A CCD ADAPTIVE FILTER WITH COEFFICIENT COMPENSATION OF CHARGE TRANSFER LOSS

G.D. Cain*, V. Cappellini**, E. Del Re**, G. Fanfani** and L. Fini**

1. INTRODUCTION

CCD filters are of increasing practical interest for signal processing. In particular variable or adaptive filter structures that are required for many signal processing applications, such as equalization, adaptive receivers, and tracking, are feasible. A problem that arises in using CCD structures for these applications is that of "charge transfer loss", which degrades performance.

In this paper some structures of variable CCD filters are first considered and then a technique is described for compensation of the charge transfer loss phenomenon.

2. TECHNIQUES FOR VARYING COEFFICIENT WEIGHTS IN A CCD FILTER

Several different techniques can be applied in order to obtain automatically varying coefficient weights in a CCD filter.

The first consists of employing variable transconductance devices in the weighting networks at the CCD's taps. In such a way coefficient weight values can be controlled by suitable current or voltage signals [1].

A second method is to use coefficient weights implemented by multiplying digital-to-analog converters (DACs). Each DAC output is proportional to the product of the value of a binary word at the digital input and a reference voltage. Coefficient weights can be represented digitally and the analog voltage samples at the CCD's taps drive the reference inputs of the DACs [2]. This method can be modified by recirculation so that a single DAC can serve to implement multi-coefficient filters.

Multiplying DAC-based methods are obviously eminently suitable for the interfacing of the filter to a digital controller whose job is to compute or at least to generate the filter coefficient weights. A block diagram of the structure described is shown in Figure 1.

Obviously, the flexibility of the filter with digitally implemented coefficients can be enormously enhanced by employing a microprocessor as a controlling unit.

A microprocessor-controlled filter architecture is shown in Figure 2. The variable filter of Figure 1 is inter-

* Polytechnic of Central London, U.K.
** Istituto di Elettronica, University of Florence, Italy.

faced by multiplexers and latches with a microprocessor which has the task of controlling the filter transfer function. Suitable timing signals from the filter clock are employed in order to synchronize the transfer of the coefficient values from the multiplexer to the filter via the latches.

Such a system can be of great interest in experimental applications where a number of different transversal filters with different transfer functions are to be implemented; each filter characteristic can of course be wholly software controlled.

Utilization of an "intelligent" control unit permits the filter structure to be used in a role more demanding than simple variability, i.e. for adaptive filtering. The microprocessor can, in fact, be programmed so that the coefficient computing strategy is determined on the basis of information from the filter operating environment. In the simplest case the microprocessor can be equipped with an input analog-to-digital converter by means of which it can receive the filter output samples from some external adaptation reference source (see Fig. 3). A suitable adaptive algorithm can then compute (in real time for many applications) the coefficient weights depending upon the reference signal and/or the filter output signal [3].

3. TECHNIQUE TO COMPENSATE CHARGE TRANSFER LOSS

We are involved in implementation of an interactive microprocessor programmable system which allows an operator to define a filter with desired characteristics by specifying only a few parameters, computes the filter coefficient weights and transmits them to the filter. The operator has only to select a filter structure from a given set (e.g. low-pass filter, band-pass filter, Hilbert transformer, differentiator and so on) and then supply the appropriate parameters needed for the coefficient computing algorithm. An early version of this variable filter system has been presented in [2]; more recently greater flexibility was afforded by using a minicomputer programmed in FORTRAN to control a 32-tap device. Efficient operator command dialog, coupled with interactive features like joystick control of such filter parameters as filter passband widths and centre frequencies, have demonstrated the desirability of rapid and convenient means of communication with the filter system when in a variable, but non-adaptive, mode of operation. The eventual system is to be totally microprocessor based. Experiments with adaptive filtering, using in particular the window algorithm [11], are underway.

The coefficient computation can be performed by anyone of the techniques well-known in digital filtering literature. The most suitable technique seems to be the use of the method of windows [4], [5], due to its simple algorithmic implementation. As a further degree of freedom the operator is able to select, in a predefined set, the desired window.

The degree to which window-designed filters fall below the performance of those produced by various optimal design strategies is often negligible (and can, in any event, be predicted [4]) and is frequently offset by the operational ease, algorithm simplicity, and calculation speed characteristic of windowing approaches. Unfortunately the design problem does not solely centre upon the best design of perfect filters; recognition of the practical limitations of the final filter must colour our design approach.

As is well-known in the literature [6], [7], [8], [9] CCD transversal filter performance can be degraded due to the loss in charge packet transfers between contiguous cells (Charge Transfer Inefficiency). Such effects, under reasonable simplifying assumptions, can be compensated by suitable steps at filter design time [6], [8], [10].

It has been proven that compensation of CTI effects on filter transfer functions may be obtained by modifying the nominal coefficient weights. The new value h'_k of a generic coefficient for the compensated filter can, in fact, be iteratively derived as a function of the coefficients h'_j (with $j = 1, \ldots, k-1$) and of the nominal value h_k [6], [10].

A simpler expression has been derived in [8] under the assumption that the relation $N\varepsilon \ll 1$, where N is the number of CCD cells and ε is the CTI value, holds. In such a case the compensated value h'_k can be obtained as a function of the preceding coefficient h'_{k-1} and of the nominal value h_k:

$$h'_k = \frac{1}{1 - k\varepsilon} \left[h_k - \varepsilon(k-1)\, h'_{k-1} \right] \qquad (1)$$

The effects of compensation on amplitude transfer function errors of typical low-pass filters are shown in Figure 4. The results shown have been obtained by digital computer simulation.

In order to perform the described CTI compensation in actual filtering applications the coefficient computation algorithm implemented on the microprocessor is designed in order to apply the coefficient compensation formula (1) as a follow-on to window design of the initial coefficient set.

4. MICROPROCESSOR CONTROLLED FILTER HARDWARE STRUCTURE

In the design of the microprocessor controlled filter the need has been recognized for a control unit with floating-point arithmetic facilities and a computing speed which would be compatible with real time operation in adaptive applications.

The implementation of a transportable software (or firmware) floating-point library would have entailed a considerable programming effort, since subprogram libraries meeting our specific requirements are not readily available and, on the other side, the system needed to employ a fast and precise CPU, e.g. a sixteen bit unit. Because of these and other considerations it has been decided to use a normal eight bit microprocessor equipped with a fast external arithmetic unit for extended precision and floating-point operation. In such a way both software implementation and computing speed problems have been cost-effectively solved.

In Figure 5 the global filter control unit block diagram is shown. The system includes a Rockwell 6502 CPU with 4 Kbytes of RAM, a ROM resident monitor, a keyboard, alphanumeric display and a small thermal printer for interactive I/O. One of the CPU I/O ports is employed for the Advanced Micro Devices AM 9511 arithmetic unit and a second port controls the CCD filter interface.

A further I/O port is provided as data input channel for adaptive structure implementation.

It is believed that the initial hardware configuration will provide sufficient operational capabilities and flexibility for general purpose use and will serve as a basis for performance evaluation of a variety of adaptive filtering approaches aimed at selected signal processing applications.

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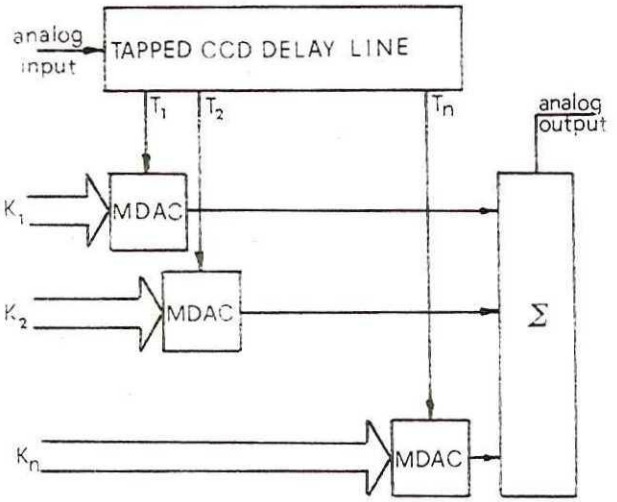

Fig. 1

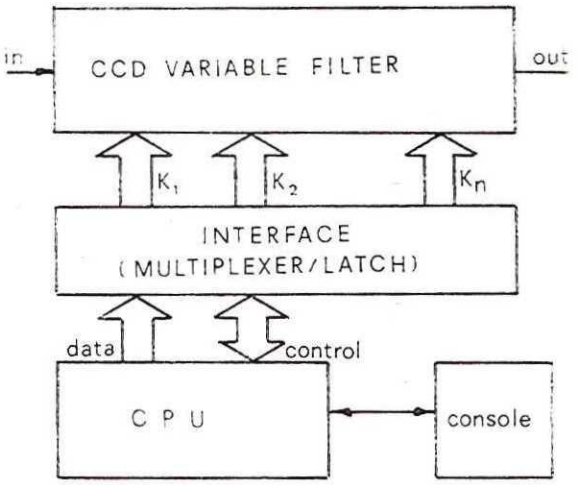

Fig. 2

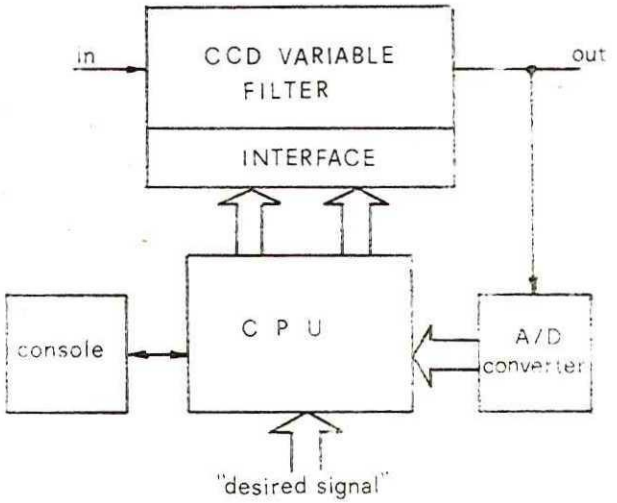

Fig. 3

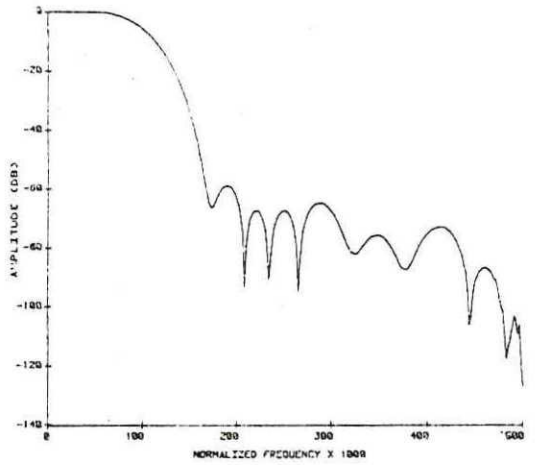

Fig. 4a

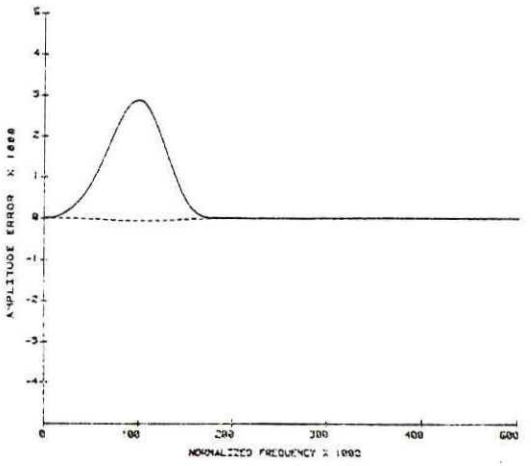

Fig. 4b

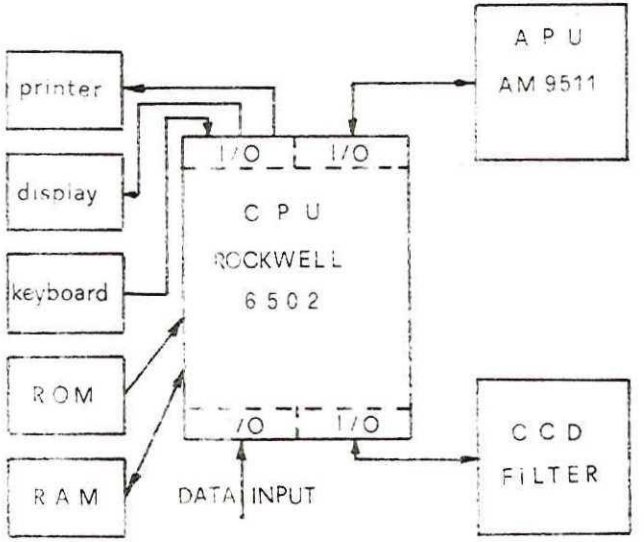

Fig. 5