THE PERFORMANCE OF A CCD SIGNAL AVERAGER CODED TO REDUCE TRANSFER INEFFICIENCY EFFECTS

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ABSTRACT

Averaging a signal containing a repetitive component by recirculation in a delay-line loop is convenient using a CCD delay element but multiple transits through a long line emphasize the spurious components in the output caused by finite transfer inefficiency, which build up much faster than the wanted signal.

A means of containing this effect which does not depend on any assumption of linearity of the signal smearing process is to multiplicatively code the signal before entry to the CCD and to decode the output with a well chosen code sequence. This leaves the signal unaffected but cancels the unwanted residuals after very few circulations. The performance of the averager is considerably enhanced in a way which can be exploited to reduce spurious levels, increase the loop gain or to deal with signals of larger time-bandwidth product.

The theory of this technique is presented to show how suitable codes may be chosen for particular lengths of CCD delay line, and a practical 100 stage system is described for comparison with the theoretical predictions.

INTRODUCTION

A repetitive signal can be enhanced with respect to noise or asynchronous interference by a recirculating delay line integrator where the loop delay matches the known repetition interval and the loop gain determines the memory or integration time constant of the system. Figure 1 shows the basic configuration, and its ideal impulse response.

Realisations of such an integrator using conventional analogue delay lines involve problems of accurate synchronisation of the loop transit time with the signal recurrence interval and requires a purpose built delay line for each application. Digital versions are flexible in this sense and can be synchronised to any repetition rate but involve fairly complex hardware and have limited bandwidth.

CCD equivalents have been studied (ref. 1, 2) since they potentially offer flexibility, bandwidths up to at least a few MHz and economical hardware. However, a practical limit to performance is set by charge transfer inefficiency because of the large number of transfers involved in several recirculations of signals of even moderate time-bandwidth product. This causes spurious contributions in the output which may dominate the signal because the enhancement factor for the smeared (untransferred charge residual) components approximates the square of that for the primary signal. A means of retrieving this situation is to code and then decode the input and output to the CCD delay line so that the secondary components tend to cancel (ref. 3,4). Coding and decoding consists in multiplying samples by code values c_i before entry to the line and by appropriately delayed decode elements $d_i = {}^1/_{c_i}$ after exit. This leaves the primary signal unaffected but secondary and higher order

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components are multiplied by terms $c_i d_j$, $i \neq j$ which can be arranged to 'slip' through the code and accumulate to a very small value after a few circulations. The criteria for choosing an efficient code sequence are:

1. Its length must not be a sub-multiple of the line length.
2. Its length should be short for cancellation after only a few circulations.
3. The code element values should all be near ± 1 to utilise the CCD dynamic range.

Approximate methods exist for finding good codes for such an integrator used either continuously (loop gain $K < 1$) or averaging blocks of signal ($K = 1$ with the signal periodically dumped). These cases are similar since only $K \simeq 1$ is of practical interest. Here we show how a code of length 3 can be derived for the continuous case with K close to unity. Analysis is necessary only for the first order residuals since other orders only arise from them. Once a code is chosen, its exact performance with any value of K, to any order of residual is easily obtained numerically.

SELECTION OF A 3 CYCLE CODE

We assume that the CCD delay unit has N stages so that we must have $N = 3i \pm 1$, where i is an integer, for the code to 'slip' and be capable of cancelling charge residuals. Taking the condition $N = 3i + 1$, subsequent circulations of a particular signal sample will be cyclically coded by sequential code values. If $N = 3i - 1$ the code values occur in the reverse cyclic order.

If we consider a continuous train of short pulses applied to the integrator of figure 2, and if the pulse repetition interval (p.r.i) is precisely equal to the loop delay, then for a code of length 3, the output will be cyclic with a period of 3 p.r.i's. Thus we may determine the effect of coding by analysing the steady state operation with the continuous pulse train input by assuming the output is as shown in figure 3. The coding values are taken as 1, a, b and the decoding values as 1, $\frac{1}{a}$, $\frac{1}{b}$ delayed by N clock periods to restore the original signal.

Assuming that the application of a unit pulse, to the delay unit alone, produces the delayed output pulse followed by the residual effects shown in figure 4 we can determine the integrator output amplitudes by noting from which contributions they originate. The fact that the CCD delay unit alone will not in general give a unit amplitude delayed pulse is allowed for in the analysis by appropriately defining the feedback amplification factor K.

In figure 3 the contributions to P_2, for example, are the input pulse, of amplitude A, and the previous output P_1 which has been coded, delayed by N clock periods, decoded and recirculated with loop gain K. Hence we obtain the equation

$$P_2 = A + P_1 \text{ (code value). (Decode value) } K$$

or $$P_2 = A + KP_1 \qquad \text{..... 1}$$

Similarly

$$P_3 = A + KP_2 \qquad \text{..... 2}$$

and $$P_1 = A + KP_3 \qquad \text{..... 3}$$

for 1, 2 and 3 $$P_1 = P_2 = P_3 = \frac{A}{1-K} = P \qquad \text{..... 4}$$

which is the standard result for an uncoded integrator and shows that the coding has not affected the performance of the integrator.

To obtain an expression for R_{21}, for example, we note that contributions to it are R_{11} delayed by N clock periods and recirulated plus P_1 coded and delayed by N + 1 clock periods, decoded and recirculated. Allowing for the coding and decoding factor, the charge residual factor and the loop gain we get,

$$R_{21} = R_{11}\, a.\, \frac{1}{a} . K + P_1\, 1.\, \frac{1}{a} . \alpha . K = R_{11}\, K + \alpha\, P_1 \frac{K}{a} \qquad \ldots\ldots 5$$

Similarly,

$$R_{31} = R_{21}\, b.\, \frac{1}{b} . K + P_2\, a.\, \frac{1}{b} . \alpha . K = R_{21}\, K + \alpha\, P_2 \frac{aK}{b} \qquad \ldots\ldots 6$$

and

$$R_{11} = R_{31} .1.\ 1.\ K + P_3\, b.\ 1.\ \alpha\ . K = R_{31}\, K + \alpha\, P_3\, bK \qquad \ldots\ldots 7$$

Solving equations 5, 6 and 7 we have on using equation 4 the results,

$$R_{11} = \frac{\alpha PK}{1-K^3} \left\{ b + K \frac{a}{b} + \frac{K^2}{a} \right\} \qquad \ldots\ldots 8$$

$$R_{21} = \frac{\alpha PK}{1-K^3} \left\{ \frac{1}{a} + Kb + K^2 \frac{a}{b} \right\} \qquad \ldots\ldots 9$$

$$R_{31} = \frac{\alpha PK}{1-K^3} \left\{ \frac{a}{b} + \frac{K}{a} + K^2 b \right\} \qquad \ldots\ldots 10$$

Note that without coding a = b = 1 and hence,

$$R_{11} = R_{21} = R_{31} = \frac{\alpha . K}{1-K} = \frac{\alpha AK}{(1-K)^2}$$

This shows that the build up of the residual is by a factor $\frac{K}{(1-K)^2}$ and this is approximately the square of the signal build up factor $\frac{1}{1-K}$ when K is close to unity. This first order residual effect is a serious problem in CCD feedback integrators and we wish to choose coding values to minimise the trouble. The higher order residuals R_{21}, R_{22}, R_{23}, etc., can be obtained by extending this analysis but a code which minimises the first order residual will also minimise the higher order ones.

The first order residual is longest when K is near to unity and therefore we assume this value of K within the brackets in equations 8, 9 and 10. Thus we obtain,

$$R_{11} \simeq R_{21} \simeq R_{31} \simeq \frac{\alpha PK}{1-K^3} \left| b + \frac{a}{b} + \frac{1}{a} \right| \qquad \ldots\ldots 11$$

Thus the first residuals will be minimised by choosing a and b so that $b + \frac{a}{b} + \frac{1}{a} = 0$. This allows a range of values to be used but it is convenient that $a = \frac{1}{b}$ so that the coder and decoder can be similar but cycled in opposite directions. Then we find that a is given by,

$$\frac{1}{a} + a^2 + \frac{1}{a} = 0 \text{ or } a = -\sqrt[3]{2} = -1.2599$$

and therefore b = -0.7937, hence the code sequence 1, -1.2599, -0.7937.

To demonstrate the effectiveness of the code we have proposed, consider the first order residual for K = 0.9. An uncoded integrator with K = 0.9 has first order residuals given by $\frac{\alpha AK}{(1-K)^2} = 90\alpha A$. With the above code the first order residuals

$$R_{11} = -0.2636\,\alpha A$$
$$R_{21} = -7.3805\,\alpha A$$
$$R_{31} = 7.6441\,\alpha A$$

and the worst case improvement is 21.42 dB. The improvement is greater with higher loop gains.

EXPERIMENTAL DEMONSTRATION OF THE EFFECT OF CODING

The integrator of figure 2 has been constructed using the MA 318, a 100 delay stage CCD. The clock rate was 50KHz giving a 2 ms delay and a continuous train of pulses with p.r.i. of 2 ms applied to the input. The operation of the integrator was observed without coding and with the use of the 3 cycle code developed in the previous section, ie 1, -1.26, -0.79.

Figure 5a shows the output of the system with no coding and loop gain of 0.9 which gives an increase of pulse amplitude, due to integration, of 10 times. It will be observed that the first order residual has built up to an unacceptably large level and higher order residuals are also appreciable. The charge transfer inefficiency per transfer is of the order of 10^{-4}.

The output with the code in use is also shown in figure 5b, c, d. This gives expanded traces for three successive output pulses when the loop gain is 0.9. As expected the output residual effects show a repetitive behaviour over 3 pulses and the first order residuals have magnitudes which are consistent with the theoretical results.

It is evident that coding has produced an improvement in performance which makes the system suitable for the integration of repetitive signals. The uncoded integrator system certainly could not be used because the signal waveform would be badly smeared by the residual effects for any useful value of loop gain. Although coding makes possible the use of CCD's in integrator, or other recursive circuits, there are drawbacks which should be noted. The main drawback becomes apparent when unipolar signals are integrated since with coding the CCD must handle bipolar signals with a small increase in amplitude for some of the negatively weighted samples (ie 1.26:1). Thus the dynamic range for the input becomes reduced by a factor of 2.26:1 when the signals entering the coder are considered. Another drawback is the need to provide d.c coupling in all units between the coder and decoder since the 3 cycle code obviously contains a d.c component.

The present experimental system still leaves some room for improvement in respect of waveform imperfections arising from clock waveform and coding spike pick up. Nevertheless we have demonstrated the usefulness of the coding technique which can be exploited to extend the performance of the uncoded system in terms of acceptable CCD inefficiency, increased number of signal samples or the number of repetitions integrated.

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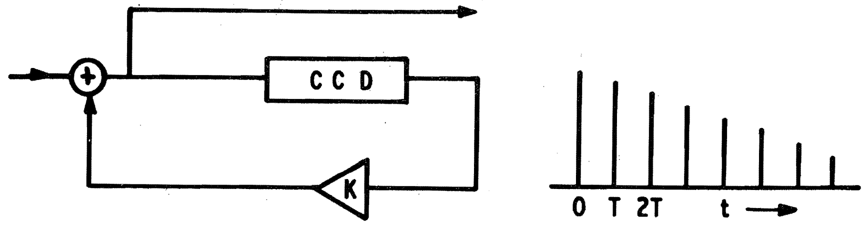


(a) CIRCUIT SCHEMATIC. (b) IDEAL IMPULSE RESPONSE.

FIG. 1.

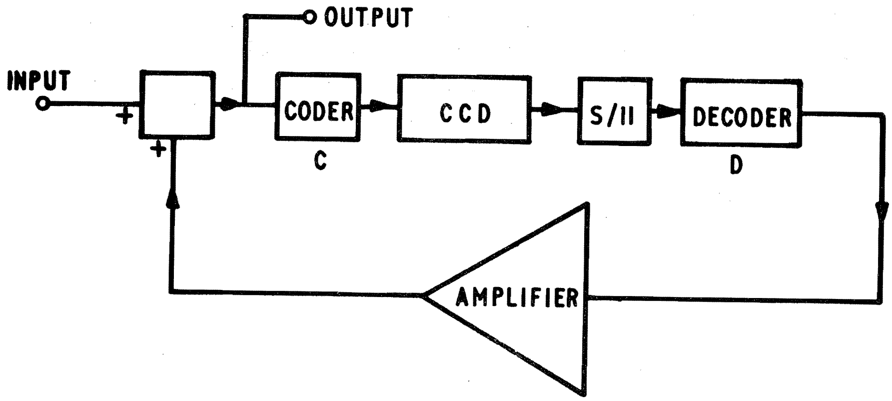


FIG. 2.

CODED C.C.D. INTEGRATOR.

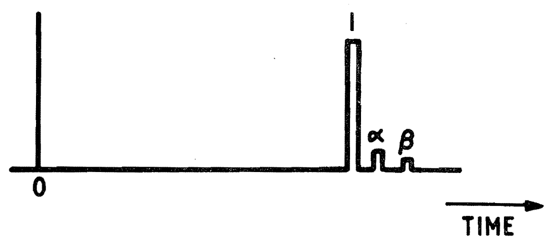


FIG. 4.

PULSE RESPONSE OF C.C.D. DELAY ALONE.

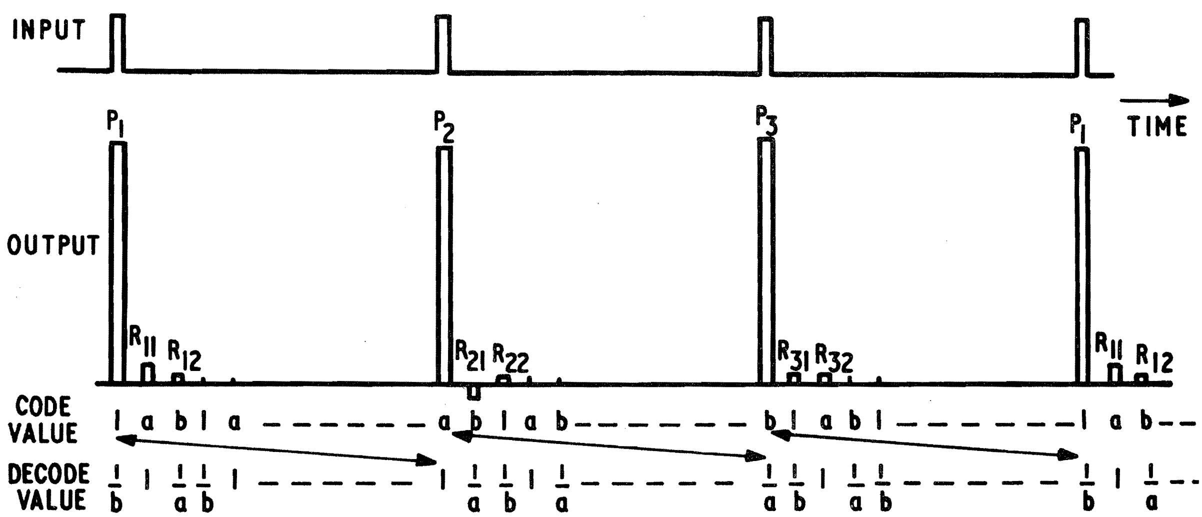


FIG. 3.

INPUT AND OUTPUT FOR 3 CYCLE CODED INTEGRATOR.

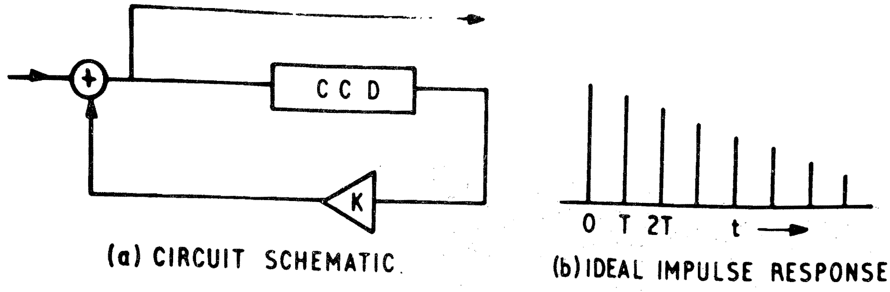


FIG. 1.

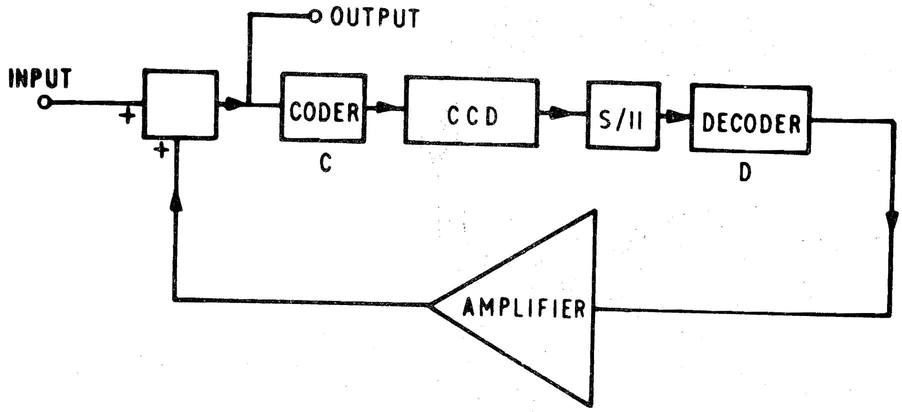


FIG. 2.

CODED C.C.D. INTEGRATOR

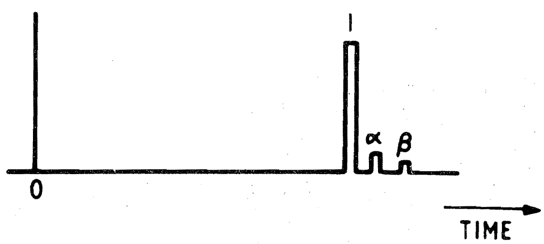
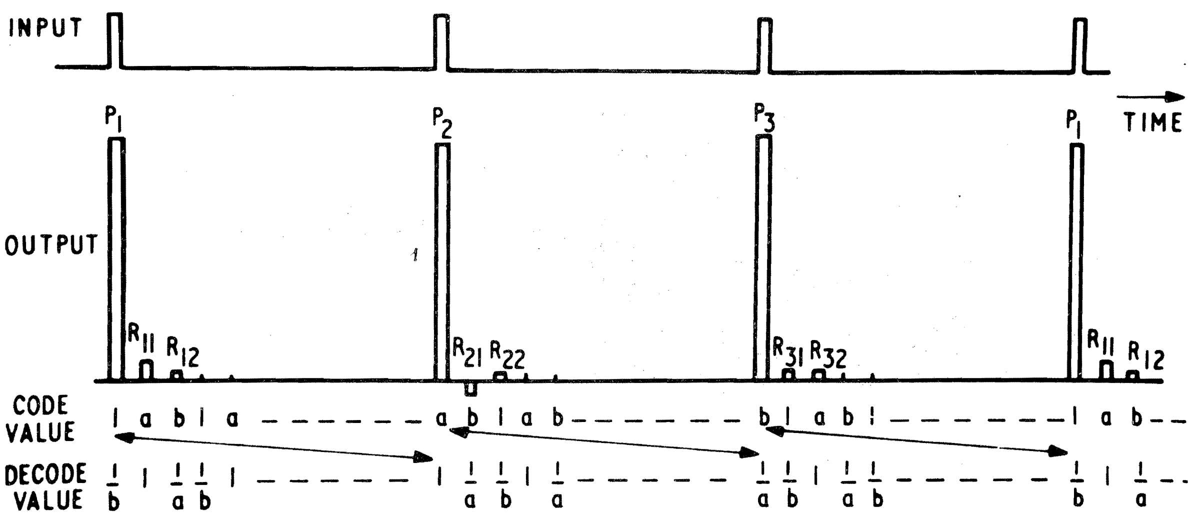


FIG. 4.

PULSE RESPONSE OF C.C.D. DELAY ALONE.



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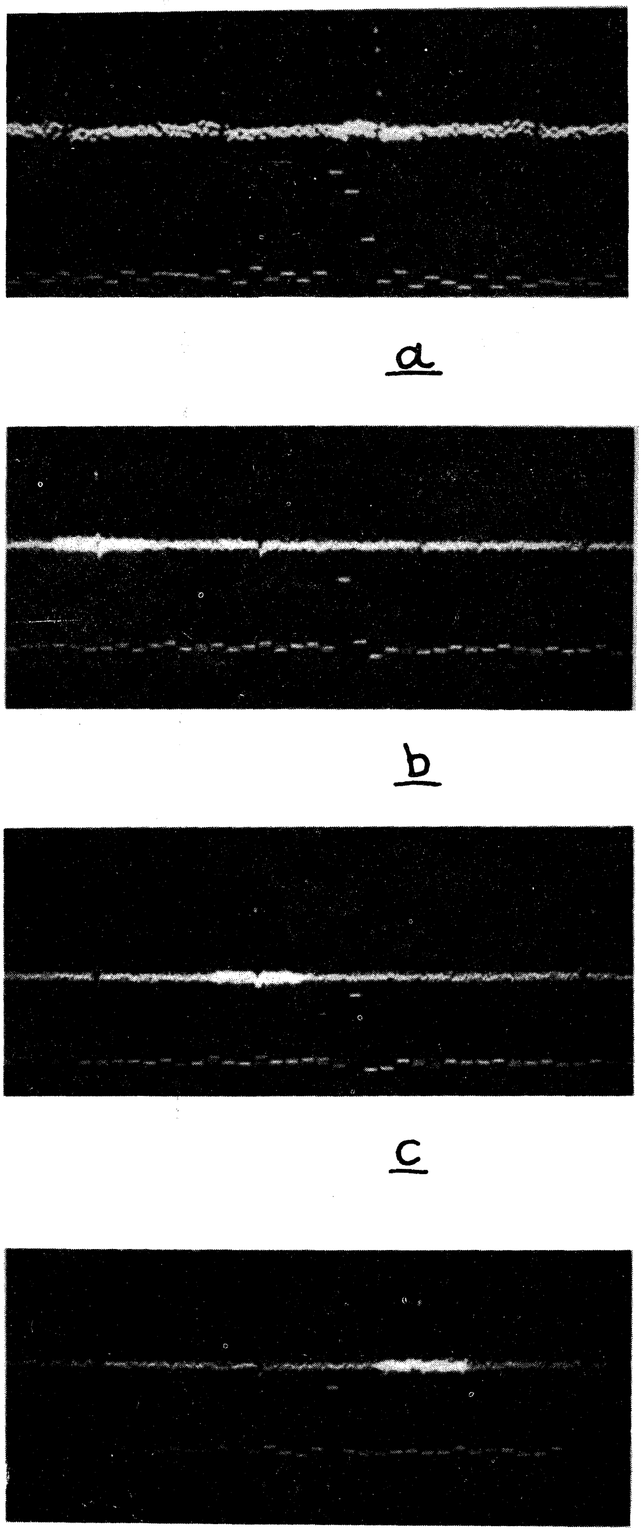

100 mV/cm

a

500 mV/cm

b

500 mV/cm

c

500 mV/cm

d

FIG. 5