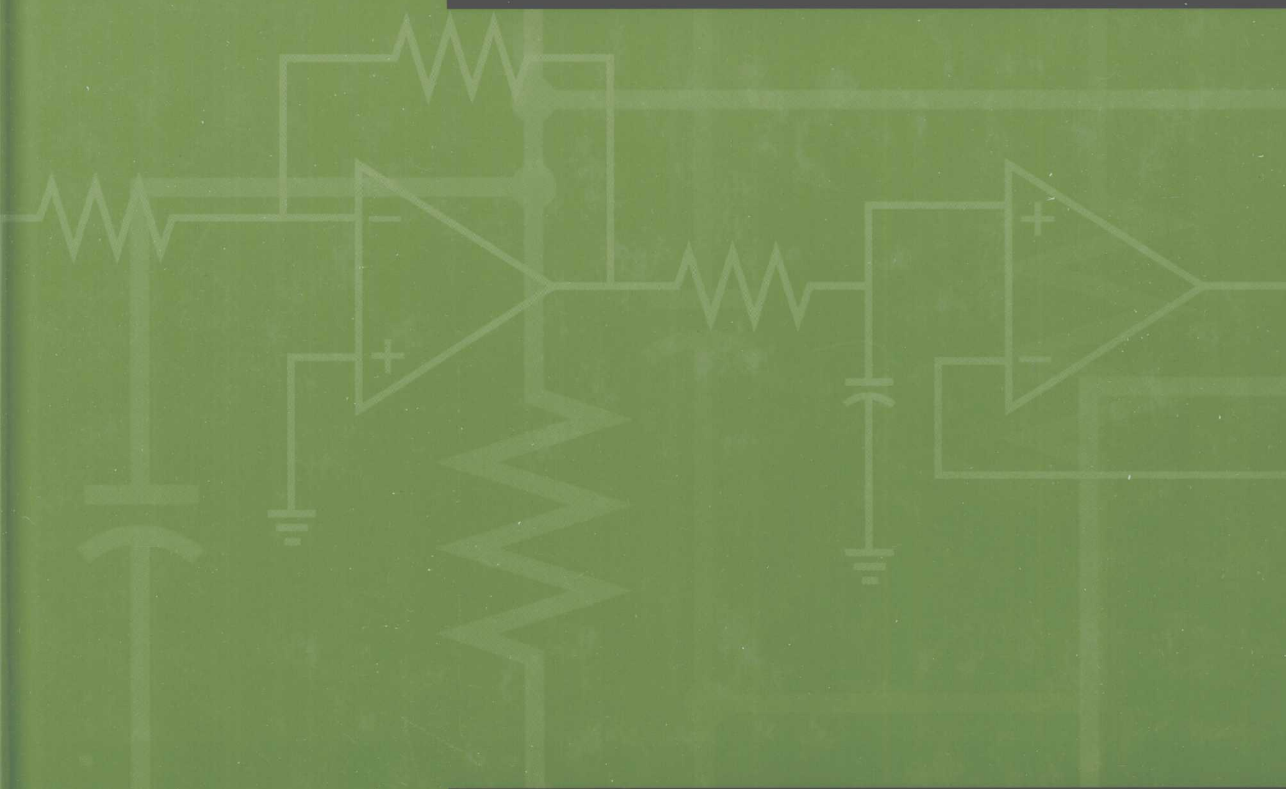
Guillermo Gonzalez



FOUNDATIONS OF OSCILLATOR CIRCUIT DESIGN

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Preface

My interest in oscillators started many years ago when I was an undergraduate student and one of the laboratory experiments was the design of a Colpitts oscillator. It was amazing to see how a sinusoidal signal appeared when the power supply was turned on. What an interesting way of controlling the motion of electrons in the circuit! My fascination with oscillators has remained to this date and, hopefully, this book will be a reflection of it.

Electronic oscillator theory and design is a topic that, in general, is barely covered in undergraduate electronic courses. However, since oscillators are one of the main components in many electronic circuits, engineers are usually required to design them. Sinusoidal carrier signals are needed in transmitters and receivers, and timing signals (square-wave signals) are needed in digital circuits.

The purpose of this book is to cover the foundations of oscillator circuit design in a comprehensive manner. The book covers the theory and design of oscillators in the frequency range that extends from the audio range to the microwave range at about 30 GHz. In this large range of frequencies the active element is usually a semiconductor, such as a BJT or FET, or an op amp. The techniques involved in the design of oscillators at the lower frequencies are different from those used at the higher frequencies. An important feature of this book is the wide and rather complete coverage of oscillators, from the low-frequency oscillator to the more complex oscillator found at radio frequencies (RF) and microwave (MW) frequencies. This book emphasizes the use of simulation techniques (i.e., CAD techniques) in the design of oscillators. In many cases the performance observed in the simulation is very similar to that obtained in the laboratory. This is mostly true for oscillators working at the lower frequencies and up to a few megahertz. As the frequency increases, the practical implementation is highly affected by the layout and by the parasitics associated with the components used. In such cases the simulation should provide a starting point to the associated practical implementation.

The advances in CAD techniques since the 1980s have certainly changed the approach to the design of many oscillators. Before the advent of advanced CAD techniques, oscillator design involved a significant amount of theoretical work, especially for those oscillators operating in the RF and MW-frequency regions. While a solid theoretical foundation is still needed, the modern CAD programs can perform a lot of nonlinear simulations that were once only a dream in oscillator analysis and design. In my experience the best oscillator designers are those who have a good understanding of the fundamental principles involved, experience with an appropriate CAD program, and a good practical sense.

In undergraduate courses I have used the transient simulator available in SPICE to analyze and design oscillators. Transient simulators work well, but in many cases it takes a lot of simulation time to get to the steady-state oscillatory waveform. As one matures in the field of oscillators, an advanced CAD program with harmonic balance capabilities is a must. The main program used in this book is the Advanced Design System (ADS) from Agilent. One of the many uses of this very powerful and state-of-the art program is for oscillator analysis and design since it contains a transient simulator, a harmonic balance simulator, a statistical design simulator, and an envelope simulator. The ADS program and associated licenses were donated by Agilent to the Department of Electrical and Computer Engineering at the University of Miami for teaching and research purposes.

One objective of this book is to cover the fundamentals of oscillator design using semiconductor devices as the active devices. A second objective, in spite of the fact that the material in electronic oscillators is volumetric, is to present the foundations of modern oscillators' design techniques. In this book the reader is first exposed to the theory of oscillators. Then, a variety of techniques that are used in the design of oscillators are discussed.

The Table of Contents clearly indicates the choice of material and the order of presentation. In short, Chapter 1 provides a general introduction to the theory of oscillators and discusses in detail several low-frequency oscillators. Chapter 2 discusses the oscillator characteristics such as frequency stability, quality factors, phase noise, and statistical considerations. Chapter 3 presents the design of tuned oscillators using BJTs, FETs, and op amps. Chapter 4 treats the design of oscillators using crystals, ceramic resonators, surface acoustic wave resonators, and dielectric resonators. The theory and design methods using the negative-resistance approach are presented in Chapter 5. Relaxation oscillators and other nonsinusoidal oscillators are discussed in Chapter 6.

This book can be used in a senior graduate-level course in oscillators. It is also intended to be used in industrial and professional short courses in oscillators. It should also provide for a comprehensive reference of electronic oscillators using semiconductors for electrical engineers.

Two large-signal simulators that are used to analyze and design oscillators are the harmonic balance simulator and the transient simulator.

The harmonic balance simulator in ADS performs a nonlinear steady-state analysis of the circuit. It is a very powerful frequency-domain analysis technique for nonlinear circuits. The simulator allows the analysis of circuits excited by large-signal sources. Also, ADS provides the function "ts" which calculates the time-domain signal from its frequency spectrum.

Transient-analysis simulation is performed entirely in the time domain. It also allows the analysis of nonlinear circuits and large-signal sources. The data displayed from the transient simulation shows the time-domain waveform. From the time-domain waveform, the oscillation build-up and the steady-state results can be viewed. The transient simulator requires an initial condition for the oscillator to begin. The initial condition can be an initial voltage across a capacitor, a voltage step for the power-supply component, or the use of a noise source. ADS provides the function "fs," which calculates the frequency spectrum from the time-domain signal.

I wish to thank all of my former students for their valuable input and helpful comments related to this book. Special thanks go to Mr. Jorge Vasiliadis who contributed to the section on DROs; to Mr. Hicham Kehdy for his contribution to the design of the GB oscillator in Chapter 5; to Mr. Orlando Sosa, Dr. Mahes M. Ekanayake, and Dr. Chulanta Kulasekere for reviewing several parts of the book; to Dr. Kamal Premaratne who provided input to the material in Chapter 1; and to Dr. Branko Avanic who did a lot of work with me on crystal oscillators. Also, I will always be grateful to Dr. Les Besser for his friendship and for the clarity that he has provided in the field of microwave electronics.

Thanks also go to the staff at Artech House, in particular for the help and guidance provided by Audrey Anderson (production editor) and Mark Walsh (acquisitions editor).

Finally, my love goes to the people that truly make my life busy and worthwhile, namely my wife Pat, my children Donna and Alex, my daughter-in-law Samantha, my son-in-law Larry, and my grandkids Tyler, Analise, and Mia. They were always supportive and put up with me during this long writing journey.

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CHAPTER 1

Theory of Oscillators

1.1 Introduction

There are many types of oscillators, and many different circuit configurations that produce oscillations. Some oscillators produce sinusoidal signals, others produce nonsinusoidal signals. Nonsinusoidal oscillators, such as pulse and ramp (or sawtooth) oscillators, find use in timing and control applications. Pulse oscillators are commonly found in digital-systems clocks, and ramp oscillators are found in the horizontal sweep circuit of oscilloscopes and television sets. Sinusoidal oscillators are used in many applications, for example, in consumer electronic equipment (such as radios, TVs, and VCRs), in test equipment (such as network analyzers and signal generators), and in wireless systems.

In this chapter the feedback approach to oscillator design is discussed. The oscillator examples selected in this chapter, as well as the mix of theory and design information presented, help to clearly illustrate the feedback approach.

The basic components in a feedback oscillator are the amplifier, an amplitude-limiting component, a frequency-determining network, and a (positive) feedback network. Usually the amplifier also acts as the amplitude-limiting component, and the frequency-determining network usually performs the feedback function. The feedback circuit is required to return some of the output signal back to the input. Positive feedback occurs when the feedback signal is in phase with the input signal and, under the proper conditions, oscillation is possible.

One also finds in the literature the term negative-resistance oscillators. A negative-resistance oscillator design refers to a specific design approach that is different from the one normally used in feedback oscillators. Since feedback oscillators present an impedance that has a negative resistance at some point in the circuit, such oscillators can also be designed using a negative-resistance approach. For a good understanding of the negative resistance method, a certain familiarity with oscillators is needed. That is why the negative resistance method is discussed in Chapter 5.

1.2 Oscillation Conditions

A basic feedback oscillator is shown in Figure 1.1. The amplifier's voltage gain is $A_v(j\omega)$, and the voltage feedback network is described by the transfer function $\beta(j\omega)$. The amplifier gain $A_v(j\omega)$ is also called the open-loop gain since it is the

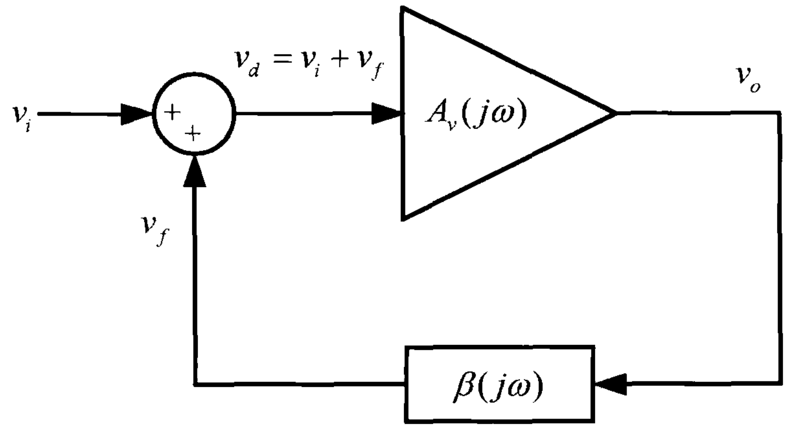

Figure 1.1 The basic feedback circuit.

gain between v_o and v_i when $v_f = 0$ (i.e., when the path through $\beta(j\omega)$ is properly disconnected).

The amplifier gain is, in general, a complex quantity. However, in many oscillators, at the frequency of oscillation, the amplifier is operating in its midband region where $A_v(j\omega)$ is a real constant. When $A_v(j\omega)$ is constant, it is denoted by A_{vo}.

Negative feedback occurs when the feedback signal subtracts from the input signal. On the other hand, if v_f adds to v_i, the feedback is positive. The summing network in Figure 1.1 shows the feedback signal added to v_i to suggest that the feedback is positive. Of course, the phase of v_f determines if v_f adds or subtracts to v_i. The phase of v_f is determined by the closed-loop circuit in Figure 1.1. If $A_v(j\omega) = A_{vo}$ and A_{vo} is a positive number, the phase shift through the amplifier is 0°, and for positive feedback the phase through $\beta(j\omega)$ should be 0° (or a multiple of 360°). If A_{vo} is a negative number, the phase shift through the amplifier is ±180° and the phase through $\beta(j\omega)$ for positive feedback should be $\pm 180° \pm n360°$. In other words, for positive feedback the total phase shift associated with the closed loop must be 0° or a multiple n of 360°.

From Figure 1.1 we can write

$$v_o = A_v(j\omega)v_d \tag{1.1}$$

$$v_f = \beta(j\omega)v_o \tag{1.2}$$

and

$$v_d = v_i + v_f \tag{1.3}$$

Thus, from (1.1) to (1.3), the closed-loop voltage gain $A_{vf}(j\omega)$ is given by

$$A_{vf}(j\omega) = \frac{v_o}{v_i} = \frac{A_v(j\omega)}{1 - \beta(j\omega)A_v(j\omega)} \tag{1.4}$$

The quantity $\beta(j\omega)A_v(j\omega)$ is known as the *loop gain*.

For oscillations to occur, an output signal must exist with no input signal applied. With $v_i = 0$ in (1.4) it follows that a finite v_o is possible only when the denominator is zero. That is, when

$$1 - \beta(j\omega)A_v(j\omega) = 0$$

or

$$\beta(j\omega)A_v(j\omega) = 1 \tag{1.5}$$

Equation (1.5) expresses the fact that for oscillations to occur the loop gain must be unity. This relation is known as the Barkhausen criterion.

With $A_v(j\omega) = A_{vo}$ and letting

$$\beta(j\omega) = \beta_r(\omega) + j\beta_i(\omega)$$

where $\beta_r(\omega)$ and $\beta_i(\omega)$ are the real and imaginary parts of $\beta(j\omega)$, we can express (1.5) in the form

$$\beta_r(\omega)A_{vo} + j\beta_i(\omega)A_{vo} = 1$$

Equating the real and imaginary parts on both sides of the equation gives

$$\beta_r(\omega)A_{vo} = 1 \Rightarrow A_{vo} = \frac{1}{\beta_r(\omega)} \tag{1.6}$$

and

$$\beta_i(\omega)A_{vo} = 0 \Rightarrow \beta_i(\omega) = 0 \tag{1.7}$$

since $A_{vo} \neq 0$. The conditions in (1.6) and (1.7) are known as the Barkhausen criteria in rectangular form for $A_v(j\omega) = A_{vo}$.

The condition (1.6) is known as the gain condition, and (1.7) as the frequency of oscillation condition. The frequency of oscillation condition predicts the frequency at which the phase shift around the closed loop is 0° or a multiple of 360°.

The relation (1.5) can also be expressed in polar form as

$$\beta(j\omega)A_v(j\omega) = |\beta(j\omega)A_v(j\omega)| \underline{/\beta(j\omega)A_v(j\omega)} = 1$$

Hence, it follows that

$$|\beta(j\omega)A_v(j\omega)| = 1 \tag{1.8}$$

and

$$\underline{/\beta(j\omega)A_v(j\omega)} = \pm n360° \tag{1.9}$$

where $n = 0, 1, 2, \ldots$. Equation (1.9) expresses the fact that the signal must travel through the closed loop with a phase shift of 0° or a multiple of 360°. For $A_v(j\omega) = A_{vo}$, then $\underline{|\beta(j\omega)A_{vo}}$ is the angle of $\beta(j\omega)$, and the condition (1.9) is equivalent to saying that $\beta_i(j\omega) = 0$, in agreement with (1.7). Also, for $A_v(j\omega) = A_{vo}$ and with $\beta_i(j\omega) = 0$, (1.8) reduces to (1.6). The conditions in (1.8) and (1.9) are known as the Barkhausen criteria in polar form.

When the amplifier is a current amplifier, the basic feedback network can be represented as shown in Figure 1.2. In this case, $A_i(j\omega)$ is the current gain of the amplifier, and the current feedback factor $\alpha(j\omega)$ is

$$\alpha(j\omega) = \frac{i_f}{i_o}$$

For this network, the condition for oscillation is given by

$$\alpha(j\omega)A_i(j\omega) = 1 \tag{1.10}$$

which expresses the fact that loop gain in Figure 1.2 must be unity.

The loop gain can be evaluated in different ways. One method that can be used in some oscillator configurations is to determine $A_v(j\omega)$ and $\beta(j\omega)$ and to form the loop gain $A_v(j\omega)\beta(j\omega)$. In many cases it is not easy to isolate $A_v(j\omega)$ and $\beta(j\omega)$ since they are interrelated. In such cases a method that can usually be implemented is to represent the oscillator circuit as a continuous and repetitive circuit. Hence, the loop gain is calculated as the gain from one part to the same part in the following circuit. An alternate analysis method is to replace the amplifier and feedback network in Figure 1.1 by their ac models and write the appropriate loop equations. The loop equations form a system of linear equations that can be solved for the closed-loop voltage gain, which can be expressed in the general form

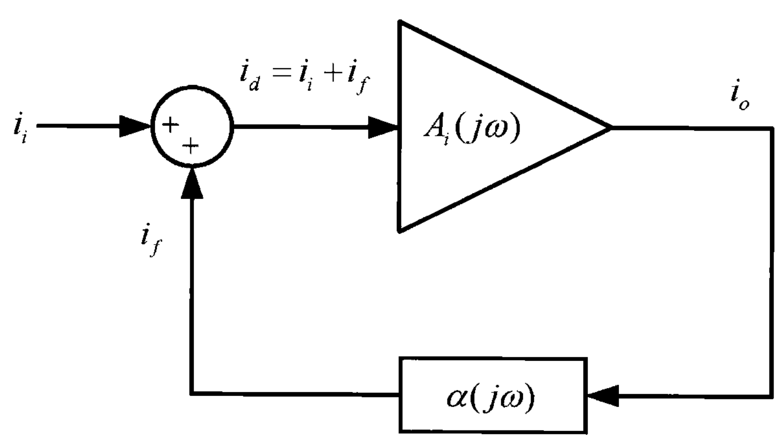

Figure 1.2 The current form of the basic feedback network.

$$A_{vf}(j\omega) = \frac{v_O}{v_i} = \frac{N(j\omega)}{D(j\omega)} \tag{1.11}$$

where $N(j\omega)$ represents the numerator polynomial and $D(j\omega)$ is the system determinant of the linear equations. In terms of (1.11) the conditions for oscillations are obtained by setting the system determinant equal to zero (i.e., $D(j\omega) = 0$). Setting $D(j\omega) = 0$ results in two equations: one for the real part of $D(j\omega)$ (which gives the gain condition), and one for the imaginary part of $D(j\omega)$ (which gives the frequency of oscillation).

From circuit theory we know that oscillation occurs when a network has a pair of complex conjugate poles on the imaginary axis. However, in electronic oscillators the poles are not exactly on the imaginary axis because of the nonlinear nature of the loop gain. There are different nonlinear effects that control the pole location in an oscillator. One nonlinear mechanism is due to the saturation characteristics of the amplifier. A saturation-limited sinusoidal oscillator works as follows. To start the oscillation, the closed-loop gain in (1.4) must have a pair of complex-conjugate poles in the right-half plane. Then, due to the noise voltage generated by thermal vibrations in the network (which can be represented by a superposition of input noise signals v_n) or by the transient generated when the dc power supply is turned on, a growing sinusoidal output voltage appears. The characteristics of the growing sinusoidal signal are determined by the complex-conjugate poles in the right-half plane. As the amplitude of the induced oscillation increases, the amplitude-limiting capabilities of the amplifier (i.e., a reduction in gain) produce a change in the location of the poles. The changes are such that the complex-conjugate poles move towards the imaginary axis. However, the amplitude of the oscillation was increasing and this makes the complex poles to continue the movement toward the left-half plane. Once the poles move to the left-half plane the amplitude of the oscillation begins to decrease, moving the poles toward the right-half plane. The process of the poles moving between the left-half plane and the right-half plane repeats, and some steady-state oscillation occurs with a fundamental frequency, as well as harmonics. This is a nonlinear process where the fundamental frequency of oscillation and the harmonics are determined by the location of the poles. Although the poles are not on the imaginary axis, the Barkhausen criterion in (1.5) predicts fairly well the fundamental frequency of oscillation. It can be considered as providing the fundamental frequency of the oscillator based on some sort of average location for the poles.

The movement of the complex conjugate poles between the right-half plane and the left-half plane is easily seen in an oscillator designed with an amplitude limiting circuit that controls the gain of the amplifier and, therefore, the motion of the poles. An example to illustrate this effect is given in Example 1.6.

The previous discussion shows that for oscillations to start the circuit must be unstable (i.e., the circuit must have a pair of complex-conjugate poles in the right-half plane). The condition (1.5) does not predict if the circuit is unstable. However, if the circuit begins to oscillate, the Barkhausen criterion in (1.5) can be used to predict the approximate fundamental frequency of oscillation and the gain condition. The stability of the oscillator closed-loop gain can be determined using the Nyquist stability test.