bruce-fm.qxd 10/3/00 12:21 PM Page i

Biomedical Signal Processing and Signal Modeling

bruce-fm.qxd 10/3/00 12:21 PM Page ii

bruce-fm.qxd 10/3/00 12:21 PM Page iii

Biomedical Signal Processing and Signal Modeling

Eugene N. Bruce
University of Kentucky

A Wiley-Interscience Publication
JOHN WILEY & SONS, INC.
New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

bruce-fm.qxd 10/3/00 12:21 PM Page iv

This book is printed on acid-free paper. ∞

Copyright © 2001 by John Wiley & Sons, Inc. All rights reserved.

Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4744. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158-0012, (212) 850-6011, fax (212) 850-6008, E-Mail: PERMREQ @ WILEY.COM.

For ordering and customer service, call 1-800-CALL-WILEY.

Library of Congress Cataloging-in-Publication Data.

Bruce, Eugene N.
Biomedical signal processing and signal modeling / Eugene N. Bruce
p. cm. — (Wiley series in telecommunications and signal processing)
Includes bibliographical references and index.
ISBN 0-471-34540-7 (cloth : alk. paper)
1. Signal processing. 2. Biomedical engineering. I. Title. II. Series.

R857.S47 B78 2001
610′.28—dc21

00-039851

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

bruce-fm.qxd 10/3/00 12:21 PM Page v

Contents

bruce-fm.qxd 10/3/00 12:21 PM Page vii

bruce-fm.qxd 10/3/00 12:21 PM Page viii

bruce-fm.qxd 10/3/00 12:21 PM Page ix

bruce-fm.qxd 10/3/00 12:21 PM Page x

PREFACE

There are two general rationales for performing signal processing: (1) for the acquisition and processing of signals to extract a priori desired information; and (2) for interpreting the nature of a physical process based either on observation of a signal or on observation of how the process alters the characteristics of a signal. The goal of this book is to assist the reader to develop specific skills related to these two rationales. First, it is hoped that the reader will enhance skills for quantifying and (if necessary) compensating for the effects of measuring devices and noise on a signal being measured. Second, the reader should develop skills for identifying and separating desired and unwanted components of a signal. Third, the reader should enhance skills aimed at uncovering the nature of phenomena responsible for generating the signal based on the identification and interpretation of an appropriate model for the signal. Fourth, the reader should understand how to relate the properties of a physical system to the differences in characteristics between a signal used to excite (or probe) the system and the measured response of the system.

A core text in biomedical signal processing must present both the relationships among different theoretical measures of signals and an understanding of the information these measures provide regarding the sources of signals and the behaviors of their sources in response to natural or imposed perturbations. A useful didactic framework to achieve these goals is one in which signal processing is portrayed as the development and manipulation of a model of the signal. In this framework the "model" becomes a surrogate for the signal source and it is natural to ask to what degree this model is reasonable given one's knowledge of the signal source and the intended application. Thus this framework provides a smooth transition from theory to application. Furthermore, the topic of filtering, in which the model of the output signal is derived from the input signal model and the properties of the filter, is included naturally. This signal modeling perspective is the framework within which this book is developed.

Because biomedical engineering involves the application of engineering methods for the improvement of human health, the signals encountered by biomedical engineers are typically derived from biological processes. Often such signals are not well represented by the simple deterministic signals favored for illustrating the basic principles of signal processing. Real-world biomedical signals usually include large stochastic components; they also may be fractal or chaotic. Often we are too ignorant of the properties of their sources to know a priori what the character of the signal will be. Therefore the biomedical engineering student must first recognize the range of possible signal types and be able to determine the most appropriate type of analysis for the signal of interest. Unfortunately, this choice is not always clear. Of special importance is knowing not only the basic ways of processing each type of signal, but also recognizing indications that the selected analysis method may have been inappropriate. Even when the method is correct (or, more likely, when there is no indication that it is *not* correct), the best way to process the signal will depend on the user's objectives.

By presenting signal processing as the process of developing and manipulating a model of the signal, this book attacks the problems discussed above using an integrated framework. Three issues—(1) choosing a class of signal model, (2) selecting a specific form of the model, and (3) evaluating indicators of adequacy of the model—are emphasized in the book. The question of what information a given class of signal models can provide naturally lends itself to a format in which each chapter discusses one class of models and how to manipulate them. It is then straightforward to discuss the criteria for choosing a "better" model, although such a discussion will encompass the models from previous chapters as well. The question of which general class of model to utilize is more difficult to discuss because of its breadth, although this question is raised in each chapter in which a new class is introduced. Part of the motivation for the interactive exercise that starts each chapter is to demonstrate the limitations to the knowledge that the reader has hopefully accumulated to that point and motivate the introduction of a new way to look at signals. Nonetheless, this question of choosing an appropriate class of signal model for a specific application needs repeated emphasis by an instructor, who should raise the question in lectures and discussions.

This book has been developed completely from a biomedical engineering perspective, in the hope of conveying to the reader that measuring, manipulating, and interpreting signals is fundamental to every practitioner of biomedical engineering, and that the concepts being presented are fundamental tools needed by all biomedical engineers. With the breadth of the field of biomedical engineering and the wide availability of computer software for signal processing, the nuances and detailed mathematical variations of algorithms are less relevant to many practitioners than is the relationship between theoretical concepts and applications. This book strives to emphasize the latter issue by presenting many examples, sometimes at the expense of omitting certain details that are common in signal processing books—for example, the various algorithmic implementations of the Fast Fourier Transform (FFT). These details are readily available from other sources. Otherwise, I have attempted to present the material in a mathematically rigorous fashion.

Although the book is self-contained, the `MATLAB` files that implement many of the examples provide repetition of the material, enhanced visual feedback, more detailed explanations of the biomedical applications, and opportunities for exploration of related topics. These files are available from a web site of the publisher and from the author's anonymous ftp site (ondine.image.uky.edu, or 128.163.176.10). The optimal way to master the material in the textbook involves reading the text while sitting in front of a computer on which MATLAB is running. Hopefully the reader will call forth the MATLAB-based demonstrations and exercises as they are encountered in the text and experiment with them. Also the value of the examples of real-world biomedical signals that are available as .mat files is greatest if they are utilized at the time they are encountered in the text. The reader is encouraged to examine these signals when the text discusses them.

Unless stated otherwise, whenever the text uses a phrase like "we can show," it is assumed that the motivated reader will be capable of supplying the missing steps of a procedure. Exceptions are those situations in which the material is beyond the scope of the book, and these situations are noted.

Of the approximately twenty exercises at the end of each chapter, about half are intended primarily to reinforce the theoretical concepts through repetition. The remainder attempt to relate the theory to biomedical applications. My intent is to emphasize the process of translating qualitative descriptions of biomedical phenomena into quantitative descriptions amenable to the analyses developed in the book. Given this emphasis and the exigencies of the book format, the discussions of the applications often are simplistic. For those who wish for more detailed and insightful discussions of specific applications, I hope that the present material provides a suitable foundation upon which to build.

This book is written at a level for use in a first-semester graduate course in biomedical engineering or an advanced undergraduate course, with the expectation that interested students will take a subsequent course in biosystems analysis. Therefore the text focuses on signal processing with the intent to present material that is relevant to students in all subspecialties of biomedical engineering and to lay a foundation for a biosystems course. It assumes the reader has prior exposure to Fourier (and Laplace) transforms and has a basic understanding of human physiology. Ideally, a graduate from an ABET-accredited undergraduate engineering program would be familiar with the basic concepts in Chapters 3–5 and would have been introduced to the material of Chapters 6 and 7. In that case, the book could be covered in a three-hour, one-semester course. Alternatively, one might incorporate the computer exercises into a companion one-hour laboratory course. The text could be used for a one-semester, senior undergraduate course, but it is likely that the instructor would need to omit major sections.

This book also could serve as an introduction to biomedical engineering for engineers from other disciplines and as a reference book for practicing biomedical engineers. It presents biomedical applications of signal processing within a framework of signal modeling. Because both classical and modern signal processing methods are developed from this same framework, it is natural to answer the same two important questions about each method: (1) What assumptions does the method make about the signal? (2) What information can the method provide? These questions are especially important to the practitioner who needs assistance in choosing a method of analysis for his or her particular application. Physiologists and neuroscientists with a background in differential equations should find the text approach-

bruce-fm.qxd 10/3/00 12:21 PM Page xiv

able. Physicists, mathematicians, or chemists who wish to apply their knowledge to biomedical problems may appreciate the breadth of biomedical examples.

Although one might be tempted to attribute the intellectual content of a book only to the creative efforts of its author, an author's teaching style and philosophy evolve through interactions with other teachers and students. I owe a debt to all of those who praised or critiqued my efforts, especially to the late Dr. Fred Grodins, whose clarity of explanation and rigor in applying theory to biomedical practice stimulated the interest of a young electrical engineer in the then new field of biomedical engineering. I also wish to recognize the insightful discussions of the role of engineering in physiology during my collaborations with Professor Curt von Euler of the Karolinska Institute, and Dr. Neil Cherniack, then at Case Western Reserve University. Although neither is a biomedical engineer by training, each is able to transcend mathematical formulas and apply theoretical concepts to real biomedical processes. Of course, one's thought processes are honed continually by graduate students. In particular, the challenge of quenching the intellectual thirsts of Mo Modarreszadeh, Mike Sammon, and Xiaobin Zhang has motivated my continual searching for new wellsprings of signal processing enlightenment!

Special thanks go to the consultants who guided my efforts to include examples of applications outside of my own fields of experience. I assume full responsibility for any errors in the presentation of these examples; the errors would have been much more numerous without their guidance. I wish to express special thanks to Tim Black and Tom Dolan, for their assistance in preparing the final typed manuscript and the artwork.

A book becomes reality only when sufficient resources are made available to the author. In this regard I am heavily indebted to the Whitaker Foundation for support through their Teaching Materials Program. This funding allowed me to reduce my academic responsibilities during the time of writing and to engage assistants who helped assemble the examples and exercises and verified that the exercises could be solved! Dr. Charles Knapp, Director of the Center for Biomedical Engineering at the University of Kentucky, has been very generous in providing relief from academic chores so that I could maintain the necessary writing schedule. More importantly, he has vigorously supported my vision of developing a textbook for this field. I also wish to thank Dr. Peter Katona, whose encouragement was the final push needed to embark on this project. Finally, without the understanding and continued support of my wife, Peggy, this book would still be a project for the future. Although she knew from experience the disruption it would cause, she also knew that some dreams have to be pursued.

EUGENE N. BRUCE
February 7, 2000