OPERATIONAL AMPLIFIERS WITH LINEAR INTEGRATED CIRCUITS

FOURTH EDITION

WILLIAM D. STANLEY

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Dedicated to the late
Joseph S. Reeves,
who introduced me to the
exciting world of electronics
when I was a teenager

PREFACE

As in the first, second, and third editions, the primary objectives of this book are

- To establish the general methods for analyzing, modeling, and predicting the performance of operational amplifiers and related linear integrated circuits
- To develop the reader's facility in designing realistic circuits to perform specified operations
- To acquaint the reader with many of the common circuit configurations and enable the student to select available devices to use with these circuits

All or portions of this book are usable for at least the following groups:

- Upper-division engineering technology students (junior or senior level)
- Lower-division engineering technology students (following the basic course sequence in discrete electronic devices and circuits)
- Applied engineering students
- Practicing design engineers, technologists, and technicians

Engineering or engineering technology students who have had a course in circuit analysis employing frequency response analysis methods and a course in calculus should be able to cover the entire book. Calculus is used where appropriate, but virtually all results and design approaches can be understood *without calculus*. The large number of example problems and exercises make the book also valuable for self-study by practicing technical personnel.

The primary emphasis throughout the book is on developing the reader's facility for analyzing and designing the various circuit functions, rather than on simply presenting a rote collection of existing circuits or showing numerous wiring diagrams for specialized integrated circuit modules. This establishes a foundation for understanding new developments as they arise. Since new devices constantly appear on the market and existing ones quickly become obsolete, we study only a few devices in detail. Those selected for this purpose have withstood the test of time and are widely used. Because the best way to adapt to new technology is to have a firm grasp of the basic principles, this book has been organized toward that goal.

Chapter 1 provides some general models of linear amplifier circuits, definitions, and parameters. Students often miss these general concepts from the detailed material covered in basic electronic courses. This common deficiency is a case of the classical pattern of "not seeing the forest for the trees," and the material provided here will help solve that problem.

Chapter 2 begins the analysis and design of operational amplifier circuits using ideal model assumptions. While the reader will not be able to see all the limitations of the circuits at this point, actual workable designs can be produced almost immediately from the information in this chapter, including amplifiers of various types, current sources, summing circuits, and various other applications.

Chapters 3 and 4 are devoted to the practical limitations of realistic operational amplifiers and the associated effects on operating performance. Chapter 3 emphasizes dc effects, including the effects of finite gain, finite input impedance, nonzero output impedance, input offset voltage, and input bias currents. Chapter 4 emphasizes ac effects, that is, those effects that are frequency dependent. Primary topics include closed-loop bandwidth relationships, effects of slew rate, and common-mode rejection. Chapter 5 considers additional linear applications, including frequency-dependent circuits such as integrators, differentiators, and phase shift networks. Instrumentation amplifiers and operation with a single power supply are also included.

Comparator circuits form the basis for Chapter 6, including both open-loop comparators and comparators with feedback (Schmitt triggers). Along with the use of general purpose op-amps, a representative dedicated IC comparator (LM311) will be considered.

Timers and oscillators are the topics of Chapter 7, which covers both analysis and design of an op-amp multivibrator and an op-amp square-wave/triangular wave generator. The Barkhausen criterion is introduced, and the Wien bridge and phase shift oscillators are included. The IC circuits considered are the 555 timer and the 8038 function generator chip.

Chapter 8 is devoted to active filters, with emphasis on the widely used Butterworth function for low-pass filters and the standard resonance characteristic for band-pass filters. Finite-gain low-pass and high-pass filter design data are included, and we also discuss the infinite-gain band-pass circuit design. The last portion of the chapter deals with the state-variable filter, for which low-pass, band-pass, high-pass, and band-rejection filters can be realized. After completing this chapter, the student should be able to design and implement a variety of practical active filters.

Rectifier, diode, and power supply circuits form the basis for Chapter 9. Precision rectifier, holding, and limiting circuits are covered in the first part of the chapter, and the latter part of the chapter is devoted to power supply circuits. The development of the voltage regulator concept is included with this material. We also consider the use of a representative IC regulator (LM117/317).

Chapter 10 considers the timely topic of data conversion, which we may think of as the bridge between the analog and digital worlds. We study both digital-to-analog and analog-to-digital conversion and some of the most common circuits. The concepts of voltage-to-frequency and frequency-to-voltage conversion are also discussed. Various miscellaneous topics that do not fit the objectives of earlier chapters appear in Chapter 11, including multipliers, logarithmic amplifiers, and phase-locked loops, along with application of an IC phase-locked loop (NE/SE565).

Changes in the Fourth Edition

The general organization of the text has remained virtually the same since the second edition. Some major changes were made then, but it appears that the information organization and flow have been quite satisfactory since that point.

The most significant change for the fourth edition has been the replacement of PSPICE example problems at the end of most chapters with Multisim (Electronics Workbench) example problems. Multisim has made great strides in recent years and is now being widely used in engineering and engineering technology programs to model a variety of linear and nonlinear circuits. It is very user-friendly, and students can acquire proficiency in its operation very quickly. Moreover, users develop the circuit through the creation of a schematic diagram. Virtual instruments are available and their functions closely parallel that of real instruments. Thus, Multisim is very close to being a true "virtual laboratory."

The Multisim examples are provided in the last sections of the chapters and generally utilize circuits that were analyzed or designed in the chapter. However, these sections may be omitted without loss of continuity for instructors who do not wish to cover this subject.

Appendix E provides an abbreviated treatment of the basic concepts of schematic creation using Multisim for readers not having this background. Multisim example problems throughout the text provide further information about the use of various functions and models.

Problems

Most chapters contain end-of-chapter problems organized in three categories: Drill, Derivation, and Design. Drill problems make up the largest category. These are designed to test the reader's understanding of chapter principles. Problems are organized loosely in groups of two based on similar principles. Based on this grouping, answers to selected odd-numbered problems appear at the back of the book. Derivation problems require the reader to develop some of the results given in the text or to extend the results to new situations. Design problems require the reader to determine element values for a known circuit or a new circuit that will meet some prescribed specifications. Some of the design problems have a unique solution; others have more than one possible solution. Answers accompanied by an asterisk (*) are *typical solutions;* other valid solutions may be possible.

Laboratory Exercises Most chapters also provide additional laboratory exercises, with a total of 52 exercises in Chapters 2 through 8. These exercises will provide sufficient work for the core of a supporting laboratory. It is assumed that the student who uses the laboratory exercises will already be familiar with basic test equipment and instrumentation such as voltmeters, ammeters, and the oscilloscope; consequently, statements such as "measure the voltage . . ." often appear without regard to the instrument type or procedure.

Safety Although most of the laboratory exercises use relatively low voltages, there are always risks associated with the use of electrical equipment. Consequently, you should always follow the safety procedures learned in basic laboratory courses. You should have this instruction before you perform the exercises in this book.

Equipment

Minimal equipment is required to perform the exercises, and equipment is of the type normally found in most basic instructional laboratories. Further, the exercises have been designed to provide as much flexibility as possible. To provide full coverage, the following units should be available:

Circuit Trainer or "Breadboard" A variety of solderless units are available, some of which also provide suppliers and a function generator. Obviously, hookup wire is also required.

Oscilloscope Any modern dual-trace general-propose oscilloscope should be adequate. In fact, a single-trace oscilloscope can be used, but phase shift measurements are somewhat more involved. For brevity, the oscilloscope is referred to in some exercises as a *CRO* (*c*athode-*r*ay *o*scilloscope).

Multimeter A general-purpose multimeter capable of measuring both dc and ac voltages and currents as well as passive resistance is appropriate. Either a digital or an analog instrument can be used. References to the multimeter in laboratory exercises are often made on the basis of the function involved; for example, "use a voltmeter to measure. . . ."

Function Generator The desired unit should provide the choice of a sine wave, a square-wave, or a triangular wave over a frequency range from several hertz to at least 100 kHz. The output amplitude should be adjustable from zero to a level of at least several volts. A variable dc offset, which may be used in conjunction with the output signal or as a separate adjustable dc voltage, is a desirable feature.

Dual Power Supply The unit should provide either two fixed voltages of +15 V and −15 V or adjustable voltages that can be set at these levels.

Fixed 5-V DC Voltage This standard digital TTL level is available in many circuit trainers and is convenient for several of the exercises.

Oscilloscope The oscilloscope is probably the most important single instrument in measurements associated with linear circuits. In many exercises, you will be asked to sketch the forms of various waveforms and to show their time relationships. In virtually all cases, you should employ dc coupling for this purpose. This is important because the base line of the trace represents a zero-voltage level, and it will be necessary to measure voltages above and below this level. The ac coupling input position should be used only when it is desirable to amplify a small time-varying component without the dc level forcing the signal to shift off the screen.

To show the time relationships, it is necessary that you establish a time reference on the trace. Often, the input voltage is the logical choice for this reference. For example, if the input signal is a sine wave, the beginning of a cycle is an ideal point at which to establish the reference.

Suppliers *Resistors* The actual number of different values required is modest, but for maximum flexibility, an assortment of resistors with 5% tolerances in ¼- or ½-W sizes covering the range from about 100 Ω to 5.6 MΩ is recommended. The most popular size is 10 kΩ, and you will need a minimum of five of that size.

Capacitors An assortment of nonpolarized low-tolerance capacitors such as polystyrene or mylar in the range from about 0.001 μF to about 0.1 μF is recommended for critical applications such as active filters, oscillators, phase shift circuits, and so forth. In addition, larger-value polarized electrolytic (e.g., tantalum) and smaller-value disc ceramic capacitors may be used in noncritical by-pass applications.

Potentiometers A few potentiometers are desirable (and sometimes necessary) when a resistance must be adjusted to an exact value. Although the ranges are flexible, some suggested values are 0–1 kΩ, 0–10 kΩ, and 0–100 kΩ.

Electronic Components You will need these electronic components:

5	741	Operational amplifiers
1	311	Comparator
1	555	Timer
1	317	Regulator
2	General purpose diodes	

CONTENTS

1

GENERAL AMPLIFIER CONCEPTS

OBJECTIVES

After completing this chapter, the reader should be able to:

- Discuss and compare the areas of *digital electronics* and *linear* (or *analog*) electronics.
- Discuss the operation of an ideal amplifier and define its *voltage gain*.
- Define the two ideal independent source models and the four controlled (or dependent) source models, and sketch the schematic forms.
- Draw the Thevenin and Norton circuit models for realistic independent sources.
- Draw the circuit model for a complete amplifier and define *input impedance*, *output impedance*, and *voltage gain*.
- Draw a complete circuit model for the combination of an amplifier with source and load, showing loading effects at the input and output terminals, and determine the loaded gain.
- Draw the complete circuit model for the cascade arrangement of several amplifier stages along with source and load, showing end loading effects and stage interaction effects, and determine the loaded gain.
- Define *power gain* and *decibel power gain*, and determine either quantity if the other is known.
- Define *decibel voltage gain* in terms of linear voltage gain, and determine either quantity if the other is known.
- Determine the decibel gain associated with a cascade of several stages.
- Define *impedance*, *resistance*, *reactance*, *admittance*, *conductance*, and *susceptance*.
- Show the steady-state ac phasor forms for each of the circuit components.
- Define *steady-state transfer function*, *amplitude response*, and *phase response*.

- State the mathematical form of the transfer function of the one-pole low-pass model, define its major parameters, and sketch the forms of the amplitude and phase response functions.
- Sketch the Bode plot break-point approximations of amplitude and phase functions of the one-pole low-pass model.

1–1 INTRODUCTION

The primary objective of this introductory chapter is to present some of the most general properties of amplifier circuits as well as their circuit models. Most readers are probably familiar with some of these properties from previous studies of electronic circuits and devices. As students seldom see the "big picture" when studying individual properties of various amplifier circuits, however, the intent here is to look at the amplifier as a complete system and focus on input, output, and gain characteristics. Such properties apply to virtually all types of amplifiers whether they are implemented with bipolar junction transistors, field effect transistors, or operational amplifiers.

We will examine individual amplifier models and discuss the effects of input and output loading. We will also consider the effects of interaction between stages in cascade arrangements.

In covering the concept of decibel gain, we will define both decibel power gain and decibel voltage gain and explore computations utilizing these definitions. We will also develop decibel gain relationships for cascade arrangements.

After reviewing the fundamental concepts of steady-state ac circuit analysis, we will introduce the concept of the steady-state transfer function as a means for modeling a circuit's frequency response. We will also define the *amplitude* and *phase* response functions.

We will also develop and discuss in some detail the one-pole, low-pass, roll-off frequency response model. This form is quite important because many amplifier circuits (including operational amplifiers) are dominated by this type of response over a wide frequency range.

1–2 LINEAR VERSUS DIGITAL ELECTRONICS

There are many ways to classify the various divisions of electronics, most of which are ambiguous because of the complexity of the field and the overlap between the different application areas. One particular classification scheme, however, deserves some attention here because of its relevance to the focus of this book. At a relatively broad level, electronics can be separated into the divisions of (1) ***digital electronics*** and (2) ***linear electronics.*** There is a temptation to call the second category *analog electronics*, but in accordance with widespread usage, the term *linear electronics* will be used.

Digital electronics is concerned with all phases of electronics in which signals are represented in terms of a finite number of digits, the most common of which is the binary number system. Digital electronics also includes all arithmetic computations on such numbers, as well as associated logic operations. The distinguishing feature of digital electronics is the representation of all possible variables by a finite number of digits. Obvious examples in which digital electronics plays the major role are computers and calculators.

Linear electronics is concerned with all phases of electronics in which signals are represented by continuous or *analog* variables. Linear electronics also includes all signal-processing functions (for example, amplification) associated with such signals.

Actually, the term *linear* is a misnomer, since many of the circuits classified as such are nonlinear in nature. On a slightly humorous note, a better term might be *nondigital electronics* to indicate that a large percentage of electronic applications other than digital are often classified under the category of linear electronics. However, the classification term *linear electronics* has become so imbedded within the electronics industry that its usage will no doubt continue. The reader should realize, however, that many nonlinear circuits are classified in this category.

This book is devoted to the consideration of linear integrated electronic circuits and devices. This major segment of the linear electronics field has widespread application to many specialty fields.

There are a number of electronic circuits that involve a combination of digital and linear electronics, and some of the most important of these are considered in this book. Foremost among such circuits are analog-to-digital and digital-to-analog converters. Such devices are used in the interfacing areas between analog and digital circuits, and they utilize both linear and digital circuit principles.

One of the most important applications in the field of linear electronics is the process of ***amplification.*** This operation was one of the very earliest applications of electronic devices, and it still remains an essential operation in virtually all phases of the industry. Consequently, many of the linear applications in this book either directly or indirectly involve amplification.

Ideal Amplifier

An ideal linear amplifier is characterized by the fact that the output signal is directly proportional to the input signal, but the level will be changed in the process. Amplifiers in system form are often represented by a block diagram such as shown in Figure 1–1. The input voltage signal is denoted as $v_i(t)$, and the output voltage signal is denoted as $v_o(t)$. The quantity t represents time, and the functional forms $v_i(t)$ and $v_o(t)$ represent the fact that both voltages are functions of time; that is, they vary in some fashion as time passes. When it is not necessary to emphasize this functional notation, the parentheses and t will be omitted, in which case v_i and v_o may be used to represent the quantities involved. The functional notation was introduced at this point so that the reader can recognize it throughout the book when it occurs.

FIGURE 1–1
Block diagram representation of a linear amplifier.