A Bibliography of the Work Done on Externally-Linear-Internally-Nonlinear Circuits during 1979-2014

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Abstract There is a continued demand of analog circuits which are capable of operating at low supply voltages and have low-power consumption and large dynamic range. There are several techniques of designing circuits satisfying such requirements a majority of which fall into the general category of *externally-linear-internally-nonlinear* (ELIN) circuits. In this paper, we present a bibliography of ELIN circuits which covers log-domain, exponential state-space domain, square root domain and other related circuits, based upon the work done during 1979 to 2014. It is hoped that this compilation (with a brief overview) should be useful to research scholars, educators, students, practicing engineers and anybody who is interested in knowing about the current state-of-the- art of log domain, translinear and square root domain circuits.

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1. A Brief Overview of ELIN Circuits

The log-domain circuits are based on natural logarithmic relation between the voltage and current of diodes and between base-emitter voltage and collector current of bipolar junction transistors. The first log-domain filter circuit was proposed by Adams in 1979 [1]. Adams conceived the first ever log-domain filter as *a circuit, composed of both linear and non-linear elements, which, when placed between a log converter and an anti-log converter (in the 'log-domain'), caused the system to act as a linear filter*. Thus, Adams circuit was also the first externally linear and internally nonlinear (ELIN) circuit, demonstrating the compressing and expanding (companding) technique.

The log-domain filters are also recognized as translinear (TL) filters. The TL filters are essentially dynamic translinear circuits, which are based upon the *dynamic translinear principle* which is inherited from the conventional *static translinear principle*, formulated by Gilbert in 1977 [2].

The last few decades have witnessed considerable interest of researchers in realising linear analog signal processing employing ELIN circuits. A number of ELIN circuits are realized by using companding techniques. Tsividis [3] showed the advantages of syllabic companding in signal processing. The log-domain circuits, dynamic translinear circuits, square-root-domain circuits

and syllabically companding filters all are the subsets of ELIN circuits.

The TL filter concept was reinvented in 1990 by Seevinck [4] who coined the term *Current-mode companding* and also introduced the first class-AB integrator. Both Adams [1] and Seevinck [4] however, proposed first-order filters and hence, these ideas unfortunately, did not attract the required attention of the researchers for many years. The idea of log-domain filtering actually took off in 1993, when Frey [5] demonstrated that higher-order log-domain filters can be systematically synthesized using state-space techniques, in which BJTs were directly used to realize the log-domain filters by mapping from state-space linear differential equations. Furthermore, Frey also proposed 'Exponential State-space Filters' in [6], and showed that this technique is also suitable for high frequency applications [9]. After that many researchers started taking interest in log-domain/translinear circuits. In 1994, Toumazou, Ngarmnil and Lande [7] proposed the first log-domain filters for implementation in MOS technology. However, the first experimental results of log-domain filters were published by Perry and Roberts in [12] in 1995 who also proposed an alternative synthesis method based on the simulation of LC ladder filters. The first experimental results of MOSFET-based circuit were presented by Ngarmnil, Toumazou and Lande [11] in 1995. On the other hand, the first application of the underlying design principle for the realization of an oscillator was proposed in 1995 by Pookaiyaudom and Mahattanakul [10].

In syllabic companding, the gains of the compressor and expander are adjusted according to slowly varying characteristic of the signal envelope or power [3,14,87].

Log-domain or dynamic translinear circuits are the examples of instantaneous companding circuits but the true instantaneous companding in log domain circuits is required to operate in class B or class AB [4,8,23,31,49,67, 69,72,74,77,81,84,91,92,94,125,126,40,153,171,181,187, 191]. Both the type of circuits are suitable to implement linear and nonlinear differential equations and several synthesis approaches have been advanced by the various researchers on their own preferences such as, the state-space methods as in [5,8,13,19,50,51,64,66,77,156,160, 171,186,181,188], wave active filter concepts as in [131, 164, 173, 203], signal flow graph based approaches as in [12, 22, 52, 53, 110], leap frog designs as in [38,158,173], synthesis based on Bernoulli operator as in [33,64,68,79], modular design approaches as in [35,70], linear transformation based methods as in [21,152,175], approaches based upon simulation of LC ladders as in [22,52,97,142,154,164,166,195], unified matrix method as in [96,133], Taylor series based design as in [73], image parameter methods as in [44] and Impedance scaling based method as in [195].

Initially, log-domain circuits employed only BJTs and capacitors but subsequently it was recognized that such circuits may also be realized by using MOS transistors as well when they are operated in subthreshold region or weak inversion, as in [7,47,65,69,71,74,80,86,89,94,97, 118,136,137,139], BiCMOS technology as in [11,16,31, 32,44,46,69,138,177,178], using lateral bipolar transistors as in [95], using floating gate MOS (FGMOS) transistors as in [125,126,129,165,191] and using multiple input translinear elements as in [99,135]. Researchers have also found scope of using Darlington topology in log-domain circuits to improve gain [151].

Many different approximation techniques have so far been used to realize log domain/translinear filters such as Chebyshev [12,16,22,31,46,53,84,86,97,154,157], Elliptic [21,22,110,181], Bessel [162,179] and Butterworth [38,58,132]. These filters have been realized by using the cascaded-biquads approach, methods based upon simulation of LC ladders or using multiple-feedback topologies. Besides filters and oscillators, work has also been done on realizing integrators [15,17,26,38,43,72,194] and differentiators [15,108] which are the basic building blocks of analog circuit synthesis.

Apart from normal filter realization techniques, researchers have also given attention on filters using common mode feedback topology [130], multiple feedback *follow the leader feedback* (FLF) topology [49, 168], inverse-follow-the leader-feedback approach [53] and wavelet based filter designs [113,143,170].

Other than conventional filters, such as those presented in [146,187], the log-domain/dynamic translinear techniques have also been used in a number of other applications, such as realization of oscillators [10,13,27,32,56,67,92,101,119,169,189,197,205,211], PLL [32,60], RF applications [19], syllabic companding filters [36,42,58,102], RMS detectors [18,147], RMS-DC converters [24,30,41,62,177,204], ΣΔ A/D convertors [122], pulse duration modulation (PDM) circuits [114] and adaptive filters [28,111,129,140,165,201].

A number of researchers have also carried out noise analysis and the analysis of other second order

effects/transistor non-idealities; for instance, see [34,37,45, 48,50,55,59,61,75,78,81,83,106,109,116,182,199,202].

The circuits containing MOS transistors operating in the quasi-quadratic law (or strong inversion) are called square-root domain circuits [25,57,124]. Exponential State-Space circuits [6,9,23], Sinh domain circuits [6,23,167], Tanh domain circuits [6,23,167], circuits with Piecewise-Linearization [63] and the circuits having voltage dependent capacitors [63] are few more examples of ELIN circuits.

In conclusion, the log-domain/translinear circuits have attracted a great deal of technological interest. Such circuits are useful for realizing high performance current mode linear and nonlinear signal processing and are highly suitable for VLSI implementation because of employing only transistors and capacitors and offering several of the following advantages such as electronic tunability of the parameters of the realized functions, use of low-voltage supply voltages, low-power consumption, extended dynamic range, low noise, low third order intermodulation distortion and low total harmonic distortion, etc.

It is hoped that the bibliography presented in this communication should be useful to research scholars, educators, students, practicing engineers and anybody who is interested in knowing about the current state of the art of log domain, translinear and square root domain circuits and their applications.

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