88 PRACTICAL OP AMP CIRCUITS YOU CAN BUILD

BY GEORGE B. CLAYTON

No. 912
$7.95

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TAB BOOKS
Blue Ridge Summit, Pa. 17214

FIRST EDITION

FIRST PRINTING—APRIL 1977

Originally published in 1975 by
THE MACMILLAN PRESS LTD., London and Basingstoke

Library of Congress Cataloging in Publication Data

Clayton, George Burbridge
88 Practical OP AMP circuits you can build.

British ed. published in 1976
Under title: Experiments with operational amplifiers.
Bibliography: p.
Includes index.
1. Operational amplifiers. 2. Electronic circuits. I. Title.
TK7871.58.06C52 1977 621.3815'35 77-7500

ISBN 0-8306-7912-X
ISBN 0-8306-6912-4 pbk.

Preface

Integrated circuit operational amplifiers are now so cheap that it is economically possible to use them freely in all types of electronic instrumentation. One can afford to think of them as some kind of 'super transistor' but their use considerably simplifies the design and construction of circuits compared with the use of discrete components and transistors. Also, operational amplifier modules make it easier for the non-electronics specialist to construct the instrumentation circuits needed for his particular field of work.

This book covers a range of practical operational amplifier applications, gives circuits which include component values and suggests measurements that can be made in order to study circuit action. The book is intended as an experimental supplement to the author's previous book on operational amplifiers[1].

It is suggested that the quickest way for the non-electronics specialist to learn about operational amplifiers is actually to use them in working circuits. It does not matter very much if a wrong connection is made in the experimental circuits, the operational amplifier type suggested for use will tolerate quite a few mistakes and even if you destroy it it should not break you. If resistor values suggested in the circuits are not at hand try other values; electronic systems will work (in a fashion) with a considerable range of component values. Having investigated the practical circuits, then is the time to start reading to find out in more detail how the circuits work and how their performance can be refined. This alternation between experimental work and reading is most rewarding. Experimental work increases confidence and leads to sounder understanding, the reading suggests further experimental work which when carried out encourages further theoretical exploration.

The experiments suggested in the book cover a wide range of operational amplifier applications which will be found useful for a variety of measurement and instrumentation systems. The emphasis is on working circuits designed to give a practical understanding of the principles underlying each application. The way in which performance errors are related to the characteristics of the particular amplifier used in the circuit are briefly treated in an Appendix.

This book should prove useful for all those interested in experimentally finding out about the capabilities of operational amplifiers. A prerequisite for the reading of the book extends little beyond a knowledge of basic d.c. and a.c. circuit theory.

References

1. G.B. Clayton. *Operational Amplifiers,* Butterworths (1971)

Contents

1. Basic Operational Amplifier Ideas

In this chapter a brief summary of elementary operational amplifier concepts is given, prior to the main body of the text which is concerned with experimental investigations of operational amplifier applications.

1.1 Introduction

A differential input operational amplifier is a device with two input terminals, an output terminal and two power supply terminals. In addition, it will normally have terminals for offset balancing (for setting the output to zero when the input is zero) and may have terminals to which external components can be connected in order to modify the frequency response characteristics of the amplifier.

The circuit symbol for an operational amplifier is a horizontal triangle; operational amplifiers are used with dual power supplies consisting of a positive and negative supply in series connected as shown in figure 1.1

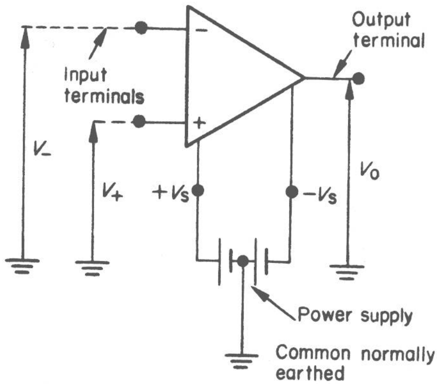

Fig. 1.1 Circuit symbol used for an operational amplifier

The two input terminals of an operational amplifier are normally distinguished from each other symbolically by a (+) and (–) sign. Input and output signals are measured with respect to the power supply common terminal which is normally earthed. Note that the (+) and (–) notation used at the input *does not* mean positive voltages go into one terminal and negative at the other, it means that signals applied to the (–) terminal cause signal changes of opposite polarity at the output, signals applied to the (+) terminal cause signal changes of the same polarity at the output. The (–) terminal inverts, the (+) terminal is non-inverting.

1.2 Open Loop Gain

The output signal of an operational amplifier is controlled by the difference in the signals applied to the (+) and (–) input terminals. We may write

$$V_0 = A_{OL}\,(V_+ - V_-) \tag{1.1}$$

A_{OL} is called the open loop gain, it is very large, even the most modest of operational amplifiers having open loop gains which exceed 10^4 (80 dB).

1.3 Open Loop Transfer Curve – Output Voltage Limits

The relationship between the output voltage and input difference voltage can be shown graphically in the form of an open loop transfer curve. A slightly idealised transfer curve for an operational amplifier is shown in figure 1.2. Note that only a very small change in the input difference voltage is required to cause the output to go between its saturated levels.

The maximum output voltage that an operational amplifier can give is usually limited to a volt or so less than the applied power supply voltages. The slope of the transfer curve gives a value for the open loop gain of the amplifier.

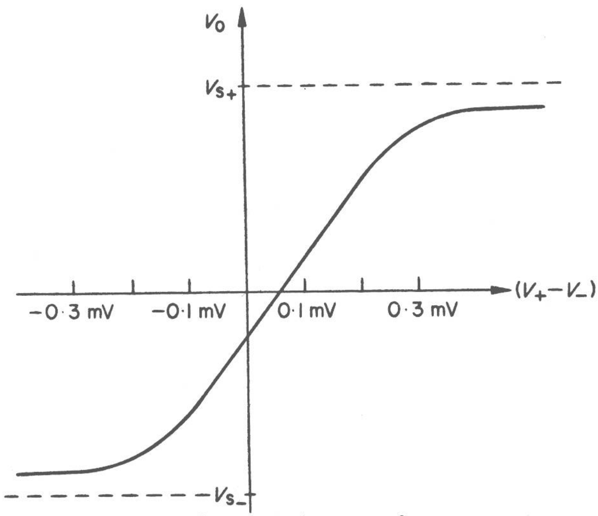

Fig. 1.2 Open loop transfer curve

Practical operational amplifiers have transfer curves which are often considerably less linear than that shown in figure 1.2. Also, in the case of a practical amplifier the curve does not usually pass through the origin. A small input difference voltage has to be applied to a practical amplifier to make its output zero;this is called the input offset voltage. Input offset voltages are typically 1 millivolt. This may appear large in comparison with the input difference voltage required to cause the output to go between maximum limits, but in the practical negative feedback circuits in which operational amplifiers are used amplifier non-linearities and offsets do not have a first order effect.

1.4 Properties of an Almost Ideal Operational Amplifier

In addition to large open loop gain, operational amplifiers are normally designed to have very high input impedance and low output impedance. Other performance parameters of operational amplifiers such as bias current, common mode rejection ratio, frequency response characteristics and slewing rate are also important but for practical purposes we confine our attention to a somewhat idealised amplifier.

In this simplified first treatment an operational amplifier is assumed to have the following properties

(1) A very large open loop gain.
(2) Output unaffected by signal frequency, no signal phase shift with change in frequency.
(3) A very large input impedance so that the amplifiers takes negligible currents at its input terminals.
(4) A very small output impedance so that the output of the amplifier is unaffected by loading.
(5) Zero output voltage for zero input voltage (offset zero).

1.5 Usefulness of an Operational Amplifier. What Can It Do?

The usefulness of an operational amplifier stems from the constraints which it can impose on passive networks externally connected to it. These constraints arise as a direct result of the foregoing properties. In operational amplifier applications a negative feedback path is normally connected in some way between the output terminal of the amplifier and the inverting input terminal. Connected in this way the output voltage of the amplifier always changes in such a way as to reduce the input difference voltage to a very small value. Some of the various circuit configurations are now discussed. For convenience power supplies will not be shown in these first circuits.

1.5.1 *Unity Gain Follower*

In the circuit shown in figure 1.3 the output terminal of the amplifier is connected directly to the inverting input terminal making $V_- = V_0$ thus using equation 1.1.

$$V_0 = A_{OL}\,(V_{in} - V_0)$$

Therefore

$$V_{in} - V_0 = \frac{V_0}{A_{OL}} \rightarrow 0 \text{ (Since } A_{OL} \text{ is very large)}$$

Thus

$$V_0 = V_{in}$$

Note that the output signal returned to the inverting input terminal takes on that value which is required to force the input difference voltage towards zero.

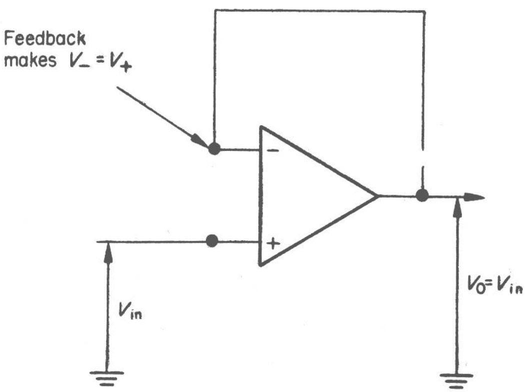

Fig. 1.3 Unity gain follower

In figure 1.3 the output voltage will always be within V_0/A_{OL} of the input voltage V_{in}. The error by which V_0 departs from V_{in} is greatest when V_0 has its maximum value of, say, 14 volts but the error is then only $14/10^5 = 0.14$ millivolts if the open loop gain of the amplifier is 10^5. The importance of the unity gain follower circuit of figure 1.3 arises from its impedance characteristics. It has a very high input impedance and a very low output impedance and serves as an excellent 'buffer' stage preventing interaction between a signal source and load.

1.5.2 *The Follower With Gain*

In the circuit of figure 1.4 the output signal is attenuated by a resistive divider (by the ratio $R_1/(R_1 + R_2)$) before being applied to the inverting input terminal. Remember it is assumed that no current flows into either input terminal of the amplifier. The output voltage, as before, takes on that value required to force the input difference voltage to zero it must thus have a value which is the inverse of the attenuation ratio multiplied by the input signal V_{in}. *Note that an infinite open loop gain makes the gain of the feedback operational amplifier circuit entirely dependent upon the external circuit elements.*

1.5.3 *The Inverter*

If in the circuit of figure 1.4 we earth the (+) input terminal of the amplifier and apply the input signal to the end of the resistor R_1; the circuit inverts the polarity of the applied input signal but the gain of the feedback circuit is still determined only by the value of the external circuit elements. In figure 1.5 the output voltage forces the voltage at the (−) input towards zero and the following relationships are established.

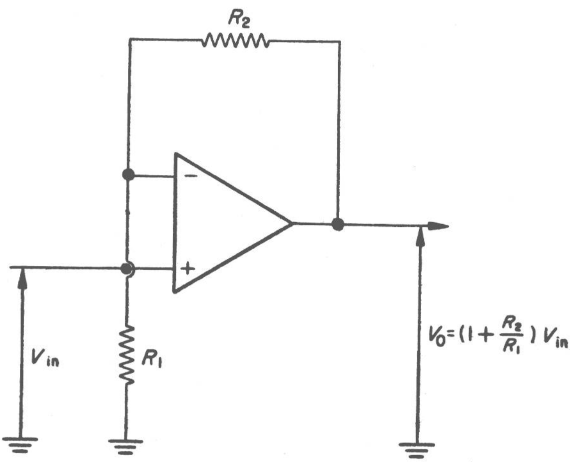

Fig. 1.4 Follower with gain

The current supplied by the input signal is

$$I_{in} = \frac{V_{in}}{R_1}$$

The effective input resistance of the circuit is thus R_1. The output voltage causes I_{in} to flow through resistor R_2 and

$$\frac{V_{in}}{R_1} = I_{in} = I_f = -\frac{V_0}{R_2}$$

Thus

$$V_0 = -\frac{R_2}{R_1} V_{in}$$

1.5.4 *Summing Amplifier*

In figure 1.5 the output voltage causes any current arriving at the minus input to flow through the feedback path. If a number of input voltages are connected in series with the resistors that meet at the (−) input terminal, the sum of the currents passing through these resistors will be made to flow through the feedback resistor. The arrangement is shown in figure 1.6. We have

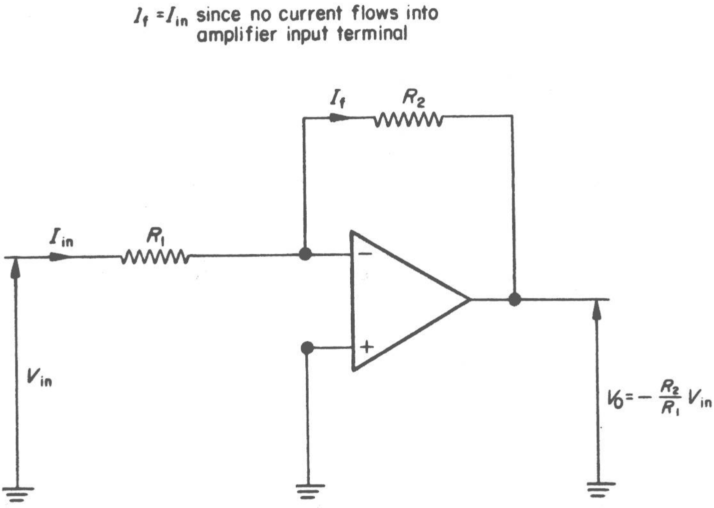

Fig. 1.5 Inverting amplifier

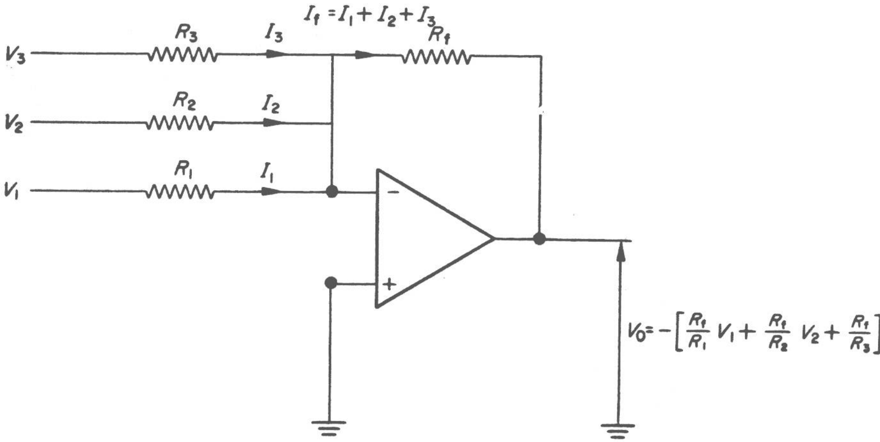

Fig. 1.6 Summing amplifier

$$I_1 + I_2 + I_3 = I_f$$

Thus

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = -\frac{V_0}{R_f}$$

or

$$V_0 = -\left[\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3\right]$$

An operational amplifier can thus be used to sum a number of voltages or currents independently; the (−) terminal of the amplifier is often called the amplifier summing point.

1.5.5 *Integrator*

Thus far only resistive circuits have been considered but many other kinds of element can be externally connected to an operational amplifier in order to obtain a required input output relationship. In figure 1.7 the feedback resistor has been replaced by a capacitor. As before, the output voltage takes on that value required to cause the current arriving at the summing point to flow through the feedback path, it must do this in order to force the input difference voltage to zero and the current has nowhere else to go.

The input current $I_{in} = \dfrac{V_{in}}{R_1}$ flows into the feedback capacitor and charges it up. Thus

$$I_{in} = \frac{dq}{dt} = C\frac{dV_c}{dt} = -C\frac{dV_0}{dt}$$

and

$$\frac{dV_0}{dt} = -\frac{1}{CR_1}V_{in}$$

or

$$V_0 = -\frac{1}{CR_1}\int V_{in}\ dt$$

The output of the amplifier is proportional to the integral with respect to time of the input signal.

1.5.6 *Further Uses*

The foregoing sections cover only a few of the operational amplifier applications that have been devised and which remain to be discovered by the ingenious operational amplifier user. Interchanging the resistance and capacitance in figure 1.7 gives a differentiator circuit, the use of non linear input or feedback elements

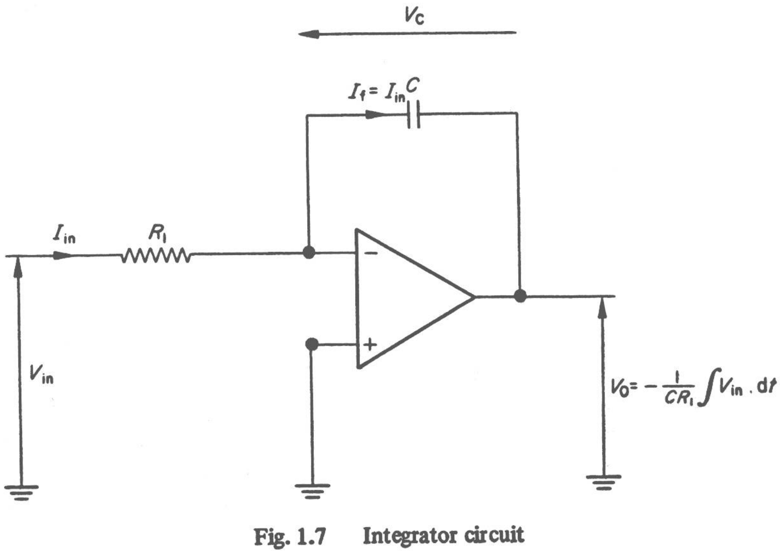

Fig. 1.7 Integrator circuit

gives non linear input output relationships. Both input terminals of a differential input operational amplifier may have signals applied to them so as to give a subtractor operation. Operational amplifiers may be used with positive feedback to give a multivibrator action, as comparators, and to generate a variety of signal waveforms including triangular waves, square waves and sinusoidal waves.

Practical circuits illustrating many of the uses of operational amplifiers are given in the following chapters of the book. The best way to learn about operational amplifiers is to use them, we suggest that the reader should now connect up the circuits given in Chapter 2. Real amplifiers do not behave exactly as the ideal amplifier considered in the previous sections but differences are small and departures between real and ideal are conveniently treated as performance errors. Do not worry initially about these performance errors, test the response of the circuits to a variety of signals, try the effect of changing component values, and generally gain familiarity with the circuits. Having done this if you need to know more about the circuits, or if you want to refine their performance by using a different amplifier type you should return to a more detailed study of real amplifier characteristics[1].

References

1. G.B. Clayton, *Operational Amplifiers.* Butterworths (1971).