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OPERATIONAL AMPLIFIER SPEED AND ACCURACY IMPROVEMENT

Analog Circuit Design with Structural Methodology

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KLUWER ACADEMIC PUBLISHERS

NEW YORK, BOSTON, DORDRECHT, LONDON, MOSCOW

eBook ISBN: 1-4020-2517-3
Print ISBN: 1-4020-7772-6

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New York, Boston, Dordrecht, London, Moscow

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Dordrecht

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Dedication

To my father Valery Nikolayevich Ivanov who led and inspired me to become an engineer

Vadim Ivanov

Contents

Preface

"Operational Amplifier Speed and Accuracy Improvement" focuses on the analog integrated circuit design methodology that is pushing the state of art limits. OpAmp development is used as an example, but the methodology is applicable in any area of the analog IC design. This work is useful for analog IC designers who would like to create new and superior circuits, as well as for graduate students who want to leapfrog the lengthy process of detailed studying of the huge legacy of analog circuits and accelerate their way to professional excellence.

The basics of this methodology, which we call structural design, were developed in 1960s and 1970s in the USSR, and were used in development of control systems for hydrofoil ships and cruise missiles. Except for a few recent papers, there are no adequate references to this methodology in English. In its analytical part, the structural design approach is close to the area of modern philosophy called *systems thinking*.

We have tailored the structural design methodology for analog IC development. This approach has influenced the designs of OpAmps, references, instrumentation and power amplifiers developed by the Tucson division of Texas Instruments, Inc. (former Burr-Brown). Effectiveness of this methodology has been confirmed by more than 30 patents and patent applications received and filed in last few years.

The circuits shown in this book have been used in micropower (< 1uA of I_q), and high power (3A load current) OpAmps, in the fastest CMOS amplifiers developed by industry, in the most accurate CMOS and bipolar OpAmps, and in many general purpose OpAmps as well.

In chapter 1, we describe the basic steps of analog design, outline the situation with modern analog processes, discuss the requirements of modern

OpAmps, and review the basic parameters and characteristics of bipolar and CMOS transistors that are important for successful analog design.

Chapter 2 outlines the application of signal graphs in the structural design methodology, discusses the content of analog cell libraries and proposes additional cells for these libraries that are proven to be useful in the analog design.

Chapter 3 is dedicated to the OpAmp biasing: supply-insensitive, proportional to the absolute temperature, and other biasing cores; current sources with high output impedance and low saturation voltage; low-noise charge pumps for bootstrapping the tail current source.

Chapter 4 examines structures which improve the power to speed ratio of the OpAmp, while maintaining high gain. The gain stage and amplification stage are differentiated, and the voltage and current gain boost circuits are discussed.

Chapter 5 discusses the input stages (including rail-to-rail stages with stable transconductance), the offset and temperature drift trimming techniques, and input protection circuits.

Chapter 6 describes the intermediate OpAmp stages - primarily the folded cascode which is an essential part of any amplifier with a rail-to-rail or single-supply input. The improvement of this stage's parameters, voltage gain boost and voltage clamping are discussed.

Chapter 7 is dedicated to the output class AB stage, its control structure, regulation and stability of the quiescent current, with emphasis on a low supply and rail-to-rail output capability.

Chapter 8 describes the implementation of special function circuits which protect or extend the boundaries of the OpAmp functionality (slew rate boost, current limiting, fast shutdown and start-up, fast overload recovery).

Chapter 9 gives a top-down OpAmp design example. Some practical tricks and honing of the common sense in distributing the current budget, in choice of the component dimensions is the subject of this chapter. The reader is moving from the general idea to final implementation and test results.

The Appendix contains the article "Structural properties and linear transformations in the multidimensional systems with symmetric links", which reveals part of the theory behind the structural design methodology. This is an adapted translation from Russian of the article written by Valery Ivanov, one of the inventors of the structural design methodology, to whom both authors are conveying their respect and gratitude.

Authors

Acknowledgments

We both express our gratitude to David Spady (Texas Instruments, Tucson) for comments on manuscript, to Misha Ivanov (Texas Instruments, Germany) who read and commented on chapters 1-5, to Rod Burt (Texas Instruments, Tucson), who took a burden to review the book.

We are thankful to David Jones, Wally Meinel, Sergey Alenin, Greg Johnson (Texas Instruments, Tucson), to Prof. Rob Fox (University of Florida) who assisted with critique and encouragement.

Prof. Mohammed Ismail (Spirea AB, Sweden) persuaded us to write this book.

One of the authors would like to express his gratitude to the staff of Electronics Research Laboratory, Delft University of Technology, The Netherlands, and especially to Dr. C. J. M. Verhoeven and Dr. J. R. Long. The unique congenial atmosphere of this laboratory encouraged this author to writing this book and making the first steps to its completion.

Notations

OpAmp	operational amplifier
A_v	voltage gain
β	current gain of the bipolar transistor
C	capacitor value
C_L	load capacitance
C_{ox}	sheet capacitance of the gate oxide
C_M	Miller capacitor value
C_{eqv}	total equivalent capacitance at the node
ESD	electro-static discharge
f	frequency
g_m	small signal transconductance
GBW	gain-bandwidth product
f_T	transit frequency of the transistor
i	small-signal current
I	current
I_C	collector current
I_B	base current
I_{BD}	body current
I_D	drain current
I_E	emitter current
I_q	quiescent current
I_S	source current
I_s	reverse current of the p-n junction
k	Boltzman's constant
K	$= \mu C_{ox}(W/L)$
L	MOS transistor channel length

M	MOS transistor
normal temperature	27°C = 300K default simulation temperature for SPICE
PTAT	proportional to the absolute temperature
q	charge of the electron
Q	bipolar transistor
r_{bp}	base body resistance
r_{dp}	drain body resistance
r_{ep}	emitter body resistance
r_{sp}	source body resistance
R	resistance
R_L	load resistance
S_E	bipolar transistor emitter area
T	absolute temperature
TC	temperature coefficient
um	micrometer
v	small-signal voltage
V	voltage
V_A	Early voltage
V_{BE}	base-emitter voltage
V_{CE}	collector-emitter voltage
V_{DD}	positive supply voltage
V_{DS}	drain-source voltage
V_{SS}	negative supply voltage
V_{GS}	gate-source voltage
V_T	$=kT/q$, thermal voltage
V_{TH}	threshold voltage
W	MOS transistor channel width
μ	charge carrier mobility