually called the *carrier*) is varied (modulated) by $m(t)$, the modulating signal. Hence the output signal $y(t)$ is the product of $x(t)$ and $m(t)$, or $y(t)$ 4 $x(t)m(t)$. A periodic carrier signal, which is readily generated from a stable clock source, is a square wave alternating between two equal values 5V. An easy way to perform modulation with a square-wave carrier is to switch the polarity of the input signal $m(t)$ periodically. A stray-insensitive switched-capacitor modulator circuit which performs according to this principle is shown in Fig. 1.6. The clock phases f_1 and f_2 are operated at the fast clock rate v_c, while the phase f_a changes at the slow carrier-frequency rate v_{ca}. Normally, v_c is much larger (by a factor of 30 or more) than v_{ca}.

Another nonlinear circuit is a full-wave rectifier that converts an input signal $v_{\mathrm{in}}(t)$ to its absolute value $|v_{\mathrm{in}}(t)|$. A simple way of implementing a switched-capacitor full-wave rectifier is to add a comparator to an amplitude modulator. The circuit of a switched-capacitor full-wave rectifier based on the modulator of Fig. 1.6 is shown in Fig. 1.7*a*. Here A is set to ‘‘1’’ if v_{in} . 0 and to ‘‘0’’ if v_{in} , 0, while B is set to A by the comparator and the latch that follows it each time f_1, goes high. The signals A and B then set the polarity of the transfer function so that it inverts the negative input signals, but not positive ones. Figure 1.7*b* shows an auto-zeroing comparator, which is discussed in detail in Chapter 5.

A peak detector is a circuit whose output holds the largest positive (or, if so specified, negative) voltage earlier attained by the input signal. An MOS peak detector is shown in Fig. 1.8. The op-amp acts as a comparator, with v_{out} 4 V_{max} and v_{in} as its inputs. If v_{in} . V_{max}, the op-amp output goes high and M_1 conducts, charging C until $v_{\mathrm{out}} \approx v_{\mathrm{in}}$ is reached. If v_{in} , V_{max}, the op-amp output is low, M_1 is cut off, and v_{out} 4 V_{max} is held by C.

One of the most important applications of the comparators is in A/D converters. A successive-approximation A/D converter is one type of medium-speed Nyquist-rate converter that can be realized using a programmable capacitor array (PCA) and a voltage comparator. A 5-bit converter is shown in Fig. 1.9. For high-speed operation, flash A/D converters can be used. In this configuration an array of 2^N comparators are used for an N-bit A/D converter. A conceptual diagram of an N-bit flash A/D converter is shown in Fig. 1.10. Analog-to-digital converters are discussed in detail in Chapter 7.

With the recent rapid progress made in MOS fabrication techniques and the emergence of the submicron CMOS technology, many intricate systems containing analog and digital functions have been combined in a fully integrated form. One drawback of the submicron CMOS technology is the reduction in the power supply voltage, which results in a reduced signal swing and hence a lower dynamic range. To improve the performance of the system and reduce the effects of noise injection from the power, ground, and clock lines, most modern high-performance mixed-signal integrated circuits make use of fully differential signal paths. With op-amps and comparators, the fully differential signal paths require fully differential outputs as well as inputs, and they are known as fully differential op-amps and comparators. Since this technique uses symmetrical layout, many of the noise voltages (power supply noise, clock-feedthrough noise, offset voltages) appear as common-mode signals. They are to a considerable extent canceled in the differential output voltage v_{out} at all frequencies. A high-frequency high-Q switched-capacitor bandpass filter that uses a fully differential signal path is shown in Fig. 1.11. This filter is typically used in a radio-frequency (*RF*) receiver system, which requires high selectivity at high frequencies [7]. The two complementary switch blocks (X_1 and X_2) are shown in Fig. 1.12. The filter uses fully differential single-pole transconductance folded-cascode op-amps with source-follower common-mode feedback as illustrated in Fig. 1.13 [8]. This op-amp achieves 100-MHz unity-gain bandwidth and 60 dB of gain with 1 mA of total current consumption. Fully differential op-amps are discussed in detail in Chapter 4.

Another application of the fully differential op-amps is in oversampling, or delta-sigma A/D converters. The oversampling converters operate at sampling rates of 16 to 512 times the Nyquist rate and increase the signal-to-noise ratio by subsequent filtering. The oversampling techniques lend themselves most favorably to applications that require a relatively low frequency (,1 MHz) and high resolution (.12 bits). The most obvious application of delta-sigma converters is in digital telephony and digital audio. Figure 1.14 shows a fully differential, switched-capacitor CMOS implementation of a second-order delta-sigma modulator [9]. It consists of two parasitic-insensitive integrators, a comparator that serves as a 1-bit A/D converter, and a two-level (1-bit) D/A converter. Use of a fully differential configuration attenuates power supply noise, clock feedthrough, and even-order harmonic distortion. The modulator operates on two-phase nonoverlapping clocks consisting of a sampling phase and an integration phase. It achieves 16-bit dynamic range with an oversampling ratio of 256 and a signal bandwidth of 20 kHz.

As the examples above illustrate, present-day CMOS op-amps and comparators and their use in analog MOS circuits have reached a certain level of maturity. Already, almost any analog signal processing task in the voice- or audio-frequency range has a possible solution using such circuits. As fabrication technology and circuits design techniques continue to advance, the speed and dynamic range of these circuits will increase, allowing their use in such large-volume applications as video and radio systems, image processing, high-speed transmission circuits, and so on.

PROBLEMS

1.1. Show that the circuit of Fig. 1.1*a* can realize the transfer function of Eq. (1.1). What should be the element values *R, L,* and *C*?

1.2. Calculate the transfer function of the active-*RC* circuit of Fig. 1.1*b*. Assume that the circuit is to realize the transfer function of Eq. (1.1). Write the available equations for the element values. How many element values can be chosen arbitrarily?

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