Preface

Recent advances in solid-state technology and the well-known advantages of integrated circuits (ICs) have made microminiaturized filters and systems an important field of study. For a particular application, the main object of the designer is to select/design a circuit, which is optimized to maximize performance and minimize cost through economic integration. At present, several methods are available to adapt the design of linear networks. Among these, networks (filters) employing resistance, capacitance, and linear active devices, i.e., active RC filters, have become very popular because of their functional versatility, ease of IC implementation and cost reduction. Now, good quality active RC filters are being produced using integrated operational amplifiers (OAs), mainly because of the commercial availability of high quality OAs at low cost.

It is for this reason that the majority of the, presently, available books on linear active filter design and the curriculum at almost all universities include OA-RC based circuit and systems design either as a full course or part of a course on linear integrated circuit design. However, it is only part of a story, which began with passive electric filter design. Approximation was used to develop filter structures, predominantly in the form of either singly or doubly terminated lossless ladders. Great strides were made in developing ladder structures and related information for different approximations, and related information like their transfer function in terms of ratio of polynomials or in terms of poles and zeros, and required values of elements used in the ladders. Not only are passive filter realizations still used today, but the large literature on it also finds application in active network synthesis. Hence, a discussion on passive filter design and properties of ladder structure finds place in books on network analysis/synthesis.

Development of filter circuits from passive to active did not stop at the OA-RC case. The simultaneous development of digital filters and systems, and the replacement of analog sub-systems with digital sub-systems, motivated further advancements in continuous-time as well as discrete-time analog filters. Employing the design procedures used with OA-RC filter synthesis, high speed sampling circuits such as the switched capacitor (SC) provided good alternatives to digital filters in many applications. As a result, SC filter design became an entity which needed a separate (and

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specialized) study and followed procedures parallel to that of the active RC case; it had its own techniques as well. However, for a large number of applications, continuous-time techniques were preferred, because they did not need anti-aliasing or smoothing filters; moreover, no clock and associated issues, such as clock feed-through, fold-over noise, etc., are present. Though, in some cases, continuous-time filter design needed specially designed OAs or devices other than OAs, such as operational transconductance amplifiers (OTAs), which are basically current mode (CM) devices. Further boost to CM filtering came with the use of current conveyors (CCs) and related devices; the application of CM devices such as CCs was researched extensively in the 1970s. Recently, other CM devices like current-feedback operational amplifiers (CFOAs) and current differencing (CDTA) have become available, creating further interest in CM filters. These devices have created another specialized field of active filter, for studies.

Hence, the subject of electric filter design has become very wide including passive filter design and its impact on active filter design, active RC filter design which is mainly OA-RC based, SC filter design and CM filter design with a number of new active devices. Of course, each area of study is not entirely separate and has many overlapping regions. It can be safely said that techniques employed with active RC filters using OA are fundamental for further studies towards the in-depth investigation of OA-RC filter design and/or SC and CM filters. Courses need to be developed as advances are made in techniques and curricula must evolve for fundamental and advanced courses.

It is obvious that such a wide area cannot be covered even in two courses of 3/4 credits. However, practically speaking, with the ever expanding areas of important studies, there is pressure to find even one 3/4 credit slot for specialized subjects like analog active filter design in a four-year undergraduate engineering curriculum. Based on the aforementioned constraint, the major aim of this book is to give enough material on continuous-time active filters using OAs, so that it provides a good understanding of the core material of active filter design in a one-semester course. Only an introduction to SC filters and some material on CM filters is included to provide connectivity with the active RC filter synthesis.

The book is written for use in a first course on active network synthesis at the advanced undergraduate level. Hence, it is assumed that the reader has already studied basic network theory and analog electronics. For example, basic filter classification, OA's characteristics, and so on, have been only briefly reviewed in Chapter 1. It needs mentioning that the material given in these 17 chapters is a bit more than can be covered in a one-semester course and the individual instructor has the choice to leave some chapters partly or fully.

A significant contribution in the book is in the form of practical applications of the continuous-time analog filter. It is expected that this component will be well received by the students and will act as a motivator for taking up studies in the area of analog filters. In addition to two chapters on practical applications, more examples are also included in other chapters.

Chapters 1 and 2 provide an introduction to the subject and related aspects of the active device (OA) and components commonly used in the realization of active filters. The chapters also review the classification of filters on the basis of signal frequency separation and the basics of different approaches to active filter synthesis like the *direct form* and the *cascade form*. Description of the characteristics of the first-order and second-order low pass (LP), band pass (BP), high pass (HP), band elimination (BE) and all pass (AP) filtering, their basic parameters, and effect of the frequency dependent gain of the OA on filter circuits is discussed for second-order sections as well.

Study of Butterworth-maximally flat, equal ripple and elliptic approximations have been undertaken in Chapter 3. Finding locations of the transfer function poles and normalized element values for different approaches have been discussed. Also included is an introduction to finite zeros with a maximally flat pass band. Since all the approximations are initiated in LP form, transformations are required to apply these approximations to other type of responses like BP, HP and BE responses. Chapter 4 deals with this issue; impedance scaling is also included to complement the topic of frequency scaling. A simpler alternative to network transformation is also discussed for converting an LP passive prototype to other responses.

A significant issue in the form of designing delay filters is studied in Chapter 5, which was not given distinct coverage while magnitude approximation was discussed. Bessel approximation filters, which are more suited for controlling delays, are studied. Delay equalization using first- and second-order AP filters have also been studied in this chapter.

Before taking up different synthesis methods, sensitivity studies of active networks are discussed in Chapter 6. Beginning with some simpler aspects of sensitivities, like incremental sensitivity, the discussion covers transfer function sensitivity and sensitivity of second- and higher-order functions.

In Chapters 7 and 8, important topics related to the realization of second-order sections is taken up employing single and multi amplifiers, respectively. Single amplifier sections, employing single-feedback and multiple-feedback while using single input as well as differential input are discussed. General active RC feedback approach leading to some well-known biquadratics is explained. In Chapter 8, the state variable multi amplifier biquad and active compensation of integrators is studied. Development of the general biquadratic section using the conventional summation method and modified summation method is included. Also included are generalized impedance converter (GIC) based second-order sections and development of the general biquadratic section from it.

After laying the foundation and discussing the issues important for active RC filter design, other important approaches in the direct form of synthesis, like element substitution and operational simulation, are studied in Chapter 9. Since element substitution is mainly concerned with the inductance fabrication problem in IC form, it is taken up in detail, followed by frequency dependent negative resistance (FDNR) simulation and their utilization in filter realization. Instead of applying direct substitution of inductance (or FDNR), an alternate approach is also taken up which is known as the *operational simulation* scheme. It is based on the modeling of circuit equations and current–voltage relations in the circuit. The technique is illustrated with the simulation of an LP ladder, a BP ladder and a general ladder.

The basics of an important higher filter design approach, namely the cascade design, is discussed in Chapter 10. Optimization of the process, aiming at increasing the filter dynamic range, is discussed. Also included is an introduction to the tuning of second-order filter sections, which are the basic building blocks (BBBs) employed in the cascade approach.

Chapters 11 and 12 are devoted to practical application examples employing continuous-time active analog filters and some case studies. Only some of the more common areas of application of analog filters are included. Chapter 11 includes some simple signal processing biomedical applications. An introduction to instrumentation amplifiers is also given as it is an essential component in such applications. Different aspects of audio signal processing and the essential requirements with widespread usage of analog filters in such applications are discussed in

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Chapter 12. The latter part of the chapter shows the importance of analog low pass filters as anti-aliasing and reconstruction filters in otherwise digital signal processing.

Another useful direct form of filter realization known as follow the leader feedback (FLF) has been described in Chapter 13. Its basic idea, structure and its different approaches are discussed. Introduction of finite transmission zeros through the use of feed-forward path is discussed in the *shifted companion* form. Also included is the general FLF structure study leading to the *primary resonator block* technique.

Switched capacitor (SC) circuit(s) forms an important study in itself and some good books are available exclusively on it or along with continuous-time filters. As these are only approximated to continuous-time filters to a certain degree, its study is suitable in sampled-data form; hence, only an introduction is given here in Chapter 14.

In Chapter 15, filter realization using OTAs and capacitors is discussed. BBBs, like simulation of resistance, integrators, voltage amplification and current and voltage addition are illustrated with examples. The conversion process from single-ended to differential output is studied and applied to OTA based filters. First- and second-order sections using two-integrator loops are included. Simulation of inductors is used for the element substitution process, and operation simulation process is also studied to realize OTA-C based higher-order filters.

Recently, CM filter realization has gained momentum and needs to be studied in a specialized form. Though OTA is also a current source device and CM filters have been obtained using OTAs, many other CM devices are being used; CC and its variations being one of the most commonly used devices. Chapter 16 begins with a brief depiction of CCII and some BBBs using CCs. First-order CM filters and second-order filter realizations with different approaches are discussed. Biquadratic section developments using one, two and more CCs are shown. Inductance and FDNR simulation is explained for application to direct form synthesis. CDTA, another CM device, has also been shown to realize CM elements and filter circuits.

In Chapter 17, the frequency dependent model of OAs is used to obtain active R and active C circuits, using OAs and resistances, and OAs and capacitances, respectively. Their advantages lie in their ability to extend the operating frequency range and obtain filter parameters in terms of ratio of resistances/capacitances. In the direct form of element substitution approach, the grounded and floating form of all the passive elements are simulated and then employed for filter realization. First-order sections and second-order filter sections are studied and then used in the cascade design in active R and active C form. Since critical frequency of these filters depends on the value of gain bandwidth product of OAs, which has large tolerance, available methods to minimize errors on this count are also briefly mentioned.

I have tried to follow a middle path between depth and width of the subject. It became necessary to limit the number of topics so that adequate detail for understanding a topic could be provided, and the undergraduate student remains interested in the subject. It is hoped that after completing a course based on the text, the student is able to design active filters and become qualified enough for further advanced studies on continuous-time or SC filters or CM filters.

The solutions manual for practice problems in this book can be accessed at *www.cambridge.org/9781108486835*. Your suggestion for further improvements are welcome. Kindly write to me at *siddiqima48@gmail.com*.