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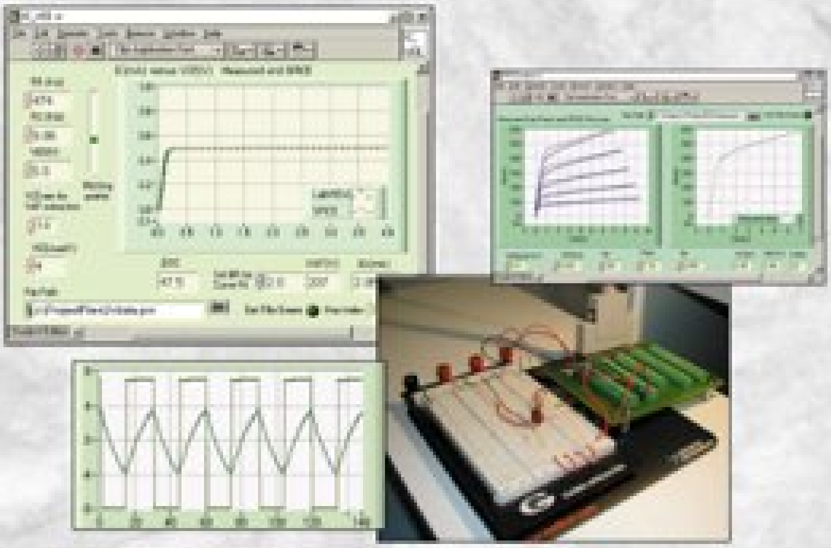

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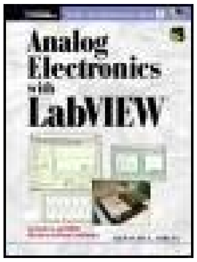
KENNETH L. ASHLEY



Analog Electronics with LabVIEW®
By Kenneth L. Ashley
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Publisher: **Prentice Hall**
Pub Date: **October 04, 2002**
Print ISBN-10: **0-13-047065-1**
Print ISBN-13: **978-0-13-047065-2**
Pages: **432**

Table of Contents | Examples

Copyright

Library of Congress Cataloging-in-Publication Data

Ashley, Kenneth L.
Analog electronics with LabVIEW / Kenneth L. Ashley.
p. cm. — (National Instruments virtual instrumentation series)
Includes bibliographical references and index.
ISBN 0-13-047065-1 (pbk. : alk. paper)
1. Electronics. 2. Electronic circuits—Computer-aided design. 3. LabVIEW. I. Title. II. Series.
TK7816 .A84 2002
621.381--dc21 2002072656

Editorial/production supervision: Patti Guerrieri

Cover design director: Jerry Votta

Cover designer: Nina Scuderi

Manufacturing manager: Alexis R. Heydt-Long

Publisher: Bernard Goodwin

Editorial assistant: Michelle Vincenti

Marketing manager: Dan DePasquale

Publishing as Prentice Hall PTR

Upper Saddle River, NJ 07458

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

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Preface

This book presents a study of analog electronics as a stand-alone course or as a course to be augmented by one of the many complete undergraduate textbooks on the subject. Theory and closely coupled laboratory projects, which are based entirely on computer-based data acquisition, follow in a sequential format. All analytical device characterization formulations are based exactly on SPICE.

In addition to traditional curricula in electrical engineering and electronics technology, the course is suitable for the practicing engineer in industry. For the engineer with a general undergraduate electronics background, for example, the course of study can provide an upgrade in basic analog electronics. Under these or similar circumstances, it can be taken as self-paced or with minimum supervision.

Two course sequences are possible, depending on the emphasis desired:

- For a course that stresses MOSFET characterization and circuits, beginning with Unit 1 and following the sequence is recommended. A brief review of relevant circuit analysis and the most rudimentary basics of electronics are presented initially, with associated projects. The projects include an introduction to LabVIEW programming along with the measurements of basic circuits. The programming aspects are directly relevant to the thrust of the course; they emphasize the measurement of analog electronics circuits. The student is thus provided with a basic understanding of LabVIEW concepts used throughout the projects.
- If, on the other hand, interest is directed more toward LabVIEW and computer data acquisition, device characterization, and circuit simulation, the appropriate beginning sequence is Units A through C. The associated projects are Project A, Projects B, Project C1, and Project C2. Project A is a programming and measurement exercise that emphasizes and explores the use of LabVIEW DAQ software, the discrete nature of analog-to-digital and digital-to-analog conversions, LabVIEW-based voltmeters with autoranging, ac voltmeters, and simultaneous sending and receiving of waveforms initiated with a function generator. This is followed with projects on transistors and transistor circuits, which are based on the bipolar junction transistor. Although the BJT is losing ground as the most important transistor in electronics (compared to the MOSFET), its inherently more complex behavior provides for a rich array of circuit simulation formulations and design challenges. The projects include the mix of NPN and PNP devices in a single amplifier. The transistors recommended are the complementary pair NTE 186 (2N6288) and NTE 187 (2N62xx). The transistors are rated at 3 A and are therefore almost indestructible. At the much lower current levels of the projects, device heating is negligible, which is important, as all measurements assume that the circuit is at room temperature. Also, highlevel model effects are avoided, whereas low-level effects abound.

With both approaches, all the measurement LabVIEW programs are provided. Many of the extraordinary features provided by LabVIEW are included in the programs. The programs therefore may serve additionally as a tutorial in advanced aspects of LabVIEW. The basics of operational amplifiers and their applications are treated in two units and two projects.

The book format consists of one or more units of background material for each laboratory project. A given set of theoretical units and the associated project have a related Mathcad problems file (Problemxx.mcd) and Mathcad exercise file (ExerciseXX.mcd), relating to the theory and project, respectively. The files are also in a pdf format (ProblemXX.pdf, ExerciseXX.pdf). A Mathcad file (ProjectXX.mcd) for evaluating the results of the projects is included with each project. Accompanying each Mathcad project file are SPICE simulator files based on PSPICE. The SPICE models for the simulations use, in each case, the parameters for the devices obtained in laboratory projects. Since the Mathcad projects use the exact SPICE formulations, the results from Mathcad and SPICE are identical in the case of the use of basic simulation levels.

Samples of all of the projects have been completed and are included. These provide for either demonstrations or simulated results without actually running the programs with circuits. The measured data are stored in LabVIEW graphics and can be extracted to obtain data files in the same manner as actually making the measurements. In some cases, the simultaneous taking of data, plotting and curve fitting is simulated. Units 13 and 14 are theoretical only but each has Mathcad problems on the topic of these respective units.

Special features of the lab experience are as follows:

- The lab projects are based entirely on computer data acquisition using LabVIEW and a National Instruments data acquisition card (DAQ) in the computer for interfacing with the circuit board.
- Each device category has an associated project for evaluating SPICE parameters in which device model parameters are obtained. Subsequent amplifier projects use the parameters in performance assessment.
- No external instrumentation is required. The function generator, voltmeters, and oscilloscopes are virtual and provided by LabVIEW and a DAQ card in the computer. The projects on the current-mirror load common-source amplifier and the operational amplifier require an external power supply.
- Circuits are constructed on a special circuit board. The board is connected to the computer DAQ card through a National Instruments shielded 68-pin cable. The circuit board allows expedient, error-free construction of the circuits, as connector strips for the respective output and input channels and ground are available directly on the board.

Topics included in this course treat many of the most relevant aspects of basic modern analog electronics without straying into peripheral areas. The course essentially streamlines the study of analog electronics. There is not a unit on, for example, feedback per se, but most basic types of feedback are addressed at some point. The role that the device plays in frequency response is omitted. This is consistent with the fact that to a large extent, the intension is that theory and measurements can be connected.

Students of electrical engineering or electronics engineering of today have a vast array of subjects to attempt to master; it is not reasonable to expect them to labor through a classical extensive study of the subject of analog electronics, although some basic knowledge should be required. Specialization can come at a later stage, if desired.

As mentioned, many LabVIEW features are utilized in the projects. To some extent, the goal of demonstrating the extensive array of the capabilities of LabVIEW influences the design of the various projects. This includes sending voltages (including waveforms), receiving voltages (including autoscaling), scanning, graphics, reading data files, writing data files, computations such as extraction of harmonic content of a signal, assembling data in a composite form, along with a host of array manipulation processes and data curve fitting.

References

CMOS analog circuits including applications (advanced):

Allen P., and R. Holberg. CMOS Analog Circuit Design, 1st Ed. Holt, Reinhart and Winston, New York, 1986.

Allen P., and R. Holberg. CMOS Analog Circuit Design, 2nd Ed. Oxford University Press, New York, 2002.

Extensive coverage of analog circuits, which includes a comprehensive discussion of feedback and frequency response (advanced):

Gray, P., P. Hurst, S. Lewis, and R. Meyer. Analysis and Design of Analog Integrated Circuits, 4th Ed. Wiley, New York, 2001.

CMOS analog circuits (with some BJT circuits) with extensive coverage of applications (advanced):

Johns D., and K. Martin. Analog Integrated Circuit Design. Wiley, New York, 1997.

Presentation of the physical and empirical association between semiconductor devices and their models, MOSFETs and BJTs:

Massobrio G., and P. Antognetti. Semiconductor Device Modeling with SPICE. McGraw-Hill, New York, 1993.

General textbook on electronics (basic):

Millman J., and A. Grabel. Microelectronics, 2nd Ed. McGraw-Hill, New York, 1987.

Physical description of semiconductor devices:

Muller R., and T. Kamins. Device Electronics for Integrated Circuits, 2nd Ed. Wiley, New York, 1986.

General textbook on electronics (basic):

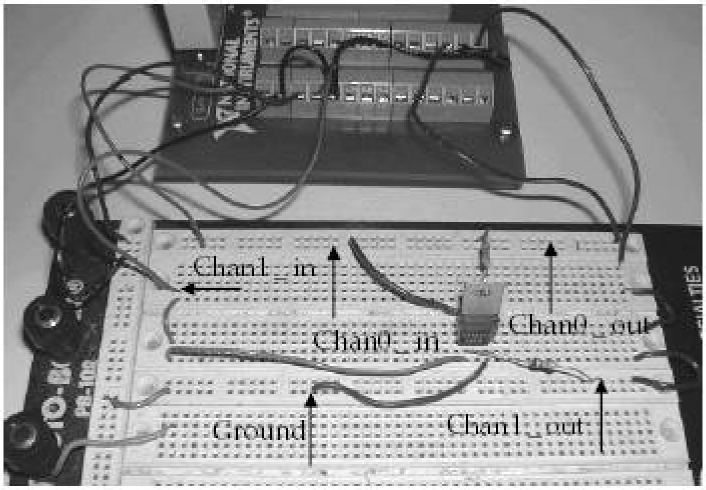
Sedra, A.S., and K.C. Smith. Microelectronic Circuits, 4th Ed. Oxford University Press, Oxford, 1998.

General treatment of analog circuits including applications (basic to advanced):

Soclof, S. Design and Applications of Analog Integrated Circuits, Prentice Hall, Upper Saddle River, N.J., 1991.

Hardware and Software Requirements

Circuit connections to the DAQ require a cable and a facility for connecting to individual pins. An efficient system is based on a National Instruments Connector Block (CB-68LP) and a basic circuit board as shown here.



Connections to the circuit board from the connector block are made one time. The two resistors of the circuit are connected to output channels 0 and 1, respecively. Thus, for example, Chan0_out, as noted, is dedicated to the top strip on the circuit board. The bottom top strip is associated with Chan0_in, and so forth.

All of the project LabVIEW files are programmed to be consistent with the plus bus (rail), Chan0_out, and the minus bus (rail), Chan1_out. Therefore, it is intuitively helpful to have the output channels physically connected in this fashion.

The project examples included with the book were conducted on a special circuit box that connects directly to the shielded 68-pin connector. This bypasses the connector block. A shielded cable is strongly recommended in any event. Many of the projects involve the measurement of relatively low voltage signals.

In addition, the lab projects included in the book require the following (or equivalent):

- Pentium PC (or equivalent).
- National Instruments DAQ PCI-MIO-16E-4.
- LabVIEW 6.0i Student Edition or LabVIEW 6.0i or later version.
- Mathcad Professional 2001 or later version.
- National Instruments Shielded 68-pin Cable.

Semiconductor Devices and Components (Recommended)

6-Transistor (3-gate) CMOS Array – CD4007[*]

CMOS Opamp – SGS-Thomson TS271[**]

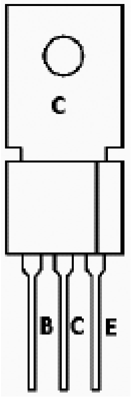
NPN - Medium-Power NPN BJT – NTE186[***]

PNP - Medium-Power PNP BJT – NTE187[****]

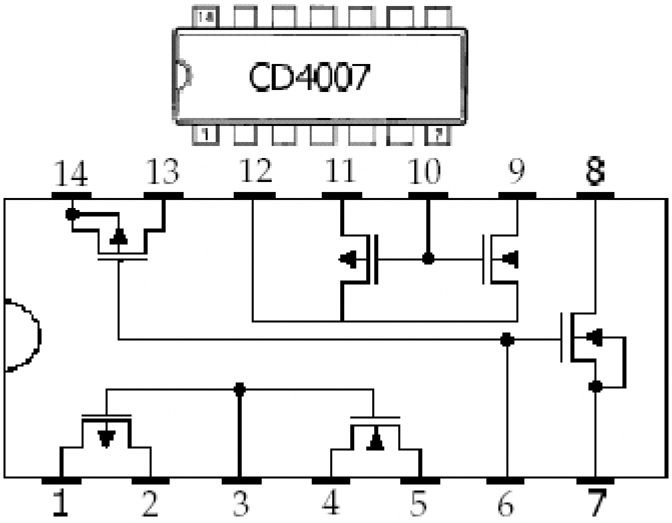
Capacitors

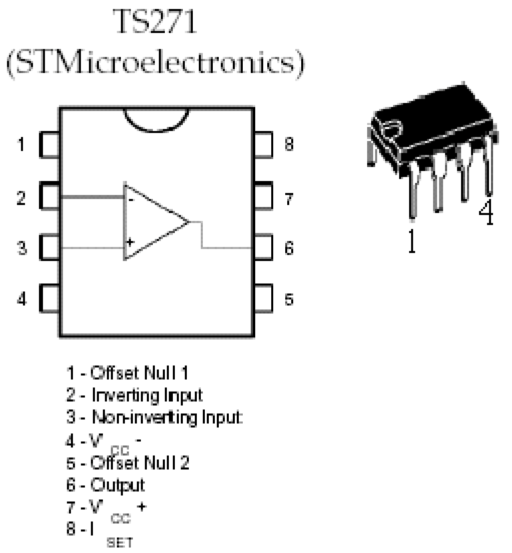
Resistors

NTE186
NPN



CD4007





Connector Block Pins (AT-MIO-E or PCI-E Series)

Chan0_out	Pin 21	Chan0_in	Pin 68	Gnd – Pin 34
Chan1_out	Pin 22	Chan1_in	Pin 33	Gnd – Pin 66
Output Channel Gnd	Pin 55	Chan2_in	Pin 65 - plus	Pin 31 - minus
Input Channel Gnd	Pin 67	Input and output grounds are connected.		
+5 V Supply Voltage	Pin 14			

[*] The CD4007 chip contains three CMOS inverters or three PMOS and three NMOS transistors. Since they are inverters, NMOS and PMOS pairs have Hardware and Software Requirements internally connected gates. However, this does not prevent having a sufficient number of the individual transistors in the analog laboratory projects.

[**] The TS271 is chosen as it has simple external resistor biasing. Thus, students can gain an intuitive feel for the relation between the characteristics of the CMOS opamp and bias current with straightforward exchange of bias resistors. In the case of a group of students, for example, each student can select a different bias current, such that all of the results can be assembled to plot the opamp characteristics, such as gain and frequency response versus bias current. In addition, the circuitry of the opamp is straightforward and may be understood within the scope of the book. Extensive experience in our laboratory with devices has demonstrated that this opamp can withstand considerable abuse without failing even though it is a MOSFET chip. It is however, strongly advised that the power supply never be turned on until the power-supply pins, input pins and output pin are connected in the circuit.

[***] The NTE186 is a rugged npn BJT that is investigated at current levels well below the normal operating range. Heating of the device is thus minimized and for the

measurements, it can be assumed to be at room temperature. Also, various high-level injection effects, which render the basic SPICE parameter set invalid, are avoided.

[****] Complementary paired with the NTE186.

LabVIEW VI Libraries and Project and Problem Folders and Files

Each project has a folder, which contains the LabVIEW library plus any related Mathcad files for that project. Mathcad files include those for the exercises and results analysis (project files). The project folder also has circuit-simulator subfolders for Schematics and Capture.

A LabVIEW VI library is included for each project. These are LabVIEW files with extension llb. The LabVIEW files within a library have extension vi. A given project library will contain most of the LabVIEW virtual instruments for that project. The additional VIs are in the User.lib folder, which is in the LabVIEW application folder. The User.lib folder contains all the LabVIEW libraries and other LabVIEW files that are not included in the individual project libraries. The folders are Read_Rite, Dat_File, FunctGen, and Subvi.

Each problem folder has a set of problems associated with the unit with the same number. Each problem set has a pdf file (Word), a Mathcad solutions file, a pdf version on the Mathcad file and a circuit-simulator subfolder.

There are also pdf files for the composite of the problems (WordProb.pdf), Mathcad problem-solution files (MathcadProb.pdf), project exercises (MathcadExer.pdf), project Schematics exercises (SchematicsExer.pdf), and project Capture exercise (CaptureExer.pdf).

The procedure for installation of the libraries from the CD onto the computer is described in the Readme files.

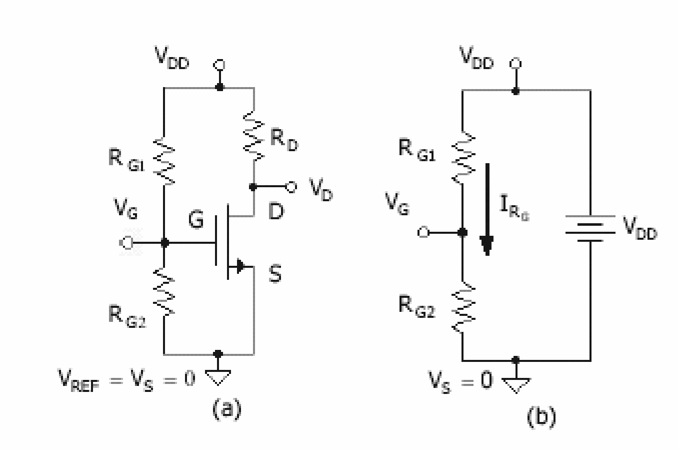
Unit 1. Elementary Circuit Analysis for Analog Electronics

In this unit, we present a basic review of segments of circuit analysis which recur repeatedly in electronic circuits. A firm grasp on these is essential to developing an understanding of the analysis and design of basic electronic circuits. A transistor is included in the circuits to show a correlation between circuit analysis and electronics. Only steady-state circuit situations are considered here. This includes dc and sinusoidal. Some transient analysis is considered in connection with operational amplifier applications with capacitors.

1.1. Resistor Voltage Divider and MOSFET DC Gate Voltage

Figure 1.1(a) shows a basic NMOS amplifier stage. This is the dc (or bias) portion of the circuit, which excludes the signal part. The terminals of the transistor are designed G (gate), D (drain) and S (source). The design calls for a dc voltage V_G, with respect to the zero reference voltage, which is obtained by dividing the supply voltage V_{DD} between bias resistors R_{G1} and R_{G2}. Since the gate terminal has zero current, the voltage, V_G, at the gate can be assessed with the resistor network separated from the circuit as in Fig. 1.1(b). The goal is to relate the node voltage V_G to the values of R_{G1} and R_{G2} and V_{DD}. The result is the basic resistor voltage-divider relation.

Figure 1.1. (a) Dc circuit for the basic NMOS amplifier. (b) Circuit for determining the gate voltage, V_G.



Note that since V_{DD} is given with respect to the reference zero volts, the V_{DD} designation at the top node is equivalent to the supply voltage, also referred to as V_{DD}. The current I_{RG} is

Equation 1.1

$$I_{R_G} = \frac{V_{DD}}{R_{G1} + R_{G2}}$$

The voltage across the resistor R_{G2} is V_G (since V_G is with respect to the zero reference) and this is

Equation 1.2

$$V_G = V_{GS} = V_{R_{G2}} = I_G R_{G2} = \frac{R_{G2}}{R_{G1}+R_{G2}} V_{DD}$$

It can be concluded that the gate voltage is the value of R_{G2} divided by the sum of the two gate-bias resistors.

1.2. Output Circuit and DC Drain Voltage

For the dc circuit in Fig. 1.1, the drain voltage is determined from

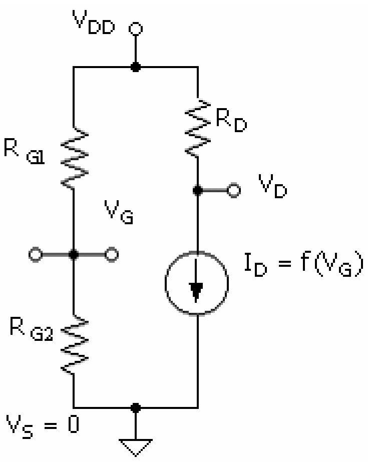
Equation 1.3

As illustrated in Fig. 1.2, for the purpose of a solution to (1.3), the transistor can be replaced by a current source as shown in Fig. 1.2. Drain current I_D is a function of V_G; that is, $I_D = f(V_G)$. Thus, in a design, the value of V_G determines the value of V_D. I_D is related to V_G according to

Equation 1.4

$$V_D = V_{DD} - I_D R_D$$

Figure 1.2. Circuit for illustrating the determination of the drain voltage, V_D.

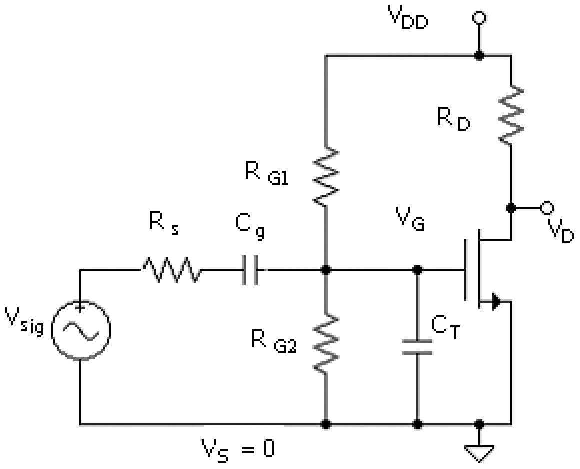


This relation and parameters V_{tno} and k_n are discussed in Unit 2.

1.3. Frequency Response of the Amplifier Stage

Capacitance associated with amplifiers may cause the output to fall off at low and high frequencies. This effect is referred to as the *frequency response* of the amplifier. A generalization of possible capacitance is shown in the circuit of Fig. 1.3. Capacitor C_g is an external capacitance, which is included to attach a sine-wave signal source, consisting of V_{sig} (e.g., sine-wave peak) and R_s, without interrupting the dc bias circuitry. Similarly, there could be an output capacitance, which couples the signal output voltage to an external load resistor. Capacitor C_T is associated with the internal capacitance of the transistor. It may be regarded as an equivalent effective capacitance that represents all of the capacitance of the transistor.

Figure 1.3. Amplifier including possible circuit capacitance.



Generally, the frequency range over which a given capacitor is effective is much different for the two capacitors. Capacitor C_g affects the output at low frequencies, while the effect of C_T is realized at the high end of the spectrum. Thus, their effects can be considered separately if, as assumed in the following, the high and low ends of the response function are widely separated in frequency, that is, by several orders of magnitude.

Figure 1.4 shows the signal circuits for the two cases of low (a) and high (b) frequencies. As discussed in Unit 2, the signal circuit is formulated from the complete circuit by setting all dc voltages to zero. This includes, for this amplifier, the power supply and dc voltage across the capacitor C_g. Note that the transistor plays no apparent role in the frequency response in the equivalent circuit. It is, of course, critically important in dictating the value of C_T.

Figure 1.4. Circuits for low (a) and high (b) frequencies.