Operational Amplifiers

2nd Edition

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Theory and Design

2nd Edition

Springer

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Contents

Summary

This 2nd edition has two main additions: a chapter on low-offset amplifiers and a part on frequency compensation at high capacitive loads. Furthermore many improvements have been made.

A systematic circuit design of operational amplifiers is presented. It is shown that the topology of all operational amplifiers can be divided in nine main overall configurations. These configurations range from one gain stage up to four or more gain stages. Many famous designs are completely evaluated.

High-frequency compensation techniques are presented for all nine configurations even at high capacitive loads. Special focus is on low-power low-voltage architectures with rail-to-rail input and output ranges.

An additional chapter on systematic design of μV-offset operational amplifiers and precision instrumentation amplifiers by applying chopping, auto-zeroing, and dynamic element-matching techniques has been added.

The design of fully differential operational amplifiers and operational floating amplifiers is being developed. Also, the characterization of operational amplifiers by macromodels and error matrices is presented, together with measurement techniques for their parameters.

Problems and simulation exercises have been supplied for self-evaluation.

Introduction

The goal of this book is to equip the circuit designer with a proper understanding of the theory and design of operational amplifiers (OpAmps). The core of the book presents the systematically design of operational amplifiers. All operational amplifiers can be classified into a periodic system of nine main overall configurations. This division enables the designer to quickly recognise, understand, and choose optimal configurations.

Chapter 1 defines four basic types of operational amplifiers on the basis of the external ground connections of the input and output ports of generalized linear active network elements. Whether an input or output port needs to be isolated from ground has a big impact on the circuit design of the input and output stages, as will be shown in later chapters.

A complete set of linear parameters, by which each of the above four basic types of operational amplifiers can be quantified, is given in Chapter 2. This provides the reader with a sense of which parameters are most important. Chapter 2 also presents macromodels and measurement techniques for OpAmp parameters.

A systematic treatment of sources of errors in important applications of the above four basic types of operational amplifiers is presented in Chapter 3.

Input stages are evaluated in Chapter 4. Important aspects such as bias, offset, noise, and common-mode rejection are considered. Low-voltage input stages with a rail-to-rail input voltage range are extensively discussed.

A classification of push-pull output stages is presented in Chapter 5. Three possible topologies are explored: voltage follower stages, compound stages, and rail-to-rail general amplifier stages. Designs are presented with feedforward and feedback biasing class-AB techniques. Emphasis is on voltage and current efficiency.

A classification of operational amplifiers into nine main overall configurations is presented in Chapter 6. The classification consists of two two-stage OpAmps, six three-stage OpAmps, and one four- or multi-stage OpAmp. High-frequency compensation techniques are developed for all configurations ranging from one gain stage up to four or more gain stages. Methods are presented for obtaining a maximum bandwidth over power ratio for certain high capacitive load conditions. Slew-rate and distortion are also considered.

Chapter 7 presents design examples of each of the nine main configurations. Many well-known OpAmps are fully elaborated. Among them are simple CMOS OpAmps, high-frequency bipolar OpAmps, Precision bipolar and BiCMOS OpAmps, low-voltage CMOS and bipolar OpAmps, and OpAmps with a high output drive capability in CMOS as well as in BiCMOS technology.

The design of fully differential operational amplifiers with common-mode feedback is developed in Chapter 8. Special focus is on low-voltage architectures.

When the output port as well as input port are designed such that they are both isolated from ground, the most universal linear active network element is created: the operational floating amplifier. The concept of this OpAmp gives the designer the freedom to work with current signals as well as voltage signals. Realizations of operational floating amplifiers are developed in Chapter 9 also in relation to instrumentation amplifiers.

An additional Chapter 10 has been added on the systematic design of μV-offset operational amplifiers and precision instrumentation amplifiers by applying chopping, auto-zeroing, and dynamic element-matching techniques.

Problems and simulation exercises have been supplied for most of the chapters to facilitate self-evaluation of the understanding and design skills of the user of this book.

Notation

OpAmp	operational amplifier
OA	operational amplifier
OIA	operational inverting amplifier
OVA	operational voltage amplifier
OCA	operational current amplifier
OFA	operational floating amplifier
GA	general amplifier stage
VF	voltage follower stage
CF	current follower stage
CM	current mirror stage
IA	instrumentation amplifier
a	temperature coefficient
A_v	voltage gain
A_{vo}	DC voltage gain
β	current gain of bipolar transistor
B_v	voltage attenuation of feedback network
C	capacitor value
Ch	Chopper
C_{ox}	specific capacitance of gate oxide
C_M	Miller capacitor value
C_P	parallel capacitor value
D	distortion
f	frequency
f_T	transit frequency of a transistor
f_o	zero-dB frequency
g_m	transconductance of a transistor
i	small-signal current
I	current
I_B	bias current
I_C	collector current

I_D	drain current
I_E	emitter current
I_S	supply current
I_Q	quiescent current
k	Boltzman's Constant
	$K = \mu C_{ox} W/L$
L	length of gate in MOS transistors
M	CMOS transistor
R	resistor value
S	signal
S	switch
S_r	slew rate
T	generalized transistor
Q	bipolar transistor
v	small-signal voltage
V	voltage
V_B	bias voltage
V_{CC}	positive supply voltage with bipolar transistors
V_{DD}	positive supply voltage with MOS transistors
V_{EE}	negative supply voltage with bipolar transistors
V_G	generator voltage
V_{GS}	gate-source voltage
V_{GT}	active gate-source voltage $(V_{GS}-V_{TH})$
V_S	total-supply voltage
V_{SN}	negative supply voltage
V_{SP}	positive supply voltage
V_{SS}	negative supply voltage with MOS transistors
V_T	thermal voltage kT/q
V_{TH}	threshold voltage of MOS device
W	width of gate in MOS transistors
μ	mobility of change carriers

Extrinsic device parameters

R_L

C_L

C_M

R_D R_C

R_G R_B

R_S R_E

Intrinsic Small-signal transistor parameters

r_{ds} r_{ce} r_o
r_{gs} r_{be}
r_s r_e
c_{ds} c_{ce}
c_{gs} c_{be}
g_m g_m
μ_n μ_p
β_n β_p