Structured Electronic Design

A conceptual approach to amplifier design

- basic design theory
- design of application-specific amplifiers
    - in CMOS , Bipolar and BiCMOS technology
    - in PCA technology
- using MATLAB® and Spice
- summary of background knowledge

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Scientific theories deal with concepts, never with reality. All theoretical results are derived from certain axioms by deductive logic. In physical sciences the theories are so formulated as to correspond in some useful sense to the real world, whatever that may mean. However, this correspondence is approximate, and the physical justification of all theoretical conclusions is based on some form of inductive reasoning.

A. Papoulis [1]

[1] A. Papoulis, *Probability Random Variables and Stochastic Processes*. New York: McGraw-Hill, 1965

To Ernst Nordholt

Contents

Preface

Structured Electronic Design

This book deals with structured design of analog electronic circuits. The design method presented in this book is based on network theory, control theory, signal processing and physics.

The design of analog electronic circuits is considered by many people to be complex. This is mainly because designers have to deal with many relevant performance aspects that can be achieved in many different ways. In other words, there are many degrees of freedom for obtaining the desired performance of an electronic circuit. Theoretical concepts, circuit topologies, electronic devices, their operating conditions and the physical lay-out of a system, together constitute an enormous design space in which it is easy to get lost. For this reason, analog electronics is often regarded as an art rather than a solid discipline.

At first glance, there doesn't seem to be a straightforward way to design analog circuits and systems: experienced designers, intuitively, use all these degrees of freedom to modify and combine known solutions into new ones. However, intuition is knowledge the origin of which has become unclear. It cannot easily be shared with novices, and therefore, it cannot be a basis for the education of designers. The design of electronic circuits, however, can be shared and understood if it is presented in a structured way. This requires a clear formulation of design goals and strategies and a clear distinction between theoretical concepts and their physical implementations.

Instead of taking numerous existing solutions to known problems as a starting point, it is far more effective to start a new design with clear distinction between theoretical concepts and study how they can be implemented in such a way that the possibilities of the implementation technology are maximally exploited. Such an approach not only results in clear and reliable designs with predictable performance, but it also provides a basis for sharing and developing knowledge.

About the author

Anton Montagne (Leiden, 1953) received his master's degree in electrical engineering in 1984 at the Delft University of Technology. In 1983, he joined Philips Semiconductors in Nijmegen where he designed analog integrated circuits for audio and video applications. At Philips, he also set up training courses on analog electronics. In 1986, he cofounded the product development company Product Partners, where he carried out many analog designs in the field of instrumentation. In 1989, together with Catena Microelectronics, Delft University of Technology and the Institute of Microelectronics in Stuttgart, he cooperated in the development of an intensive training course, covering many topics of analog information processing. Since 1997, he has worked as an independent consultant, trainer and designer in the field of analog electronics. Over the past 30 years, he developed analog electronics for instrumentation and communication systems for the industry and carried out many training courses on analog electronics at, amongst others, Catena Microelectronics, Philips Semiconductors, Philips Medical Systems, NXP, Er-

icsson, Plessey, Texas Instruments, ASML, TNO, Bruco IC design, 3T, Carl Zeiss SMT and TMC.

Anton Montagne is the inventor and coinventor of patents in the fields of position sensors, imaging, charge coupled devices and high-stability crystal oscillators.

Since 2017 Anton Montagne is coaching students and giving guest lectures and masterclasses "Structured Analog Design" at the Delft University of Technology.

Acknowledgments

This book is based upon the workshops I have given and the design projects I have participated in during the past 30 years. The writing of such a book is never the result of a single person's effort. I am indebted to the many people I worked with, as well as to the many students I have taught. They taught and inspired me, and they have contributed in their very own way to its creation.

The design approach for analog electronic signal processing systems, as presented in this book, was suggested around 1987 by Dr. Ernst H. Nordholt. At that time, we were both cooperating in the education of circuit designers around Europe. Ernst suggested that any analog electronic signal processing system could be designed using a limited number of basic information-processing and reference functions. Due to the fundamental physical limitations of information processing, and due to technological limitations, the performance of these basic functions would deviate from that of their idealized function concepts. The manifestation of signal processing errors, however, could be reduced through application of a limited number of so-called error reduction techniques. Limitation of both the number of basic functions and the number of techniques that can be exploited for improvement of their performance-to-costs ratio, helps in solving day-to-day design problems in a structured way and facilitates the education in circuit design. Moreover, it can be a basis for a partial automation of the complex design process. In the subsequent years we started to develop design courses based on this approach. In our day-to-day design work, we applied and improved this design strategy. I am very grateful to have cooperated with Ernst and to be inspired by him. Without this cooperation, this book would not have been written.

Despite my interest in signal processing, during my education in analog electronics, I was primarily focussed on all kinds of aspects of circuit design. I am therefore very grateful to have cooperated with Dr. Huib Dane. His ability to explain complex topics from statistical signal processing helped me with my professional development and inspired me during the development of training courses for the design education of professionals.

It has been a pleasure and honor to work together with Catena Microelectronics in Delft. Since 1999 this company offered me the possibility to participate in the education of their novice analog IC designers, and in this way it contributed very much to the development of this material.

I am also very grateful to cooperate with The High-Tech Institute and with Hans Vink. Since 2010, they organize my training courses, allowing me to spend my time on teaching, serving my customers and writing this book.

A special word of gratitude is reserved for my friend Dr. Jan Deiman. I am indebted to him for the pleasant conditions he offered me in his guest house in Bali, which facilitated the writing of this course book in a most inspiring way.

I also want to thank Dr. Chris Verhoeven from the TU Delft for giving me the opportunity to coach students during the execution of their master thesis and for giving guest lectures and masterclasses at the TU Delft. Cooperation with him very much encouraged me in finishing this work. Thanks to him,

this book is now used for teaching "Structured Electronic Design" at the Delft University of Technology.

With Jeroen van Duivenbode, fellow at the TU Eindhoven, I had many fruitful discussions about this material. He inspired me very much in writing the MATLAB version of SLiCAP and contributed the name *servo function* to this work. I want to thank Jeroen for this contribution and our pleasant and inspiring cooperation.

Of the many students I have taught and professionals I have worked with, I would like to devote special words of gratitude to the ones who gave me most valuable feedback on this book. I am indebted to Lokesh Rajendran, Ugur Bagci, Hongming Yu, Ernesto Gonzalez Huaman, Georgios Sarris and Paul Nekeman for their eagerness in studying this material, for their useful comments and for the pleasant cooperation.

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1.4.1 What you will know after studying this book

1. You will know the characteristic properties of ideal(ized) amplifiers, and you will be able to derive the functional requirements for amplifiers from their application:
   (a) The input and output impedance
   (b) The source-to-load transfer
   (c) The port isolation
2. You will be able to characterize the non-ideal behavior of amplifiers, and you will know to derive performance requirements from the application description:
   (a) The small-signal noise behavior
   (b) The small-signal dynamic behavior
   (c) The instantaneous nonlinear behavior
   (d) The dynamic nonlinear behavior
   (e) The influence of temperature and ageing
3. You will come to understand other relevant design aspects of amplifiers, such as:
   (a) Environmental conditions
   (b) Cost factors
4. You will understand the operating principle of amplification
   (a) You will be able to evaluate the available power gain of a two-port
   (b) You will understand the concept of biasing
5. You will be understand the operation and modeling of active devices
   (a) BJT: Gummel-Poon model: relate the parameters of small-signal and noise model to device parameters, geometry and operating point
   (b) JFET: Shichman and Hodges model: relate the parameters of the small-signal and noise model to the device parameters, the geometry and the operating point
   (c) MOS: Shichman and Hodges model: relate the parameters of the small-signal and noise model to the device parameters, the geometry and the operating point
   (d) MOS: Meyer capacitance model: relate the small-signal capacitances to the device parameters, the geometry and the operating point
   (e) MOS: Ward-Dutton capacitance model: relate the small-signal capacitances to the device parameters, the geometry and the operating point
   (f) MOS: EKV model: relate the parameters of the small-signal and noise model to the device parameters, the geometry and the operating point
6. You can design a basic CS or CE stage amplifier stage
   (a) You can select a transistor or design the transistor geometry considering its noise contribution and source impedance
   (b) You can select a transistor or design its geometry considering its load and its required voltage and current drive capability
   (c) You can design the operating point and bias the basic stage
   (d) You can determine the source to load transfer, the input impedance and the output impedance of a CE and CS stage for resistive and/or R//C type source and load impedances
7. You can apply balancing techniques
   (a) You will understand the concepts of additive compensation and balancing

(b) You know the behavioral modifications resulting from anti-series connection
(c) You can apply this to evaluate the behavior of a differential pair
(d) You can bias a differential pair using only common-mode current sources
(e) You know the behavioral modifications resulting from complementary-parallel connection
(f) You can apply this to evaluate the behavior of a push-pull stage
(g) You can bias a push-pull stage using only common-mode voltage sources

8. You will be able to design low-noise and power efficient amplifier structures for arbitrary port impedance and port isolation requirements with the aid of feedback techniques, balancing techniques and isolation techniques:
   (a) Direct feedback and indirect (model-based) feedback
   (b) Nonenergic, passive and active feedback
   (c) Balancing and port isolation
9. You will be able to relate the properties of the components in the feedback network to important performance aspects and costs factors of the amplifier:
   (a) Inaccuracy
   (b) Noise
   (c) Nonlinearity
   (d) Power efficiency
10. You will be able to model individual performance aspects of voltage-feedback and current-feedback operational amplifiers:
   (a) Noise behavior
   (b) Gain and input and output impedances, including their dynamic behavior
   (c) Offset and bias quantities
   (d) PSRR and CMRR

   And you will become familiar with other relevant performance aspects, such as:

   (a) Input voltage range
   (b) Output voltage and current drive capability
   (c) Voltage slew rate
11. You will know in which way and to what extent the equivalent input noise sources of an operational amplifier affect the noise performance of the negative feedback amplifier.
12. You will be able to apply the asymptotic gain negative feedback model to derive budgets for properties of the operational amplifiers and the passive components of the negative feedback amplifier
13. You will be able to design the dynamic behavior of a negative feedback amplifier with the aid of frequency compensation techniques:
   (a) Phantom-zero compensation
   (b) Pole-splitting by means of capacitive feedback
   (c) Pole-splitting by means of pole-zero canceling
   (d) Resistive broadbanding
   (e) Bandwidth reduction
   (f) Nested loops

And you will qualitatively know in which way these high-frequency compensation techniques interact with other performance aspects:

(a) Noise behavior
(b) Accuracy
(c) Distortion
(d) Overdrive recovery

14. You will know in which way and to what extent the temperature behavior of an operational amplifier affects the operating point of a negative feedback amplifier, and you will be able to derive requirements for the temperature behavior of the operational amplifier from the performance requirements of its application.

    You will be able to apply techniques to reduce this influence:

    (a) AC coupling
    (b) Negative-feedback biasing
    (c) Auto-zero techniques

15. You can apply negative feedback to a CS or CE stage

    (a) You can design single-transistor feedback stages
    (b) You will be able to relate the properties of local feedback stages to those of the CE or CS stage by considering the behavioral modifications resulting from application of negative feedback
    (c) You will understand that the CD and CC stage can be considered as non-inverting, unity-gain, negative feedback voltage amplifiers
    (d) You will understand that the CG and CB stage can be considered as non-inverting, unity-gain, negative feedback current amplifiers
    (e) You will understand that the current mirror can be considered as an inverting indirect feedback current amplifier
    (f) You can apply balancing techniques to local feedback amplifier stages
    (g) You can design cascode stages and the CC-CB and CD-CG cascade stages

16. You can design multiple-stage negative feedback amplifiers

    (a) You will be able to define the type of input stage, its geometry and operating point on ground of its noise performance
    (b) You will be able to define the type of output stage, its geometry and operating point on ground of its current and voltage drive capability
    (c) You will be able to define the number of stages on grounds of the static accuracy, the low-pass and high-pass cut-off frequencies and the distortion of the amplifier
    (d) You will know how to combine multiple stages in a controller
    (e) You will be able to apply common-mode feedback biasing techniques and optimize the biasing concept of a multiple-stage controller

17. You can design the bias sources

    (a) You will be able to define the specifications for the bias sources considering their influence on the noise performance, the dynamic performance, the static accuracy and the temperature stability
    (b) You will be able to design the bias sources

1.4.2 Contents part 1: design of application-specific amplifiers

The design method presented in this book has been introduced by Nordholt[11] and further developed at the TU-Delft by Verhoeven, van Staveren, Monna, Kouwenhoven and Yildiz[12]. This book is an updated and extended version based upon course material for post-graduate education in structured electronic design developed by the author. The first part of this book presents the design method for amplifiers.

[11] E. H. Nordholt, *Design of High-Performance Negative Feedback Amplifiers*, 1st ed. Amsterdam - Oxford - New York: Elsevier Scientific Publishing Company, 1983, ISBN: 0-444-42140-8

[12] C.J.M. Verhoeven, A. van Staveren, G.L.E. Monna, M.H.L. Kouwenhoven and E. Yildiz, *Structured Electronic Design*. Boston - Dordrecht - London: Kluwer Academic Publishers, 2003, ISBN: 1-4020-7590-1

Application, modeling and characterization of amplifiers

In Chapter 2, we will briefly mention some amplifier applications and discuss the function of amplification. We will give a formal definition of the function of amplification and of an amplifier. We will discuss its ideal behavior as well as the nature of information processing errors of practical amplifiers and introduce some important performance aspects.

In this chapter, we will also discuss the different physical appearances of amplifiers. The physical structure of an amplifier is the result of trade-offs between performance and costs made during the design process. Cost factors for amplifiers can be numerous, and examples of some commonly important cost factors will be given. In order to take design decisions at various stages of the design, it is convenient to have some kind of design figure of merit at one's disposal. Such a figure of merit is the most compact representation of the performance-to-cost ratio of an amplifier.

After this brief introduction of amplifiers and the amplification function, we will focus on the modeling and characterization of amplifiers and present models that describe their ideal or *conceptual* behavior. As a result of the fundamental physical limitations of noise speed and power, and imperfect implementation of the principle of amplification, the behavior of practical amplifiers will deviate from this ideal behavior. Generic, as well as application-specific description methods for information processing errors that are the result of these limitations, will be given.

Principle of amplification

In Chapter 3, we will study the principle of amplification as it is applied in electronic amplifiers. We will show that amplification can be obtained through proper interconnection of electrical power sources and passive, nonlinear, electronic devices. Examples of such devices are MOS transistors, bipolar transistors and vacuum tubes. It will be shown that these devices, when used in combination with power sources, can provide an available power gain larger than unity; which is a distinguishing property of amplifiers. For this reason these devices are often called *active devices*. In practice, the required power sources need to be derived from a limited number of supply voltages. This process is known as *biasing*, and this chapter will be concluded with the introduction of the *conceptually biased* amplifier stage. Such a stage consists of a single amplifying device and four independent sources that establish a quiescent operating point which is, at a given temperature and for the given device, independent of the stage's drive and termination resistance.

Modeling of semiconductor devices

Knowledge of the operation and modeling of modern semiconductor devices is indispensable when designing analog electronic circuits. However, an in-depth treatment of semiconductor physics and modeling techniques

is beyond the scope of this book. Chapter 4 briefly describes the construction, operation and modeling of BJTs, JFETs and MOS transistors. The main goal is to provide a basic understanding of the construction and operation of the devices as a basis for modeling the device's performance aspects during various stages of the design. The Gummel-Poon[13] model for BJTs and the Shichman and Hodges[14] model for JFETs will be presented and more simple models for hand calculations will be derived from these simulation models. An overview of models for MOS transistors will be given. The basic Shichman and Hodges model, the Meyer[15] capacitance model and the Ward and Dutton[16] capacitance model will be discussed in more detail. The latter capacitance model is used in the small-signal representation of the BSIM3[17] simulation model, which is often used in SPICE. Special attention will be paid to the EKV model[18]. With this model, the small-signal model parameters can easily be written as a function of the device geometry, the drain current and the drain-source voltage. This can be done with continuous expressions that are valid from weak inversion to strong inversion, including short-channel effects. Having such expressions makes it possible to design the small-signal dynamic transfer and the noise performance independent from the biasing circuitry. SLiCAP has built-in small-signal models for CMOS18 devices of which the parameters are written as functions of the channel width and length, the operation current and voltage and a limited number of EKV model parameters for CMOS18 technologies. This facilitates the design of CMOS circuits based upon the use of the inversion coefficient or the transconductance efficiency, as described by Binkley[19].

[13] H. K. Gummel and H. C. Poon, "An integral charge control model of bipolar transistors," *Bell Syst. Tech. J.*, vol. 49, no. 5, pp. 827–852, May-June 1970

[14] H. Shichman and D. Hodges, "Modeling and simulation of insulated-gate field-effect transistor switching circuits," *IEEE J. Solid-State Circuits*, vol. 3, no. 3, pp. 285–289, September 1968

[15] J. Meyer, "MOS models and circuit simulation," *RCA Review*, vol. 32, pp. 42–63, 1971

[16] D. Ward and R. Dutton, "A Charge-Oriented Model for MOS Transistor Capacitances," *IEEE Solid-state Circuits*, vol. sc-13, no. 5, pp. 703–708, October 1978

[17] Cheng, Y. et al., *BSIM3 Version 3.0 Manual*, University of California/Berkeley, Electronics Research Laboratory, 1995

[18] Christian C. Enz, and Eric A. Vittoz, *Charge-based MOS Transistor Modeling*. John Wiley & Sons Inc., 2006, ISBN: 978-0-470-85541-6

[19] Binkley, David M., *Tradeoffs and Optimization in Analog CMOS Design*. John Wiley & Sons Inc., 1997, ISBN: 978-0-470-03136-0

Basic amplification with CS stage

In Chapter 5, we will study the performance limitations and the design considerations for the common-source (CS) stage, which can be considered as the basic MOS transistor amplifier stage. At a later stage we will show that other MOS amplifier stages can be derived from the CS stage through application of error reduction techniques such as compensation or negative feedback.

The common-emitter (CE) stage can be regarded as the basic BJT amplifier stage. Performance limitations and design considerations for this stage will be added in a future version of this book.

For these basic amplifier stages, we will discuss the way in which their performance can be altered by design. We will see that the designer does not have many degrees of freedom to optimize the performance of such elementary amplifier stages. The operating conditions, the fabrication technology and the geometry or the device type are the only design variables at the disposal of the designer to optimize their performance-to-costs ratio. Moreover, the various performance aspects of single-transistor amplifiers cannot be designed independently[20] and compromises between performance aspects often need to be made. In particular cases, however, the performance of such amplifiers will be adequate at acceptable costs.

[20] This is called "orthogonal design".

Application of balancing techniques: differential pair and push-pull stages

If the desired performance-to-cost ratio of an amplifier cannot be achieved with basic amplifier stages, error reduction techniques can be applied for its improvement. In Chapter 6, we will study the application of balancing techniques and their impact on the performance-to-cost ratio of an amplifier. Two particular applications of balancing techniques will be discussed in more detail: anti-series connection of equal devices and parallel connection of complementary devices.[21]

[21] Shortly: anti-series connection and complementary-parallel connection.

Anti-series connection of basic amplifier stages provides a four-terminal stage with an odd transfer characteristic and improved isolation between the input port and the output port. The behavioral modifications that are

a result of series, complementary-series and anti-series connection will be investigated. It will be shown that the properties of the MOS and the BJT differential pair can easily be related to those of the CS and the CE stage, by considering such behavioral modifications, respectively. We will see that, when applied in a truly balanced environment, the small-signal transfer and the noise performance of the differential pair can equal those of the basic CE or CS stage at the costs of four times the area and four times the operating current. As a result of the anti-series connection, offset voltages are canceled and the bias sources change from differential-mode to common-mode. The large-signal transfer of these anti-series stages has an odd characteristic with current saturation.

Complementary-parallel connection of amplifier stages provides push-pull stages of which the current drive (source and sink) capability exceeds their quiescent current. Such stages can be used as high-efficiency amplifier stages. The CMOS inverter can be regarded as a complementary parallel stage. These stages can also be used to split an input signal into a push and a pull current; a popular technique in current-feedback operational amplifiers. The behavioral modifications that are the result of parallel, anti-parallel and complementary-parallel connected amplifiers or amplifier stages will be investigated. It will be shown that the properties of the MOS and the BJT push-pull stage can easily be related to those of the CS and the CE stage, respectively.

Although balancing techniques can be used to improve the performance-to-cost ratio of an amplifier or amplifier stage, their application is not beneficial to all performance aspects. The (gain) accuracy, the dynamic transfer and their temperature dependencies of balanced stages equal those of their unbalanced version. Hence, improvement of those aspects requires the application of techniques that have better error reduction capabilities.

Design of negative feedback amplifier configurations

Negative feedback is considered a powerful *error reduction technique*. The characteristics of negative feedback amplifiers are fixed with the aid of reference networks or *feedback networks*. These networks are built with nonenergic or passive components of which the electrical properties are more accurately fixed than those of active devices. A feedback network generates an accurate copy of the source signal from the load signal. The key of negative feedback is that generation of such a copy can be done with the aid of accurate attenuators: networks of which the available power can be equal or less than unity. A high-gain *controller* or *error amplifier*, that comprises one or more amplifier stages, is used to minimize the difference between the source signal and its copy. By doing so, the properties of the amplifier are predominantly determined by those of the feedback networks. The error amplifier provides the available power gain, but does not define the source-to-load transfer.

The design of application-specific negative feedback amplifiers is discussed in Chapter 7. In this chapter, we will learn how to design negative feedback amplifier concepts for specific source and load requirements. We will see that the amplifier types, introduced in Chapter 2 can all be synthesized by combining voltage and/or current sensing at the load with voltage and/or current comparison at the signal source. During the conceptual design of negative feedback amplifiers, nullors will be used as ideal *controllers*. The nullor is a network element with an infinite available power gain and no speed limitation. At a later stage of the design, these nullors need to be replaced with error amplifiers that will be implemented with amplifier stages or with operational amplifiers.

In this chapter, will show that all amplifier types, introduced in Chapter 2, can be designed using so-called nonenergic feedback elements. Nonenergic feedback elements exhibit no power dissipation and no energy storage.

Moreover, two of them, the ideal transformer and gyrator behave as natural two-ports. Unfortunately these two network elements do not have nonenergic implementations. The use of more practical passive feedback elements limits the number of negative feedback amplifiers that can be implemented and other feedback techniques need to be considered. *Active feedback*, balancing and *indirect feedback* will be introduced as techniques to design the negative feedback amplifier types that cannot be designed using passive feedback networks only.

The operational amplifier as controller in feedback amplifiers

Operational amplifiers are intended as controllers for negative feedback amplifiers. With their high voltage gain, high common-mode and differential-mode input impedance, high common-mode rejection ratio and low output impedance early types were versatile building blocks for negative feedback voltage amplifiers. Nowadays, the behavior of current-feedback and rail-to-rail output operational amplifiers strongly deviates from this behavior, which complicates their application.

Chapter 8 deals with the modeling of operational amplifiers. Aside from modeling all behavioral aspects with so-called macro models, attention will be paid to the modeling of individual performance aspects, which is considered to be more useful for deriving budgets for different performance limitations and for taking early-stage design decisions.

Another aspect that is limiting the application of operational amplifiers as universal controller is the fact that their output port, which is usually a high-efficiency push-pull output stage, has a split return path connected to both supply terminals. This imposes difficulties to the implementation of grounded current sensing techniques and limits the number of amplifier configurations that can be realized using solely operational amplifiers as controllers. This limitation as well as various ways to deal with it will also be discussed in this chapter.

Introduction to biasing

An introduction to the biasing of negative feedback amplifiers will be presented in Chapter 9. In this book, we will advocate a strict separation between the design of the signal transfer and the design of the biasing of amplifiers and amplifier stages. At an earlier stage we have already shown that the principle of amplification requires the application of properly interconnected power sources and passive nonlinear electronic devices. Biasing refers to the derivation of all these power sources from the power supply source(s).

Biasing of (cascaded) amplifier stages will only be presented after we have discussed the design of the signal processing properties of an amplifier. The reason for this is that biasing of stages and of interconnected stages only needs to be done if the signal processing by the conceptually biased stages is adequate. Biasing of a configuration of which the signal processing is not according to the requirements is meaningless and regarded as a lost of valuable design time. In this introductory chapter, we will only discuss the consequences of errors that are a result of imperfect biasing of controllers. Such errors occur due to device tolerances and temperature deviations. These errors are usually modeled with the aid of equivalent-input offset and bias currents and voltages. Statistical description methods will be given and error reduction techniques to minimize their effects, will be discussed. Examples will be given for negative feedback amplifiers equipped with operational amplifiers, but the theory is not limited to these cases. Compensation, *AC coupling* and *negative feedback biasing* will be introduced as methods for the reduction of biasing errors. The latter two can only be applied if frequency components of the signal differ from those of temperature changes. These techniques es-

tablish a high-pass character of the signal transfer and design criteria for the high-pass cut-off frequency will be given. Proper high-pass filter characteristic can be established using frequency compensation techniques.

Modeling of negative feedback circuits

After we are able to design all kinds of application-specific amplifier configurations with nullors as controllers, we need to find specifications for practical controllers. To this end, we need a way of feedback modeling that facilitates a two-step design:

1. Design of the ideal transfer which is fixed by the feedback network
2. Design of an acceptable deviation from this ideal behavior caused by the nonideal controller.

The widely used negative feedback model introduced by Black[22] provides accurate performance analysis of negative feedback amplifiers only under limited conditions. It does not account for the so-called direct transfer from the source to the load, and it assumes unilateral transfer and ideal sensing at the load and comparison at the source. As a result of these limitations, it is suited for the analysis of negative-feedback systems rather than for the two-step design of negative-feedback amplifier circuits. The feedback theory introduced by Bode[23] in 1945 and described by Chen[24] gives a method to analyze the stability of a feedback loop. Middlebrook[25] introduced the double injection theory to measure the loop gain. However, all these models focus on stability analysis, rather than on a two-step design of a well-defined dynamic behavior of the feedback amplifier.

The only feedback model that facilitates the two-step design is the *asymptotic gain model* as described by Rosenstark[26]. This model shows that the design of a negative feedback amplifier can be performed in the two subsequent and independent steps that have been mentioned above. Moreover, the source-to-load transfer obtained from this model equals the one found from network analysis. The asymptotic gain model will be discussed in Chapter 10.

[22] H. S. Black, "Stabilized feed-back amplifiers," *Electrical Engineering*, vol. 53, no. 1, pp. 114–120, January 1934

[23] H. Bode, *Network Analysis and Feedback Amplifier Design*. New York: Van Nostrand, 1945

[24] W. Chen, *Active Network Analysis*. Singapore: World Scientific Publishing Co. Pte. Ltd., 1991, ISBN: 9971-50-912-1

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[26] S. Rosenstark, "A Simplified Method of Feedback Amplifier Analysis," *Transactions on education*, vol. E-17, no. 4, pp. 192–198, November 1974

Setting up controller performance specifications

With the aid of the asymptotic gain model, we are able to relate performance aspects of the controller to those of the negative feedback amplifier. This enables use to derive budgets for the performance aspects of the controller, which is a minimum requirement for the two-step design approach described above. In Chapter 11 this will be done for the static accuracy, the nonlinearity and the bandwidth of the amplifier. We will find that:

1. The static error of a feedback amplifier sets a requirement for the controller's contribution to the static or DC loop gain.
2. The low-pass cut-off frequency of a feedback amplifier sets a requirement for the contribution of the controller to the gain-poles product of the dominant poles of the loop gain.
3. The static differential-gain error of the negative-feedback amplifier sets a requirement for the contribution of the controller to the static differential error to gain ratio of the DC loop gain.

Design conclusions for other performance aspects such as the high-pass cut-off frequency will also be derived. The derivation of budgets for noise and power losses of the controller has already been dealt with in Chapter 7.

In this chapter, we will also introduce techniques for the evaluation of the stability of negative feedback amplifiers. Techniques known from control theory, such as the Nyquist stability criterion, the Routh array analysis method

and the root-locus technique will be summarized and elucidated with examples. Frequency compensation techniques for establishing the desired filter characteristics will be discussed at a later stage.

Frequency compensation

Frequency compensation techniques for establishing proper high-pass or low-pass filter characteristics will be extensively discussed in Chapter 12. Concepts and strategies for frequency compensation will be introduced and implementation examples will be given. Special attention will be paid to the impact that frequency compensation may have on other performance aspects such as bandwidth, linearity, overdrive recovery and noise. It will be shown that frequency compensation with the aid of phantom zeros is the most powerful method because it has the lowest interaction with other performance aspects. Implementation of both active and passive phantom zeros will be discussed and illustrated with examples. Other techniques such as pole-splitting techniques, resistive broadbanding and nested control will be discussed as well.

Design of local feedback stages

Amplifier stages that use a single, unbalanced or balanced CE or CS stage as controller are called *local feedback stages*. Local feedback stages can be used as single-stage amplifiers, or as stages in negative feedback amplifiers. In Chapter 13, we will discuss the design of local feedback stages. We will show that the well-known CD stage or *source follower* as well as its bipolar version, known as the *emitter follower* or CC stage, can be considered as unity-gain voltage amplifiers that exploit nonenergic feedback and that have the CS or CE stage as controller, respectively. Similarly, the common-gate (CG) or the common-base (CB) stage can be considered as nonenergic negative feedback current followers. The advantage of such an description method is evident. If those stages are feedback versions of the basic CS or CE stages, then the loop gain, which can be regarded as a measure for the amount of negative feedback, indicates the extend to which their behavior deviates from that of the CE or CS stage. It will then become clear that commonly known properties, such as the low output impedance of the CC stage, are only true if the stage is driven from an impedance that establishes a relatively large loop gain. If such a stage is driven from a current source, accurate input voltage comparison cannot be performed, the loop gain will be low and the output impedance does not differ from that of a CS stage. In addition, since the CS and CE stages are nonenergic negative feedback amplifiers, they inherit the properties of nonenergic feedback amplifiers. Without further analysis it then becomes clear that the equivalent input noise sources of a CD or the CC stage equal those of the CS or the CE stage of which they are constituted, respectively. Similar things can be said about their power efficiency.

Aside from the design of CD, CC, CG and CB stages, the design of other basic local feedback stages, such as the series, the shunt stage and some dual-loop local feedback stages, as well as the application of balancing techniques will be discussed as well. A separate section will be devoted to the so-called *cascode* stage. This stage consists of a cascade connection of the CS and CG stage (MOS version) or a CE and a CB stage (BJT version). Its interesting properties makes it an ideal inverting amplifier stage in multiple-stage negative feedback amplifiers that ensures low interaction between stages. It will be shown that the CD-CG cascode and its bipolar version, the CC-CB cascode, can similarly be regarded as basic non-inverting amplifier stages.

Design of multiple-stage negative feedback amplifiers

High-gain amplifiers may be constructed from a cascade connection of amplifier stages. High-performance negative feedback amplifiers, however, require controllers that comprise multiple amplifier stages. The CS or the CE stage, the cascode stages, the local feedback stages as well as the balanced versions of all these stages may be candidates for amplifier stages in such a multiple-stage controller. In Chapter 14 we will discuss the design of multiple-stage controllers. We will show that by selecting a CS or CE (cascode) stage, or their balanced version, the controller will have the best possible noise performance if the noise performance of this stage is optimized for the given source impedance and feedback network(s). Similarly, by selecting a CE or CS (cascode) stage or its balanced version the contribution to the differential error to gain ratio of the loop gain will be as low as possible.

Design criteria for the number of stages and the preferred type(s) for intermediate stages will also be given. It is important to have a rough estimate for the number of stages at an early stage of the design. If the number of stages is more that two or three, frequency compensation may become difficult and one may consider to construct the amplifier from a number of multiple-stage feedback amplifiers. Nested feedback techniques will also be discussed and illustrated with examples.

The motivation of the type of stages inside the controller may also be driven from practical limitations such as the power supply voltage and the complexity of the biasing. In modern analog CMOS design, the low power supply voltage may put a serious constraint to the architecture of the controller. Since biasing considerations may seriously influence the design of amplifiers, they need to be accounted for during all stages of the design process. However, this does not change the design approach for amplifiers. If the signal processing performance of an optimally designed signal path does not leave room for any degradation possibly resulting from biasing, the detailed design of the bias sources is of no use. Hence, the design of the noise performance, the bandwidth, the linearity and the frequency compensation should always be done before implementing the bias sources.

Biasing

The biasing and design of the biasing elements is performed in four steps:

1. Simplification of the biasing scheme.

   During the design of the *signal path* of the amplifier we use *conceptually biased* amplifier stages as introduced in Chapter 3. Such stages use four bias sources. During this design step, this biasing scheme will be simplified and the remaining bias sources will be replaced with the power supply and nonlinear resistive elements that exhibit a voltage or current source character. This step will be elucidated in Chapter 15.

2. Setting up specifications for the resulting bias sources.

   After a biasing scheme has been developed, the performance requirements for the bias sources need to be derived from error budgets for noise, bandwidth and nonlinearity. This step will also be elucidated in Chapter 15.

3. Design of the bias sources.

   The design of bias sources will be added to a future edition of this book.

4. Application of error reduction techniques for minimization of biasing errors resulting from device tolerances and temperature changes.

   This has been discussed in Chapter 9.

1.4.3 Contents part 2: background knowledge

Part 4 summarizes background knowledge and places it in the context of the design method.

1. Selected topics from signal, data and information modeling can be found in Chapter 17.
2. Selected topics from system modeling can be found in Chapter 18.
3. Selected topics from network theory are included in Chapter 19.

   This summary requires knowledge of linear algebra. Four topics are usually not found in other books, but helpful for a better understanding amplifier design:

   (a) The time constant matrix and its eigenvalues

   (b) Estimation of poles and zeros of a transfer function by network inspection

   (c) Decomposition of balanced circuits into differential-mode and common-mode equivalent circuits

   (d) Two-port conditions
4. Physical mechanisms, modeling and characterization of noise in electronic circuits is summarized in Chapter 20.

1.4.4 How to use this book

This book is organized in such a way that it can be used in three *subsequent* courses:[27]

[27] Each course requires the knowledge of its preceeding course.

1. An introduction course

   The introduction course summarizes the background knowledge that is required to study the BSc and MSc level courses. It comprises deterministic and random modeling of signals and systems, network theory, basic knowledge about noise in electronic circuits and hands-on experience with MATLAB, SLiCAP and SPICE.
2. A BSc level course

   At the end of the BSc level course the students are able to specify and design an application-specific negative feedback amplifier using an operational amplifier as controller. This course is intended for board designers who need to design signal conditioning amplifiers between sensors and analog-to-digital converters and amplifiers that convert output signals from digital-to-analog converters to actuators. A chapter about the design of class D amplifiers will be added in future versions of this book.
3. An MSc level course

At the end of the MSc level course, the students are able to specify and design an application-specific amplifier using in Bipolar, BiCMOS or CMOS technology. This course is intended for board designers who want to construct amplifiers using both operational amplifiers and discrete transistors, and for IC designers. Table 1.2 gives an overview of the chapters for each class.

Chapter	Description	Courses Intro	BSc	MSc
1	Introduction to structured electronic design		✓	
2	Amplifiers: application, classification, modeling & characterization		✓	
3	Principle of amplification			✓
4	Modeling of active devices			✓
5	Basic amplification: CS stage			✓
6	Balancing techniques			✓
7	Design of negative feedback amplifier configurations		✓	
8	Application and modeling of operational amplifiers		✓	
9	Introduction to biasing		✓	
10	Modeling of negative feedback circuits		✓	
11	Deriving controller requirements from amplifier specifications		✓	
12	Frequency compensation		✓	
13	Design of local feedback amplifier stages			✓
14	Design of multiple-stage negative-feedback amplifiers			✓
15	Design of controller biasing concepts			✓
17	Signal modeling (selected topics)	✓		
18	System modeling (selected topics)	✓		
19	Network theory (selected topics)	✓		
20	Noise in electronic systems (selected topics)	✓		

Table 1.2: Subsequent course programs: Introduction, BSc level and MSc level.

Structured Electronic Design

This book deals with structured design of analog electronic circuits. It is intended for BSc and MSc students Analog Electronics and used at the Delft University of Technology. The design of analog electronic circuits is considered by many people to be complex. This is mainly because designers have to deal with many relevant performance aspects that can be achieved in many different ways. In other words, there are many degrees of freedom for obtaining the desired performance-to-cost ratio of an electronic circuit. Experienced designers intuitively use all these degrees of freedom to modify and combine known solutions into new ones. However, intuition is knowledge the origin of which has become unclear. It cannot easily be shared with novices, and therefore, it cannot be a basis for the education of designers.
The design of electronic circuits can be shared and understood if it is presented in a structured way. This requires a clear formulation of design goals and strategies and a a clear distinction between theoretical concepts and their physical implementations. Such an approach not only results in clear and reliable designs with predictable performance, but it also provides a basis for sharing and developing knowledge.

Anton Montagne (Leiden, The Netherlands, 1953) received his master's degree in 1984 at the Delft University of Technology. In 1983, he joined Philips Semiconductors in Nijmegen where he designed analog integrated circuits for audio and video applications. At Philips, he also developed training courses on analog electronics. In 1989, together with Catena Microelectronics, the Delft University of Technology and the Institute of Microelectronics in Stuttgart, he cooperated in the development of an intensive training course, covering many topics of analog circuit design. Since 1997, he works as an independent consultant, trainer and designer in the field of analog circuit design. Over the past 35 years, he developed analog electronics for instrumentation and communication systems and carried out many training courses on analog electronics. Since 2016 Anton Montagne is coaching students and giving guest lectures and masterclasses "Structured Analog Design" at the Delft University of Technology.

Supporting material

SLiCAP is a free Symbolic Linear Circuit Analysis Program based on MATLAB®
and its symbolic math toolbox, developed by the author.
It is intended for setting up and solving design equations for analog electronic circuits and it accepts SPICE-like netlists, that can be generated with LTSPICE®.

For SLiCAP, exersises and design examples, please visit:
https://www.analog-electronics.eu

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