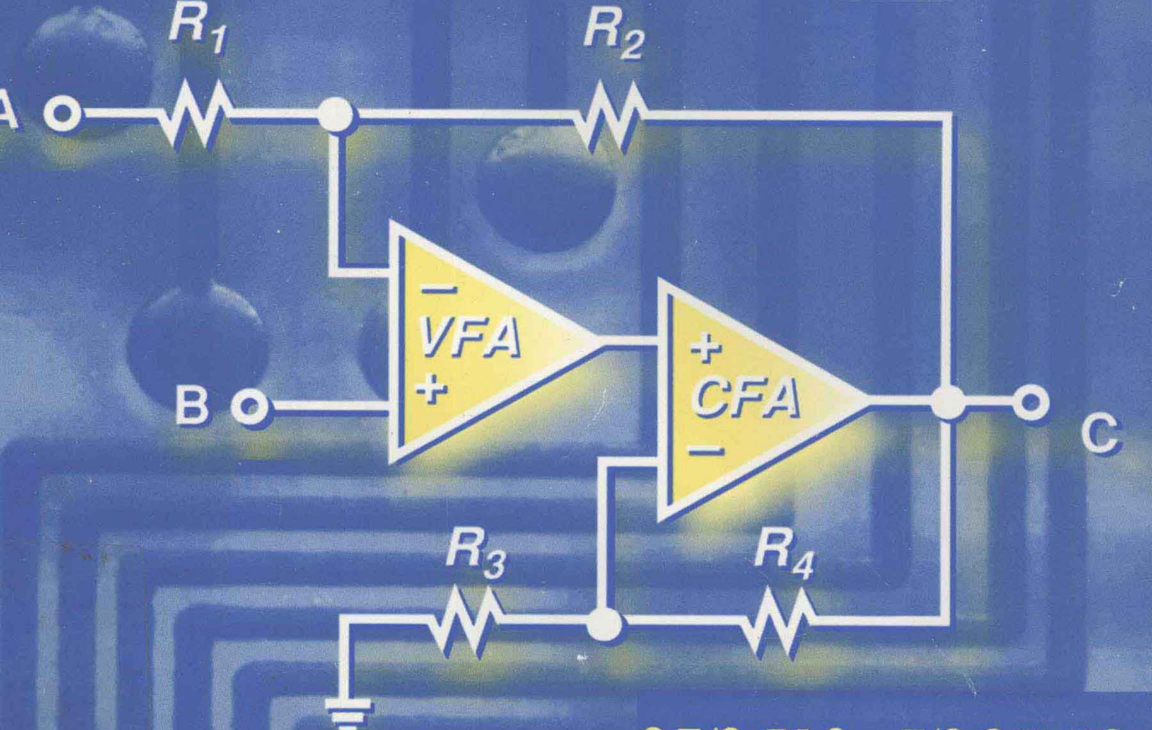
DESIGN WITH OPERATIONAL AMPLIFIERS AND ANALOG INTEGRATED CIRCUITS

SECOND EDITION



SERGIO FRANCO

Design with Operational Amplifiers and Analog Integrated Circuits

SECOND EDITION

Sergio Franco
San Francisco State University

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In Memory of My Mother

PREFACE

The success of the first edition and the desire to reflect the exciting advances of analog electronics have provided the motivation for a major revision of the book. The primary objective continues to be the illustration of general analog principles and design methodologies using practical devices and applications; however, considerable effort has been made to *enhance the pedagogy* of the book as well as to reflect *current technological developments and practices.*

The principal features of the new edition are as follows.

1. **Enhanced pedagogy.** The revision contains 176 worked examples and 526 end-of-chapter problems, many of which are design-oriented. Greater emphasis has been placed on the loop gain T as a gauge for assessing the performance level of a circuit. Complex-plane systems concepts have been covered more deeply.
2. **PSpice simulation.** Recognizing that circuit simulation by computer has become an indispensable verification tool both in analysis and design, we emphasize the use of PSpice® and its Probe® post-processor as a form of software oscilloscope for a rapid test of such critical issues as stability and the effects of device nonidealities. (PSpice and Probe are trademarks of the Microsim Corporation.)
3. **Expanded subject coverage.** The revision includes more recent material, such as *current-feedback amplifiers* and *sigma-delta converters,* along with topics that were absent from the first edition, such as *switching regulators* and *phase-locked loops.*

The book is intended as a textbook for undergraduate and graduate courses in design and applications with analog integrated circuits (analog ICs), as well as a reference book for practicing engineers. The reader is expected to have had an introductory course in electronics, to be conversant in frequency-domain analysis techniques, and to possess basic skills in the use of PSpice. Though the book contains enough material for a two-semester course, it can also serve as basis for a one-semester course after suitable selection of topics. The selection process is facilitated by the fact that the book as well as its individual chapters have generally been designed to proceed from the elementary to the complex.

At San Francisco State University we use the book for a one-semester senior course that students take concurrently with a course in analog IC design and fabrication. For an effective utilization of analog ICs, it is important that the user be cognizant of their internal workings, at least qualitatively. To serve this need, the book provides intuitive explanations of the technological and circuital factors intervening in a design decision.

The Web Site

We exploit the availability of modern communications tools to provide a forum for the exchange of analog-design ideas related to the book. To this end, we are maintaining a Web site at http://www.mhhe.com/franco, where the reader can find updates, downloadable software referenced in the book, and information about analog IC manufacturers and seminar events. Students, instructors, and practicing engineers alike—and not necessarily in that order—are encouraged to contribute new design ideas and problems, design projects, and whatever information will help make the book a dynamically evolving aid for the benefit of its entire readership. The author welcomes feedback also via e-mail, at sfranco@sfsu.edu.

The Contents at a Glance

Although not explicitly indicated, the book consists of three parts: part I (Chapters 1–4) introduces fundamental concepts and applications based on the op amp as a predominantly ideal device. We feel that the student needs to develop sufficient confidence with ideal (or near-ideal) op amp situations before being able to appreciate the consequences of practical device limitations. Limitations are the subject of part II (Chapters 5–8), which covers the topic in more systematic detail than the first edition. Finally, part III (Chapters 9–13) exploits the maturity and judgment developed by the student in the first two parts to address a variety of design-oriented applications. Following is a brief chapter-by-chapter description of the material covered.

Chapter 1 reviews basic amplifier concepts, including negative feedback. Much emphasis is placed on the loop gain T as a gauge of circuit performance. The student is introduced to simple PSpice models, which become more sophisticated as we progress through the book.

Chapter 2 deals with *I-V*, *V-I*, and *I-I* converters, along with various instrumentation and transducer amplifiers. The present edition places greater emphasis on feedback topologies and the role of the loop gain T.

Chapter 3 covers first-order filters, audio filters, and popular second-order filters such as the *KRC*, multiple-feedback, state-variable, and biquad topologies. The chapter emphasizes complex-plane systems concepts, and concludes with filter sensitivities.

The reader who wants to go deeper into the subject of filters will find Chapter 4 useful. This chapter covers higher-order filter synthesis using both the cascade and the direct approaches. Moreover, these approaches are presented both for the case of active *RC* filters and the case of switched-capacitor (SC) filters.

Chapter 5 addresses input-referrable op amp errors such as V_{OS}, I_B, I_{OS}, CMRR, PSRR, and drift, along with operating limits. The student is introduced to data-sheet interpretation, and also to different technologies and topologies.

Chapter 6 addresses dynamic limitations in both the frequency and time domains, and investigates their effect on the resistive circuits and the filters that were studied in part I using mainly ideal op amp models. Voltage-feedback and current-feedback are compared in detail, and PSpice is used extensively to visualize both the frequency and transient responses of significant circuits.

The subject of ac noise, covered in Chapter 7, follows naturally since it combines the principles learned in Chapters 5 and 6. Noise calculations and estimation represent another area in which PSpice proves a most useful tool.

Part II concludes with the subject of stability, in Chapter 8. Compared to the first edition, the material has been rearranged to facilitate topic selection and puts greater emphasis on a systems-oriented approach. Again, PSpice is used profusely to visualize the effect of the different frequency-compensation techniques presented in this chapter.

Part III begins with nonlinear applications, in Chapter 9. Here, nonlinear behavior stems from either the lack of feedback (voltage comparators) or the presence of feedback, but of the positive type (Schmitt triggers), or the presence of negative feedback, but using nonlinear elements such as diodes and switches (precision rectifiers, peak detectors, track-and-hold amplifiers).

Chapter 10 covers signal generators, including Wien-bridge and quadrature oscillators, multivibrators, timers, function generators, and *V-F* and *F-V* converters.

Chapter 11 addresses regulation. In this edition, voltage references and linear voltage regulators have been combined into a single chapter. Moreover, the material has been expanded to include basic switching regulators.

Chapter 12 deals with data conversion. Data-converter specifications are now treated more systematically, more applications with multiplying DACs are covered, and the material has been expanded to include oversampling-conversion principles and sigma-delta converters.

Chapter 13 concludes the book with a variety of nonlinear circuits, such as log/antilog amplifiers, analog multipliers, and operational transconductance amplifiers with a brief exposure to g_m-C filters. The material has been expanded with the inclusion of phase-locked loops.

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Sergio Franco
San Rafael, California, 1997

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CHAPTER 1

Operational Amplifier Fundamentals

1.1 Amplifier Fundamentals
1.2 The Operational Amplifier
1.3 Basic Op Amp Configurations
1.4 Ideal Op Amp Circuit Analysis
1.5 Negative Feedback
1.6 Feedback in Op Amp Circuits
1.7 The Loop Gain
1.8 Op Amp Powering
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Appendix 1A

The term *operational amplifier*, or *op amp* for short, was coined in 1947 by John R. Ragazzini to denote a special type of amplifier that, by proper selection of its external components, could be configured for a variety of operations such as amplification, addition, subtraction, differentiation, and integration. The first applications of op amps were in analog computers. The ability to perform mathematical operations was the result of combining high gain with negative feedback.

Early op amps were implemented with vacuum tubes, so they were bulky, power-hungry, and expensive. The first dramatic miniaturization of the op amp came with the advent of the bipolar junction transistor (BJT), which led to a whole generation of op amp modules implemented with discrete BJTs. However, the real breakthrough occurred with the development of the integrated circuit (IC) op amp, whose elements are fabricated in monolithic form on a silicon chip the size of a pinhead. The first such device was developed by Robert J. Widlar at Fairchild Semiconductor Corporation in the early 1960s. In 1968 Fairchild introduced the op amp that was to become the industry standard, the popular μA741. Since then the number of op amp families and manufacturers has swollen considerably. Nevertheless, the 741 remains one of the most popular types in spite of competition from devices of comparable cost but superior performance. Because of its enduring popularity and the fact that it is the most widely documented op amp in the literature, we shall use it as a vehicle to illustrate general op amp principles and also as a yardstick to assess the relative merits of other op amp families. However, we shall not hesitate to turn to other op amp types if they prove better suited to the application at hand.

Op amps have made lasting inroads into virtually every area of analog and mixed analog-digital electronics. Such widespread use has been aided by dramatic price drops. Today, the cost of an op amp that is purchased in volume quantities can be comparable to that of more traditional and less sophisticated components such as trimmers, quality capacitors, and precision resistors. In fact, the prevailing attitude is to regard the op amp as just another component, a viewpoint that has had a profound impact on the way we think of analog circuits and design them today.

The internal circuit diagram of the 741 op amp is shown in Fig. 5A.2 of the Appendix at the end of Chapter 5. The circuit may be intimidating, especially if your understanding of BJTs is not sufficiently deep. Be reassured, however, that it is possible to design a great number of op amp circuits without a detailed knowledge of the op amp's inner workings. Indeed, in spite of its internal complexity, the op amp lends itself to a black-box representation with a very simple relationship between output and input. We shall see that this simplified schematization is adequate for a great variety of situations. When it is not, we shall turn to the data sheets and predict circuit performance from specified data, again avoiding a detailed consideration of the inner workings.

To promote their products, op amp manufacturers maintain applications departments with the purpose of identifying areas of application for their products and publicizing them by means of application notes and articles in trade journals. You are encouraged to start building your own reference library of linear data books and application notes. Browse through them in your spare time, and you will be amazed by the wealth of information they provide. For your convenience, we maintain an updated list of the major op amp manufacturers. This list can be accessed by visiting the Web site at http://www.mhhe.com/franco.

This study of op amp principles should be corroborated by practical experimentation. You can either assemble your circuits on a protoboard and try them out in the lab, or you can simulate them with a personal computer using any of the various CAD/CAE packages available, such as SPICE. For best results, you may wish to do both.

After reviewing basic amplifier concepts, this chapter introduces the op amp as well as analytical techniques suitable for investigating a variety of basic op amp circuits. Central to the operation of these circuits is the concept of *negative feedback.* In particular, the reader is introduced to the concept of *loop gain* as the most important characteristic of negative-feedback circuits. The chapter concludes with some practical considerations, such as op amp powering, output saturation, and internal power dissipation.

1.1 AMPLIFIER FUNDAMENTALS

Before embarking on the study of the operational amplifier, it is worth reviewing the fundamental concepts of amplification and loading. Recall that an amplifier is a two-port device that accepts an externally applied signal, called *input,* and generates a signal called *output* such that *output* = *gain* × *input,* where *gain* is a suitable proportionality constant. A device conforming to this definition is called a *linear amplifier* to distinguish it from devices with nonlinear input-output relationships, such as quadratic and log/antilog amplifiers. Unless stated to the contrary, the term *amplifier* will here signify *linear amplifier.*

An amplifier receives its input from a *source* upstream and delivers its output to a *load* downstream. Depending on the nature of the input and output signals, we have different amplifier types. The most common is the *voltage amplifier,* whose input v_I and output v_O are voltages. Each port of the amplifier can be modeled with a Thévenin equivalent, consisting of a voltage source and a series resistance. The input port usually plays a purely passive role, so we model it with just a resistance R_i, called the *input resistance* of the amplifier. The output port is modeled with a voltage-controlled voltage source (VCVS) to signify the dependence of v_O on v_I, along with a series resistance R_o called the *output resistance.* The situation is depicted in Fig. 1.1, where A_{oc} is called the *voltage gain factor* and is expressed in volts per volt. Note that the input source is also modeled with a Thévenin equivalent consisting of the source v_S and series resistance R_s; the output load, playing a passive role, is modeled with a mere resistance R_L.

We now wish to derive an expression for v_O in terms of v_S. Applying the voltage divider formula at the output port yields

$$v_O = \frac{R_L}{R_o + R_L} A_{\text{oc}} v_I \tag{1.1}$$

We note that in the absence of any load ($R_L = \infty$) we would have $v_O = A_{\text{oc}} v_I$. Hence, A_{oc} is called the *unloaded,* or *open-circuit,* voltage gain. Applying the voltage divider formula at the input port yields

$$v_I = \frac{R_i}{R_s + R_i} v_S \tag{1.2}$$

Eliminating v_I and rearranging, we obtain the *source-to-load gain,*

$$\frac{v_O}{v_S} = \frac{R_i}{R_s + R_i} A_{\text{oc}} \frac{R_L}{R_o + R_L} \tag{1.3}$$

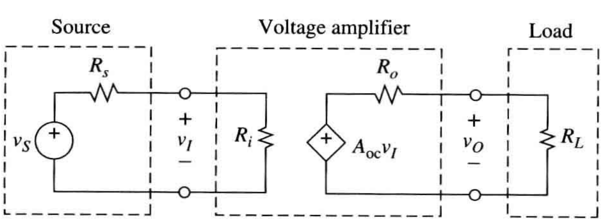

FIGURE 1.1
Voltage amplifier.

As the signal progresses from source to load, it undergoes first some attenuation at the input port, then magnification by A_{oc} inside the amplifier, and finally additional attenuation at the output port. These attenuations are referred to as *loading*. It is apparent that because of loading, Eq. (1.3) gives $|v_O/v_S| \le |A_{oc}|$.

EXAMPLE 1.1. (*a*) An amplifier with $R_i = 100\ \text{k}\Omega$, $A_{oc} = 100$ V/V, and $R_o = 1\ \Omega$ is driven by a source with $R_s = 25\ \text{k}\Omega$ and drives a load $R_L = 3\ \Omega$. Calculate the overall gain as well as the amount of input and output loading. (*b*) Repeat, but for a source with $R_s = 50\ \text{k}\Omega$ and a load $R_L = 4\ \Omega$. Compare.

Solution. (*a*) By Eq. (1.3), the overall gain is $v_O/v_S = [100/(25 + 100)] \times 100 \times 3/(1 + 3) = 0.80 \times 100 \times 0.75 = 60$ V/V, which is less than 100 V/V because of loading. Input loading causes the source voltage to drop to 80% of its unloaded value; output loading introduces an additional drop to 75%. (*b*) By the same equation, $v_O/v_S = 0.67 \times 100 \times 0.80 = 53.3$ V/V. We now have more loading at the input but less loading at the output. Moreover, the overall gain has changed from 60 V/V to 53.3 V/V. ◀

Loading is generally undesirable because it makes the overall gain dependent on the particular input source and output load, not to mention gain reduction. The origin of loading is obvious: when the amplifier is connected to the input source, R_i draws current and causes R_s to drop some voltage. It is precisely this drop that, once subtracted from v_S, leads to a reduced voltage v_I. Likewise, at the output port the magnitude of v_O is less than the dependent-source voltage $A_{oc}v_I$ because of the voltage drop across R_o.

If loading could be eliminated altogether, we would have $v_O/v_S = A_{oc}$ regardless of the input source and the output load. To achieve this condition, the voltage drops across R_s and R_o must be zero regardless of R_s and R_L. The only way to achieve this is by requiring that our voltage amplifier have $R_i = \infty$ and $R_o = 0$. For obvious reasons such an amplifier is termed *ideal.* Though these conditions cannot be met in practice, an amplifier designer will strive to approximate them as closely as possible by ensuring that $R_i \gg R_s$ and $R_o \ll R_L$ for all input sources and output loads that the amplifier is likely to be connected to.

Another popular amplifier is the *current amplifier.* Since we are now dealing with currents, we model the input source and the amplifier with Norton equivalents, as in Fig. 1.2. The parameter A_{sc} of the current-controlled current source (CCCS) is called the *unloaded,* or *short-circuit, current gain.* Applying the current divider

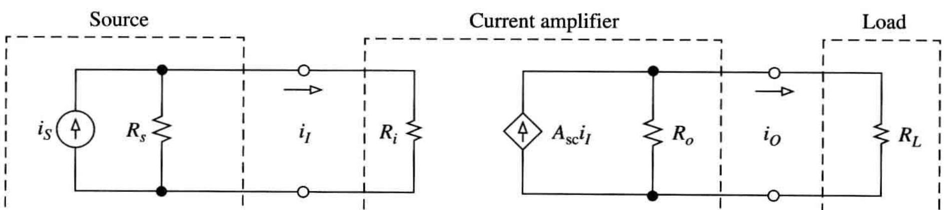

FIGURE 1.2
Current amplifier.

TABLE 1.1
Basic amplifiers and their ideal terminal resistances

Input	Output	Amplifier type	Gain	R_i	R_o
v_I	v_O	Voltage	V/V	∞	0
i_I	i_O	Current	A/A	0	∞
v_I	i_O	Transconductance	A/V	∞	∞
i_I	v_O	Transresistance	V/A	0	0

formula twice yields the source-to-load gain,

$$\frac{i_O}{i_S} = \frac{R_s}{R_s + R_i} A_{sc} \frac{R_o}{R_o + R_L} \tag{1.4}$$

We again witness loading both at the input port, where part of i_S is lost through R_s, making i_I less than i_S, and at the output port, where part of $A_{sc} i_I$ is lost through R_o. Consequently, we always have $|i_O/i_S| \leq |A_{sc}|$. To eliminate loading, an *ideal* current amplifier has $R_i = 0$ and $R_o = \infty$, exactly the opposite of the ideal voltage amplifier.

An amplifier whose input is a voltage v_I and whose output is a current i_O is called a *transconductance amplifier* because its gain is in amperes per volt, the dimensions of conductance. The situation at the input port is the same as that of the voltage amplifier of Fig. 1.1; the situation at the output port is similar to that of the current amplifier of Fig. 1.2, except that the dependent source is now a voltage-controlled current source (VCCS) of value $A_{sc} v_I$, with A_{sc} in amperes per volt. To avoid loading, an ideal transconductance amplifier has $R_i = \infty$ and $R_o = \infty$.

Finally, an amplifier whose input is a current i_I and whose output is a voltage v_O is called a *transresistance amplifier*, and its gain is in volts per ampere. The input port appears as in Fig. 1.2, and the output port as in Fig. 1.1, except that we now have a current-controlled voltage source (CCVS) of value $A_{oc} i_I$, with A_{oc} in volts per ampere. Ideally, such an amplifier has $R_i = 0$ and $R_o = 0$, the opposite of the transconductance amplifier.

The four basic amplifier types, along with their ideal input and output resistances, are summarized in Table 1.1.

1.2 THE OPERATIONAL AMPLIFIER

The operational amplifier is a voltage amplifier with extremely high gain. For example, the popular 741 op amp has a typical gain of 200,000 V/V, also expressed as 200 V/mV. The OP-77, a more recent type, has a gain of 12 million V/V, or 12 V/μV. In fact, what distinguishes op amps from all other voltage amplifiers is the size of their gain. In the next sections we shall see that the higher the gain the better, or that an op amp would ideally have an infinitely large gain. Why one would want gain to be extremely large, let alone infinite, will become clearer as soon as we start analyzing our first op amp circuits.