low·noise electronic design

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Low-Noise Electronic Design

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PREFACE

This book is intended for use by practicing engineers and by students of electronics. It can be used for self-study or in an organized classroom situation as a quarter or semester course or short course. A knowledge of electric circuit analysis, the principles of electronic circuits, and mathematics through an introduction to the calculus is assumed.

The approach used in this text is practice or design oriented. The material is not a study of noise, but rather of methods to deal with the everpresent noise in electronic systems.

Electrical noise is a problem in industrial, military, and consumer equipment design. The designer must be cognizant not only of the sources of noise, but also of the methods of noise reduction that are available to him. He will strive toward an optimum design. In this quest he must use all available and applicable tools. One such tool is the digital computer. In Chapter 8, computer-aided design of low-noise systems is considered. Another powerful tool is the laboratory. Chapter 14 discusses noise measurement methods and techniques.

The book is divided into two parts. Part I, Chapters 1 through 6, is primarily concerned with noise mechanisms, noise models, and the analysis of noisy circuits and systems. Part II, starting with Chapter 7, focuses on the design of low-noise circuits and systems. Many design examples are given.

The treatment may be considered to be oriented toward low- and mid-frequency applications. The examples given are applicable to the instrumentation, audio, and control fields. Whereas there are few direct references to high-frequency communications, much of the material presented can be applied to that area of activity.

A summary of the most important points and topics is included at the end of each chapter. It is hoped that these summaries will be useful to the reader who does not have the time to start from the beginning. For the student who is encountering this material for the first time, the summaries serve to accentuate the more important aspects of the presentation. A controlled amount of repetition is included in the text, and many cross-references are made to other sections of the book for prerequisite or additional material. Problems are included at the end of each chapter and answers to the problems are given following Appendix IV.

This book is an outgrowth of our research, development, design, and teaching experiences. Special recognition is given to Honeywell, Incorporated, for cooperation and support.

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SYMBOLS

Symbol	*Definition*	*First used or Defined in Equation*
A_i	Current gain	10–1
A_v	Voltage gain	1–5
A_{vo}	Midband voltage gain	1–5
BW	Bandwidth	2–27
C	Capacitance	1–16
C	Correlation coefficient	1–8
C	Coulombs, electric charge	1–12
$C_{b'c}$, $C_{b'e}$	Hybrid-π transistor model capacitances	4–4
C_p	Shunt capacitance	3–10
CMV	Common-mode voltage	Ch. 11
C_π	Base-emitter capacitance ($C_{b'e}$)	12–66
E, E_1, E_2 etc.	rms noise voltages	1–7
E_A, E_B, . . . , E_F	rms noise voltage of resistors R_A, R_B, . . . , R_F	12–3
E_b	Thermal noise of $r_{bb'}$	4–10
E_f	rms noise voltage with $1/f$ *power* spectrum	1–10
E_n	rms equivalent noise voltage generator	2–7
E_{nb}	rms narrowband noise voltage	2–24
E_{ni}	Equivalent input noise	2–1
E_{no}	rms noise at output of network	1–16
E_{ns}	rms noise of source resistance	3–3
E_{nT}	Total equivalent input noise voltage	12–73
E_{n1}, E_{n2}, E_{n3}	Noise voltage generators of stages 1, 2, 3	12–11
E_s	rms noise of source resistance R_s	4–10
E_{sh}	Shot noise voltage of a diode	14–19

Symbol	*Definition*	*First used or Defined in Equation*
E_t	rms thermal noise voltage of a resistance or conductance	1–3a
E_{wb}	rms wide band noise voltage	2–24
F	Noise factor	2–9
f	Frequency	1–10
1/f	(read "one-over-f") noise source whose power level is inversely proportional to frequency	1–9
f_{hfe}	Beta-cutoff frequency $=f_\beta$	4–5
f_h	High frequency 3 dB point	1–9
f_l	Lower frequency 3 dB point	1–9
f_L	Lower noise-corner frequency Hybrid-π transistor model	4–8
F_{opt}	Optimum noise factor	2–14
f_T	Gain-bandwidth product	4–5
G_a	Available power gain	2–17
g_m	Transconductance	4–2
G_o	Peak power gain	1–4
I_B	dc base current	4–14
I_b	Shot noise of base current	4–10
I_{bb}	Burst noise current generator	5–1
I_C	dc collector current	4–14
I_c	Shot noise of collector current	4–10
I_{CBO}	Collector-base leakage current with emitter open	8–3
I_{DC}	Direct current	1–12
I_E	dc emitter current	1–13
I_{ex}	Excess 1/f noise current	3–11
I_f	1/f noise current in Hybrid-π model	4–8
I_n	rms equivalent noise current generator	2–7
I_{no}	rms noise current out of a network	4–10
I_{nT}	Total equivalent input noise current	12–74
I_{n1}, I_{n2}, I_{n3}	Noise current generators of stages 1, 2, 3	12–11
I_0	Saturated value of reverse diode current	1–13
I_{sh}	rms shot noise current	1–12
I_t	rms thermal noise current of a resistance	1–7
k	Boltzmann's constant 1.38×10^{-23} W-sec/°K	1–1
K, K_1, K_2 etc.	Arbitrary constants	1–9
K_t	System transfer voltage gain	2–3
K_{tc}	Transfer voltage gain of cascaded stages	12–16

Symbol	*Definition*	*First used or Defined in Equation*
N_f	Noise power of signal source with 1/f frequency distribution	1–9
N_i	Input noise power	2–10
N_o	Output noise power	2–10
N_o	Available noise power	2–17
N_t	Available noise power	1–1
NEP	Noise equivalent power	3–14
NF	Noise figure	2–11
NI	Noise index in μV/V/Decade	9–2
Q	Quality factor of a tuned circuit	8–9
q	Electronic charge 6.02×10^{-19} coulomb	1–12
R	Resistance, real part of Z	1–2
r_b	Base resistance for 1/f noise	4–9
r_b	Base resistance in T-equivalent transistor model	4–30
$r_{bb'}$, $r_{b'e}$, r_{ce}, $r_{b'c}$	Hybrid-π transistor model resistances	4–3
R_C	Collector resistor	10–4
R_E	Emitter resistor	10–10
R_e	Absolute value of emitter impedance	10–3
r_e	Schockley emitter resistance, emitter resistance in common-base T model	1–15
R_i	Input resistance	10–6
R_L	Load resistance	10–1
R_n	Equivalent noise resistance	2–15
R_o	Optimum source resistance	2–13
R_p	Parallel resistor	3–5
R_s	Resistance of signal source	2–2
r_x	Base resistance ($r_{bb'}$)	12–1
r_0	Output resistance ($\simeq r_{ce}$)	12–1
r_π	Base-emitter resistance ($r_{b'e}$)	12–1
S/N	Signal-to-noise ratio	3–3
S_i	Input signal power	2–10
$S(f)$	Noise spectral density	1–6
S_o	Output signal power	2–10
T	Temperature in degrees Kelvin (°K)	1–1
T	Transformer turns ratio	7–3
T_s	Equivalent noise temperature	2–16
V_{BE}	Potential applied between base and emitter	1–13
V_{CC}	dc collector supply voltage	10–10

Symbol	*Definition*	*First used or Defined in Equation*
V_m	Peak value of ac signal	11–1
V_o	Signal voltage at the output of a network	2–3
V_s	Signal voltage at the source	2–3
V_1, V_2, etc.	Signal voltages	1–7
X_C	Reactance of a capacitance	1–16
Z_i	Input impedance	2–2
Z_s	Source impedance	7–5
α	Transistor current gain, *T*-equivalent circuit	4–32
β_o	Short-circuit current gain	4–1
Δf	Noise bandwidth	1–4
γ	Exponent in 1/f noise model	4–8
Λ	q/kT	4–2
ω	$2\pi f$	1–16

CONTENTS

INTRODUCTION

Sensors, detectors, and transducers are basic to the instrumentation and control fields. They are the "fingers" and "eyes" that reach out and measure. They must translate the characteristics of the physical world into electrical signals. We process and measure these signals and interpret them to be the reactions taking place in a chemical plant, the environment of an orbiting satellite, or the odor of an onion. An engineering problem often associated with sensing systems is the level of electrical noise generated in the sensor and in the electronic system.

In recent years, new high-resolution sensors and high-performance systems have been developed. All sensors have a basic or limiting noise level. The system designer must interface the sensor with electronic circuitry that contributes a minimum of additional noise. To raise the signal level an amplifier must be designed to complement the sensor. Achieving optimum system performance is a primary consideration in this book.

The following chapters answer several important questions. When we are given a sensor with specific impedance, signal and noise characteristics, how can we design or select an amplifier for minimum noise contribution, and concurrently maximize the signal-to-noise ratio of the system? If we have a sensor-amplifier system complete with known signal and noise, we must determine the major noise source; is it sensor, amplifier, or pickup noise? Are we maximizing the signal? Is improvement possible?

This book is a study of low-noise electronic design, not a treatise on noise as a physical phenomenon. It is divided into two parts. The first six chapters are concerned with *Noise Mechanisms and Models*; Part II, Chapters 7 through 13, deals with *Design Techniques and Examples*. The final chapter is a treatment of noise measurement methods.

In Part I we are concerned with the sources of noise; these sources include sensors and other devices, amplifiers, and associated circuitry. Noise models are developed for circuit components and for subsystems, and the relations between noise sources, biasing circuits, and operating point selection are examined. Analysis uses the noise models of system components to predict the expected minimum noise performance.

To realize the noise performance predicted from a system analysis many design decisions are required. Part II examines all the areas of possible noise problems, including component noise, noise in power supplies, shielding, biasing circuit noise, feedback, multistage configurations, as well as the associated gain, stability, and frequency response behavior. Design examples are given of noiseless biasing, low-noise power supplies, amplifier pairs, and complete low-noise systems.

SYMBOLS

To designate electric circuit quantities the system of symbols used in this book conforms to standard practice in the semiconductor field.*

1. *Dc values of quantities are indicated by capital letters with capital subscripts* (I_B, V_{CE}). *Direct supply voltages have repeated subscripts* (V_{BB}, V_{CC}).
2. *Rms values of quantities are indicated by capital letters with lowercase subscripts* (I_c, V_{ce}).
3. *Maximum or peak values are designated as rms values but bear an additional final subscript* m (V_{cm}, V_{bem}).
4. *The time-varying components of voltages and currents are designated by lowercase letters with lowercase subscripts* (i_e, v_{ce}).
5. *Instantaneous total values are represented by lowercase letters with capital subscripts* (i_C, v_{CE}).

An example may be helpful. A time-varying waveform.

$$i_b = I_{bm} \sin \omega t$$

when added to a dc wave of average value I_B, is represented by its total value

$$i_B = I_B + i_b$$

So a complete expression is

$$i_B = I_B + I_{bm} \sin \omega t$$

The rms value of the time-varying portion of this composite wave is I_b.

The symbols for rms, peak, and instantaneous quantities (2, 3, and 4) apply only to the time-varying portion of a waveform. No symbols are proposed for the rms and peak values of a wave containing both time-varying and dc components.

PREFIXES

The following prefixes are used to indicate decimal multiples or submultiples of units:

* "IEEE Standard Letter Symbols for Semiconductor Devices," *IEEE Trans. Electron Devices*, ED-11, No. 8, August 1964.