ELECTRONIC FILTER DESIGN HANDBOOK

Arthur B. Williams
Fred J. Taylor

Fourth Edition

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From Arthur B. Williams
To my Family
Ellen, Howard, Bonnie, Robin, Mitchell
and grandchildren Leviah and Ilona

From Dr. Fred J. Taylor
To my grandchildren Schuyler, Bennett,
and Graysen and their
devoted grandmother Lori

ABOUT THE AUTHORS

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PREFACE

This is the fourth edition of the *Electronic Filter Design Handbook,* which was first published in 1981. It was expanded in 1988 to include five additional chapters on digital filters and then updated in 1995. This revised edition contains new material on both analog and digital filters. A CD-ROM has been included containing a number of programs which allow the rapid design of analog filters for input requirements without the tedious mathematical computations normally encountered. The digital filter chapters are all integrated with a profusion of MATLAB examples.

Prior to the introduction of this book in 1981, the design of *LC* and active filters had been reserved for specialists. The *Electronic Filter Design Handbook* treated the design of these filters in a practical manner and provided extensive tabulated data so that the average engineer who had no previous experience could design passive or active filters. This philosophy was expanded to include digital filters in the second edition in 1988, where, for the first time in any book, the design of all three classes of filters was covered in a practical easy-to-follow style. The book was then further updated in its third edition in 1995 to include a number of new technologies and design methods. In this fourth edition, the book now contains additional material and chapters on analog filters, and has been updated on available components to include surface mount technology. A number of powerful design programs have been included on the CD-ROM. Some of the previously included tables on normalized elliptic-function low-pass filters have been replaced by a powerful program, *Filter Solutions* (from Nuhertz Technologies®), which can directly design these filters and create a schematic without tedious calculations. An EXCEL spreadsheet contains formulas from the individual chapters keyed to the text so that the tedious calculations required in the past are no longer necessary.

The digital filter chapters have been completely revised and the vast majority of the material is new. This new edition contains all the topics and studies found in the previous version of the *Electronic Filter Design Handbook,* plus many more that cover the full range of modern fixed-coefficients digital filter design. The coverage provides the reader with both a conceptual understanding of digital filters and the ability to design digital filters for use in a number of application domains. The presentation keeps in mind that traditional digital filters, used a decade ago, remain in popular use today. It's also recognized that nontraditional and multirate filters are of growing importance. Thus, basic digital filter design methods are presented, along with an enriched treatment on multirate solutions. Strong emphasis is placed on achieving filter-technology synergy, which considers issues related to the physical implementation of a digital filter in either hardware or software. This fourth edition also presumes that contemporary engineers will increasingly turn to the computer software to support filter design and analysis activities. These activities are motivated and supported with a profusion of computer-generated examples using the ubiquitous MATLAB software package.

Chapter 1 introduces the concept of modern network theory and discusses the trade-off between active and passive filter implementations.

The mathematical properties of standard filter response types are covered in Chapter 2, including Butterworth, Chebyshev, Bessel, linear phase with equiripple error, transitional, synchronously tuned, and constant delay with Chebyshev stopband. Extensive normalized curves for both frequency and time-domain parameters of these standard polynomial transfer functions are provided. The highly efficient elliptic-function filter response is also discussed in this chapter and emphasized throughout the handbook. Two programs contained on the CD-ROM, *Filter Solutions (book version)* and *ELI 1.0* (for the design of elliptic-function filters), are introduced.

In Chapter 3 the design of both passive and active low-pass filters is covered using normalized tables. Specialized passive low-pass filter design techniques are illustrated, such as designing for unequal terminations and compensating for the effects of component dissipation (low *Q*). Various active low-pass filter structures are covered for both all-pole and elliptic-function types.

High-pass filters for both passive and active implementations are discussed in Chapter 4.

Chapter 5 covers bandpass filters. Various passive filter transformations, approximations, and identities are illustrated to ensure practical element values even for extreme conditions of center frequency, bandwidth, or impedance level. Some active bandpass implementations are offered that exhibit low sensitivity at frequencies previously considered too high for active filters.

Techniques for band-reject filter design are presented in Chapter 6, where passive and active types are covered.

Chapter 7 covers the design of networks having properties best described in the time domain. All-pass delay and amplitude equalizers are discussed in detail. Methods are shown for the design of *LC*, as well as active delay lines and wideband 90° phase shift networks.

Refinements in *LC* filter design are covered in Chapter 8. Special techniques are presented to manipulate element values so that practical values can always be obtained. Here, measurement techniques are shown, and the design of various forms of resistive attenuators for attenuation and impedance matching is covered. The theory and design of power splitting networks is also explained.

The successful operation of *LC* filter design is highly dependent upon the proper selection and manufacture of inductors. The design of magnetic components is presented in Chapter 9. The entire process—ranging from the selection of various magnetic material types and shapes to coil-winding methods to achieve the optimum characteristics over the operating frequency range—is explained in detail. New magnetic materials and shapes are covered. *Q* curves are also provided, as well as those for MPP torroidal cores, ferrite RM and potcores, and surface mount RF inductors.

The component selection for *LC* and active filters is discussed in Chapter 10. Coverage includes capacitor characteristics and the selection of fixed and variable resistor types. Johnson (Thermal) noise is also discussed. Operational amplifier theory is reviewed both from a theoretical and a practical standpoint, and expanded and updated device selection charts are provided to enable the rapid choice of the appropriate operational amplifier for a given filter configuration and required operating frequency range. Surface-mount (SMD) components are also emphasized, as well as the manufacturing considerations using this technology.

Chapter 11 contains normalized tables for the rapid design of both passive and active filters. In addition to the standard polynomial types, tables are provided for the unique constant-delay low-pass filters with Chebyshev stopband characteristics.

Chapter 12 introduces digital filters. The presentation begins with a differentiation of analog and digital systems, representations, and design strategies. The sampling theory is established as being a core element in the understanding and realization of digital filters, and issues such as quantifying sampling modalities and aliasing are discussed. Data conversion principles and mechanics (to and from the analog domain) are developed, and the chapter closes with a discussion of computer arithmetic and spectral analysis.

Finite impulse-response filters (FIR) are discussed in Chapter 13. The chapter begins with a general characterization of FIR filters, including stability. Both linear and non-linear phase FIR are studied in detail, and FIR design procedures based on the window, least-squares, and equiripple methods are presented, as well as the extension of their use as Hilbert and differentiating FIRs. FIR special cases, such as comb, moving average, L-band, mirror, complement, and frequency sampling forms are also described and illustrated. The FIR design strategies are reinforced using MATLAB FIR architectures, including direct, transpose, symmetric, lattice, distribute, and canonic digit form are developed in detail. The chapter concludes with a study of finite word length effects.

Chapter 14 covers the infinite impulse-response (IIR) filters. The presentation begins with a general characterization of FIR filters, including stability. A review of classic analog filters, Butterworth, Chebyshev I and II, and elliptic (Cauer) are presented and used to define classic digital IIR filters. The conversion of analog filters to digital IIR filters are examined in terms of impulse invariant and bilinear z-transforms. The design of an IIR, based upon measured input-output responses, is also presented in terms of auto-regressive models. The IIR filter design process is illustrated using MATLAB IIR filters are described using a natural state variable analysis framework, which is interpreted in terms of a Direct I and II, Cascade, Parallel, Normal, and Lattice architectures. The state variable models are next reinforced using MATLAB. The chapter concludes with an exposition of the analysis procedures required to insure a successful fixed-point IIR implementation and how to minimize run-time finite wordlength (fixed-point) errors.

Multirate filters are discussed in Chapter 15. The presentation begins with a general characterization of multirate systems and their use. Following this, the process of decimation and interpolation are developed, along with sample rate conversion. Multirate systems are then presented using a polyphase framework that is extended to the design filter banks and DFT filter banks. The chapter concludes with the development of high decimation rate filters and frequency masked filters.

Chapter 16 covers the field of digital filter technology. The presentation begins with an overview of technology types including general purpose μps, DSP μps, application-specific integrated circuits (ASIC), and field programmable gate arrays (FPGA). Various processor organizations are examined. Processor architectural variations and their impact on design choices are developed and compared. A discussion of analog to digital (ADC) architectures is presented and used to define and compare various types of converter architectures. Next, software issues and opportunities are developed and analyzed. The chapter concludes with a filter implementation case study based on Texas Instruments DSP μp processor architecture.

Chapter 17 covers switched-capacitor filters. The underlying theory behind this technology is presented, and some design examples are shown using standard building-block ICs. A survey and a convenient selection guide (updated) is included, as well as a program called FilterCAD on the CD-ROM. The latter program (from Linear Technology) can help to quickly design a switched-capacitor filter from a set of input parameters. It then provides a schematic of the filter along with both the predicted frequency response and time response.

Chapter 18 is an introduction to microwave filters. It discusses Kuroda's Identities and Richards' Transformation and illustrates some design examples of microstrip filters.

Appendix A provides a review of DSP mathematics. The presentation begins with a comprehensive study of the z-transform and inverse z-transform. Transforms are then investigated using MATLAB. The chapter concludes with a discussion of the discrete Fourier transform (DFT).

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