

**A STUDY OF TRANSVERSAL FILTERING
USING CHARGE TRANSFER DEVICES**

by

NAVIN KUMAR KAPUR

Department of Electrical Engineering

A Thesis Submitted
in Partial fulfilment of
the requirement of the Degree of
DOCTOR OF PHILOSOPHY

to the

INDIAN INSTITUTE OF TECHNOLOGY, DELHI

January 1982

CERTIFICATE

This is to certify that the thesis entitled, ' A Study of Transversal Filtering Using Charge Transfer Devices' being submitted by Navin Kumar Kapur to the Department of Electrical Engineering, Indian Institute of Technology, Delhi, for the award of degree of Doctor of Philosophy is a record of bonafide research work carried out by him under my supervision and guidance and in my opinion it has reached the standard fulfilling the requirements of the regulations relating to the degree.

The results contained in this thesis have not been submitted to any other institution for the award of any degree or diploma.

S.C. Dutta Roy

(S.C. Dutta Roy)
Professor of Electrical Engineering,
Indian Institute of Technology, Delhi.

ABSTRACT

The capability for design and manufacture of large scale integrated (LSI) circuits which contain both analog and digital circuitry on the same chip has made possible self-contained monolithic sampled data filters suitable for a wide variety of applications. Three filter structures are prominent - the CTD (CCD and BBD) transversal, the switched capacitor ladder and the CCD passive recursive. An important application for CTD transversal filters, in particular, is in spectrum analysis using convolutional algorithms such as the chirp z-transform (CZT) and the prime transform (PT).

In this thesis we have proposed a number of techniques for improving the performance of CTD signal processors using the transversal architecture. The main concern has been increase in response accuracy, dynamic range and bandwidth and, reduced chip area and power consumption; in addition we have suggested techniques for the realization of DFT processors with greater versatility and faster throughput (i.e. computation rate) than is possible at present. We have in fact aimed at what can be called an analog version of the FFT i.e. a fast CZT or fast PT.

We have derived analytical expressions for the error in frequency response due to the shift in the pole and zero locations, caused by charge transfer inefficiency (CTI); these

expressions are explicitly in terms of the polar coordinates of the pole/zero. We have also derived expressions for the coefficient sensitivity of phase response and group delay.

For frequency selective filters, a new technique has been proposed in this thesis for implementing the tapweights, in which the fraction of the signal charge sensed is larger than that sensed with conventional techniques. This results in a reduced coefficient sensitivity and a smaller insertion loss. In addition the output sensing circuitry gets simplified, thus requiring smaller area and reduced power.

For the realization of CTD based spectrum analyzers, we have proposed a number of convolutional architectures by which the computation can be performed using a smaller number of filter stages i.e. fewer number of transfers and multiplies. There is a direct saving in chip area and power consumption and smaller errors due to charge transfer inefficiency (CTI); there is also a significant increase in dynamic range, and the maximum frequency of operation. In addition we have proposed techniques for (i) compensating for CTI, (ii) minimizing errors due to dark current and (iii) implementing the sliding prime transform.

ACKNOWLEDGEMENTS

I express my deep sense of gratitude to Professor S.C. Dutta Roy for his constant encouragement and critical and inspiring supervision of the entire work. Any compliments to him can only be inadequate.

I gratefully thank Professor A.B. Bhattacharyya for his very keen interest, support and constant encouragement throughout the course of the work. I owe him a lot.

I am greatly inspired by Dr. J. Vasi; I sincerely thank him for his very keen interest and many useful discussions.

My sincere thanks to the Head, Centre for Applied Research in Electronics (CARE) for being accorded the various facilities and the spare time to carry out the research work. I sincerely hope that this work will be useful for the various projects in the Centre.

I am grateful to Professor J. Mavor, Dr. M.A. Jack and Dr. C.F.N. Cowan of the Department of Electrical Engineering, University of Edinburgh for many useful discussions and for their assistance, cooperation and support in carrying out the experimental work. I thank the Head, Wolfson Microelectronics Institute for the use of the facilities. I take this opportunity to thank the Department of Electronics, Government of India and the British Council for their financial support.

I thank Dr. B. Mathur and Professor D. Nagchoudhuri for their continued interest and assistance.

I recall the keen interest and support extended by a large number of my friends and colleagues. The excellent work spirit in CARE has been a very great motivating factor. My thanks to Dr. U.K. Chakrabarti and Dr. Sudhir Chandra for their help whenever I needed it.

I acknowledge the numerous tremendously useful discussions with S.K. Madan and L. Shankarnarayan. These have contributed greatly to my understanding of devices and circuits.

I am very grateful to Rajinder Singh, L. Shankarnarayan, V.R. Balakrishnan, K.S. Chari, S.K. Madan and R.K. Singh for their assistance in compilation of the thesis.

I thank Mr. V.P. Gulati and Mr. R. Kapoor for their painstaking typing and drafting.

I have no words to thank my family members for their enormous encouragement, assistance and patience without which it would not have been possible to carry out this work.

At this point I must state that my debt to the starving millions of my countrymen defies description or acknowledgement.

LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|-----------------|---|
| CTD | : Charge transfer device |
| CCD | : Charge coupled device |
| BBD | : Bucket brigade device |
| CTI | : Charge transfer inefficiency |
| PTF | : Programmable transversal filter |
| FTW | : Fixed tapweight |
| SC | : Switched capacitor |
| DFT | : Discrete Fourier transform |
| DCT | : Discrete cosine transform |
| CZT | : Chirp z-transform |
| PT | : Prime transform |
| CDO | : Code dependent offset |
| SE, SSE, DSE | : Split electrode, single split electrode, double split electrode |
| Op amp | : Operational amplifier |
| lpf | : Lowpass filter |
| bpf | : Bandpass filter |
| ϵ | : Charge transfer inefficiency |
| η | : Charge transfer efficiency |
| r, θ | : Polar coordinates of pole/zero in z-plane |
| z^{-1} | : Unit delay operator |
| f_c, T_c | : Clock frequency, period |

f_p, f_s : Passband edge, stopband edge
 Δf : Transition width; $(f_s - f_p)/f_c$
 R : Primitive root
 $f(n), g(n), x(n)$: Signal under test (SUT)
 $a(n)$: SUT multiplied by chirp for the CZT algorithm
and reordered SUT for the PT algorithm
 $X(k)$: Discrete Fourier transform of $x(n)$
 $X_s(k)$: Sliding discrete Fourier transform of $x(n)$
 Q : Tapweight quantization step size
 $h_i^*(n)$: Unnormalized weighting coefficients (full precision)
 $h_i(n)$: Normalized weighting coefficients (full precision)
 $h(m)$: Actual (realized) weighting coefficients of
filter
 $H(z)$: z-transform of $h(m)$
 $H(e^{j\omega})$: Frequency response of filter with tapweights
 $h(m)$.

CONTENTS

| | | PAGE |
|-----------|--|------|
| | CERTIFICATE | |
| | ACKNOWLEDGEMENTS | |
| | ABSTRACT | |
| | LIST OF SYMBOLS | |
| CHAPTER-1 | INTRODUCTION REVIEW AND SCOPE .. | 1 |
| 1.1 | Introduction .. | 1 |
| 1.1.1 | CTD Transversal Filter Preliminaries .. | 3 |
| 1.1.2 | Comparison of CTD and Digital Filtering Techniques .. | 7 |
| 1.2 | CTD Transversal Filters - A Review of Design Considerations .. | 8 |
| 1.2.1 | Choice of Device and Weighting Technique .. | 8 |
| 1.2.2 | Performance Limitations of CTD Transversal Filters .. | 15 |
| 1.2.2.1 | Nonidealities in signal inputting .. | 15 |
| 1.2.2.2 | Nonidealities in charge transfer and storage .. | 16 |
| 1.2.2.3 | Weighting, summing and post-processing - a detailed discussion .. | 24 |
| 1.2.3 | Concluding Remarks and Formulation of Problem for Further Study .. | 35 |

| | PAGE |
|-----------|---|
| 1.3 | Spectrum Analysis Using CTD Transversal Filters .. 36 |
| 1.3.1 | Chirp z-Transform Algorithm .. 36 |
| 1.3.2 | Prime Transform Algorithm .. 40 |
| 1.3.3 | Operational Aspects and Performance Limitations of CTD Based DFT Processors.. 42 |
| 1.3.4 | Applications of CTD Based DFT Processors .. 46 |
| 1.3.5 | Comparison Between the Chirp z-Transform and the Prime Transform Algorithm .. 47 |
| 1.4 | Architectures for Programmable Transversal Filters (PTF) .. 48 |
| 1.5 | Scope and Organization of the Thesis .. 56 |
| CHAPTER-2 | EFFECT OF CHARGE TRANSFER INEFFICIENCY ON THE FREQUENCY RESPONSE OF CTD BASED (TRANSVERSAL AND RECURSIVE) FILTERS .. 60 |
| 2.1 | Introduction .. 60 |
| 2.2 | Expressions for Error in the Magnitude and Phase of the Transfer Function due to an Arbitrary Pole or Zero .. 61 |
| 2.2.1 | Computation of Error in the Magnitude of the Transfer Function .. 62 |
| 2.2.1.1 | Error due to zeros .. 62 |
| 2.2.1.2 | Error due to poles .. 64 |
| 2.2.1.3 | Discussion .. 66 |

| | PAGE |
|-----------|--|
| 2.2.2 | Computation of Error in the Phase of the Transfer Function .. 71 |
| 2.2.2.1 | Error due to zeros .. 71 |
| 2.2.2.2 | Error due to poles.. 72 |
| 2.2.2.3 | Discussion .. 73 |
| 2.3 | Examples of Error Calculations for GTD Based Filters .. 75 |
| 2.4 | Concluding Discussion .. 80 |
| | Appendix 2.1 .. 82 |
| CHAPTER-3 | COEFFICIENT SENSITIVITY OF CHARGE TRANSFER DEVICE TRANSVERSAL FILTERS .. 83 |
| 3.1 | Introduction .. 83 |
| 3.2 | Nature and Origin of Tapweight Errors .. 85 |
| 3.3 | Computation of Error in Frequency Response due to Tapweight Errors .. 89 |
| 3.3.1 | Effect of Weighting Coefficient Errors on Magnitude Response .. 89 |
| 3.3.2 | Comparison with Previously Reported Results .. 92 |
| 3.3.3 | Effect of Weighting Coefficient Errors on Phase Response and Group Delay .. 95 |
| 3.4 | A Method for Reducing the Coefficient Sensitivity in GTD Transversal Filters - the Modified form Realization .. 97 |

| | | PAGE |
|-----------|---|------|
| 3.5 | Lowpass Filters with Improved Performance .. | 98 |
| 3.6 | Bandpass/Bandstop Filters with Improved Performance .. | 110 |
| 3.7 | Differentiators with Improved Performance .. | 122 |
| 3.8 | Effect of Tapweight Errors on the Modified Form Realization .. | 129 |
| 3.9 | Concluding Discussion .. | 139 |
| | Appendix 3.1 .. | 142 |
| CHAPTER-4 | SPECTRUM ANALYSIS USING CTD TRANSVERSAL FILTERS .. | 151 |
| 4.1 | Introduction .. | 151 |
| 4.2 | Methods for Implementing a Circular Convolution .. | 154 |
| 4.3 | Computation of the Discrete Cosine Transform Using a CCD Programmable Transversal Filter .. | 166 |
| | 4.3.1 Implementation .. | 166 |
| | 4.3.2 Experimental Results .. | 170 |
| 4.4 | Discussion and Conclusions .. | 172 |
| CHAPTER-5 | IMPROVING THE PERFORMANCE OF CTD BASED SPECTRUM ANALYZERS .. | 177 |
| 5.1 | Introduction .. | 177 |
| 5.2 | Implementation of the CZT and PT Algorithms Using CTD Programmable Transversal Filters .. | 178 |

| | PAGE |
|--|------|
| 5.2.1 Chirp z-Transform Algorithm .. | 181 |
| 5.2.2 Prime Transform Algorithm .. | 183 |
| 5.2.3 A Potential Application of PTF Based DFT Processors .. | 188 |
| 5.3 Reduction in the Number of Stages Required for Spectrum Analysis .. | 190 |
| 5.3.1 Prime Transform Algorithm .. | 191 |
| 5.3.1.1 Implementation using PTF's .. | 191 |
| 5.3.1.2 Implementation using fixed tapweight filters .. | 199 |
| 5.3.2 Chirp z-Transform Algorithm.. | |
| 5.3.2.1 Implementation using PTF's .. | 203 |
| 5.3.2.2 Implementation using fixed tapweight filters .. | 211 |
| 5.4 Effect of Charge Transfer Inefficiency on the Performance of CTD Based DFT Processors .. | 214 |
| 5.4.1 The Charge Transfer Model .. | 215 |
| 5.4.2 Examples .. | 217 |
| 5.4.2.1 CZT implementation by Method A .. | 217 |
| 5.4.2.2 CZT computation by Method B .. | 220 |
| 5.4.2.3 Sliding CZT using fixed tapweight filters .. | 221 |

| | PAGE |
|--|---------|
| 5.4.2.4 Sliding CZT using PTF's .. | 221 |
| 5.4.2.5 Normal CZT, Method C implementation .. | 222 |
| 5.4.2.6 Normal CZT, IDFT computation using Method C1 .. | 223 |
| 5.4.2.7 Prime transform algorithm .. | 223 |
| 5.4.3 Results of Computer Simulation of the Effect of CTI on the Perform- ance of CTD Based DFT Processors .. | 224 |
| 5.4.4 Compensation for CTI in CTD Based DFT Processors .. | 249 |
| 5.5 Realization of Matched Filters and CTD Based DFT Processors Using the 'Modified Form' for Implementing the Tapweights .. | 250 |
| 5.5.1 Realization of Matched Filters in the Modified Form .. | 252 |
| 5.5.2 Realization of Chirp z-Transform Processors in the Modified Form .. | 253 |
| 5.6 Concluding Discussion .. | 257 |
| CHAPTER-6 CONCLUSIONS .. | 259 |
| 6.1 Main Results of the Thesis .. | 259 |
| 6.2 Suggested Further Work .. | 263 |
| REFERENCES .. | 265-286 |
| LIST OF PUBLICATIONS .. | 287 |