IMPLEMENTATION OF HIGH-PERFORMANCE INTEGRATED ANALOG FILTERS AND FILTER BANKS

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Analog filters constitute one of the key subsystems that are an integral part of almost all DSP/communication systems. Integrated analog filters are therefore a necessity in highly integrated implementations, so-called system-on-a-chip and they are often the performance limiting subsystem.

This project involves the design and implementation of advanced integrated analog filters and filter banks targeted for use in wideband interfaces. That is, in antialiasing and reconstruction filters in ADC and DAC, respectively. However, there is a strong trend towards using analog signal processing instead of digital signal processing for wideband signals, particularly for application with relatively low requirements on SNR. In such cases an analog datapath can often be implemented using lower power consumption. Hence, we can expect an increasing use of analog filtering.

One such important application is as front-end in wideband ADC based on hybrid filter banks. This type of ADC uses an analog filter bank to divide the input signal spectrum into several frequency bands, which are then digitized by a set of ADC. The requirements on the ADCs are significantly relaxed in this approach. The digitized signals are finally combined using a digital filter bank. Major problems in current design and implementation approaches are to achieve sufficiently accurate and stable components, dynamic signal range, and alleviate non-linear effects. These problems are much worse in integrated analog filters than in their discrete component counterparts.

Keywords: Analog filters, filter banks, distortion, noise, A/D converters, D/A converters, mixed mode circuits.

1. DIVISION OF ELECTRONICS SYSTEMS

The division of Electronics Systems, former Applied Electronics, has since the mid 70´s been working on theory, design, and implementation of both analog and digital signal processing subsystems. Focus has mainly been on analog, discrete-time, like switched capacitor (SC) and switched current (SI), and digital filter structures, as well as on fast transforms. Another line of work involves A/D and D/A converters and mixed-mode circuits. A major activity in the group has been on issues involving the VLSI implementation of such circuits. In fact, this group is one of the leading groups in theory and design of analog, discrete-time, and digital filters and their implementation.

2. COOPERATION

In this and related projects we currently cooperate with professors Tor Ramstad in Trondheim and Tapio Saramäki in Tampere and more recently with professor Heinz Göckler in Bochum. This cooperation provides access to special competence and skills in key areas that complement and strengthens our own. Hence, this group has an excellent background and competence for developing the proposed approach.

We already have one SSF project working on wideband ADCs (Per Löwenborg), but his work mainly involves the design of filter banks and analysis of the whole ADC. Another SSF project (Robert Hägglund) studies the use of digital control and measurement techniques to tune and stabilize components in integrated analog filters.

Further, we have an ongoing locally financed project on mixed-mode circuits that have relevance for this project (Universitetslektor Mark Vesterbacka). We also have within our group two industrial Ph.D. students, which are supported by Ericsson Components, that work with similar problems.

3. INTEGRATED ANALOG FILTERS

Historically analog filters were an active research topic for most of the last century. However, active filter research was more or less discontinued at the end of the 70-ties when switched-capacitor filters become in fashion. This was due to the fact that they could be integrated using standard CMOS processes. The work on active filters was mainly focused on low sensitivity structures using operational amplifiers with high bandwidth. The work was mostly of an experimental nature and relatively few results on, for example, dynamic range was obtained. Instead these issues was resolved within the digital filter community, but the theory was not widely adopted by the active filter community although dynamic range is directly related to element sensitivity. Dynamic signal range limitations are caused by other mechanisms in active filters compared to digital filters. Neither theoretical nor computer-based tools for analysis of noise and distortion were widely available. Hence, the dynamic range issue was never satisfactory resolved, i.e., neither design methods nor efficient analysis methods or tools were developed. Current applications of integrated active filters must operate with a much lower ratio between the amplifier bandwidth and filter bandwidth. This causes second-order effects to become important.

Today the situation is very different. Currently, efficient symbolic analysis tools based on *Mathematica*™ are available. This tool, which is very powerful, allows symbolic analysis of *Spice*-models with an accuracy that can be set by the user. Hence, it is now possible to perform symbolic analysis of thermal noise, amplifier noise as well as nonlinear effects. This means that it is possible to develop guidelines for high dynamic range filters.

4. OUR APPROACH

Wideband analog filters are used in many applications. Here we will mainly target integrated high dynamic range, wideband filters and filter banks for use in wideband interfaces.

A. High Dynamic Range Active Filters

Dynamic range is closely related to the element sensitivity. Hence, this work will include the evaluation and optimization of classical as well as novel reference filters (doubly terminated *LC* filters) with low element sensitivity that are being developed by Per Löwenborg. We have developed techniques to design *LC* filters with a magnitude response with diminishing ripple that have much lower sensitivity than classical approximations. Further, we have developed *LC* diplexers that have an order of magnitude lower element sensitivity than classical approximations. These two approaches will in this project be combined to achieve even lower sensitivity with an expected improvement in the dynamic range.

These *LC* filters are not implemented as such. Instead they are recognized as a system of differential equations, with very special properties, that are implemented by using an active network. This network, if properly designed, inherits the low sensitivity of the *LC* filter. This system of differential equations can be simulated using many different techniques as well as many types of active components. Hence, we need to analyse and compare a large number of alternatives. Further we need to develop design guidelines for design of such active filters with optimized dynamic range. This part forms the core of the project.

B. Efficient Implementation Tool

When implementing an analog filter a considerable amount of time need to be spent in the layout phase whereas the physical layout of digital circuits to a large extent is automated, i.e., the layout of analog filters is still a manual, time-consuming task. Further, analog filters are highly sensitive to parasitic elements associated with the placement of building blocks and the interconnection wires. It is difficult to manually create, for example, a routing channel and at the same time take all the aspects of interference and parasitic effects between the analog signals into account. Hence, this phase of the design generally requires an experienced analog layout expert. By using an automated design approach in conjunction with a knowledge-bank we believe that these problems can be alleviated. A layout automation approach also gives the possibility of taking a substantial amount of design parameters into the layout phase than what could be done using a manual implementation.

In order to support and obtain an efficient implementation route we have therefore started to develop a highly structured way of implementing integrated active and switched-capacitor filters. An efficient filter layout tool is being developed within this project because we need not only to experimentally verify our theoretical findings, but also because different filter implementations need to be implemented using the same technique in order to allow comparison. Further such a tool will vastly increase the feasibility to evaluate suitable candidates for low-noise, low-distortion filter structures. The design time can be expected to be significantly reduced and the tool will enable a comparison of filter structures under as fair conditions as possible. This phase of the project has already started and a first generation active filter layout tool is expected at the end of 2000.

C. Active Components

High performance active amplifiers, e.g., operational amplifiers, transconductors, transresistances, current conveyors, etc. must of course be developed and experimentally verified. This work will be done in cooperation with Robert Hägglund which work on tuning and controlling the active components using digital signal processing techniques.

D. Tunig and Control of Integrated Active Filters

Integrated active filter must be tuned using on-line techniques. We are convinced that this area is not adequately developed and significant gain can be achieved by combining filter structures and digital signal processing techniques. The tuning strategy may in the filter bank case exploit higher level information, i.e., between the different channels. Note that in one of the main target applications for analog filters is A/D converters in which we inherently have access to signals in the digital domain.

5. STUDENT

The following new student, which is highly qualified, Emil Hjalmarsson is currently in the final stage of his final year project. Hjalmarssons work involves the development of an automatic layout generator for both active and SC filters and filter banks. This tool is an important vehicle for the experimental work that is an integral part of this project.

6. SUPERVISORS

Supervisors for this project are Professor Lars Wanhammar and Universitetslektor Håkan Johansson.

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