SELECTIVE LINEAR-PHASE SWITCHED-CAPACITOR AND DIGITAL FILTERS

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For Iman

"Und ein erstuant, ein fragend Lächeln quilt
Auf meinen Mund, ob mich kein Traum betrüge,
Dass nun in dir, zu ewiger Genüge,
Mein kühnster Wunsch, mein einziger, sich erfüllt?.."

From the Mörike-Lieder
Hugo Wolf

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Preface

In some applications, filters are designed on amplitude basis alone. For example, in the audio frequency range, it is claimed that the human ear is insensitive to phase distortion, and the optimum solution to the filter design problem is usually taken to be the elliptic filter, giving the lowest degree filter for a given set of specifications on the amplitude response. Other applications place more importance on the phase response while tolerating a moderate amount of amplitude distortion. In this case, certain phase-oriented approximations are acceptable. However, in modern high-capacity communication systems, filters are required to meet stringent specifications on both the amplitude and phase characteristics simultaneously.

The use of switched-capacitor filters was, for some time, confined to audio frequencies. Recently, however, the operating range of these filters has been extended to frequency ranges where phase linearity in the passbands becomes a major design consideration.

This is also true in the case of applications employing pulses for data transmission. Thus, the phase response of switched-capacitor filters is becoming of increasing importance. Digital filters have long been entrenched in a wide range of applications that require passband phase linearity in addition to amplitude selectivity.

The traditional approach to satisfying a given set of specifications on the amplitude and phase responses of the filter is to, first, design a filter which meets the amplitude specifications, then design an all-pass phase equalizer to correct for the deviation from phase linearity of the amplitude- oriented filter. Such an approach is, however, unacceptable due to the non-optimum nature of the design. This means that one obtains a filter with a higher degree than necessary to meet the given set of specifications. For switched-capacitor filters, this leads to an unnecessarily large number of active components including operational amplifiers and switches, as well as an increase in the number of capacitors. This leads to an increase in the chip area, power consumption, noise, and all other associated non-ideal effects. Similarly, in the case of digital filters, the non- optimum nature of the design leads to an unnecessarily large number of multipliers.

It follows that the traditional approach which is the one usually adopted in all available computer-aided filter design programs, is unacceptable in many applications. This is particularly true since recent advances in approximation theory make it possible to design filters which satisfy the amplitude and phase specifications simultaneously at the outset in an optimum manner. That is, the filter transfer function is derived to possess the required properties without any need for further equalization of either the phase or amplitude response; thus exploiting all the available degrees of freedom. This is the subject of this book in relation to switched-capacitor and digital filters.

In addition to the above considerations regarding the optimality of a design technique, there are filter structures which possess low-sensitivity properties of their responses with respect to variations in element values. This is a highly desirable attribute from the practical view-point. These low-sensitivity structures are usually obtained by imitating passive filter structures such as the resistively-terminated ladders, which are known to possess excellent sensitivity properties. It is for this reason that these classes of filters are emphasized in this book. These include switched-capacitor ladder filters and the corresponding wave digital structures. Nevertheless, more general approximation techniques are also given.

Naturally, the transfer functions treated in this book are realizable in other forms of discrete-time circuits, but it is generally accepted that switched-capacitor and digital filters are the most important types of discrete systems, and the treatment is therefore, focused on these categories.

Of course, only sampled-data filters of the *infinite duration impulse response(IIR)* type are considered, since *finite duration impulse response(FIR)* filters can be designed with exact linear phase at all frequencies so that the phase approximation problem is, loosely speaking, trivial.

Although the synthesis techniques of the various types of filters are mentioned, and numerous examples given, the book concentrates largely on the approximation problem, that is: the derivation of the transfer function which, on the one hand, meets the specifications on the amplitude and phase characteristics, and on the other satisfies the realizability conditions in a particular structure of a filter type.

Chapter 1 sets the scene for the exposition in the book, defining the categories of filters treated, and examining the problems involved in the phase approximation problem. Both low-sensitivity switched-capacitor and wave digital structures are examined in addition to more general synthesis techniques leading to cascade realizations of discrete-time transfer functions.

Chapter 2 gives relatively simple analytic techniques for the design of low-sensitivity switched-capacitor filters on phase basis alone, and to possess a good approximation to passband phase linearity together with moderate amplitude selectivity.

Chapter 3 gives a very powerful technique, together with the associated algorithm, for the derivation of low-pass switched-capacitor and wave digital ladder filter transfer functions with an optimum compromise between passband phase linearity and amplitude selectivity. Complete design examples are given to illustrate the technique.

Chapter 4 generalizes the results of Chapter 3 to the more difficult case of band-pass ladder filters. Again the optimum solution to the simultaneous amplitude and phase approximation problem is given together with complete design examples.

In **Chapter 5**, the constraint of realizability in ladder form is dropped, and a most general design technique is given for non-minimum phase transfer functions which are capable of meeting very stringent specifications on both the ampliude and phase characteristics, while being realizable in, say, cascade form. This is the most comprehensive design technique available to-date, and is also very instructive.

In writing this book, I have attempted to maintain a unity of presentation that is essential for a smooth reading of the material. It is for this reason (among other more subtle ones!) that I have decided to include only material based on my own research contributions. This approach, I believe, has produced a coherent treatnment of the subject.

The book should be useful to professional electronic engineers and researchers. It is slso suitable for use in an advanced graduate course at universities which attempt to transcend the traditional courses in filter design, by supplementing the usual material with this book.

Finally, I would like to acknowledge the contributions of my past and present research students whose collaboration has resulted in much of the material in the book. In particular, I would like to mention Dr. Mark O'Malley and Mr. Songxin Zhuang. Thanks are also due to my research student Mr. Emad Afifi whose help in the preparation of the manuscript has been invaluable.

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