Applications of Analog Integrated Circuits

SIDNEY SOCLOF

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Preface

This is a book on the characteristics and applications of analog integrated circuits. The integrated circuits discussed in this book are used in a wide variety of applications in the areas of communications, control systems, signal processing, optoelectronics, digital systems interfacing, and as transducers for temperature, pressure, magnetic fields, and light sensing. There is enough material in this book for a two-semester senior or graduate-level course. By suitable selection of material, this book can also serve quite well for just a one-semester course. The background and preparation needed for this book is two semesters of basic electronics. This should preferably include some introductory material on the basic operation and characteristics of operational amplifiers.

Chapter 1 is a compendium of representative examples of the applications of operational amplifiers. Also presented in this chapter are some examples of applications of voltage comparators, which are devices that are very closely related to operational amplifiers. Only applications material is presented here since the basic characteristics of operational amplifiers are covered in many other books.

Integrated-circuit voltage regulators are discussed in Chapter 2. In addition to a presentation of the basic theory, characteristics, and the protective circuitry of voltage regulators, there are examples of various types of voltage regulators given including adjustable-positive and negative regulators, three-terminal fixed regulators, and switching-mode regulators.

In Chapter 3, integrated-circuit power amplifiers are investigated. The power conversion efficiency and distortion of power amplifiers is considered and examples are given of integrated-circuit audio power amplifiers. Examples of power-operational amplifiers are also presented.

In Chapter 4, attention is turned to the high-frequency performance of integrated circuits with a discussion of wide bandwidth or video amplifiers. First there is a discussion of the performance of common-emitter, cascode, emitter-follower, and FET circuits at high frequencies. This is followed by a presentation of examples of video-amplifier integrated circuits. Then some examples of operational amplifiers that have very wide bandwidths and high slewing rates are given. At the end of the chapter, unity gain buffers are discussed.

Modulators, demodulators, and phase-detector integrated circuits are discussed in Chapter 5. These are very closely related topics since the same basic circuit can be used for all three functions. The chapter opens with an analysis of the basic circuit configuration that is used for these three functions. Then some applications examples are given including amplitude modulation and demodulation, frequency modulation and FM detection, frequency doubling, and phase detection.

Integrated circuits that are used to generate various types of waveforms are presented in Chapter 6. Examples of voltage-controlled oscillators in which the frequency can be varied by an input voltage are considered first, followed by a discussion of waveform generators for the production of square, triangular, pulse, and sinusoidal waveforms.

The phase-locked loops of Chapter 7 are an important element of many communications and signal processing systems. The basic operation of these devices are discussed first, followed by examples of various applications such as AM and FM detection, frequency synthesis, and stereo demodulation.

The nonlinear characteristics of transistors and diodes can be used to good advatage to make circuits capable of multiplication, division, squaring, square rooting, rms-to-dc conversion, logarithmic conversion, exponential conversion, and other functions. This is the subject of Chapter 8, where the basic principles and examples of circuits to perform these various operations are presented.

Most integrated circuits have electrical inputs and outputs. In Chapter 9 integrated-circuit transducers are presented in which there is a non-electrical input such as temperature, pressure, or magnetic field. The related topic of light-sensitive devices is presented in Chapter 15.

Analog-to-digital and digital-to-analog converters are essential elements for the communication between analog and digital systems. These integrated circuits are discussed in Chapter 10 and various examples are given.

In Chapter 11, analog switches and sample-and-hold circuits are analyzed. These circuits are used in various signal processing applications such as signal multiplexing and demultiplexing and are also used in conjunction with analog-to-digital converters.

A very different type of integrated circuit considered in this book is the charge transfer device of Chapter 12. The two basic types of charge transfer devices considered are the charge-coupled device and the bucket-brigade device. After a study of the basic principles of operation of these devices, a number of applications examples are presented.

There are many monolithic and hybrid integrated circuits that are rather specialized in application and these are presented in Chapter 13. These include instrumentation amplifiers, isolation amplifiers, micropower and low-voltage integrated circuits, high-voltage integrated circuits, frequency-to-voltage converters, compandors, electronic attenuators, two-wire transmitters, tuned amplifiers, FM circuits, AM radio circuits, and integrated circuits for television.

The subject of Chapter 14 is not a specific integrated circuit, but rather the general topic of noise in integrated circuits and electronic systems. This is an important topic since electrical noise will set the lower limit on the detectibility of signals. Various noise sources in electronic devices including bipolar transistors and field-effect transistors are first considered, followed by a noise analysis of differential amplifiers. Next, operational amplifiers are considered, and at the end of the chapter some examples of low-noise operational amplifiers are discussed.

An important area of applications for integrated circuits is in optoelectronics and this is the subject of Chapter 15. Topics included in this chapter are photodiodes and phototransistors, radiation detectors and radiation damage, optically-coupled isolators, optoelectronic analog signal transmission, slotted and reflective emitter-sensor modules, and linear and area image sensors. The last topic dealing with image sensors represents an increasingly important type of integrated circuit and is discussed at length.

At the end of every chapter, (except Chapter 13), there are problems representative of the material covered in the chapter. Also at the end of every chapter is a list of general references for further reading or study.

SIDNEY SOCLOF

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Applications of Operational Amplifiers and Voltage Comparators

1

The operational amplifier (op amp) is a basic building block for many analog integrated-circuit (IC) systems and is useful in a very wide range of applications. In this chapter a number of op-amp applications are presented and briefly described. The equations presented for the op amp in this chapter are based on the assumption of an ideal op amp, with a very high open-loop gain. They do not take into account such effects as the input offset voltage, the input bias current, and the input offset current, nor is the effect of a finite open-loop gain and the frequency variation thereof considered.

A device closely related to the op amp is the voltage comparator. Some examples of circuits using voltage comparators are presented in this chapter.

A detailed description of the characteristics and internal circuitry of op amps and voltage comparators is beyond the scope of this book. Such descriptions may be found in many other books, as indicated by the references at the end of this chapter. Particular reference is made to ***Analog Integrated Circuits***, by the present author, and ***Analog Integrated Circuit Analysis and Design***, by Gray and Meyer.

For all the op-amp and voltage comparator circuits presented in this chapter, the usual convention with respect to inverting (−) and noninverting (+) input terminals will be used; that is, the inverting (−) input terminal is the upper input terminal and the noninverting (+) input is the lower input terminal.

1.1 OP-AMP APPLICATIONS

1. *Voltage follower* (Figure 1.1): This circuit produces a unity voltage gain with $V_O = V_S$. It is characterized by a very high input impedance Z_{IN} and a very low output impedance Z_O and is very useful as a buffer in coupling high-impedance sources to low-impedance loads.

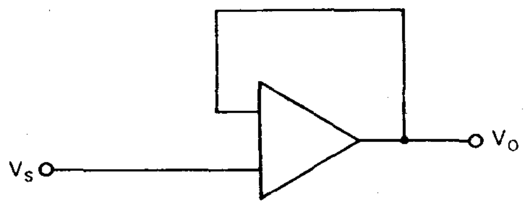

Figure 1.1 Voltage follower.

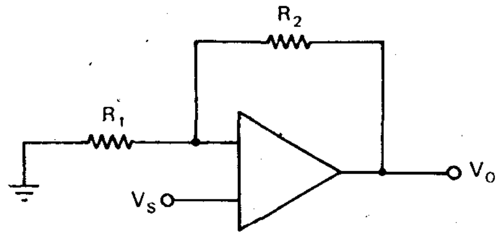

Figure 1.2 Noninverting amplifier.

2. *Noninverting amplifier* (Figure 1.2): For this circuit $V_O = (1 + R_2/R_1)V_S$. It has a very high Z_{IN} and a low Z_O.
3. *Inverting amplifier* (Figure 1.3): For this circuit $V_O = -(R_2/R_1)V_S$. It has an input impedance of $Z_{IN} = R_1$ and a very low output impedance.
4. *Summing amplifier* (Figure 1.4): For this circuit $V_O = -R_F(V_1/R_1 + V_2/R_2 + V_3/R_3 + V_4/R_4 + \cdots)$. The input impedance with respect to the various input signals V_1, V_2, V_3, . . . will be R_1, R_2, R_3, . . . , respectively.
5. *Difference amplifier* (Figure 1.5): This circuit produces an output voltage that is directly proportional to the difference of the two input signals as given by $V_O = (R_2/R_1)(V_1 - V_2)$. The input impedance with respect to the V_1 input is $R_1 + R_2$, and for the V_2 signal input it is R_1.
6. *Algebraic summation amplifier* (Figure 1.6): This circuit is an extension of the simple summing circuit, and the output voltage will represent an algebraic summation of the various input signals with coefficients determined by the resistance ratios.
7. *Current-to-voltage converter* (Figure 1.7): This circuit produces an output voltage that is directly proportional to the input current as given by $V_O = -I_S R_F$. The input impedance is equal to the feedback resistance divided by the amplifier open-loop gain A_{OL} as given by $Z_{IN} = R_F/A_{OL}$. In addition to this very low input resistance, it has a very low output impedance.
8. *Voltage-to-current converter* (Figure 1.8): The current I_L through the load resistance R_L is given by $I_L = V_S/R_1$ and is thus independent of R_L so that this circuit acts as a constant-current source. Since the current produced by

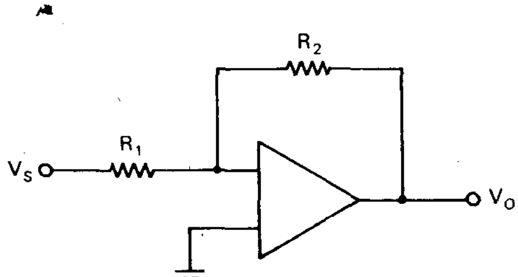

Figure 1.3 Inverting amplifier.

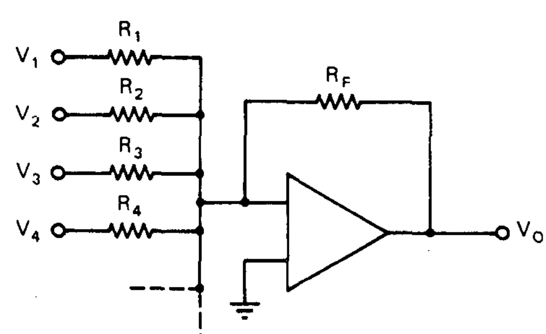

Figure 1.4 Summing amplifier.

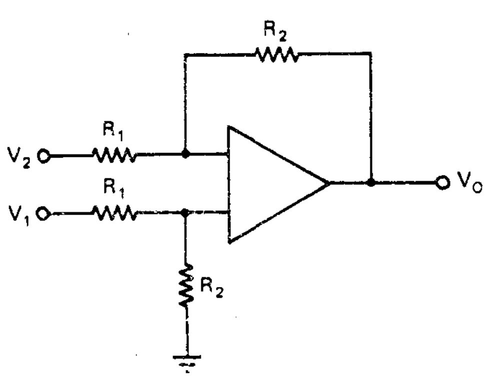

Figure 1.5 Difference amplifier.

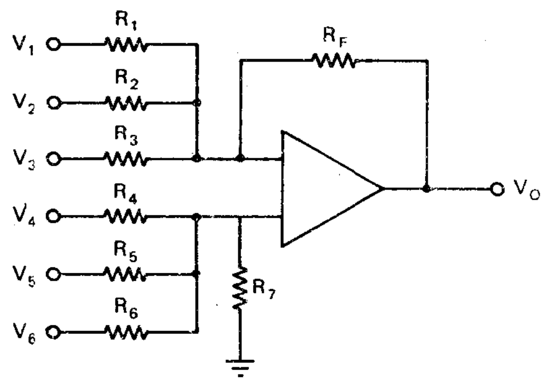

Figure 1.6 Algebraic summation amplifier.

this circuit is independent of the load resistance R_L but is directly proportional to the signal or control voltage V_S, this circuit is a voltage-controlled constant-current source. Note that neither end of the load resistance may be grounded.

9. *Constant-current source with grounded load* (*Howland current source*) (Figure 1.9): The current I_L through the load resistance R_L is given by $I_L = (V_1 - V_2)/R_1$ and is thus independent of R_L. Since the current is independent of R_L but is directly proportional to the input voltage differential, this circuit is a voltage-controlled constant-current source. Note that in this circuit a grounded load resistor may be used.

10. *Integrator* (Figure 1.10): The output voltage V_O will be proportional to the integral of the input voltage V_S over the integration period T as given by $V_O = -(1/R_1C_1)\int_0^T V_S\,dt$. The integration period is controlled by switch S_1, which opens at time $t = 0$ to start the integration process and closes at $t = T$ to terminate the integration and discharge the capacitor C_1 in preparation for the next integration cycle.

    Resistor R_1 can be omitted and this circuit can be operated as a current integrator with $V_O = (1/C_1)\int_0^T I_S\,dt = Q/C_1$, where Q is the total electrical charge delivered to the circuit over the integration period.

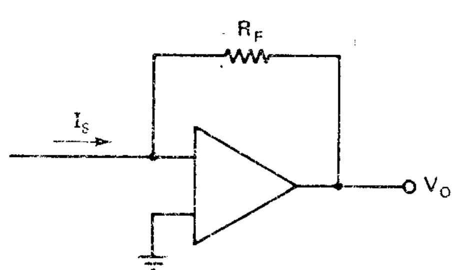

Figure 1.7 Current-to-voltage converter.

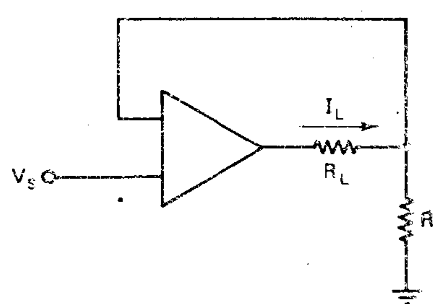

Figure 1.8 Voltage-to-current converter

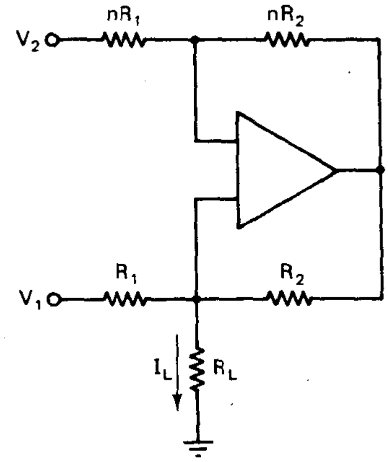

Figure 1.9 Constant-current source with grounded load (Howland current source).

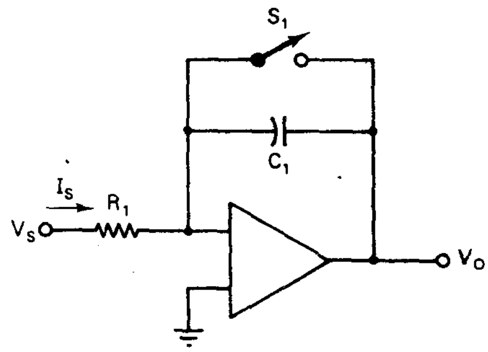

Figure 1.10 Integrator.

11. *Active low-pass filter* (Figure 1.11): In the frequency domain (sinusoidal excitation) the closed-loop gain of this circuit is given by $A_{CL} = -(R_F/R_1)/(1 + j\omega R_F C_F)$. It is a low-pass amplifier with a zero-frequency gain of $A_{CL}(0) = -R_F/R_1$ and a 3-dB bandwidth $BW = 1/(2\pi R_F C_F)$. In the time domain the response to a unit-step-function voltage input will be given by $V_O(t) = -(R_F/R_1)[1 - \exp(-t/R_F C_F)]$. For input signals whose period T is short compared to the $R_F C_F$ time constant ($T \lesssim R_F C_F/5$) the output voltage will be approximately the integral of the input voltage.
12. *Differentiator and active high-pass filter* (Figure 1.12): If $R_1 = 0$, this circuit will be an "ideal" differentiator with the output voltage being the time derivative of the input voltage as given by $V_O = -R_F C_1(dV_S/dt)$. The use of a small-value resistor for R_1 may, however, be desirable to limit the high-frequency gain. An excessively high-frequency gain can be a problem due to the amplification of the noise voltage. The value of R_1 should be chosen such that the $R_1 C_1$ time constant will be small compared to the period of the input signal.

    In the frequency domain (sinusoidal excitation) this circuit acts as a high-pass amplifier with a gain given by $A_{CL} = V_O/V_S = j\omega R_F C_1/(1 + j\omega R_1 C_1)$.
13. *Summing integrator* (Figure 1.13): This is a simple extension of the simple

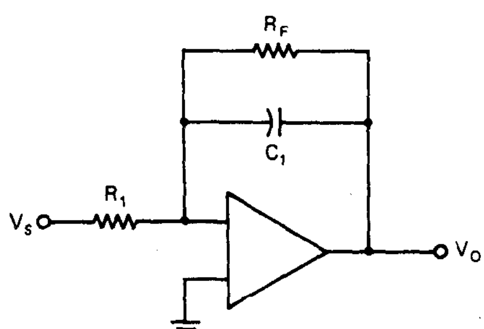

Figure 1.11 Active low-pass filter.

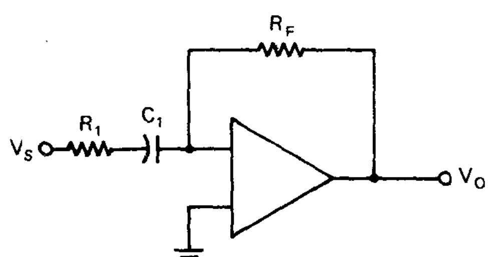

Figure 1.12 Differentiator and active high-pass filter.

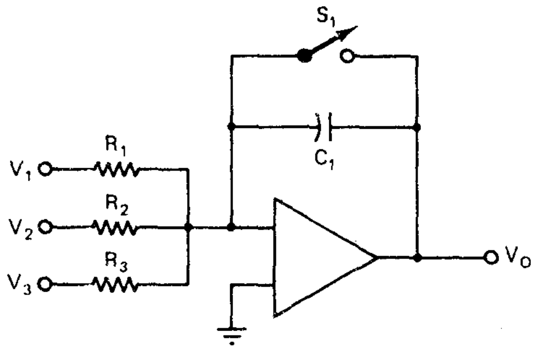

Figure 1.13 Summing integrator.

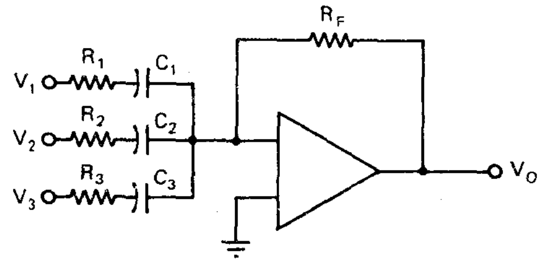

Figure 1.14 Summing differentiator.

integrator circuit. For this circuit

$$V_O = -\frac{1}{C_1}\int_0^T \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right) dt$$

14. *Summing differentiator* (Figure 1.14): This is an extension of the simple differentiator circuit. For this circuit

$$V_O = -R_F\left(\frac{C_1 dV_1}{dt} + \frac{C_2 dV_2}{dt} + \frac{C_3 dV_3}{dt}\right)$$

if $R_1C_1 \ll T$, $R_2C_2 \ll T$, and $R_3C_3 \ll T$, where T is the period of the input signal.

15. *Precision half-wave rectifier* (Figure 1.15): This circuit produces $V_O = V_S$ for $V_S > 0$ and $V_O = 0$ for $V_S \leqslant 0$. It acts as a precision half-wave rectifier, or detector for communications circuits, as a result of the forward voltage drop of the diode being divided by the amplifier open-loop gain.
16. *Precision full-wave rectifier* (*absolute-value circuit*) (Figure 1.16): For this circuit $V_O = |V_S|$. Again, in this case the effect of the forward voltage drop of the diode is essentially nullified as a result of the very high open-loop gain of the amplifier.
17. *Precision peak detector* (Figure 1.17): The output voltage will be equal to the highest positive peak value of the input voltage. Amplifier A_2 is used as a unity-gain buffer for load isolation so that the current drawn by the load will not discharge C_1.
18. *Amplifier with electronic gain control* (Figure 1.18): This circuit is useful for

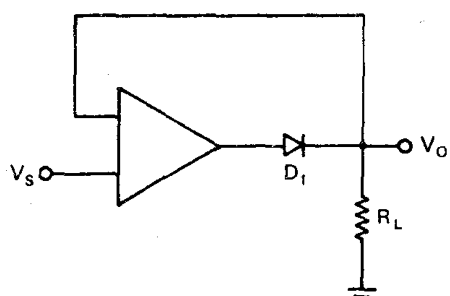

Figure 1.15 Precision half-wave rectifier.