Raj Senani · D. R. Bhaskar
V. K. Singh · R. K. Sharma

Sinusoidal Oscillators and Waveform Generators using Modern Electronic Circuit Building Blocks

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Preface

Sinusoidal oscillators and waveform generators have numerous applications in electronics, instrumentation, measurement, communications, control systems, and signal processing, due to which they have continued to remain a dominant and popular topic of research in the Circuits and Systems literature. Consequently, well over 1500 research papers have so far been published on the analysis, synthesis, and design of oscillators and wave form generators in various international journals. By contrast, only a handful of books have so far been written on oscillators, which suffer from one or more of the following limitations: (1) a number of books are more than a decade old; (2) several of the books deal with very specific types of sinusoidal oscillators only and, hence, have a very limited coverage; (3) a number of books deal with only general issues related to oscillators; (4) even those books which have been written after 2004 do not deal with oscillators and waveform generators using new electronic circuit building blocks which find very prominent space in modern analog circuits journals; (5) as far as could be known, there is no book written so far on non-sinusoidal relaxation oscillators or waveform generators. By contrast, the present monograph is intended to cover a wide variety of sinusoidal oscillators and waveform generators, using a variety of modern electronic circuit building blocks, which do not appear to have been dealt in any of the available books so far. This monograph is intended to provide the following:

- Single-source reference on sinusoidal oscillators and waveform generators using classical as well as modern electronic circuit building blocks (such as operational transconductance amplifiers, current conveyors and their numerous variants, current feedback operational amplifiers, differential difference amplifiers, four-terminal floating nullors, unity gain voltage/current followers, operational transresistance amplifiers, current differencing buffered amplifiers, current differencing transconductance amplifiers, current follower transconductance amplifiers, voltage differencing inverting buffered amplifier, voltage differencing differential input buffered amplifiers, and numerous others).

- State-of-the-art review of a large variety of sinusoidal oscillators and non-sinusoidal waveform generators/relaxation oscillators.
- A catalogue of over 600 chosen topologies of oscillators and waveform generators, from amongst those evolved during the last four decades, with their design details and their salient performance features/limitations highlighted.
- A comprehensive collection of well over 1500 references on oscillators and waveform generators for readers interested in further studies.
- A number of interesting research problems in almost every chapter of the monograph for the research-oriented readers.
- A useful reference for educators, students, researchers, practicing engineers, and hobbyists who have an interest in the design of sinusoidal oscillators and non-sinusoidal waveform generators/relaxation oscillators.

Lastly, we must acknowledge that in a monograph based upon over 1500 published research papers, there might have been some inadvertent omissions of some references; however, the same is not intentional. Aggrieved authors, whose works might have been omitted, are most welcome to bring to our attention (using the e-mail ID: senani@ieee.org) any missing reference(s) which we would surely like to include in the next edition of this monograph. Any other suggestions are also most welcome!

New Delhi, India
July 07, 2015

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Acknowledgements

After having written a monograph on *Current Feedback Operational Amplifiers and Their Applications* and another on *Current Conveyors*: *Variants*, *Applications and Hardware Implementations*, both published by Springer, it was rather obvious for the first author to think about writing a monograph on *Sinusoidal Oscillators*—a topic on which he and his several collaborators have worked extensively and quite intimately. Having convinced ourselves about this, we then set out to write this monograph and proposed the same to Charles Glaser, the Executive Editor, Springer, who gave us the signal to go ahead.

Let us admit that writing this monograph did not turn out to be an easy task! All the four authors went through a lot of difficulties and turmoil in their personal lives, one by one, during the entire period in which the preparation of the manuscript took place. Nevertheless, with the kind support and understanding of Charles Glaser, we somehow persisted and completed the assignment, though somewhat later than anticipated.

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The authors have been involved in teaching a number of ideas contained in the present monograph to their students in the UG courses on *Linear Integrated Circuits* and *Bipolar and CMOS Analog Integrated Circuits* and PG courses on *Signal Acquisition and Conditioning* and *Advanced Network Synthesis*, during which a persistent query from our students has been as to *in which book the material taught to them could be found?* We thank our numerous students for this and do hope that this monograph provides an answer to their query.

New Delhi, India

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Abbreviations

A/D	Analog to digital
ABB	Active building block
AD	Analog devices
ADC	Analog to digital converter
AGC	Automatic gain control
AGPE	All grounded passive elements
AM	Analog multiplier
AP	All pass
APF	All-pass filter
BDI	Bilinear discrete integrator
BDI-DOCC	Balanced dual input–dual output current conveyor
BE	Band elimination
BiCMOS	Bipolar complementary metal oxide semiconductor
BIT	Built-in testing
BJT	Bipolar junction transistor
BO-CCII	Balanced output-current conveyor, second generation
BO-COA	Balanced-output current operational amplifier
BOICCII	Balanced output inverting current conveyor, second generation
BOOA	Balanced output op-amps
BO-OTA	Balanced-output-operational transconductance amplifier
BO-VOA	Balanced-output voltage mode operational amplifier
BP	Band pass
BPF	Band-pass filter
BR	Band reject
BS	Band stop
BSF	Band stop filter
BW	Bandwidth
C/f	Capacitance-to-frequency
C/T	Capacitance-to-time period

CAB	Configurable analog block
CB	Complementary bipolar
CC	Current conveyor
CCC	Composite current conveyor
CC-CBTA	Current controlled current backward transconductance amplifier
CC-CC	Current-controlled current conveyor
CC-CFOA	Current controlled current feedback operational amplifier
CCCCTA	Current controlled current conveyor transconductance amplifier
CC-CDBA	Current-controlled current differencing buffered amplifier
CC-CD-CCC	Current-controlled current differencing current copy conveyor
CC-CDTA	Current-controlled current differencing transconductance amplifier
CC-CFA	Current-controlled current feedback amplifier
CC-CFOA	Current-controlled current feedback operational amplifier
CCCII	Controlled current conveyor, second generation
CCCS	Current controlled current source
CCDDCC	Current controlled differential difference current conveyor
CCDDCC	Current controllable differential difference current conveyor
CCDDCCTA	Current controlled differential difference current conveyor transconductance amplifier
CCI	Current conveyor, first generation
CCII	Current conveyor, second generation
CCIII	Current conveyor, third generation
CCO	Current controlled oscillator
CCTA	Current controlled transconductance amplifier
CCVS	Current controlled voltage source
CCW	Counterclockwise
CDA	Complimentary differential amplifier
CDBA	Current differencing buffered amplifier
CDIBA	Current differencing inverting buffered amplifier
CDTA	Current differencing transconductance amplifier
CDU	Current differencing unit
CE	Characteristic equation
CF	Current follower
CFA	Current feedback amplifier
CFBCCII	Controlled fully balanced current conveyor, second generation
CFC	Current feedback conveyor
CFOA	Current feedback operational amplifier
CFTA	Current follower transconductance amplifier
CG-CCCTA	Current gain controlled current controlled transconductance amplifier
CM	Current mode; also, current mirror
CMOS	Complementary metal oxide semiconductor
CMRR	Common mode rejection ratio

CO	Condition of oscillation
COA	Current mode operational amplifier or current-mode output
CPFSK	Continuous phase frequency shift keying
CR	Current repeater
CTTA	Current through transconductance amplifier
CVC	Current voltage conveyor
CW	Clockwise
D/A	Digital to analog
DAC	Digital to analog converter
DBTA	Differential-input buffered transconductance amplifier
DC	Direct current
DCC	Differential current conveyor
DCC-CFA	Double current-controlled current feedback amplifier
DCCCTA	Differential current controlled conveyor transconductance amplifier
DCFDCCII	Digitally controlled fully differential current conveyor, second generation
DCVC	Differential current voltage conveyor
DDA	Differential difference amplifiers
DDCC	Differential difference current conveyor
DDCCC	Differential difference complimentary current conveyor
DDCCFA	Differential difference complimentary current feedback amplifier
DDCCTA	Differential difference current conveyor transconductance amplifiers
DDOFA	Differential difference operational floating amplifier
DDOMA	Differential difference operational mirrored amplifier
DIBO-COA	Differential input balanced output-current operational amplifier
DIBO-OTA	Differential input balanced output operational transconductance amplifier
DIBO-VOA	Differential input balanced output-voltage mode operational amplifier
DI-COA	Differential input current mode operational amplifier
DIDO	Differential input differential output
DI-OTA	Differential input-operational transconductance amplifier
DISO	Differential-input-single-output
DI-VOA	Differential input voltage (mode) operational amplifier
DOCC	Dual output current conveyor
DO-DVCC	Dual-output-differential voltage current conveyor
DOICCII	Dual output inverting current conveyor, second generation
DPDT	Double-pole double-throw
DRAM	Dynamic random access memory
DVCC	Differential voltage current conveyor
DVCC+	Differential voltage current conveyor (positive-type)

DVCCC	Differential voltage complimentary current conveyor
DVCCCTA	Differential voltage current-controlled conveyor transconductance amplifier
DVCCII	Differential voltage current conveyor, second generation
DVCCS	Differential voltage controlled current source
DVCCTA	Differential voltage current conveyor transconductance amplifier
DVCFA	Differential voltage current feedback amplifier
DVCFOA	Differential voltage current feedback operational amplifier
DVCVS	Differential voltage controlled voltage source
DVTA	Differential voltage transconductance amplifier
DXCCII	Dual-X current conveyor, second generation
ECC	Extended current conveyor
ECC	Electronically controlled current conveyor
ECCII	Electronically tunable current conveyor, second generation
ECO	Explicit current output
ELIN	Externally linear but internally nonlinear
FAC	Floating admittance converter
FBCCII	Fully balanced current conveyor, second generation
FBDDA	Fully balanced differential difference amplifier
FC	Floating capacitance
FCC	Floating current conveyor
FCCNR	Floating current controlled negative resistance
FCCPR	Floating current controlled positive resistance
FDCC	Fully differential current conveyor
FDCCII	Fully differential current conveyor, second generation
FDCFOA	Fully differential current feedback operational amplifier
FDNC	Frequency-dependent negative conductance
FDNR	Frequency-dependent negative resistance
FDPR	Frequency-dependent positive resistance
FET	Field effect transistor
FGPIC/ FGPII	Floating generalized positive immittance converter/inverter
FI	Floating immittance or floating inductance or floating impedance
FM	Frequency modulation
FO	Frequency of oscillation
FPAA	Field programmable analog array
FPBW	Full power bandwidth
FPGA	Field programmable gate array
FSK	Frequency shift keying
FTFN	Four-terminal-floating-nullor
FVCR	Floating voltage controlled resistor
GBP	Gain bandwidth product
GC	Grounded capacitor
GCC	Generalized current conveyor

GCFTA	Generalized current follower transconductance amplifier
GFTC	Generalized frequency/time period converter
GI	Grounded impedance
GIC	Generalized impedance converter
GNIC	Generalized negative impedance converter
GNII	Generalized negative impedance inverter
GPIC	Generalized positive impedance converter
GPII	Generalized positive impedance inverter
GVC	Generalized voltage conveyor
HP	High pass
HPF	High-pass filter
IC	Integrated circuit
ICC	Inverting current conveyor
ICCII	Inverting current conveyor, second generation
ICCIII	Inverting current conveyor, third generation
INIC	Current inversion negative impedance converter
KHN	Kerwin–Huelsman–Newcomb
L/f	Inductance-to-frequency
L/T	Inductance-to-time period
LC	Inductance-capacitance
LDI	Lossless discrete integrator
LHS	Left hand side
LNA	Low noise amplifier
LP	Low pass
LPF	Low-pass filter
MCC-CDTA	Modified current controlled current differencing transconductance amplifier
MCCCII	Multi-output controlled current conveyor, second generation
MCCIII	Modified current conveyor, third generation
MCFOA	Modified current feedback operational amplifier
MDAC	Multiplying digital-to-analog converter
MDCC	Modified differential current conveyor
MDO-DDCC	Modified dual output-differential difference current conveyor
MICCII	Modified inverting current conveyor, second generation
MIDCC	Multiple input differential current conveyor
MIMO	Multiple-input–multiple-output
MISO	Multiple-input–single-output
MMCC	Multiplication-mode current conveyor
MOCC	Multiple output current conveyor
MO-CCCA	Multiple output current-controlled current amplifier
MO-CCCDTA	Multi-output-current-controlled current differencing transconductance amplifier
MO-CC-CTTA	Multiple output current controlled current through transconductance amplifier

MOCCII	Multiple output current conveyor, second generation
MOCF	Multiple output current follower
MOSFET	Metal oxide semiconductor field effect transistor
MOTA	Multi-output operational transconductance amplifier
MRC	MOS resistive circuit
MSO	Multi-phase sinusoidal oscillator
MTC	Mixed translinear cell
NAM	Nodal admittance matrix
NE	Node equation
NF	Notch filter
NIC	Negative impedance converter
NMOS	N-type metal oxide semiconductor
OC	Operational conveyor
OCC	Operational current conveyor
OFA	Operational floating amplifier
OFC	Operational floating conveyor
OFCC	Operational floating current conveyor
OLTF	Open loop transfer function
OMA	Operational mirrored amplifier
OTA	Operational transconductance amplifier
OTA-C	Operational-transconductance-amplifier-capacitor
OTRA	Operational transresistance amplifier
PCA	Programmable current amplifier
PIC	Positive impedance converter
PII	Positive impedance inverter
PLL	Phase locked loop
PM	Phase modulation
PMOS	P-type metal oxide semiconductor
QO	Quadrature oscillator
R/f	Resistance-to-frequency
R/T	Resistance-to-time period
RC	Resistance-capacitance
RHS	Right hand side
SCCO	Single-capacitor-controlled oscillator
SCIC	Summing current immittance converter
SCO	Switched capacitor oscillator
SEC	Single element controlled
SECO	Single-element-controlled oscillator
SFG	Signal flow graph
SIFO	Single input five output
SIMO	Single input multiple output
SIO	Switched current oscillator
SISO	Single input single output
SR	Slew rate

SRC	Single resistance controlled
SRCO	Single-resistance-controlled oscillator
SVIC	Summing voltage immittance convertor
TA	Transconductance amplifier
TAC	Transconductance and capacitance
TAM	Trans-admittance-mode
TCCII	Transconductance current conveyor, second generation
THD	Total harmonic distortion
TI	Texas Instruments
TIM	Trans-impedance-mode
TL	Trans-linear
TO-ICCII	Triple output-inverting current conveyor, second generation
TX-TZ CCII	Two-X two-Z current conveyor, second generation
UCC	Universal current conveyor
UGA	Unity gain amplifier
UGB	Unity gain buffer
UGC	Unity gain cell
UGDA	Unity gain differential amplifier
UGS	Unity gain summer
UVC	Universal voltage conveyor
VC	Voltage conveyor
VCC	Voltage-controlled capacitance
VCCS	Voltage-controlled-current-source
VCFI	Voltage controlled floating impedance
VCG	Voltage and current gain
VCG-CCII	Voltage and current gain current conveyor, second generation
VCL	Voltage controlled inductance
VCO	Voltage-controlled oscillator
VCR	Voltage-controlled-resistance
VCVS	Voltage-controlled voltage source
VCZ	Voltage-controlled impedance
VDCC	Voltage differencing current conveyor
VD-DIBA	Voltage differencing differential input buffered amplifier
VDIBA	Voltage differencing inverting buffered amplifier
VDTA	Voltage differencing transconductance amplifier
VF	Voltage follower
VFO	Variable frequency oscillator
VLF	Very low frequency
VLFO	Very low frequency oscillator
VLSI	Very large scale integrated circuits
VM	Voltage mirror; also voltage-mode
VMQO	Voltage mode quadrature oscillator
VNIC	Voltage inversion negative impedance converter
VOA	Voltage (mode) operational amplifier voltage-mode output

WBO	Wien Bridge oscillator
WCDMA	Wide-band code division multiple access
ZC-CCCITA	Z-copy current controlled current inverting transconductance amplifier
ZC-CCCITA	Z-copy current-controlled current inverting transconductance amplifier
ZC-CDU	Z-copy-current differencing unit
ZC-CG-CDBA	Z-copy current gain current differencing buffered amplifier
ZC-CG-CDTA	Z-copy current gain current differencing transconductance amplifier
ZC-CG-VDCC	Z-copy current gain voltage differencing current conveyor

Part I
Introductory Chapter

Chapter 1
Basic Sinusoidal Oscillators and Waveform Generators Using IC Building Blocks

Abstract This chapter discusses the basic principle of generating sinusoidal oscillators, reviews the classical sinusoidal oscillators and nonsinusoidal waveform generators, enumerates a number of other sinusoidal oscillator topologies, and outlines some basic methods of oscillator analysis and synthesis.

1.1 Introduction

Sinusoidal oscillators and nonsinusoidal waveform generators play an essential role in various instrumentation, measurement, communication, control, and other electronic systems, and therefore, discussion of a number of classical sinusoidal oscillators is an important topic dealt with in almost all standard text and reference books on electronics and electronic circuits (for instance, see [1–6]).

However, during the past four decades, a large number of circuits and techniques have been advanced by various researchers for realizing sinusoidal oscillators, using a variety of active devices and active circuit building blocks such as bipolar transistors, FETs, IC op-amps, operational transconductance amplifiers (OTA), current conveyors (CC), current feedback op-amps (CFOA), and numerous others. The analog circuit's literature is flooded with a huge number of papers on oscillators and their various aspects. Concurrently, a lot of effort has gone on the analysis, synthesis, and design of oscillators together with or the study of a variety of related aspects such as amplitude stabilization and control, start-up phenomenon, as well as a number of important performance-related issues like amplitude stability, frequency stability, jitter, phase noise, etc. (for instance, see [7–109]). Whereas several authors have concentrated on evolving systematic methods for realizing sinusoidal oscillators, a number of researchers have also worked on evolving design strategies or methods for improving practical performance of RC-active oscillators.

This chapter is concerned with the discussion about well-known as well as some not-so-well-known RC sinusoidal oscillators and nonsinusoidal waveform generators using op-amps in case of the former and using op-amps and IC 555 timer in case of the latter. The remaining chapters of this monograph will gradually unfold a

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variety of circuit configurations and types of oscillators and waveform generators employing modern electronic circuit building blocks.

1.2 Classical Sinusoidal Oscillators

Sinusoidal oscillators, being closed active RC circuits without functional input (other than the DC power supplies used for biasing the active device(s)), can be analyzed in a number of ways. From the classical theory of feedback oscillators, the sinusoidal oscillator, which is usually made from an amplifier and a frequency-selective RC circuit or LC circuit arranged in a positive feedback, can be analyzed by using Barkhausen criterion. A typical block diagram model of an oscillator shown in Fig. 1.1 contains an amplifier of gain A and a frequency-selective feedback network having gain β.

According to Barkhausen criterion, in order that such a system can generate sinusoidal oscillations, the necessary conditions are $|A\beta| = 1$ and $\angle A\beta = 0°$ or an integral multiple of 360°.

It is well known that a number of classical oscillators such as a Wien bridge oscillator, RC phase-shift oscillator, twin-T oscillator, and bridge-T oscillators can be readily seen to be belonging to the general block diagram of Fig. 1.1.

1.2.1 Wien Bridge Oscillator

In case of the Wien bridge oscillator (Fig. 1.2a), the op-amp is configured as non-inverting amplifier, whereas the feedback network consisting of two resistors and two capacitors is a second-order band-pass filter such that at the center frequency of the band-pass filter given by

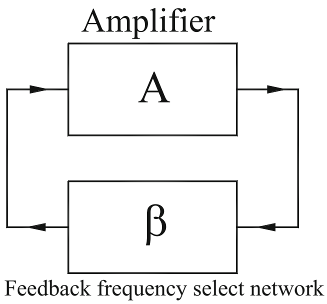

Fig. 1.1 The basic topology of the classical sinusoidal oscillators