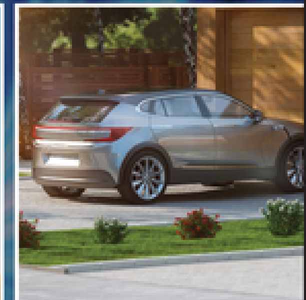
SECOND EDITION

NOISE AND VIBRATION ANALYSIS

SIGNAL ANALYSIS AND EXPERIMENTAL PROCEDURES

ANDERS BRANDT



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Signal Analysis and Experimental Procedures

Second Edition

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About the Author

Anders Brandt is currently professor and Head of the Department of Mechanical and Production Engineering at Aarhus University in Denmark. He received a MSc degree in electrical engineering from Chalmers University of Technology, Sweden, in 1986, and a Licentiate of Engineering degree in medical electronics from the same university in 1989 with a thesis on bone conduction hearing. For the next 20 years, he worked with support, education, and consultancy in industry in Sweden and abroad, in the areas of applied signal analysis. In 1996, he started Axiom EduTech, a company dedicated to serve industry and academia with his expertise in advanced signal analysis methods for vibration analysis. During this time he gave over 250 short courses on various topics such as frequency analysis, modal analysis, order tracking, and vibration testing. He was also teaching at universities on similar topics. In 2009, he left the company and joined University of Southern Denmark (SDU) as an associate professor, building up a research group focusing on research within operational modal analysis and structural health monitoring. He has supervised and cosupervised 11 PhD students and 31 master's students to completion and was promoted to full professor in 2019. He has published over 100 cited papers in the fields of vibration analysis and structural health monitoring. He left SDU to become Head of Department at Aarhus University in 2021. He is the author of the free ABRAVIBE toolbox for MATLAB and GNU Octave, and maintains the site www.abravibe.com from which the toolbox and other educational material may be downloaded. The toolbox is used throughout universities and industry worldwide and has over 5,000 registered users. He also has a YouTube channel which contains lectures for many of the chapters of his book.

Preface

The second edition of this book includes three new chapters: Chapter 16 on experimental modal analysis (EMA) and modal parameter estimation, Chapter 17 on operational modal analysis (OMA), and Chapter 19 in which I have included several examples of how to apply the many techniques presented in the book, both on real data and on synthesized data, i.e., data generated by some numerical model. The latter chapter includes real data from some of my recent research that are also available through my website. It is my hope that these new chapters will make the book even more comprehensive for educators, students, and practitioners alike. In addition to these new chapters, I have also rewritten a few parts, notably the part about correlation function estimators (Sections 10.4.1 and 10.4.2), for which I have found in recent years, that it is easier for my students to understand if presented for correlation as a convolution. Chapter 10 now includes a section presenting a new framework for signal processing that I developed in my recent research. In chapter 19 is also included a presentation of a new way of implementing impact testing which offers new advantages not found in traditional measurement systems. This is also available in the accompanying toolbox, ABRAVIBE, which is available from my website www.abravibe.com, along with almost everything from this book, including a solutions manual for all problems in the book. The ABRAVIBE toolbox for MATLAB (or GNU Octave) is a very comprehensive toolbox with functionality for most of the techniques presented in this book, including rotating machinery analysis, spectrum analysis, EMA, and OMA. My YouTube channel also complements this book with many lectures.

The material in the first edition of this book, published in 2011, had been developing in my mind for more than 20 years of teaching at the time of its first publication. During these years, I had been teaching over 250 shortcourses for engineers in the industry on techniques for experimental noise and vibration analysis and also on how to use commercial measurement and analysis systems. In addition, in the late 1990s, I developed and taught three master's level courses in experimental analysis of vibrations at Blekinge Institute of Technology in Sweden.

Noise and vibration analysis is an interdisciplinary field, incorporating diverse subjects such as mechanical dynamics, sensor technology, statistics, and signal processing. Whereas there are many excellent and comprehensive books in each of these disciplines, there has been a lack of introductory material for the engineering student who first starts to make noise and/or vibration measurements, or the engineer who needs a reference in their daily life. In addition, there are few textbooks in this field presenting the techniques as they are actually used in practice. This book is an attempt to fill this void.

My aim for this book is that it may serve both as a course book and as supplementary reading in university courses, as well as providing a handbook for engineers or researchers who measure and analyze acoustic or vibration signals. The level of the book makes it appropriate both for undergraduate and graduate levels, with a proper selection of the content. In addition, the book should be a good reference for analysts who use experimental results and need to interpret such results. To satisfy these rather different purposes, for some of the topics in the book I have included more detail than would be necessary for an introductory text. To facilitate its use as a handbook, I have also included a short summary at the end of each chapter where some of the key points of the chapter are repeated.

This book contains background theory explaining the majority of analysis methods used in modern commercial software for noise and vibration measurement and analysis. It also includes a number of tools which are usually not found in commercial systems, but which are still useful for the practitioner. With modern computer-based software, it is easy to export data to, e.g., MATLAB/Octave (see below), and apply the techniques there.

Since it is an introductory text, most of the content of this book is of course available in more specialized textbooks and scientific papers. A few parts, however, include some improvements of existing techniques. I will mention these points in the descriptions of the appropriate chapters below.

Signal analysis is traditionally a field within electrical engineering, whereas most engineers and students pursuing noise and vibration measurements are mechanical or civil engineers. The aim has therefore been to make the material accessible particularly to students and engineers of these latter disciplines. For this reason, I have included introductions to the Laplace and Fourier transforms – both essential tools for understanding, analyzing, and solving problems in dynamics. Electrical engineering students and practitioners should still find many of the topics in the book interesting.

Signal analysis is a subject which is best learned by practicing the theories (perhaps that is a universal truth for all areas?). I have therefore incorporated numerous examples using MATLAB or GNU Octave throughout the book. Further examples and an accompanying toolbox which can be used with either MATLAB or GNU Octave can be downloaded from my website. More information about this is located in Section 1.6. I strongly recommend the use of these tools as a complement to reading this book, regardless of whether you are a student, a researcher, or an industry practitioner.

Chapter 2 introduces dynamic signals and systems with the aim of being an introduction particularly for mechanical and civil engineering students. In this chapter, the classification of signals into periodic, random, and transient signals is introduced. The chapter also includes linear system theory and a comprehensive introduction to the Laplace and Fourier transforms, both important tools for understanding and analyzing dynamic systems.

In Chapter 3, some fundamental concepts of sampled signals are presented. Starting with the sampling theorem and continuing with digital filter theory, this chapter presents some important applications of digital filters for fractional octave analysis and for integrating and differentiating measured signals.

Chapter 4 introduces some applied statistics and random process theory from a practical perspective. It includes an introduction to hypothesis testing as this tool is sometimes used for testing stationarity of data. This chapter also gives an introduction to the application of statistics for data quality assessment, which is becoming more important with the large amounts of data collected in many applications of noise and vibration analysis.

Chapters 5 and 6 provide an introduction to the theory of mechanical vibrations. I anticipate that the contents of these two chapters will already be known to many readers, but I have found it important to include them because my presentation focuses on the experimental implications of the theory, unlike the presentation in most mechanical vibration textbooks, and because some later chapters in the book need a foundation with a common nomenclature.

In Chapter 7, the most important transducers used for measurements of noise and vibration signals are presented, specifically the accelerometer, the force sensor, and the microphone. Because piezoelectric sensors with built-in signal conditioning (the so-called IEPE sensors) are widely used today, this technology is presented in some depth. In this chapter, I also present some personal ideas on how to become a good experimentalist.

The analysis techniques mostly used in this field are based on the Discrete Fourier Transform (DFT), computed by the FFT. Spectrum analysis is therefore an important part of this book and Chapters 8–10 are spent on this topic. Chapter 8 introduces basic frequency analysis theory by presenting the different signal classes, and the different spectra used to describe the frequency content of these signals.

In Chapter 9, the DFT and some other techniques used to experimentally determine the frequency content of signals are presented. The properties of the DFT, which are very important to understand when interpreting experimental frequency spectra, are presented relatively comprehensively.

Chapter 10 includes a comprehensive presentation of how spectra from periodic, random, and transient signals, and mixes of these signal classes should be estimated in practice. Chapter 10 also includes a comprehensive explanation of Welch's method for PSD estimation, including overlap processing, as this is the method used in virtually all commercial software. The treatment of practical spectral analysis in this chapter should also be of use to engineers outside the field of acoustics and vibrations who want to calculate and/or interpret spectra by using the FFT.

In Chapter 11, the design of modern data acquisition and measurement systems is described from a user perspective. In this chapter, both hardware and software issues are penetrated.

Chapter 12 addresses order tracking, which is a common technique for analysis of rotating machinery equipment. The chapter describes the most common techniques used to measure such signals both with fixed sampling frequency and with synchronous sampling.

Frequency response functions are important measurement functions in experimental noise and vibration analysis and are used, for example, in EMA. Chapter 13 therefore covers techniques for measuring frequency responses for single-input/single-output (SISO) systems. Both impact excitation and shaker excitation techniques are presented in detail. In Chapter 14, the techniques are extended to multiple-input/multiple-output (MIMO) systems.

Chapter 15 presents some relatively advanced techniques used for multichannel analysis, namely principal components and virtual signals. These techniques are commonly used for noise path analysis and noise source identification in many of the sophisticated software packages available commercially. I present these concepts in some depth, since they are not readily available in other textbooks.

Chapter 16 is a new chapter introducing EMA in terms of how to perform such tests. The chapter also includes a thorough explanation of the mathematical background of modal parameter estimation (MPE) with the Unified Matrix Polynomial Approach (UMPA) framework, and presents most algorithms currently used in commercial systems for EMA, and also for OMA, since the MPE is essentially the same for these two techniques, with some small differences.

Chapter 17 is a new chapter that presents OMA. Since most MPE algorithms are common for EMA and OMA, only those methods that are unique for OMA are presented in this chapter. The chapter also presents the fundamental basis for OMA; the decomposition of correlation functions and spectral densities into modal parameters.

In Chapter 18, which is essentially what constituted Chapter 16 in the first edition of the book, I have collected a number of more advanced techniques that engineers in this field should be acquainted with. This chapter presents, in order, the shock response spectrum, the Hilbert transform with applications, the cepstrum and envelope spectrum, and how to produce Gaussian time signals with known spectral density. The chapter has also been extended with two recently developed methods for removing harmonics, or separating signals into random and harmonic parts, cepstral editing, and the frequency domain editing method.

In the Appendices, I have included some fundamentals on complex numbers, logarithmic diagrams and the decibel unit, matrix theory, eigenvalues, and the singular value decomposition. The reader who does not feel confident with some of these concepts will hopefully find enough theory in these appendices to follow the text in this book. The last appendix contains some references to good sources for more information within the noise and vibration community. I hope the newcomer to this field can benefit from this list.

Acknowledgments

In the second edition of this book, I have added examples from my teaching and research performed at University of Southern Denmark (SDU). I am very grateful for the support of SDU during 12 years, as I am also grateful to my current affiliation, Aarhus University, Denmark. And to all my many colleagues who have shown so much friendliness and support – thanks!

During my time at SDU, I had the honor of receiving financial support from the EU Fund for Regional Development, through the Interreg 4A and Interreg 5A programs, for which I owe many of the results presented in this book, including the data of the RO-LO ship used in Chapter 19. I am also grateful to Innovation Fund Denmark for several industrial PhD and PostDoc projects, and to Siemens Gamesa, Vattenfall, Dinex A/S, Lindø Offshore Renewables Center, and the German Aerospace Center, DLR, for their support. Furthermore, I am grateful for support from the Danish Maritime Fund and to Linnaeus University in Sweden for a period as guest professor.

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I am also grateful for the help to review parts of the manuscript to the second edition. Thanks to Stefano Manzoni, Goran, POS! The errors remaining in the book are my own.

The first edition of this book was inspired partly by class notes I wrote for two classes at Blekinge Institute of Technology, BTH. I am especially grateful to Professor Ingvar Claesson and the Department of Signal Processing at BTH for supporting me in writing these early texts. Also, Timothy Samuels did a great job translating an early manuscript from Swedish to English.

My most sincere appreciation goes to Professor Kjell Ahlin, my colleague and friend for many years. Our many long discussions have strongly contributed to my understanding of this subject and I am grateful for the data provided by Professor Ahlin for examples in Chapters 16 and 19.

Dr Per-Olof Sturesson and the noise and vibration group at SAAB Automobile AB were invaluable resources of feedback and have provided data for Chapters 12 and 15. For this, and many ideas and discussions, I am very grateful. Special thanks also goes to Mats Berggren. Also, thanks to Volvo Car Corporation and William Easterling for providing data.

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Svend Gade and Brüel and Kjær A/S are acknowledged, along with Niels Thrane, for allowing me to reuse an illustration and an overview description of the Discrete Fourier Transform from an old B&K Technical Review, which I find is of great value for presenting the DFT.

I also wish to thank Flensburg Shipyard in Germany for allowing us to collect data on the RO-LO ship used in Chapter 17.

I have always found the many participants at the International Modal Analysis Conference (IMAC), organized by Society for Experimental Mechanics (SEM), an invaluable source of inspiration and knowledge. Special thanks to Tom Proulx (in memoriam), Al Wicks, Dave Brown, Randall Allemang, Pete Avitabile, and Dan Rixen for their outstanding support and encouragement and continuous willingness to give from their wealth of knowledge. I am also grateful for the many good discussions over the years with Bob Randall.

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Finally I am, of course, thankful to a great number of people who have inspired and supported me, and to all those I have forgotten here – sorry!

List of Abbreviations

2DOF	two degrees-of-freedom system
AC	alternating current
ADC	analog-to-digital converter
AFDE	automatic frequency domain editing
BT	bandwidth-time (product)
CMIF	complex mode indicator (indication) function
CSD	cross-spectral density function
DAC	digital-to-analog converter
DC	direct current
DFT	discrete Fourier transform
DOF	degree-of-freedom (point and direction)
EMA	experimental modal analysis
ESD	energy spectral density
FDD	frequency domain direct identification
FDE	frequency domain editing
FDPI	frequency domain direct parameter Identification
FE	finite element
FEM	finite element method
FFT	fast Fourier transform
FIR	finite impulse response (filter)
FRF	frequency response function
HF	high frequency
HP	highpass
IDFT	inverse discrete Fourier transform
IEPE	integrated electronics piezoelectric (sensor)
IFFT	inverse fast Fourier transform
IIR	infinite impulse response (filter)
IRF	impulse response function
ITD	Ibrahim time domain
LF	low frequency
ISO	international standardization organization
LSCE	least squares complex exponential
LSCF	least squares complex frequency domain

LSFD	least squares frequency domain
MAC	modal assurance criterion
MEMS	microelectro-mechanical systems (sensors)
MDOF	multiple degrees-of-freedom
MIF	mode indicator function
MITD	multiple-reference Ibrahim time domain
MIMO	multiple-input/multiple-output
MISO	multiple-input/single-output
MMITD	modified multiple-reference Ibrahim time domain
MPE	modal parameter estimation
MPSS	multiphase stepped sine
MrMIF	modified real mode indicator function
MvMIF	multivariate mode indicator function
NSI	noise source identification
NSR	noise-to-signal ratio
ODS	operating deflection shape
OMA	operational modal analysis
PDF	probability density function
PRD	periodogram ratio detection
PSD	power spectral density
PTD	polyreference time domain
RMS	root mean square
RPM	revolutions per minute
SDOF	single degree-of-freedom
SIMO	single-input/multiple-output
SISO	single-input/single-output
SNR	signal-to-noise ratio
SRS	shock response spectrum
SVD	singular value decomposition
TEDS	transducer electronic data sheet