Symbolic Analysis for Automated Design of Analog Integrated Circuits

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Kluwer Academic Publishers

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by

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Kluwer Academic Publishers
Boston/Dordrecht/London

Distributors for North America:
Kluwer Academic Publishers
101 Philip Drive
Assinippi Park
Norwell, Massachusetts 02061 USA

Distributors for all other countries:
Kluwer Academic Publishers Group
Distribution Centre
Post Office Box 322
3300 AH Dordrecht, THE NETHERLANDS

Library of Congress Cataloging-in-Publication Data

Gielen, Georges.
Symbolic analysis for automated design of analog integrated circuits / by Georges Gielen and Willy Sansen.
p. cm. — (The Kluwer international series in engineering and computer science ; SECS 137)
Includes bibliographical references and index.
ISBN 0-7923-9161-6
1. Linear integrated circuits—Design and construction—Data processing. 2. Electronic circuit design—Data processing. 3. Computer—aided design. I. Sansen, Willy M.C. II. Title. III. Series.
TK7874.G54 1991
621.381'5—dc20 91-15032
CIP

Printed on acid-free paper.

Printed in the United States of America

SYMBOLIC ANALYSIS FOR AUTOMATED DESIGN OF ANALOG INTEGRATED CIRCUITS

THE KLUWER INTERNATIONAL SERIES IN ENGINEERING AND COMPUTER SCIENCE

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LIST OF SYMBOLS AND ABBREVIATIONS

A/D : analog/digital
ADC : analog-to-digital converter
A_o : differential-mode gain
ASIC : application-specific integrated circuit
CAD : computer-aided design
C_C : compensation capacitor
C_i : node capacitance
C_L : load capacitor
CMNA : compacted modified nodal analysis
CMRR : common-mode rejection ratio
D/A : digital/analog
DA : design automation
DAC : digital-to-analog converter
DSLE : double sparse Laplace expansion
DSLEM : double sparse Laplace expansion with memo storage
DSP : digital signal processor
ε_A : accumulated absolute error
ε_N : accumulated effective error (or nominal error)
f : frequency
FDSLEM : factoring double sparse Laplace expansion with memo storage
GBW : gain-bandwidth
HD2 : second harmonic distortion ratio
HD3 : third harmonic distortion ratio
MNA : modified nodal analysis
NA : nodal analysis
opamp : operational amplifier
OTA : operational transconductance amplifier
$\underline{p}$: vector of symbolic circuit parameters
p_i : ith pole

PM : phase margin
PSRR : power-supply rejection ratio
R_L : load resistor
s : complex frequency variable of the Laplace transform
SC : switched capacitor
SLE : sparse Laplace expansion
SLEM : sparse Laplace expansion with memo storage
SLEMP : sparse Laplace expansion with memo storage and preordering
SLEP : sparse Laplace expansion with preordering
SOP : sum of products
SR : slew rate
T_s : settling time
VLSI : very large scale integration
VLSIC : very large scale integrated circuit
V_{os} : offset voltage
ω : pulsation
x : complex frequency variable
z : complex frequency variable of the z-transform
z_i : ith zero

Notational conventions

variables are denoted in lowercase

vectors are denoted in underlined lowercase

MATRICES are denoted in uppercase

All examples are ended by ♦

FOREWORD

It is a great honor to provide a few words of introduction for Dr. Georges Gielen's and Prof. Willy Sansen's book *"Symbolic analysis for automated design of analog integrated circuits"*. The symbolic analysis method presented in this book represents a significant step forward in the area of analog circuit design. As demonstrated in this book, symbolic analysis opens up new possibilities for the development of computer-aided design (CAD) tools that can analyze an analog circuit topology and automatically size the components for a given set of specifications. Symbolic analysis even has the potential to improve the training of young analog circuit designers and to guide more experienced designers through second-order phenomena such as distortion. This book can also serve as an excellent reference for researchers in the analog circuit design area and creators of CAD tools, as it provides a comprehensive overview and comparison of various approaches for analog circuit design automation and an extensive bibliography.

The world is essentially analog in nature, hence most electronic systems involve both analog and digital circuitry. As the number of transistors that can be integrated on a single integrated circuit (IC) substrate steadily increases over time, an ever increasing number of systems will be implemented with one, or a few, very complex ICs because of their lower production costs. As a result of these trends, there has been and will continue to be a steady increase in the number of mixed analog-digital ICs designed. One recent study of The Technology Research Group, Inc., reported that in 1990 approximately 60% of all CMOS and BiCMOS Application Specific IC (ASIC) designs currently incorporate analog circuit modules. Designing the analog portion of a mixed analog-digital IC is frequently the bottleneck that limits one of the most important economic aspects of ASIC manufacturing: time-to-market. Therefore, to decrease the required design time for the analog circuitry, more electrical engineers skilled in analog circuit design must be trained, and more sophisticated computer-aided analog design tools must be developed.

Symbolic analysis has the potential to offer insight to students and practitioners of analog circuit design. Too many circuit designers rely only on multiple numerical circuit simulations (e.g. SPICE) to provide insight into the behavior of a circuit - symbolic analysis can provide a much richer understanding of the behavior of a given analog circuit topology.

Recent successes in automating the design of basic analog building blocks such as opamps and comparators have almost uniformly employed an "equation-based" approach that substitutes analysis equations for simulation in order to predict the performance of an analog circuit. Unfortunately, these analysis equations are circuit topology specific and their development normally requires a great deal of time and effort on the part of expert analog circuit designers. The analog design problem is compounded by the fact that to respond efficiently to a broad range of applications usually requires that a wide variety of analog circuit topologies be available. As this book demonstrates, symbolic analysis can be used to automatically generate a significant fraction of the analysis equations needed to characterize a new circuit topology. Therefore, symbolic analysis is an important step forward in the development of CAD tools that aid in analog circuit design.

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PREFACE

Analog design automation is a field of increasing interest in industry. Analog circuits are demanded for interfacing as well as for many high-performance applications. At the same time, economical reasons drive ASICs into integration of complete mixed analog-digital systems on one chip. In both applications, however, the lack of analog CAD tools results in long design times and costly design errors. This forms a major obstacle for the realization of completely integrated mixed-signal systems, fully utilizing the potential of the technology. This explains the large industrial demand for analog design automation tools nowadays. Accordingly, many research activities are going on in this emerging field. Our group, the ESAT-MICAS division of the Katholieke Universiteit Leuven, Belgium, was one of the first to start with this research [DEG_84]. Then, since about 1985, we have noticed a strong increase worldwide in the analog CAD research, resulting now in the first prototype programs for the automated sizing and layout of (mostly lower-level) analog circuits.

Recently, we also have initiated some courses at our university about this analog design automation. However, when looking through the literature, we cannot find any general text which adequately describes the major aspects and the state of the art in the field, and which presents a broad overview and general comparison of the different approaches. This book was written to fill this gap. Historically, it has evolved from the PhD dissertation of the first author [GIE_90d], which describes the research carried out in the ESAT-MICAS group. As such, the book has two purposes. Firstly, it provides a general introduction to analog design automation, points out the major areas and discusses the major realizations and difficulties. Secondly, it focuses in more detail on one particular aspect: the symbolic simulation of analog integrated circuits, in which we have built up a strong experience. Symbolic simulation is indeed of increasing interest to analog designers for it provides both experienced and inexperienced designers with insight into the behavior of a circuit. This is especially true for more complicated characteristics such as the PSRR and the harmonic distortion at higher frequencies and in the presence of mismatches. In addition, as will be described in this book, symbolic analysis techniques can be used to create an open analog design system in which the inclusion of new circuit topologies is highly simplified.

The book addresses both practicing designers and CAD developers. It therefore tries to keep a good balance between general introduction, applications and examples on one hand, and still providing enough algorithmic details on the other hand. We believe that we have succeeded in this goal and that both groups of readers will find enough useful material in this book. At the same time, the book can also be used for advanced graduate courses in electrical engineering, more particular in CAD courses covering analog CAD.

Finally, we have to express our gratitude to all persons who contributed towards the realization of this book. In particular, we wish to thank prof. Hugo De Man and prof. Joos Vandewalle, who proofread the thesis and made many useful comments. We also want to thank Koen Swings, Herman Walscharts and Piet Wambacq, who cooperated on analog CAD research in our group. Finally, we are also grateful to the Belgian National Fund of Scientific Research and to the Philips Research Laboratories, Eindhoven, The Netherlands, for logistic support of our research.

This book is dedicated to Patricia and Hadewych.

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1 INTRODUCTION TO ANALOG DESIGN AUTOMATION

1.1. Introduction

Advances in VLSI technology nowadays allow the realization of complex integrated electronic circuits and systems. Application-specific integrated circuits (ASICs) are moving towards the integration of complete systems. These microsystems include both digital and analog parts on a single chip. At the same time, the use of computer-aided design (CAD) tools has become indispensible to reduce the total design time and cost. For digital VLSI, several methodologies and design tools have been developed in the past, resulting in complete digital silicon compilers [GAJ_88]. The first analog design tools and methodologies, however, are just now being introduced [DEG_87c, GIE_90a, HAR_89b, KOH_90, etc.]. Most of the design is still carried out manually by analog experts. These experts derive simplified circuit expressions by hand, iteratively use numerical circuit simulators by trial and error and handcraft the layout. This explains why the analog part - though usually small in area - takes more and more of the overall design time and cost of the present mixed analog-digital chips. This is especially true in high-performance applications, requiring for example high-frequency performance, high precision, low noise and/or low distortion. Besides, due to the hand design and hand layout, errors frequently occur in the small analog section, leading to several reruns. This delay cannot be tolerated in most applications where the time to market is critical for profit.

The reasons for this present lack of analog design automation tools can be found in the nature of analog design itself. Designing high-performance analog circuits is a very knowledge-intensive and complicated task because of the many (functional and parasitic) interactions and trade-offs to be managed. The quality (and often the functionality) of the resulting design strongly relies on the insight and expertise of the analog designer. This expert knowledge though is quite intuitive, poorly structured and far from generally accessible in a knowledge base. On the other hand, digital design allows for more modularity, design abstraction and hierarchy. All this makes the automation of the analog design process to a very complicated task. It also explains why analog CAD nowadays is far behind its digital counterpart and, to some large extent, also why integrated electronics nowadays is characterized by a high digitalization.

Nevertheless, analog circuits are still required in many applications. Signals in the real world are analog in nature and all interface circuitry (such as analog-to-digital and digital-to-analog converters) then necessarily contain some analog parts. In addition, analog still outperforms digital for various high-performance applications, such as high-frequency circuits for cellular mobile telephony or low-noise data-acquisition systems for sensor interfaces or particle/radiation detectors.

This inevitable need for analog circuits and the economics-driven tendency in ASIC design to integrate total mixed analog-digital systems onto a single chip has created the present large industrial demand for analog computer-aided design (CAD) and design automation (DA) tools. This book therefore presents the state of the art in this increasingly important field. The basic concepts are illustrated by discussion of a flexible methodology for the automated design of analog functional modules (or building blocks), such as operational amplifiers, comparators, filters or converters. The key aspect of this methodology is that it uses symbolic simulation and design equation manipulation as a solution to build an open analog synthesis system, in which the inclusion of new circuit schematics and design knowledge is highly simplified. This then provides the motivation for the detailed discussion of symbolic simulation which is the major topic of this book. Both the functional and the algorithmic aspects of the symbolic simulation of analog circuits are described in great detail. The present state of the art in this field, which is of increasingly growing interest to the design community, is also depicted. Finally, a design example shows how to use the symbolic analysis techniques to put new knowledge into the synthesis system and to apply this knowledge to size practical circuits.

At this point, it is important to emphasize that this text focuses on the automated design of integrated circuits and not on board-level design. Up till now, however, no real analog design tools are available at the level of an integrated (most likely mixed analog-digital) system. **This book therefore explains about analog symbolic simulation and its use in a methodology for the automated design of analog integrated modules (or functional blocks).**

The context of the book is explained in this first chapter which presents a general introduction into analog design automation. Firstly, in the next section 1.2, some important definitions with respect to analog design are presented. These definitions are extensively used throughout the remainder of this text. Section 1.3 briefly reviews the characteristics of analog design and points out the similarities and differences with digital design in order to provide some feeling for the complexity of the analog design automation task. The application domains for analog integrated circuits are then described in section 1.4. This results in the formulation of the goals of analog design automation. Section 1.5 then summarizes the different approaches or styles used to design analog circuits from firmware over semi-custom to full-custom design techniques. For most high-performance applications, however, the analog circuits must be tailored and tuned to the actual application. This leads to an analog silicon compiler which automates the design process from system specifications down to layout. A methodology outline for the synthesis of analog or mixed analog-digital integrated systems is then presented in section 1.6. It divides the overall design task in system design and module design. Section 1.6 also shortly describes the tools needed at the system level. The methodology for the synthesis of the analog modules will then be presented in the next chapter. Finally, section 1.7 gives the general outline of this book.

1.2. Definitions in analog design automation

As analog design automation is a rather new research field, with many different approaches and try-outs currently being published, there still is large confusion and disagreement about the applied terminology. Therefore, in this section, we provide some important definitions, which are extensively used throughout the remainder of this book. These definitions have to clarify the terminology to the reader and are stated generally enough to serve as a reference base for future publications in this field.

1.2.1. Definitions of analog design and analog design automation

The overall context of this book is the automation of the design of analog integrated circuits, both time-continuous and time-discrete (e.g. switched-capacitor). These analog circuits are usually part of larger, more complicated VLSI systems, which are integrated on a single chip and which most often also contain digital circuits. This leads us to the following general definition of analog design.

Definition: analog design
Design is the translation of a behavioral system description into an interconnection of circuit schematics (structure) and physical layout (silicon) over several levels of hierarchy.

For analog (sub)systems, the behavioral description describes what the (sub)system has to do (not how to do it!) and what the (sub)system's performance specifications are. Design is then the translation of this description into structure and layout such that the resulting silicon after processing performs the specified behavior. To give an idea of the kind of systems and complexity we are talking about, consider the following example of a transmitter chip for a full-duplex modem.

Example
Fig. 1.1 shows the simplified principle schematic for the use of a modem. The modem forms the interface between a digital data source/receiver, such as a personal computer, and the telephone line, and consists of a transmitter and a receiver part. The transmitter chip has to transform the digital bits at its input into the appropriate

analog waveforms to be sent over the telephone line according to some CITT norm with a given baud rate, accuracy, dynamic range, etc. (e.g. 9600 bits/s, 0.1% accuracy, less than -60 dB in-band noise and distortion). It contains functions such as modulation, filtering, line equalization and line driving. The receiver chip then performs the inverse operation. ♦

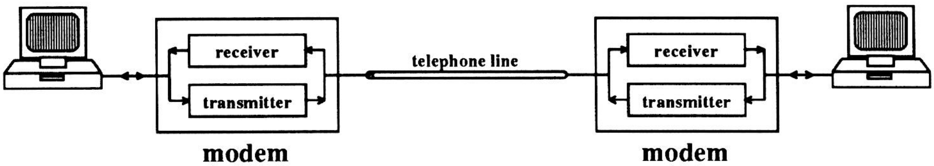

Fig. 1.1. Simplified principle schematic of the use of a modem to illustrate the complexity of present-day integrated-system designs.

With respect to automating analog design, the two following definitions are important.

Definition: computer-aided design (CAD)
Computer-aided design tools are computer programs, such as a simulator or a symbolic layout editor, which support the designer in some particular design task in order to make design easier.

Definition: design automation (DA)
Design automation tools are tools which automate some design tasks, such as automatic sizing and circuit optimization, and which are normally integrated into one global software system covering the whole design path from behavioral system description to layout.

The above distinction between CAD tools and DA tools, however, is somehow artificial, since many tools are used both interactively to support human designers and as part of an integrated design automation system. A typical example is a numerical simulator, such as SPICE [VLA_80b], which designers use to verify their circuit designs. The same simulator is used in an automated design system as well, but the automatic verification of say an operational amplifier requires many different simulations as well as other tests to be carried out.

After these definitions of analog design and analog design automation, the following subsection investigates the need for introducing hierarchy during the automated design of analog or mixed analog-digital systems.