Operational Amplifiers

Operational Amplifiers

ROBERT G. SEIPPEL

RESTON PUBLISHING COMPANY, INC.
A Prentice-Hall Company
Reston, Virginia

Library of Congress Cataloging in Publication Data

Seippel, Robert G.
Operational amplifiers.

Bibliography.
Includes index.
1. Operational amplifiers. I. Title.
TK7871.58.06S44 1983 621.381'735 82-12253
ISBN 0-8359-5242-8

A Prentice-Hall Company
Reston, Virginia 22090

10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

Preface

The operational amplifier integrated circuit (IC) has become a workhorse in modern solid-state circuitry. Its uses and variations in design are almost unlimited. Such information immediately instills in many the fear that anything this versatile must also be complex. The purpose of this book is to remove the mystery that may surround operational amplifier application.

The author wishes to acknowledge the fine operational amplifier books available on the market. The best of these are listed in the bibliography. Some of them have been referenced in the text.

What, then, makes this book different from others, and why is it unique?

The book begins with an introduction to electricity—electronics and integrated-circuit operational amplifiers. Enough history is supplied in the first dozen or so pages to stimulate the reader to study more about the marvelous background of the electrical/electronic field.

Chapter 2 provides an integrated-circuit hierarchy; it sets the stage for operational amplifier studies and lets the reader know just where op amps stand in this massive IC chain of command.

Chapter 3 reviews the entire fabrication process. This is probably the first op amp book (or any other) that discusses the fabrication process from raw silicon to the finished solid-state device. A pictorial display of the Czochralski method of silicon crystal growing has been provided by Siltec Corporation. Planar fabrication process data were supplied by Analog Devices.

Operational amplifier fundamentals are examined in Chapter 4. These are much the same as you would find in any op amp book.

Chapter 5 presents preliminary design information. Special considerations—such as how to choose an op amp and how to deal with minus signs in design—are covered.

Chapter 6 contains the meat of the book. It begins with a description of the operational amplifier circuit, then describes its peculiar characteristics and its operation. Description is followed by design procedures and examples. Most basic circuits are covered in detail. Each application has a circuit; each circuit is succeeded by a step-by-step design procedure. Immediately following the procedure is a design example in "cookbook" style. Test verification is provided as a final topic. The entire process is fundamental but thorough.

Chapters 7 and 8 are slanted toward instrumentation. Since instrumentation engineers and technicians utilize the bridge and the op amp, the author believes these chapters are required. Further, instrumentation and isolation amplifiers are outgrowths of the op amp, directed toward that need in instrumentation.

Finally, Chapter 9 describes a large selection of op amp circuits, from amplifiers to tachometers. This will provide the reader with a variety of instant applications.

The author believes this book can fill several voids. First, it can furnish the experienced designer with instant applications, thereby saving precious time. Second, it can provide all interested electronic-minded people with a do-it-yourself tool for operational amplifier design. Finally, it can provide instructors at all levels of learning with student-centered instructional material that does not require preparation.

It is recommended that this book be used in post solid-state device courses as an interface between courses on the transistor and those on integrated circuits. However, this suggestion is not necessary for understanding. With the rapidly expanding world of solid-state electronics, people do not have time to wade through a lot of rhetoric to arrive at basic objectives.

ACKNOWLEDGMENTS: No writer can develop a technical book without the support of many people in industry. When readers see a new book containing new and innovative ideas or techniques, you can rest assured that the technical data were derived from industry. Research leads us all to the originators of processes and applications.

For instance, Chapter 3 of this book describes the process of developing a solid-state device from raw silicon to finished product. The author traveled to Siltec Corporation in Menlo Park, California to see the process for himself. This chapter would not be possible had it not been for the support of Siltec Corporation and Susan Phinney. Likewise, a trip to Analog Devices in Massachusetts and the support of J. Eric Janson led to the writing of another part of Chapter 3, Chapter 7, and Chapter 8. National Semiconductor provided data for Chapter 9. I'd like to thank Steve Sields and Scott Foote for their support.

Dave Howell of IC Masters and Clive McCarthy of Fairchild Camera and Instrument Corporation, Linear Division, were helpful in developing the Appendices. I'd also like to thank an old-timer by the name of Hugo Gernsback. Hugo is the father of today's electronic publications and electronic apparatus. In 1908 he published Volume I of *Modern Electrics*, which led to *Radio Craft Magazine*, *Radio Electronics*, and *Popular Electronics*. He also supplied amateurs of the day with apparatus for their experiments. Without Hugo Gernsback, we would not be nearly as informed as we are about this electronic world of ours.

In a final tribute, I'd like to thank Charles Barnes and Jo Anne Bly for the fine artwork, my editor Patricia Rayner at Reston, and my loving wife Hazel for her typing and general all-around everything.

ROBERT G. SEIPPEL

References & Permissions

CHAPTER 3:

Fabrication process information in this chapter was provided in part by Eric Janson, Analog Devices Corporation, Norwood, Massachusetts. Wafer manufacturing process information in this chapter was provided by Anthony Bonora, Vice President of Research, Siltec Corporation, Menlo Park, California.

CHAPTER 7:

The author highly recommends the Transducer Interfacing Handbook, a book written by a number of engineers with Analog Devices Corporation and edited by Daniel H. Sheingold. It is a handbook to be used as a guide to Analog Signal Conditioning. Bridge networks are, of course, an integral part of signal conditioning.

Illustrations in this chapter are reprinted with permission of Analog Devices, Norwood, Massachusetts. All copyrights © are reserved.

CHAPTER 8:

Illustrations in this chapter are reprinted with permission of Analog Devices, Norwood, Massachusetts. All copyrights © are reserved.

Contents

5 Preliminary Design Considerations 75

6 Design Procedures and Examples 86

Appendices

1

Introduction to Electronics

The history of electronics probably started when people noticed the spark-producing properties of amber, as this material was rubbed on cloth or fur. Around 600 B.C. Thales, the Greek, discovered that mysterious sparks resulted when he rubbed the mineral amber. The Greek word for amber is *electrum*, which serves as the root for the word "electricity."

The lodestone also interested the ancients, who believed that its magnetic potency was destroyed by garlic. This myth lasted for many centuries; it was mentioned as late as 1544 in a treatise on physics written by Philip Melanchton, a German Protestant reformer. Similar theories arose concerning amber and diamonds. The most notable of these was that iron rubbed by a diamond became a magnet, and that diamonds, when rubbed, would attract bits of paper and particles of dust.

Dr. William Gilbert (1540–1603), an English scientist, called such ideas "the chattering of barbers"; instead of accepting such talk at face value, he set out to disprove the myths and in so doing, became the "Father of Electricity."

Gilbert compiled a huge list of materials that could be charged. These included such items as "true jewels, sulphur, sealing wax, rock salt, alum, and resin." He assigned the title "electric" to the phenomenon, and a new era in science came into being. Practically everything he rubbed turned "electric," and this ultimately led Gilbert to invent the electroscope, which he used to test his materials. The electroscope consisted of a straw that was pivoted like a compass needle to indicate the approach of a charged body. Gilbert also conceived of the earth as a huge magnet with magnetic poles and a field of force about it. This laid a positive foundation for many future scientific discoveries.

Sir Thomas Browne (1604–1682), English physicist and author, performed many experiments with the lodestone and magnetism. The first of these refuted the possibility of magnetism losing its potency when subjected to garlic juice. By far the most important of Browne's experiments was his "wireless communication." Using an idea previously conceived by John Baptista Porta, Browne employed two compasses with letters written around their perimeters. He imagined that if the two needles were magnetized together, then separated, the turning of one would cause the other to follow to the same position. Letters selected could make words. If this happened, it would mean that remote communication could take place. However, the second compass needle remained at North—according to Browne, it stayed "like the Pillars of Hercules." Nevertheless, this first attempt at remote communications inspired many more people of the day to continue to work on the idea.

Otto von Guericke (1602–1686), a German burgomaster, was famous for the "Magdeburg" experiment, in which he proved atmospheric pressure. It was his experiments with static electricity that were important to the electronics field, however. In 1672 he constructed an electrical generating device made of a globe of sulphur mounted on an axle and turned by a crank. The globe was rubbed by the hand when it was rotated and after some rubbing became electrified (statically charged). Although charging had taken place, von Guericke noticed, particles would be attracted and remain for a while, then be repelled. The particles were assuming a like charge to that of the sulphur, then they were repelled because, as we know today, "like charges repel." Here he was laying the foundation for what we know to be fact. In a further experiment von Guericke repelled a feather from his sulphur globe and chased it around the room with the globe in his arms. The feather was repelled by the electron stream from a lit candle, which reversed its charge. When the feather flew back to the globe, von Guericke was observing electronic emission without knowing it. Three centuries passed before anyone knew more of this phenomenon. Von Guericke had also observed electricity in a static condition, but left the study of dynamic electricity to Ben Franklin and his kite.

Stephen Gray (1695–1736), an Englishman, studied the effects of charged bodies being transmitted. He discovered the effects of materials we know as conductors and insulators.

About the same time, in France, Paris Dufay (1698–1739) experimented with Gray's discoveries. He found that metal wire or wet objects were the best conductors, though the most difficult to electrify. He also found that the best insulators were easy to electrify. Dufay built a quarter-mile-long line, held up by glass tubes and wetted down. Then he transmitted a charged impluse from one end to the other. This finding was probably the first transmission and consequently an important step in electricity. Historians also suggest that this was the first time wire was used as a conductor.

In these times, scientists and experimenters were still playing around with friction apparatus, since no means for generating electricity had been found. In 1745, E. G. von Kleist of Germany invented the first condenser. Later the same year, Peter van Musschenbroek, of Leyden, Holland, built a Leyden jar (a more publicized condenser) with the help of his assistant Cunaeus. Musschenbroek believed that electricity could be bottled up and saved for later use. His idea was to charge water up in a jar, place a cork on it, and, since the glass was a good insulator, save the charge for the future. A circuit was made of a gun barrel, a friction machine, and a brass wire which entered a jar half-filled with water. Musschenbroek cranked the friction machine while his assistant held the jar in one hand and tried to draw off sparks with the other. If Cunaeus had placed the jar on the table, nothing would have happened. The improvised condenser finally charged up, and Cunaeus was in the middle of it all. The spark that resulted was tremendous, and Cunaeus' body provided a good path for electron flow. We can assume that Cunaeus, shocked by the whole situation, took the next few days off with pay.

Another scientist of the day, Nollet, a French Abbé (1700–1770), heard about the Leyden jar experiment and duplicated it in a big way. He had 200 soldiers stand hand in hand in a circle and placed a severe charge through them. To his delight, all 200 soldiers jumped at the same time. This pleased Nollet immensely; the soldiers were not so happy.

Both Musschenbroek and Nollet wanted to find out what caused this effect—but were lacking in volunteers to repeat the experiment too many times. They found that when the jar was placed on a table, this nullified the experiment. In further experiments, the jar was placed on a metal-plate base on the table. Later, an outside tinfoil cover was substituted, and thus the condenser was born.

Benjamin Franklin (1706–1790) made history in electricity with his famous kite and lightning experiment in 1751. Franklin was a statesman, philosopher, and, by no means least, a scientist. It was he who discovered the principle of conservation of electrical charge, establishing that there are positive- and negative-type charges. He further related lightning and sparks obtained from electrically charged bodies that become discharged. He invented the lightning rod to prevent damage caused by lightning. Probably the best-known theory of this man is that "like charges repel, unlike charges attract."

Luigi Galvani (1737–1798) was an Italian professor of anatomy. Up to his time, there were only two known methods for creating electricity: by means of a frictional machine, and by means of lightning and the clouds, as in Franklin's experiment. In 1780 Galvani noticed that an electrical charge applied to a dead frog's leg made the leg twitch. He further noted that several dead frogs he had suspended on a metal balcony responded to a lightning storm with some motion before the storm. Later, he determined that any two metals joined together would cause the twitching if attached to the frog in two separate places. Galvani reasoned that the electricity was a fluid which made a circuit from muscles to the nerves of the frog then through the metal conductor and back to the muscle. He called this fluid "animal electricity." Galvani thought the electricity originated in the frog. We know it now as "galvanic" electricity caused by two dissimilar metals in contact.

Alessandro Volta (1745–1827), an Italian professor, invented the *voltaic pile.* It was simply a pile of alternately stacked zinc and copper discs separated by a water-wet pasteboard. Volta discovered that a distinct shock was achieved when the fingertips were placed on each end of the pile. He also noted that when the watered pasteboard dried out, the shock diminished. He then placed his zinc and copper discs in separate jars containing a light acid. This was the first battery (storage device) known to man. It was of course a great help to future scientists. Volta's name became immortal when the electrical unit of force, the *volt*, was named after him.

A follow-up modification was made on the principle of the voltaic pile by English experimenters William Nicholson (1753–1815) and Sir Anthony Carlisle (1769–1840). They found that water could be decomposed into its elements of hydrogen and oxygen when an electrical current was passed through it. Hence we had the discovery of *water electrolysis*, as we know it today.

Hans Christian Oersted (1777–1851) was a Danish physics professor who for thirteen years had experimented with electricity and its effects on the compass needle. Oersted had read Franklin's reports on the effects and relations of the two. While lecturing to a class in 1820, he noticed that a compass needle wavered when a switch was closed on a circuit to the voltaic pile. He dismissed his class, closed the switch, and positioned the compass at different points on the wire. Along the wire the compass needle deflected; across the wire, the needle came to a stationary position. Above the wire, the needle went to the opposite direction than when it was below the wire. Oersted had determined the basis for establishing magnetic lines of force, thus providing the fundamentals for measuring and indicating electrical instruments.

In the same year, reportedly only a week after Oersted made his discovery, André Marie Ampere (1775–1836), a French physicist, found that two parallel wires carrying electricity and free to move, attract each other if the current flows in the same direction but repel each other if the current flows in opposing directions. Ampere also found that the wire carrying an electrical current would attract a magnetized needle and that the needle attracted the wire as well. The basic unit of current, the *ampere*, was named in this scientist's honor.

In the same year, 1820, French physicist François Arago (1786–1854) developed the first electromagnet by placing a current through a coil of wire.

In 1826, the basic law for all circuit analysis was born. George Simon Ohm (1789–1854), a Bavarian physicist, had analyzed current flow in relation to voltage and resistance. The law that bears his name is this: "A current flowing in any closed circuit is proportional to the force or voltage and inversely proportional to the resistance of the wire." Today we express this law simply as

$$I = \frac{E}{R}, \quad \text{where } I = \text{current}, \quad E = \text{voltage}, \quad \text{and} \quad R = \text{resistance}$$

Joseph Henry was an American physicist (1797–1878) who improved on the electromagnet developed by Arago in 1820. He used silk-covered wire which allowed the use of many layers of turns. This development of insulated wire (1836) permitted him to make electromagnets large enough to lift several pounds. The electrical unit of inductance is called the *henry* to honor this scientist.

The name of Samuel F. B. Morse (1791–1872), an American artist, is important in the history of electrical discoveries. Morse created the telegraph system (1832–1837) and conceived a code (the Morse code) which permitted the transmission and reception of messages. The Morse code is still used in telegraphy.

Michael Faraday (1791–1867), an Englishman, was one of the most productive of all scientists. His first studies in electricity dealt with the basic principle of the electric motor. Faraday reasoned that if a current in a wire caused a magnetized needle to rotate, then a magnet should cause a wire carrying current to do likewise. Faraday formulated the laws of induction, which allowed him later to build the first electric generator. In fact, it was he who discovered alternating current. He also created the first transformer and developed the dielectric constant from his study of condensers. Faraday was probably one of the most important and productive scientists that ever lived.

The "electromagnetic theory of light" was mathematically elaborated upon by the Scottish physicist, James Clerk Maxwell (1831–1879), though the thought was conceived by Faraday. According to this theory, light, electric waves, and magnetic waves of varying frequency travel in the same medium (namely, ether). Since ether permeates all matter, a current may exist in and about a conductor but is essentially guided by it.

In 1865, Dr. Mahlon Loomis, an American dentist, conducted some of the first experiments in transmitting and receiving messages. He reasoned that the earth's atmosphere could be used as a conductor, since he had read somewhere that the atmosphere is continuously charged with electricity. To test his theory, Loomis sent up two kites from high mountains in West Virginia, 18 miles apart. The kites were covered with large squares of copper screen, and the connecting cord had fine copper wire within. The wire from each kite string was connected to one side of a galvanometer. The other side of the galvanometer was held in readiness by Loomis so he could establish a connection to a coil buried in the earth. The receiving station was connected between meter and earth coil. The transmitting end held by Loomis was grounded, and the galvanometer at the receiving station actually dipped.

In 1875, the microphone (magnetic transducer) was invented by Alexander Graham Bell (1847–1922). Bell, of course, was a major contributor to electronics. Two years later, D. E. Hughes, an Englishman, invented the carbon microphone.

In 1885, Sir William H. Preece and A. W. Heaviside, both Englishmen, sent signals to each other over a distance of 1,000 yards. They placed two telegraph lines parallel, with a telephone receiver on the receiving end. The telegraph signals could be clearly heard in the phone receiver without actual connection between the two lines—this was due to what is known now as induction. In lay language, the phenomenon is called "cross-talk."

Heinrich Hertz (1857–1894), a German physicist, shares the title "Father of Radio" with Marconi. Indeed, for his work in the field we use his name to designate cycles per second. Radio waves are also called Hertzian waves. Hertz was extremely interested in Maxwell's theories on light, magnetism, and electrical waves. In an attempt to learn more, Hertz made the the first spark transmitter and receiver. The transmitter consisted of a Leyden jar and a coil of wire, the ends of which were left open so that a small gap was formed. For the receiver, he employed a similar coil, with a gap arrangement, located in the opposite end of the room. When the Leyden jar was sufficiently charged, it discharged through the gap in the wire coil and the oscillating waves generated were launched in the air of the room and swept across the receiving coil, causing sparks to jump the gap in the receiving coil. Hertz measured the velocity of these waves and found that they were the same velocity as light (186,000 miles per second). He also measured their length and therefore verified Maxwell's theories.

Nikola Tesla (1856–1943) was a Serbo-American inventor. In 1893 he invented what we know as the Tesla coil. His idea was to use the earth as a conductor and create stationary electrical waves on it. His coil (really a broadband transmitter) created high-frequency oscillations of a broad nature. Tesla made no effort to detect the oscillations, and allowed that golden opportunity to go to Marconi. He did, however, develop the receiving capability later, some five years after Marconi.

Guglielmo Marconi (1874–1937) was the Italian physicist who designed the wireless telegraph. Considered by some scientists of the time as an interloper, Marconi nevertheless had the designer's insight to put together knowledge and devices of the time to create a workable wireless telegraph. He combined the coherer (invented by Brauley in 1892), the Russian Popoff's decoherer, the Hertzian theories, and a number of scientific writings to create his telegraph. In fact, when his first patent was granted in England in 1896 for wireless telegraphy, the apparatus differed only slightly from that developed by his predecessors. Marconi was a master designer, and after his first British patent he made rapid strides. He was only 23 years old when he formed the Wireless Telegraph and Signal Company. His first major accomplishment was transmission and reception between warships 12 miles apart. In 1899 he adapted Sir Oliver Lodge's principle of syntony (tuning of circuits), which eliminated much of the interference in transmission, and obtained a patent for it in 1900. Also in 1899, he designed longer-distance units that were used in ship-to-shore installations. When Marconi was asked by the *New York Herald* to cover the international yacht race, he accepted, and the American people thus knew who the winners were before the yachts arrived ashore. Marconi wanted to sell the telegraph to the U. S. Navy, but it rejected his contract terms. His famous transatlantic transmission of the letter S was probably the high point of his design career.

Two Americans, Reginald A. Fessendon and Lee De Forest, are co-bearers of the title "Father of American Radio." Fessendon was very much aware of Marconi's work. He himself had experimented with the wireless for years with the same devices. Fessendon knew that Marconi's design was adapted only to dampened wave transmission; thus it would not tolerate superimposing on its voice or other irregular waves. Consequently, Fessendon began experiments in continuous-wave (cw) transmission. In these efforts he invented the arc transmitter. Since the coherer would not work with the oscillating wave produced by the transmitter, Fessendon created the electrolytic detector (the forerunner of the diode), which allowed current to flow in only one direction. The detector consisted of a solution of acid and water with a fine silver wire inserted. This device was a hugh improvement over the coherer. Later Fessendon conceived of the idea of employing an alternator that produced sine waves greater than 120 cycles per second. This was truly an advance, because it eliminated the spark gaps and arcs and laid the foundation for carrier waves.