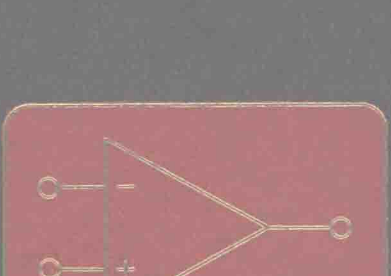
OPERATIONAL AMPLIFIER
Characteristics and Applications

Robert G. Irvine



OPERATIONAL AMPLIFIER CHARACTERISTICS AND APPLICATIONS

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Preface

For years during the 1940s and 1950s, George Philbrick had developed his company around the vacuum-tube operational amplifier. It was a self-contained device with two dual triodes in a phenolic housing, which in turn plugged into an octal socket. It was a mystery to many electrical and electronics engineers just what this device did when used in an instrumentation circuit.

In 1948, the transistor was developed; by 1954 it was in some general use by specific industries but was still a novelty to most engineers. Companies such as Philbrick, Burr-Brown, and others began to develop operational amplifiers in small modules using transistors. The use of an operational amplifier in an electronic circuit was still a specialized application not frequently employed.

Then, in 1965, an engineer named Bob Widlar, working for Fairchild, developed an operational amplifier as a monolithic integrated circuit chip. It was called the μA 709. Almost immediately, engineers who had no intentions of ever using an operational amplifier found one in a neat little 8-pin TO-5 can. It was an overnight success, and the 709 became famous along with Fairchild and Mr. Widlar, who later joined National Semiconductor and led them into the forefront of integrated-circuit technology.

Today, the operational amplifier is in almost as common usage as the transistor was in 1965. And as the technology progresses, the operational amplifier will surely overshadow the transistor in new designs.

It therefore behooves anyone interested in electronics, to become as familiar with the integrated operational amplifier as he or she is with the transistor. His or her future value to the industry depends upon this capability.

This text provides a thorough investigation of the design rules for operational amplifiers. Even though the reader will seldom, if ever, be required to design a monolithic operational amplifier, it is imperative that the reasons for design criteria be understood so that quantitative as well as qualitative judgments can be made by the user. When feedback is placed around an operational amplifier, it tends to mask all but the most obvious of failures. If the user is not equipped to make quantitative judgments about the operation, a failure exhibiting a subtle change in operational characteristics may go unnoticed.

Material usually omitted from texts at the technology level is included in this text. The examples and problems are written around real-life applications and situations. An extensive group of derivations, which support the equations in the text, is provided in an appendix. The use of this appendix actually upgrades the level of the text to include material not usually found in an engineering technology or engineering-level text. It also allows the more inquisitive student to seek out the roots of the equations given without searching through innumerable references. It is the intention of the author that this text should stand alone, at its level, and include all the supporting reference material on the subject of operational amplifiers.

The book was written for two groups of people. First, for the student pursuing a formal education at a college or university. Second, for the person practicing in the field of engineering. The book is a teaching text. It was not specifically meant for self-study, but the presentation and worked examples make that a viable option for those inclined to do so.

This text is taught by the author in two quarters: Chapters 1 through 6 are taught in the first quarter, and Chapters 7 through 11 are taught in the second quarter, both at the junior level.

The text could be used for a semester course by either including Chapter 7 for the more comprehensive course or by beginning at Chapter 2 and proceeding through Chapter 11, excluding Chapter 9 (active filters). Chapter 9 should be used only in the more comprehensive course. It takes between three and four weeks to present this chapter as it is written. Section 2.6 should be excluded from the presentation in Chapter 2; it should then be presented just before the phase-locked-loop section in Chapter 11.

The problems are written to correlate closely with the presentation and examples in the chapters. Wherever possible, problems are presented which parallel the examples in method of solution. Where the problem is difficult, or an ambiguity seems to exist, the problem is worded exactly as in the example to assure clarity. SI metrics are used throughout the book. This only affects electrical students in nomenclature and in conductance, where mho (℧) is replaced by the SI metric unit Siemen (S). No mathematics beyond algebra is required for solution of any of the problems or examples. Where differentiation or integration is required, the solution is given and the student is then asked to understand examples or work problems using that solution.

Chapter 9 is presented in such a manner as to enhance the student's understanding without diminishing the quality of presentation. The six major filter types are all presented, and examples and problems using these ensure a feeling of ease by the student after finishing the chapter. A special method of performing the required mathematics has been developed to prevent the student from becoming bogged down in math and not seeing the function being analyzed. In every case, the pole–zero diagram is shown opposite the filter's frequency response to give the student a "feeling" for the numbers in the equations and the pole locations for a particular filter type.

The book has been written to give students the tools with which to analyze and understand unfamiliar or special op amp circuits which will be encountered during the course of a career. Almost all circuits encountered by the author in industry were combinations or variations of the classical circuits presented in this book. A solutions manual, with all problems worked in detail, is available to instructors and those practicing engineering.

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This book began as a one-man effort. Very soon, though, it became evident that outside help would speed its completion. Thus the following people have contributed to the manuscript during the 27 months of its development.

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Contents

1

Construction of the Operational Amplifier

1.1 INTRODUCTION

The operational amplifier is a special-purpose amplifier intended to be used with external feedback components for proper operation. Only the operational amplifier itself will be discussed in this chapter. Its use with feedback elements will be reserved for later chapters, where an in-depth analysis will be presented.

1.2 NOTATION

The notation used in this text will be as follows:

1. Average (dc), maximum, and effective (root-mean-square or rms) values are represented using uppercase letters (V for voltage, I for current, and P for power).
2. Instantaneous values of quantities that vary with time are represented using lowercase letters (v, i, or p).
3. Instantaneous total values and average (dc) values are represented using an uppercase subscript letter for the appropriate terminal of the device being described (v_E).
4. Varying component values are indicated using a lowercase subscript letter for the appropriate device terminal (i_b).
5. A double subscript is used in two cases:

   a. Where the power-supply voltage (V_{CC} or V_{SS}) is referenced.

b. Where the voltage being represented is not ground-referenced; that is, it is the potential difference *between* two points in the circuit neither of which is at ground potential (zero volts). An example is V_{BE} for a transistor circuit with an emitter resistor.

6. E or e will be used in place of V or v for voltage sources. Power-supply sources are excluded from this notation.
7. The zero-volts reference plane for circuits will be represented using the terms "ground" and "common" interchangeably. These only differ in systems employing a chassis. There, the chassis is *ground* and the circuit *common* is a bus wire that is attached to the chassis at one point.

1.3 SI METRIC UNITS

The use of SI (International System of Units) metric units will be followed. As a result, the reader will encounter a few units that differ from the previous MKS or CGS systems. The symbols, together with the SI metric units, are listed in Table 1-1.

Table 1-1 SI Metric Units

Quantity	*Symbol*	*Unit Name*	*SI Metric Units*
Voltage	VE	(V) Volt	MV, kV, V, mV, μV
Current	I	(A) Ampere	kA, A, mA, μA, nA, pA
Power	P	(W) Watt	MW, kW, W, mW, μW
Energy (work)	W	(J) Joule	MJ, kJ, J, mJ, μJ
Resistance	R	(Ω) Ohm	MΩ, kΩ, Ω, mΩ
Conductance	G	(S) Siemen	kS, S, mS, μS
Capacitance	C	(F) Farad	F, mF, μF, nF, pF
Inductance	L	(H) Henry	H, mH, μH
Electric charge	Q	(C) Coulomb	kC, C, mC, μC, nC, pC
Frequency	f	(Hz) Hertz	THz, GHz, MHz, kHz, Hz
Force	F	(N) Newton	MN, kN, N, mN, μN
Length	l	(m) Meter	km, m, mm, μm
Mass	M	(kg) Kilogram	Mg, kg, g, mg, μg
Time	t	(s) Second	s, ms, μs, ns, ps
Angular velocity	ω	(ω) rad/s	ω
Damping force[a]	d	(N) Newton	N
Spring constant[a]	K	(N/m) $\frac{\text{Newtons}}{\text{Meter}}$	N/m

[a]Not actually SI units but represented as their SI equivalents.

1.4 DIFFERENTIAL-AMPLIFIER OPERATION

Much emphasis and time will be spent on the differential amplifier. Many of the good and most of the bad characteristics of the operational amplifier originate in the differential amplifier.

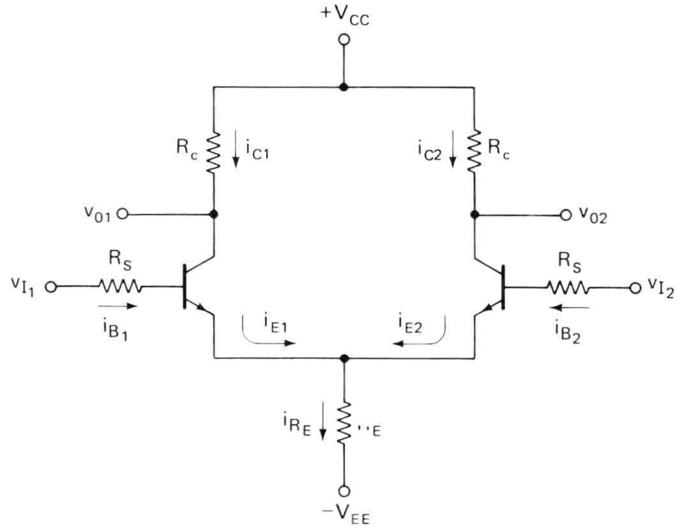

Fig. 1-1. Bipolar transistor differential amplifier.

A basic differential amplifier is shown in Fig. 1-1. It functions in such a manner that voltages common to both inputs (v_{I1} and v_{I2}) cause both collector voltages to move in unison, whereas voltages differing on the two inputs cause the two collector voltages to move in opposition. The basic rules of transistor action still apply; the collector voltage moves in opposition to the base voltage direction, regardless of whether the base change was caused by common or differing voltages.

1.4.1 Common-Mode Voltages

The voltage, common to both inputs, is labeled *common-mode input voltage* ($v_{I_{CM}}$). If v_{I1} is the voltage on base 1 and v_{I2} is the voltage on base 2, the common-mode input voltage is the average of these two voltages, as expressed by

$$v_{I_{CM}} = \frac{v_{I_1} + v_{I_2}}{2} \tag{1-1}$$

If $v_{I_1} = v_{I_2}$, then $v_{I_{CM}} = v_{I_1} = v_{I_2}$.

The voltage, common to both outputs, is labeled *common-mode output voltage* (v_{OCM}). If v_{O_1} is the voltage on collector 1 and v_{O_2} is the voltage on collector 2, the common-mode output voltage is the average of these two voltages at any instant in time, as expressed by

$$v_{O_{CM}} = \frac{v_{O_1} + v_{O_2}}{2} \tag{1-2}$$

With the two inputs connected together, v_{O_1} should be equal to v_{O_2}, presuming matched components, but that is seldom the case for actual circuits. Example 1-1 will help to clarify the use of Eqs. (1-1) and (1-2).

EXAMPLE 1-1

A differential amplifier has the characteristics that cause the common-mode output voltage to be +5.5 V when the input common-mode voltage is zero and to have an output common-mode voltage of +5.0 V when the input common-mode voltage is +1 V. Determine the input and output voltages for the following set of voltages:

Case	v_{I_1}	v_{I_2}	v_{O_1}	v_{O_2}	Find
1	0	0	+5.5		v_{O_2}
2	+1.1	+0.9	+2.0	+8.0	$v_{I_{CM}}, v_{O_{CM}}$
3	+0.01	−0.01		+6.1	$v_{I_{CM}}, v_{O_1}$

SOLUTION

Case 1

$$v_{I_{CM}} = \frac{0+0}{2} = 0 \qquad \text{thus} \qquad v_{O_{CM}} = +5.5\ \text{V}$$

$$+5.5 = \frac{+5.5 + v_{O_2}}{2} \qquad v_{O_2} = +5.5\ \text{V}$$

Case 2

$$v_{I_{CM}} = \frac{+1.1 + 0.9}{2} = +1.0$$

$$v_{O_{CM}} = \frac{2.0 + 8.0}{2} = +5.0$$

Case 3

$$v_{I_{CM}} = \frac{+0.01 + (-0.01)}{2} = 0\ \text{V}$$

$$v_{O_{CM}} = +5.5 = \frac{v_{O_1} + 6.1}{2} \qquad v_{O_1} = +4.9\ \text{V}$$

In the most frequently encountered case for common-mode voltages, the two input voltages are varying at different rates, thus producing a changing dc or an ac common-mode voltage. In this situation Eq. (1-1), between two instants in time, becomes

$$\Delta v_{I_{CM}} = \frac{\Delta v_{I_1} + \Delta v_{I_2}}{2} \tag{1-3}$$

and Eq. (1-2), between two instants in time becomes

$$\Delta v_{O_{CM}} = \frac{\Delta v_{O_1} + \Delta v_{O_2}}{2} \tag{1-4}$$

where the individual v_I's or v_O's must be established at two separate instants of time to determine the variation over the time interval.

EXAMPLE 1-2

A differential amplifier has v_{I_1} grounded while v_{I_2} is connected to an ac voltage of $v_{I_2} = 6\text{ mV}\sin(2\pi\cdot 0.1t)$. The output common-mode voltage is $+5.0$ V when $v_{I_{CM}} = 0$, $+5.001$ V when $v_{I_{CM}} = -3$ mV, and $+4.999$ V when $v_{I_{CM}} = +3$ mV. Determine the input and output common-mode voltages.

SOLUTION

$$\Delta v_{I_{CM}} = \frac{0 + 6\text{ mV}\sin(2\pi\cdot 0.1t)}{2} = 3\text{ mV}\sin(2\pi\cdot 0.1t)$$

which is a sine wave with peak instantaneous voltages of ± 3 mV. The collector voltage decreases as the base voltage increases, which results in a phase reversal on the output. Thus $\Delta v_{O_{CM}} = +5\text{ V} - 1\text{ mV}\sin(2\pi\cdot 0.1t)$. [*Note:* The (−) sign indicates the phase reversal.]

EXAMPLE 1-3

A differential amplifier has the following input and output voltages at different instants of time:

Instant	v_{I_1}	v_{I_2}	v_{O_1}	v_{O_2}
t_1	− 3.4 V	− 3.6 V	+ 4.2 V	+ 4.4 V
t_2	+ 1.8 V	+ 1.2 V	+ 2.6 V	+ 3.2 V

Determine the change in the input and output common-mode voltage.

SOLUTION

Δv_{I_1} is v_{I_1} at t_2 minus v_{I_1} at t_1; Δv_{I_2} is v_{I_2} at t_2 minus v_{I_2} at t_1. The same is true for the output voltages.

$$\Delta v_{I_{CM}} = \frac{[1.8 - (-3.4)] + [1.2 - (-3.6)]}{2} = \frac{5.2 + 4.8}{2}$$

$$= +5.0\text{ V}$$

$$\Delta v_{O_{CM}} = \frac{(2.6 - 4.2) + (3.2 - 4.4)}{2} = \frac{-1.6 + (-1.2)}{2}$$

$$= -1.4\text{ V}$$

which illustrates that, as the input common-mode voltage increases by 5 V, the output common-mode voltage decreases by 1.4 V.

The *common-mode gain* is defined as the change in common-mode output voltage divided by the change of input common-mode voltage, or

$$A_{CM} = +\frac{\Delta v_{O_{CM}}}{\Delta v_{I_{CM}}} \tag{1-5}$$

where A_{CM} becomes negative when numerical values are applied.

EXAMPLE 1-4

Using the values determined in Example 1-3, find A_{CM}.

SOLUTION

$$A_{CM} = \frac{-1.4\text{ V}}{+5.0\text{ V}} = -0.28$$

Common-mode gains are typically less than unity (1). The most desirable case is for the common-mode gain to be zero, and, as will be seen in subsequent sections, this is the motivation for particular circuit selections.

1.4.2 Differential Voltages

The differential voltage must be considered for two cases: (1) where the deviation voltage is swinging around a zero common-mode voltage, and (2) where the deviation voltage is swinging around a nonzero common-mode voltage. The first case should only be considered for the inputs, as the collector voltages of a differential amplifier generally swing around a nonzero common-mode voltage.

The differential voltage swing about any common-mode voltage, including zero volts, is called the *deviation voltage*. The input deviation voltage,* at any instant in time, is given by one-half the difference voltage at the input or

$$v_{I_{DEV}} = \pm \frac{v_{I_1} - v_{I_2}}{2} \tag{1-6}$$

where $(v_{I_1} - v_{I_2})$ is called the *differential input voltage* and is given an individual label (v_{I_d}); thus

$$v_{I_d} = v_{I_1} - v_{I_2} \tag{1-7}$$

and

$$v_{I_d} = \pm 2v_{I_{DEV}} \tag{1-8}$$

The output deviation voltage, at any instant in time, is given by

$$v_{O_{DEV}} = \pm \frac{v_{O_1} - v_{O_2}}{2} \tag{1-9}$$

which is the voltage deviation around the common-mode output voltage at any instant in time on each collector.

EXAMPLE 1-5

A differential amplifier has zero input and output common-mode voltages (not physically possible). The input and output voltages are:

v_{I_1}	v_{I_2}	v_{O_1}	v_{O_2}
−0.01	+0.01	+1.4	−1.4

Determine the input and output deviation voltages and the differential input voltage.

*The (±) sign indicates that the deviation voltage swings to each side of the common-mode voltage. This (±) indicator is dropped when discussing v_{I_d}, and this seems to be a mathematical error, but the differential voltage has only one algebraic sign, because it is a single voltage value.