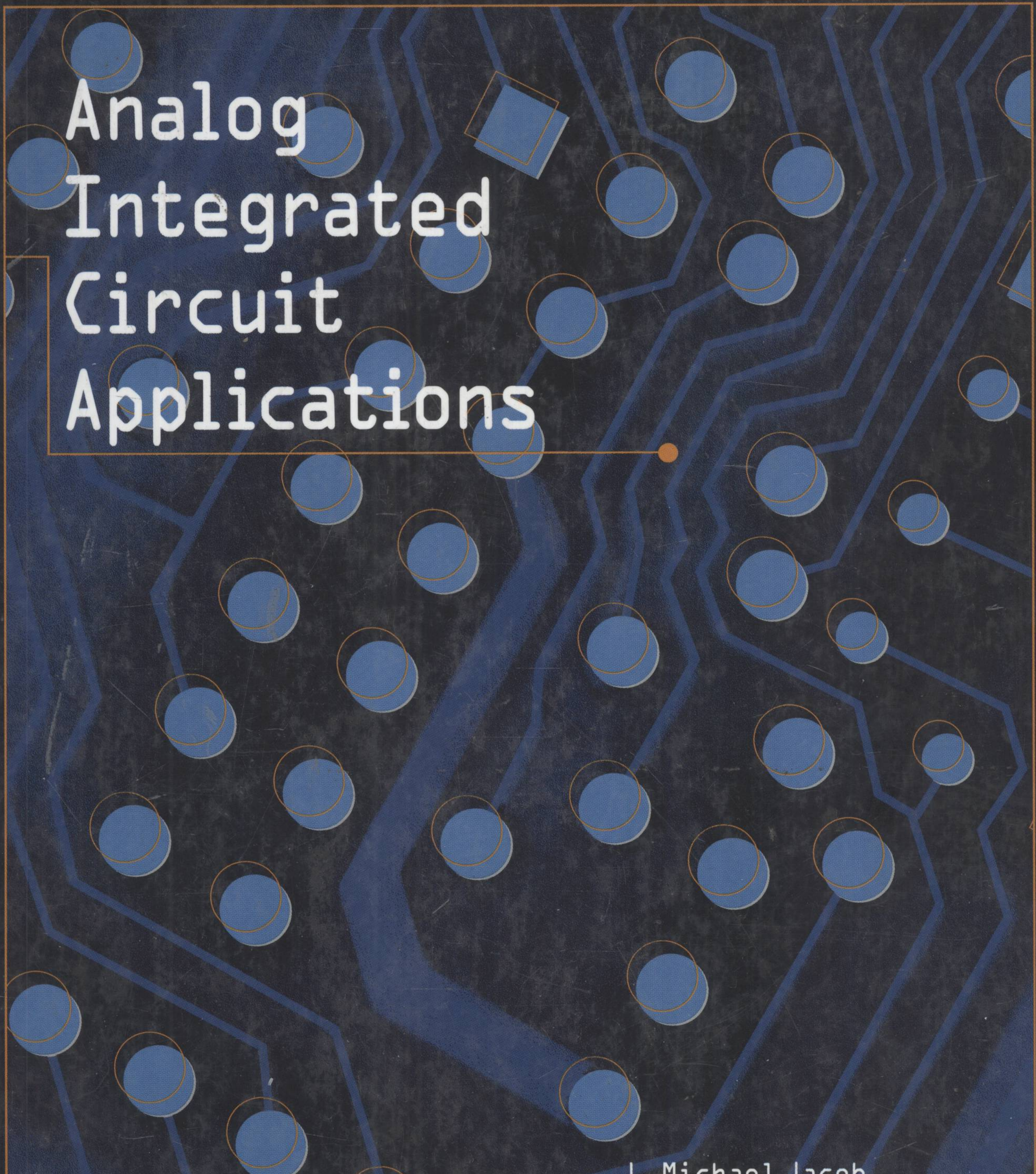

Analog Integrated Circuit Applications

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Preface

The integrated circuit, particularly the operational amplifier, is the true building block of analog electronics. Transistors, like vacuum tubes (remember those?), are used in applications where very high power requirements demand their unique abilities. The bulk of analog signal processing is done with integrated circuits.

This book is an extension of *Applications and Design with Analog Integrated Circuits, Second Edition*. It presents a detailed overview of the use of operational amplifiers, analog switches, digital potentiometers, digital to analog converters, both linear and switching integrated circuit regulated power supplies, single supply operation, op amp selection, analog circuit board layout, phase locked loops, direct digital synthesizers, active filters, log amps, and multipliers. Characteristics and limitations of each integrated circuit are discussed. Extensive applications and designs are outlined; the operation of each application is derived or analyzed; and the performance limitations are pointed out. This book enables you to select the appropriate device and circuit configuration for your need, calculate the component values required, build the circuit, and analyze its overall behavior. Throughout, the book is tutorial but not overly brief as with many handbooks.

Three decades of experience teaching analog integrated circuits courses at both the associate degree and the bachelor degree engineering technology levels underlie this book. A reasonable ability in algebra is needed. Passages using calculus have been kept to a minimum and can be skipped without loss in your ability to apply that information. Although this book is intended as a sophomore or upperclass electrical engineering technology text, extensive transistor circuit knowledge is not required. Combined with a basic diode and transistor characteristics supplement, the first five or six chapters work well for the first course in analog electronics in engineering, technology, or industrial electronics, or for personal instruction.

Integrated circuits are treated as functional devices. Analysis of internal transistor circuitry is minimized and used only briefly, when discussing device limitations. This is not a book on the design of analog integrated circuits. It is a text on the application of the integrated circuit devices. As such, circuits using these devices are rigorously analyzed, and all performance or design equations are derived.

To help organize your thoughts, give you specific goals, and help you evaluate what you have learned, each chapter begins with a detailed list of learner outcome objectives. These tell you precisely what you will learn as you work your way through the chapter. The problems at the end of the chapter are based on these objectives. Not only are you required to repeat what was done in the chapter, but many of the problems require that you apply the techniques to new circuits. This gives you the chance to drill and to think and stretch your abilities.

Compared to other linear integrated circuits texts, this book has several noteworthy features. The coverage is as broad as that of many handbooks, but it provides the rigor to help you understand why circuits are built as they are.

Computer simulation is applied as a tool throughout the body of the text. It has not been stuck on as an afterthought at the end of the chapter. Examples use the student version of *Electronics Workbench®* and MicroSim's *PSpice®* to illustrate key points in the performance of the analog IC under study. You can obtain more information about *Electronics Workbench®* at *www.electronicsworkbench.com*. For the latest version of PSpice contact Cadence Design Systems at *www.orcad.com* and select FREE OrCAD Starter Kit. Many end-of-chapter problems are solvable with one of the simulation packages.

There are one or two laboratory exercises at the end of each chapter. These exercises have undergone several iterations of student testing. They provide good hardware verification of the theory in the chapter and are consistent in technology, terminology, and pedagogy with the text. A separate lab manual is no longer needed.

Of major significance is a generic approach to analyzing any negative feedback circuit. Digital control (multiplying D/A, digital pots, switched capacitor cells, etc.) and the applications of nonstandard amplifier configurations (multipliers, several feedback loops, active feedback, composite amplifiers, and cascaded control) are prevalent. It is critical that you be able to determine how any combination of analog ICs function together, even if they do not fit into one of the standard amplifier types. A direct, simple approach is presented in Chapter 2 and then applied throughout the rest of the text.

Microprocessor control is now common in all but the most trivial circuitry. It is important that the uses, and abuses, of digital to analog conversion be clearly integrated with the analog ICs presented. So there is a chapter on digital control of analog functions (Chapter 3) early in the text. These techniques are then included in many subsequent chapters, illustrating how digital circuitry can control the analog ICs being presented.

Chapter 4 gives a unique, practical, simple design approach to linearly regulated power supplies. In addition to the principles and design details of buck and boost switching regulators, continuous operation is compared to discontinuous. Two types of advanced higher power switching regulators that run directly from the line voltage are also explained.

The central element in any op amp circuit is the op amp IC. Its selection is critical to the overall performance of the circuit. Chapter 5 gives a description of how to decide which op amp type fits your circuit application, including an overview of the types of op amps and their performance envelope. CMOS, chopper stabilized, and current feedback op amps are included.

Layout is as critical as any other element in an analog circuit. Poor layout can doom an otherwise fine design. Proper analog layout can be taught; it is not black magic or a rare art form. This section is too often omitted in analog texts. The basics of circuit layout are simple and belong in the hands of the circuit designer, not the graphics artist. Chapter 6 is a short but proven step-by-step recipe for the layout of analog circuits. Since it deals with principles, it applies equally to fabrication on a protoboard with solderless connections, wire-wrap, point-to-point solder fabrication, or printed circuit board design. It is also independent of the mechanics of the software you may choose to use to aid in the board layout.

Active filters are presented rigorously. All transfer functions and tuning parameters are completely derived. However, application of these results is given equal emphasis with many designs and analysis examples. First- through sixth-order filters with varying damping for low pass, high pass, notch, state variable, and voltage controlled circuits are illustrated.

The phase locked loop is a key element in digitally controlled signal generation. Too often, however, either it is treated as magic, with a few diagrams and hand waving, or it is overwhelmed with pages of Laplace transforms. Chapter 8 finds the middle ground. Enough detailed explanation of each block is given to allow you to analyze or design a digitally controlled phase locked loop. However, stability issues are left to more advanced texts, using instead a simple, overdamped response. The phase locked loop is then combined with the XR2206 function generator IC and several op amps. This allows precise control of sinusoidal frequency, amplitude, and offset. Direct digital synthesis allows the creation of sinusoids with purely digital techniques. Each element is explained, with enough detail to allow you to design your own. A complete DDS IC is also presented.

The characteristics and applications of nonlinear circuits are given extended treatment in Chapter 10.

Presented under a new title, this book is effectively a third edition of *Applications and Design with Analog Integrated Circuits*. I would like to express my appreciation to the many students and teachers who have worked through the first two editions. Their comments and encouragement have kept the book practical but rigorous, timely but true to the fundamentals. I hope that you find in reading this text some of the wonder and excitement that I experienced in its creation.

J.M.J.

1

Introduction to the Operational Amplifier Integrated Circuit

Integrated circuit technology has allowed the construction of inexpensive, reliable digital systems, such as the pocket calculator and the digital watch. The same basic techniques have allowed the construction of inexpensive, complex analog amplifiers with very stable characteristics. These **integrated circuits** (ICs) are amazingly easy to use. Because of this simplicity, and because of a high performance-to-cost ratio, analog integrated circuits have replaced most discrete transistor amplifier circuits. This chapter introduces the operational amplifier, the most widely used analog IC. It is treated as a functional block. Its characteristics are described, and techniques and considerations for breadboarding are presented.

OBJECTIVES

After studying this chapter, you should be able to do the following:

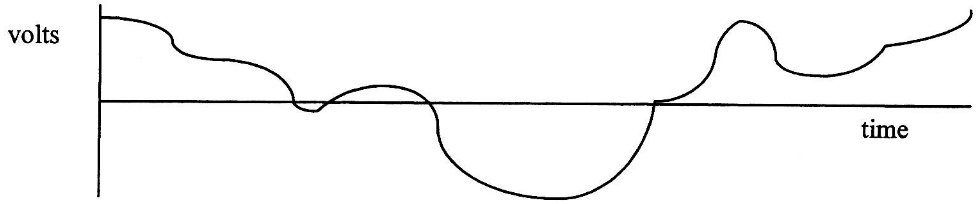
1. Briefly describe the two IC fabrication techniques.
2. State the differences between an analog and a digital circuit. Give examples of each.
3. List the characteristics of an ideal amplifier.
4. Compare actual operational amplifier characteristics to those of an ideal amplifier.
5. State the requirements and precautions associated with operational amplifier power supplies.
6. Identify IC packages and lead convention.
7. Describe good breadboarding techniques.

1-1 Analog Integrated Circuit

What is an analog integrated circuit? To begin the study of analog integrated circuits, you should first understand what makes them unique. What is the difference between an integrated circuit and a circuit built with discrete transistors? How do analog circuits differ from digital circuits?

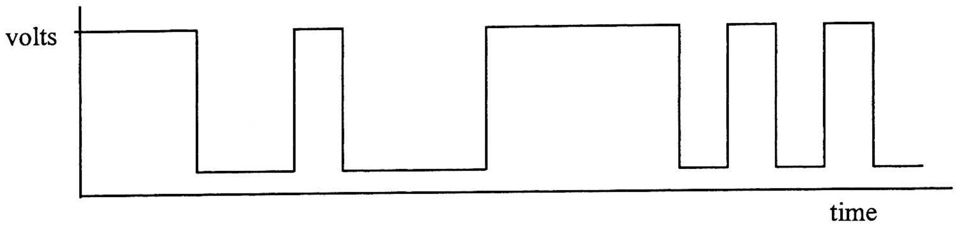
An integrated circuit (IC) is a group of transistors, diodes, resistors and sometimes capacitors wired together on a very small substrate (or wafer). Tens of thousands of components can be contained in a single integrated circuit. Functions as simple as single-stage amplifiers to those as complex as complete computers have been built in a single integrated circuit. This drastic decrease in size has also yielded a similar reduction in weight, power consumption, and production cost, while giving a proportional increase in reliability. Integrated circuits have swept every field of electronics and are strongly altering the automotive, medical, entertainment, communications, and business industries.

Integrated circuits are divided into two main groups according to the way they are built (monolithic or hybrid). Two divisions may also be made according to the function of the integrated circuit (analog or digital). The output of an analog IC may be any value whatever and may change continuously from one value to another. The output of a digital IC will be recognized only as either a logical low or a logical high. Only two output values are accepted. Furthermore, in many digital systems, changes from one level to the other can occur only at specific times. An analog IC output and a digital IC output are shown in Figure 1-1.



(a) Analog IC output. There is continuous variation between values.

Figure 1-1 Comparison of analog and digital IC outputs



(b) Digital IC output. Only two output levels are allowed.

Figure 1-1 (Cont.) Comparison of analog and digital IC outputs

Computers, calculators, digital watches, communication switching, digital instruments, and some industrial control systems use digital ICs. Analog ICs are used in radios, televisions, stereo amplifiers, voltage regulators, signal generators, filters, test instrumentation, and extensively in industrial measurement and control.

There are two main IC fabrication techniques, monolithic and hybrid. Monolithic integrated circuits are built in a wafer of silicon. Transistors and resistors (and occasionally capacitors) are produced by diffusion processes, just as discrete transistors are. However, instead of being cut apart, the individual transistors are interconnected by very thin metal runs. Isolation between transistors relies on reverse-biased junctions between the transistors and the silicon substrate (wafer).

Design of monolithic integrated circuits requires the tedious preparation of a large number of photographic masks. These are used to control the areas of diffusion for isolation, collectors, bases, emitters (or channels and gates for FETs), resistors, surface insulation, and connection metalization. These masks are reduced in size and are used, one at a time, to produce the desired parts of the monolithic IC. Of course many separate integrated circuits may be made in each wafer, with many wafers processed simultaneously. The wafers are tested, and the good ICs (called chips at this point) are cut apart and placed in one of many different style packages.

For monolithic integrated circuits, the initial design of the masks needed to produce the IC is very time-consuming and expensive. However, hundreds to thousands of monolithic ICs can be produced simultaneously. Consequently, large volume production keeps the price per chip quite low. The major advantage of monolithic integration, then, is low cost per chip if many of the ICs are to be produced.

However, there are several disadvantages. Capacitors are difficult to produce in monolithic ICs. Tuning the IC by adjusting (trimming) internal resistor values to meet custom or very demanding specifications is also difficult. Power dissipation from the small silicon wafer substrate is very limited. Isolation between transistors is not adequate for large voltages. All of these disadvantages place some limits on the use of monolithic ICs.

In applications where these limitations cannot be tolerated, hybrid integrated circuits may be used. In the hybrid IC, discrete resistors, capacitors, diodes, transistors, and even monolithic ICs are placed on a ceramic wafer and then interconnected.

The wafer actually serves as a miniature chassis with discrete components attached and interconnected. This technique provides excellent isolation between components, allows the use of practically any device, and can be easily custom tuned before encasing. Although the hybrid IC can eliminate most of the monolithic IC's disadvantages, the hybrid IC is considerably more expensive because the hybrid ICs must be assembled individually from more expensive components.

1-2 The Ideal Operational Amplifier

The **operational amplifier**, or **op amp** for short, is a high gain, wide band, DC amplifier with high noise rejection ability. The schematic symbol for an op amp is shown in Figure 1-2.

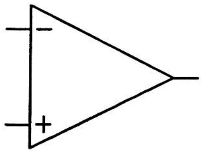


Figure 1-2 Schematic symbol for an operational amplifier

It has two inputs and one output. The output voltage, with respect to circuit common (ground), depends on the difference in potential between the two input voltages (e_{NI} - e_{INV}), as shown in Figure 1-3.

The operational amplifier was first built with vacuum tubes. Originally designed by C.A. Lovell of Bell Laboratories, these high gain, general purpose amplifiers were initially used to control the movement of artillery during World War II. In 1948, George Philbrick produced a single tube version. Soon, these amplifiers were used in analog computers to do addition, subtraction, integration, and scaling. Because the computer's mathematical **operations** were performed by these amplifiers, they became known as **operational amplifiers.**

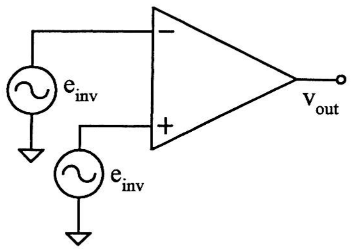


Figure 1-3 Output/input voltage relationship of an op amp

In the early 1960s the tubes were replaced by transistors. A single op amp then required only one printed circuit card full of components. This reduction in size and power consumption broadened its applications. Op amps were used in many signal conditioning areas, test and measuring equipment, and industrial controls.

With the advent of integrated circuit techniques, it became possible to place the entire op amp into a single eight-lead mini-DIP package. The first generation 709 was introduced by Fairchild in 1965, with the still popular second generation 741 op amp available in 1968. Surprisingly, the cost of these op amp ICs is comparable to that of a single discrete transistor. Most small signal analog circuits designed today use operational amplifiers as the basic active device, and most rely on the discrete transistor only when the op amp will not solve the problem.

If you were going to design an ideal operational amplifier, what characteristics would you want? Since the purpose of the circuit is to amplify a signal, you would want an arbitrarily large gain. That is, no matter how small the input signal ($e_{NI} - e_{INV}$ in Figure 1-3), the open loop voltage gain, A_{OL}, would be large enough to provide an output signal (v_{out}) of adequate size.

$$A_{OL} = \frac{v_{out}}{e_{NI} - e_{INV}} = \infty \tag{1-1}$$

This means that the difference between the inputs ($e_{NI} - e_{INV}$) can be negligibly small.

Second, it is important that all of the output signal be applied to the load. However, the output impedance of the op amp (Z_{out}) forms a voltage divider with the load, as shown in Figure 1-4. For all of the op amp's output voltage to be applied to the load (and none dropped across Z_{out}), the output impedance must be zero.

$$v_{load} = \frac{Z_{load}}{Z_{load} + Z_{out}} v_{out}$$

$$v_{load} = v_{out} \quad \text{if} \quad Z_{out} = 0$$

So, for an ideal op amp: $Z_{out} = 0$ (1-2)

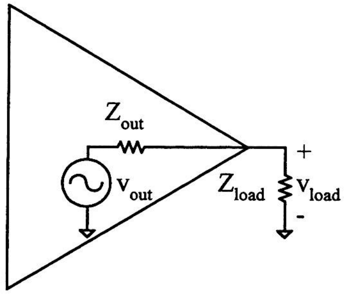


Figure 1-4 Effect of output impedance on the load voltage of an op amp

On the input side of an ideal operational amplifier, it is important to assure that the amplifier does not load down the source. The input impedance of the op amp forms a voltage divider with the output impedance of the source. This is illustrated in Figure 1-5. If all of the source voltage is to be applied to the inputs of the op amp, and none lost across the source output impedance (R_s), then the op amp's input impedance must be arbitrarily large compared to R_s.

$$v_{in} = \frac{Z_{in}}{Z_{in} + R_S} e_{INV}$$

$$v_{in} = e_{INV} \quad \text{if} \quad Z_{in} \approx \infty$$

So, for an ideal op amp:

$$Z_{in} = \infty \qquad (1\text{-}3)$$

This also means that no significant signal current will flow into the input of an ideal op amp.