CHAPTER 1

The Op Amp's Place in the World

1.1 The Problem

In 1934, Harry Black [1] commuted from his home in New York City to work at Bell Labs in New Jersey by way of a railroad/ferry. The ferry ride relaxed Harry enabling him to do some conceptual thinking. Harry had a tough to solve; when phone lines were extended long distances, they needed amplifiers, and undependable amplifiers limited phone service. First, initial tolerances on the gain were poor, but that problem was quickly solved with an adjustment. Second, even when an amplifier was adjusted correctly at the factory, the gain drifted so much during field operation that the volume was too low or the incoming speech was distorted.

Many attempts had been made to make a stable amplifier, but temperature changes and power supply voltage extremes experienced on phone lines caused uncontrollable gain drift. Passive components had much better drift characteristics than active components had, thus if an amplifier's gain could be made dependent on passive components, the problem would be solved. During one of his ferry trips, Harry's fertile brain conceived a novel solution for the amplifier problem, and he documented the solution while riding on the ferry.

1.2 The Solution

The solution was to first build an amplifier that had more gain than the application required. Then some of the amplifier output signal was fed back to the input in a manner that makes the circuit gain (circuit is the amplifier and feedback components) dependent on the feedback circuit rather than the amplifier gain. Now the circuit gain is dependent on the passive feedback components rather than the active amplifier. This is called negative feedback, and it is the underlying operating principle for all modern day op amps. Harry had documented the first intentional feedback circuit during a ferry ride. I am sure unintentional feedback circuits had been built prior to that time, but the designers ignored the effect!

I can hear the squeals of anguish coming from the managers and amplifier designers of the era. I imagine that they said something like this, "it is hard enough to achieve 30 kHz gain−bandwidth (GBW), and now this fool wants me to design an amplifier with 3 MHz GBW. But, he is still going to get a circuit gain GBW of 30 kHz". Well, time has proven

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Harry right, but there is a minor problem that Harry did not discuss in detail, and that is the oscillation problem. It seems that circuits designed with large open loop gains sometimes oscillate when the loop is closed. A lot of people investigated the instability effect, and it was pretty well understood in the 1940s, but solving stability problems involved long, tedious, and intricate calculations. Years passed without anybody making the problem solution simpler or more understandable.

In 1945, H.W. Bode presented a system for analyzing the stability of feedback systems by using graphical methods. Until this time, feedback analysis was done by multiplication and division, so calculation of transfer functions was a time-consuming and laborious task. Remember, engineers did not have calculators or computers until the 1970s. Bode presented a logarithmic technique that transformed the intensely mathematical process of calculating a feedback system's stability into graphical analysis that was simple and perceptive. Feedback system design was still complicated, but it no longer was an art dominated by a few electrical engineers kept in a small dark room. Any electrical engineer could use Bode's methods to find the stability of a feedback circuit, so the application of feedback to machines began to grow. There really was not much call for electronic feedback design until computers and transducers become of age, however.

1.3 The Birth of the Op Amp

The first real-time computer was the analog computer! This computer used preprogrammed equations and input data to calculate control actions. The programming was hard wired with a series of circuits that performed math operations on the data, and the hard wiring limitation eventually caused the declining popularity of the analog computer. The heart of the analog computer was a device called an operational amplifier because it could be configured to perform many mathematical operations such as multiplication, addition, subtraction, division, integration, and differentiation on the input signals. The name was shortened to the familiar *op amp*, as we have come to know and love them. The op amp used an amplifier with a large open loop gain, and when the loop was closed, the amplifier performed the mathematical operations dictated by the external passive components. This amplifier was very large because it was built with vacuum tubes and required a high-voltage power supply, but it was the heart of the analog computer, thus its large size and huge power requirements were accepted as the price of doing business. Early op amps were designed for analog computers, and it was soon found out that op amps had other uses and were very handy to have around the physics lab.

At this time, general-purpose analog computers were found in universities and large company laboratories because they were critical to the research work done there. There was a parallel requirement for transducer signal conditioning in lab experiments, and op amps found their way into signal conditioning applications. As the signal conditioning applications expanded, the demand for op amps grew beyond the analog computer requirements, and even when the analog computers lost favor to digital computers, the op amp survived because of its importance in universal analog applications. Eventually digital computers replaced the analog computers (a sad day for real-time measurements), but the demand for op amps increased as measurement applications increased.

1.3.1 The Vacuum Tube Era

The first signal conditioning op amps were constructed with vacuum tubes prior to the introduction of transistors, so they were large and bulky. During the 1950s, miniature vacuum tubes that worked from lower voltage power supplies enabled the manufacture of op amps that shrunk to the size of a brick used in house construction, so the op amp modules were nicknamed *bricks*. Vacuum tube size and component size decreased until an op amp was shrunk to the size of a single octal vacuum tube.

One of the first commercially available op amps was the model K2-W, sold by George A. Philbrick Research. It consisted of two vacuum tubes, and operated from a ± 300 V power supplies! If that is not enough to make a modern analog designer cringe—then its fully differential nature would be sure to. A fully differential op amp, as opposed to the more familiar single-ended op amp, has two outputs—a noninverting output and an inverting output. It requires the designer to close two feedback paths, not just one. Before panic sets in—the two feedback pathways only require duplication of components, not an entirely new design methodology. Fully differential op amps are currently enjoying resurgence—because they are ideal components for driving the inputs of fully differential analog to digital converters. They also find use in driving differential signal pairs such as DSL and balanced 600 Ohm audio. Suffice it to say, op amps have come full circle since their original days.

1.3.2 The Transistor Era

Transistors were commercially developed in the 1960s, and they further reduced op amp size to several cubic inches, but the nickname brick still held on. Now the nickname brick is attached to any electronic module that uses potting compound or nonintegrated circuit (IC) packaging methods. Most of these early op amps were made for specific applications, so they were not necessarily general purpose. The early op amps served a specific purpose, but each manufacturer had different specifications and packages; hence, there was little second sourcing among the early op amps.

1.3.3 The IC Era

ICs were developed during the late 1950s and early 1960s, but it was not till the middle 1960s that Fairchild released the μA709. This was the first commercially successful IC op amp, and Robert J. Widler designed it. The μA709 had its share of problems, but any competent analog engineer could use it, and it served in many different analog applications. The major drawback of the μA709 was stability; it required external compensation and a competent analog engineer to apply it. Also, the μA709 was quite sensitive because it had a habit of self-destructing under any adverse condition. The self-destruction habit was so prevalent that one major military equipment manufacturer published a paper titled something like, *The 12 Pearl Harbor Conditions of the μA709*.

The legacy of the μA709 continues today, but it is a negative legacy. The μA709 would not work if applied incorrectly, primarily due to its external compensation. The engineers of today may not even know the part, but memory of its instability remains—few uncompensated amplifiers are sold today due to the problem of misapplication. Stability remains one of the least understood aspects of op amp design, and one of the easiest ways to misapply an op amp. Even engineers with years of analog design experience have differing opinions on the topic. The wise engineer, however, will look carefully at the op amp data sheet and not attempt a gain less than its specification. It may be counter intuitive, but the op amp is least stable at its lowest specified gain. Future chapters will delve deeply into this phenomenon.

The μA741 followed the μA709, and it is an internally compensated op amp that does not require external compensation if operated under data sheet conditions. Also, it is much more forgiving than the μA709.

The legacy of the μA741 is much more positive than that of its predecessor. In fact, the part number "741" is etched into the memory of practically every engineer in the world, much like the "2N2222" transistor and the "1N4148" diode. It is usually the first part number that comes to mind whenever an engineer thinks of an op amp. Unlike the μA709, the μA741 will work unless grossly misapplied—a fact that has endeared it generations of engineers. Its power supply requirements of ± 15 V have given rise to hundreds of power supply components that generate these levels, much as +5 V has been driven by TTL logic and ± 12 V has been driven by RS232 serial interfaces. For many years, every op amp introduced used the same ± 15 V power supplies as the μA741. Even today, the μA741 is an excellent choice where wide dynamic range and ruggedness are required.

There has been a never-ending series of new op amps released each year since the introduction of the μA741, and their performance and reliability has improved to the point where present day op amps can be used for analog applications by anybody.

The IC op amp is here to stay; the latest generation op amps cover the frequency spectrum from 5 kHz GBW for extremely low power devices to beyond 3 GHz GBW. The supply voltage ranges from guaranteed operation at 0.9 V to absolute maximum voltage ratings of 1000 V. The input current and input offset voltage has fallen so low that customers have problems verifying the specifications during incoming inspection. The op amp has truly become the universal analog IC because it performs all analog tasks. It can function as a line driver, amplifier, level shifter, oscillator, filter, signal conditioner, actuator driver, current source, voltage source, and many other applications. The designer's problem is how to rapidly select the correct circuit/op amp combination and then, how to calculate the passive component values that yield the desired transfer function in the circuit.

It should be noted that there is no op amp that is universally applicable. An op amp that is ideal for transducer interfaces will not work at all for RF applications. An op amp with good RF performance may have miserable DC specifications. The hundreds of op amp models offered by manufacturers are all optimized in slightly different ways, so the designer's task is to weed through those hundreds of devices and find the handful that are appropriate for their application. This edition includes a design methodology for doing so—at least in the case of signal chains.

This book deals with op amp circuits—not with the innards of op amps. It treats the calculations from the circuit level, and it does not get bogged down in a myriad of detailed calculations. Rather, the reader can start at the level appropriate for them, and quickly move on to the advanced topics. If you are looking for material about the innards of op amps, you are looking in the wrong place. The op amp is treated as a completed component in this book.

The op amp will continue to be a vital component of analog design because it is such a fundamental component. Each generation of electronics equipment integrates more functions on silicon and takes more of the analog circuitry inside the IC. Do not fear; as digital applications increase, analog applications also increase because the predominant supply of data and interface applications are in the real world, and the real world is an analog world. Thus, each new generation of electronics equipment creates requirements for new analog circuits; hence, new generations of op amps are required to fulfill these requirements. Analog design, and op amp design, is a fundamental skill that will be required far into the future.

Reference

[1] H.S. Black, Stabilized feedback amplifiers, BSTJ 13 (January 1934).