AN ANALYSIS OF CCD RECURSIVE FILTERS WITH APPLICATION TO MTI RADAR FILTERS

A. Chowaniec* and G. S. Hobson**

ABSTRACT

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In the implementation of moving target indicator (MTI) radar filters, it has been shown that there is some smearing of the main target signal into the following range bin. This smearing effect is magnified when the doppler frequency approaches the edge of the passband and could be severe in practical filters which require a large number of CCD stages i.e. range bins. These effects are attributed to the presence of feedback loops in the filter design in which spurious signal growth occurs in a similar manner to that in CCD video integrators.

An analysis of CCD video integrators in the time domain gives a detailed account of the growth of secondary signals as a function of loop gain, transfer inefficiency and number of transfers. This paper presents an extension of this analysis to the situation where the input signal has a sinusoidal variation as in the case of an MTI filter with input signal synchronized to the clock. It provides a link between the time and frequency domain analyses of recursive filter devices and the results are applicable to the design of such filter configurations. Some experimental results will be discussed.

INTRODUCTION

Whilst most of the interest in CTD filtering has centered on transversal filters the use of recursive structures has also been demonstrated(1),(2). Although these do not have the linear phase advantage of transversal structures they can provide the desired amplitude response with a lower order filter. Performance limitations of recursive filters include noise, linearity and dynamic range(3) but the principle limitation is feedback coefficient accuracy. Small errors in the coefficients can cause large shifts of the poles of the filter function and there is a danger of instability. The sensitivity of the coefficients to error increases with the order of the filter.

Errors in the coefficients arise from the limited stability and the accuracy with which the feedback loop gain can be realized(4) as well as charge transfer inefficiency(5). In the case of the latter, which is typically 10^{-3} or lower, the effect on the transfer function of the filter is likely to be small in comparison to the gain problem. In recursive filter applications such as video integrators(6) or MTI

* Bell Northern Research, Ottawa, Canada.

** Department of Electronic & Electrical Engineering, University of Sheffield, England.

radar filters[7] however, where the output from the CCD filter is viewed in the time domain, the effect of transfer inefficiency in producing secondary or trailing signals can become a severe limitation.[8]

This paper looks at the effect, in the time domain, of charge transfer inefficiency on a simple recursive structure fed with a sinusoidal input signal. The growth of secondary signals is considered as a function of the input signal frequency and the transfer inefficiency. The results can be simply related to the familiar transfer function of the filter and are applicable to more complex recursive (MTI) filters.

Filter Transfer Function

The transfer function of the simple recursive structure of Fig. 1 can be written in terms of the z transform as

$$\frac{z^{-n}}{1 - Kz^{-n}} \tag{1}$$

where n is the number of ideal delay elements and K is the feedback loop gain. Transfer inefficiency can be taken into account by modelling each element of the CCD as shown in Fig. 2[9]. The CCD transfer function per element can then be written as

$$\frac{(1 - \varepsilon)z^{-1}}{1 - \varepsilon z^{-1}} \tag{2}$$

where ε is the transfer inefficiency per element. For an n element delay this becomes

$$\frac{(1 - \varepsilon)^n z^{-n}}{(1 - \varepsilon z^{-1})^n} \approx (1 - n\varepsilon)z^{-n} \cdot (1 + n\varepsilon z^{-1})$$

and equation (1) is modified to

$$\frac{(1 - n\varepsilon)z^{-n} (1 + n\varepsilon z^{-1})}{1 - K(1 - n\varepsilon)z^{-n} (1 + n\varepsilon z^{-1})} \tag{3}$$

The effect of the transfer inefficiency is to scale and shift the pole of the transfer function.

Time Domain Analysis

The transfer function of Fig. 1 may also be derived by looking at the growth of signals in the time domain. This gives a physically meaningful picture of the growth process as well as the magnitude of the filter output signal after only a finite number of circulations. For an input signal $\cos \omega t$ the output from the ideal delay line is $\cos \omega(t - n\tau)$ where $n\tau$ is the delay time. After one circulation the input to the delay line is

$$\cos \omega t + K\cos \omega(t - n\tau)$$

and after a number of circulations the output builds up as

$$\cos \omega(t - n\tau) + K \cos \omega(t - 2n\tau) + K^2 \cos \omega(t - 3n\tau) \tag{4}$$

The transfer function is then the real part of

$$e^{-j\omega n\tau} (1 + Ke^{-j\omega n\tau} + K^2 e^{-2j\omega n\tau} + \dots) \tag{5}$$

For an infinite number of circulations this reduces to

$$\frac{e^{-j\omega n\tau}}{1 - Ke^{-j\omega n\tau}} \tag{6}$$

which is comparable to equation (1) with $z^{-n} = e^{-j\omega n\tau}$.

For a non-ideal delay line the output on the first pass is[10]

$$(1 - n\varepsilon) \cos \omega(t - n\tau) + (1 - n\varepsilon) \cdot n\varepsilon \cdot \cos \omega(t - \{n + 1\}\tau) + \dots \tag{7}$$

where the first term is the attenuated and delayed signal and the second and subsequent terms, each delayed by one element from the preceding one, are the result of transfer inefficiency. After a number of circulations each of the signals will grow at different rates. For an infinite number of circulations, the output signal can be written as (10).

$$\frac{1 - n\varepsilon\; e^{j\omega(t - n\tau)}}{1 - K(1 - n\varepsilon)e^{-j\omega n\tau}} + \frac{n\varepsilon(1 - n\varepsilon)e^{j\omega(t - (n + 1)\tau)}}{(1 - K(1 - n\varepsilon)e^{-j\omega n\tau})^2} + \dots \tag{8}$$

If the signal samples in the CCD are spaced by several empty elements the output from the filter appears as a primary signal whose amplitude approaches that of a filter whose effective gain is $K(1 - n\varepsilon)$, followed by secondary and subsequent signals in the initially empty elements. For a loop gain approaching unity and a relatively poor overall transfer inefficiency the secondary amplitude can be a significant fraction of the primary. The magnitude of the primary signal is

$$|S_A| = \frac{(1 - n\varepsilon)}{(1 + K^2(1 - n\varepsilon)^2 - 2K(1 - n\varepsilon) \cos \omega n\tau)^{\frac{1}{2}}}$$

and the magnitude of the secondary

$$|S_B| = \frac{n\varepsilon}{(1 - n\varepsilon)} \cdot |S_A|^2$$

$|S_A|$ and $|S_B|$ are shown in Fig. 3 for $n\varepsilon = 10^{-2}$ and $K = 0.95$.

The result of equation 8 can also be derived by expansion of equation 3. Conversely, the sum of all the terms in equation 8 will give the transfer function of the filter. In a frequency domain application the signal samples naturally add together and the individual terms of equation 8 are not distinguishable. At signal frequencies which are low compared with the clock frequency, adjacent signal samples in the CCD will be of similar phase and magnitude (τ small compared with the time period of the signal) and the effect of transfer inefficiency is minimal. In applications where the analog signal is not reconstituted the physcial presence of a secondary signal in an empty element presents a serious problem.

Discussion

In any recursive structure where there is a sharp transition in magnitude at a pole then there will be some growth of secondary signals close to the pole in a similar manner to that shown in Fig. 3. In the implementation of MTI radar filters it has been shown that transfer inefficiency effects are magnified when the doppler frequency approaches the edge of the filter passband(7). In these MTI filters the circuit was realized with a 3 pole recursive CCD filter. The filter consists essentially of a first order recursive section in cascade with a second order section and has a third order zero at $z = 0$. The second order section has a pole (close to the unit circle) at either end of the passband. There will therefore be significant secondary growth close to these poles and hence the observed increase in smearing as the edge of the passband is approached. Some reduction in secondary growth could be attained by using similar techniques to those proposed for video integrators(10).

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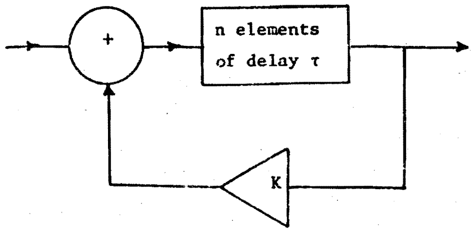

FIGURE 1 One Pole Recursive Filter

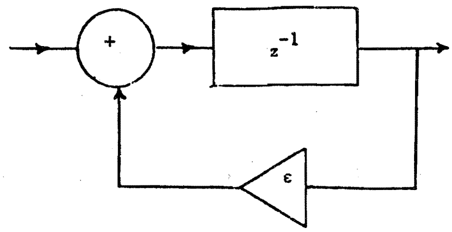

FIGURE 2 Model for Unit Transfer Element.

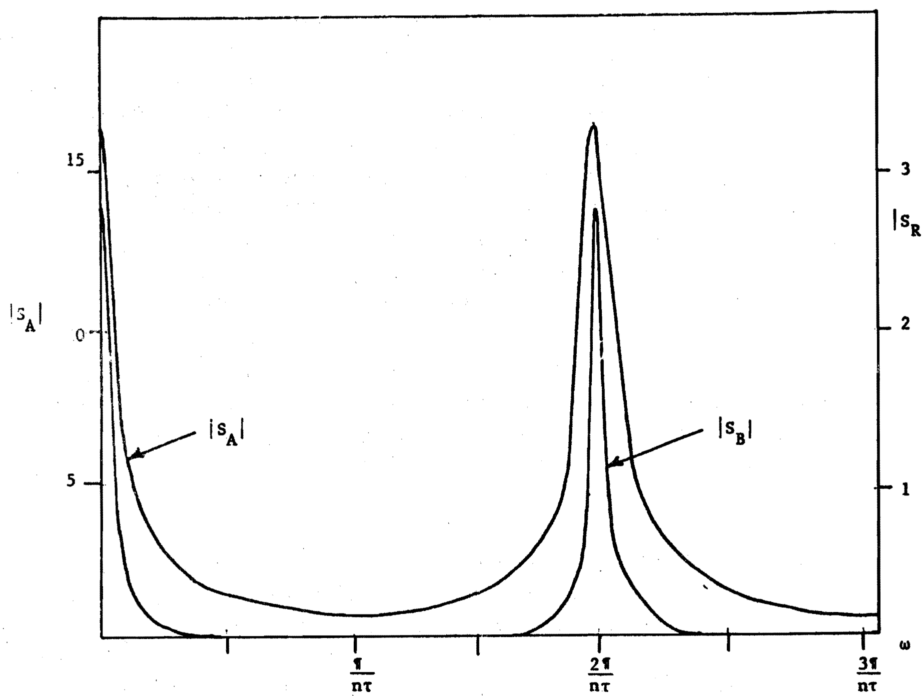

FIGURE 3: The Magnitude of the Primary and Secondary Signals (For Unit Amplitude Input Signal) as a Function of Signal Frequency. ($n\varepsilon$ = .01, K = 0.95)