APPLICATIONS OF A CCD LOW-PASS TRANSVERSAL FILTER

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ABSTRACT The application of a CCD low pass filter to several different systems is described. These applications include; a channel filter for a frequency division multiplex communication system, an anti-alias filter for a time division multiplex communication system, an anti-alias filter for a digital monitoring system and an interface between two asynchronous sampled data systems.

I. INTRODUCTION

Low pass filters are required in a large number of systems. In some cases the required filter characteristics are easily obtained with simple passive networks, but in many cases, system performance can be improved if higher performance filters are used. Until now, it may not have been economically attractive to use higher quality filters in these applications, but with the advent of low cost CCD low-pass transversal filters having very sharp cut-off characteristics and low in-band ripple, many opportunities now exist for improving cost/performance by upgrading the quality of the low pass filters.

Sampled data analog systems, for example, all require a low pass filter for the elimination of alias responses. This filter must have a pass band that is adequate for the signal bandwidth, but for typical applications it must be down by 40 to 50 dB by the Nyquist frequency. In the past, this has been accomplished by oversampling the data by a factor of three or four so as to move the Nyquist frequency sufficiently far above the signal pass band that a relatively simple filter can suffice. While this practice simplifies the filter, it requires that three to four times as many samples be stored, processed, or transmitted (depending on the system) as are actually needed.

In these cases, a low-pass filter with sharper cut-off characteristics can reduce the number of samples that have to be stored (thereby effecting a cost saving in memory) or processed (thereby effecting a saving in CPU loading) or transmitted (thereby effecting a saving in bandwidth).

Sampled data systems whose pass bands are close to the Nyquist limit also pose problems at the output end. Since the sample rate is only about one octave above the pass band edge, it is also necessary to employ a high quality low pass filter at the output of these systems.

The function of the CCD low-pass filter is to perform an interpolation between the output samples, thereby increasing the sample rate without appreciably changing the signal spectrum.

An experimental CCD low-pass filter has been designed and tested, and the application of this filter to a number of systems has been explored. The frequency characteristics of this filter are first presented, and the application of this filter to the following systems is then discussed in detail:

A. Frequency division multiplexed channel filter.

B. Alias filter for time division multiplexed communication system.

C. Alias filter for digital patient monitoring system.

D. Interface between two asynchronous sampled data systems.

  1. Video communications system.

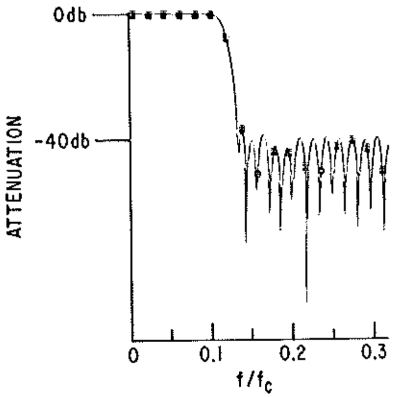
  2. ERTS image processor.

II. FILTER CHARACTERISTICS

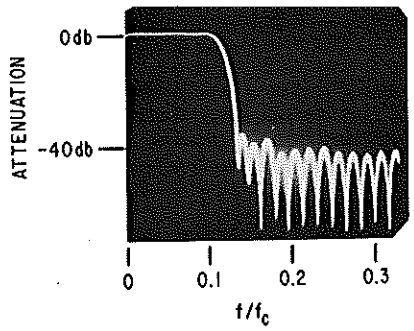
The low-pass filter discussed in this paper was designed for the frequency division multiplexed communication application discussed in the following section. The pass band for each channel extends from 200 Hz to 3200 Hz, and the channels are to be frequency division multiplexed on 4.0 KHz centers. Thus, the stop band to pass band ratio required is 4.2/3.2 = 1.31.

Within the pass band, the ripple may not exceed 0.1 dB, and the adjacent channel suppression must be greater than 34 dB. Using the Parks and McClellan algorithm,[1] a 63 tap filter design was generated where the pass band and stop band edges were chosen to be 0.1 and 0.131 times a clock frequency of 32 KHz, respectively.

The resulting tap weight values were rounded off to the closest of 600 discrete values to accommodate the automatic mask making apparatus that was used to generate the art work for the chip, thereby introducing a tap weight roundoff error of at most one part in 1200 at each tap. A comparison between the calculated and measured performance of this filter is shown in Fig. 1.[2]



CALCULATED FILTER RESPONSE



OBSERVED FILTER RESPONSE

Fig. 1-CCD low pass filter response

A tap weight accuracy of the order of 0.1% due to random processing variations can be achieved in practice.[3,4] This is comparable to the roundoff error.

III. SYSTEM APPLICATIONS

A. FREQUENCY DIVISION MULTIPLEXED CHANNEL FILTER

In this application, each channel is represented as a single sideband signal of 3.0 KHz bandwidth (200 Hz-3.2 KHz) with channels on 4.0 KHz centers. These channels are conventionally separated with a bank of high quality band pass elliptic filters whose outputs are then modulated to the audio range. Although this approach could be implemented directly with appropriate CCD band pass filters, the passive band pass filter cannot be eliminated because of the alias responses of the CCD. A preferable approach from the point of view of cost appears to be to perform the band pass function with low pass filters rather than with band pass filters.[5] This introduces a problem of image rejection, which is not present when band pass filters are employed, but it can be solved either by phase cancellation or by using the Weaver method. In the Weaver method, the desired channel is first modulated to base band I and Q channels with appropriate modulators, and these are low pass filtered and combined to form the desired audio signal as shown

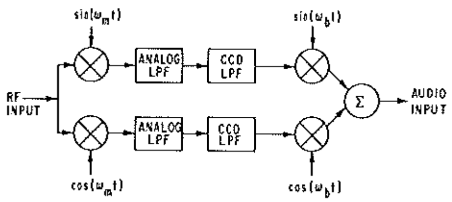


Fig. 2-Block diagram of Weaver demodulator

in Fig. 2.

In the CCD implementation, which is inherently a sampled system, the function of the modulators can be provided automatically by the samplers themselves. Since these samplers can be operated from a frequency divider driven by a single clock running at four times the sample rate, a precise 90° phase shift can be obtained without using any critically balanced components.[6] A block diagram showing this implementation is shown in Fig. 3.

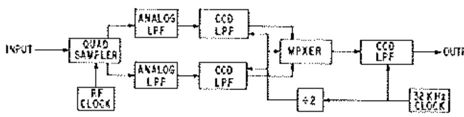


Fig. 3-CCD implementation of Weaver demodulator

In addition to the CCD low pass filter, an analog filter must also be employed to eliminate the alias response of the CCD. For the filter described above, where the pass band extends to .13 times the sample rate, the analog filter must be down by about 40 dB at .87 times the sample rate. This can be accomplished by a three pole filter (one pole on the real axis plus one conjugate pair) and can be implemented with a single op-amp. The responses of the CCD filter and the three pole Chebyshev filter are shown superposed in Fig. 4. Since the combined response is the product of the two individual filters, the net result is a single sharp cut-off low pass filter with no alias responses.

Previous attempts to use the Weaver method have been limited by phase tracking errors in the low pass filters. This problem is considerably alleviated by using

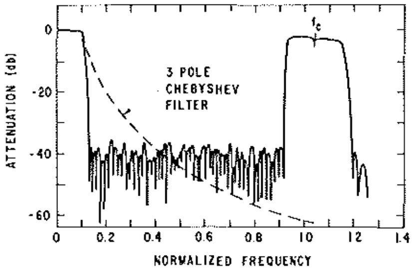


Fig. 4-Alias response of CCD filter and 3 pole Chebyshev anti-alias filter

CCD's because their phase shift characteristics are independent of component variations and are therefore much easier to control. Excellent band pass characteristics were obtained as shown in Fig. 5, and suppression of spurious responses by an average of 45 dB was achieved as indicated in Fig. 6.

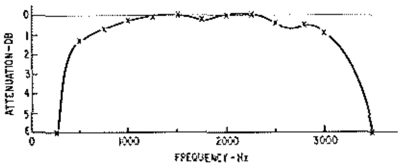


Fig. 5-Band pass characteristics of the CCD Weaver demodulator

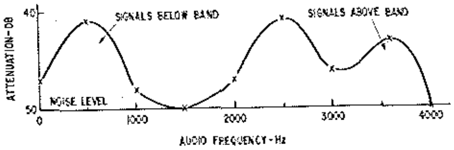


Fig. 6-Out of band suppression of the CCD Weaver demodulator

B. TIME DIVISION MULTIPLEXED COMMUNICATIONS SYSTEM

In this system, 24 audio channels are low pass filtered and sampled at 8.0 KHz, and these samples are multiplexed and converted to a digital data stream by a single A/D converter and transmitted. At the receiving end, the samples are converted back to analog by a single high speed D/A converter and demultiplexed in the analog domain. In this application, the most significant aspect is cost. CCD low pass input filters appear advantageous because most of the overhead circuitry can be shared by all of the filters. Under these conditions, the trade-off is between two or three active filter stages with precision trimmed components and the CCD filter chip and its associated level-shift and signal recovery circuits. From the point of view of component count, this trade-off is approximately equal, but in terms of component tolerance and immunity to component drift, the CCD approach appears preferable.

C. DIGITAL MONITORING SYSTEM

The amount of risk associated with recovery from serious illness can be dramatically reduced by continuous monitoring of physiological data such as the electrocardiogram. Since the warning signs contained in these data are sometimes quite subtle, digital processing appears to be the most practical approach for automatically providing appropriate warning signals. Since the output signals from the transducers are sampled, a low pass filter must be provided to prevent distortion due to frequency folding. This filter should fall off as sharply as possible so that oversampling is not required, but to prevent phase distortion, it should also have a linear phase response. A further complication is the relatively low cut-off frequency required. (For an ECG waveform, a bandwidth of about 50 Hz is appropriate.) The conventional solution to this problem is to use a low pass filter with a cut-off frequency several times higher than necessary and to oversample by a factor of two or three. This approach reduces the bulk of the filter and permits good phase response, but memory requirements and processor speeds are increased. In this application, the linear phase and sharp cut-off characteristics of CCD filters such as the one described above provide a more optimum solution. The cut-off frequency can be reduced to the appropriate value with no increase in component size or degradation of phase response, so operation up to about 80% of the Nyquist limit becomes practical. This means that the digital system only sees about half as many samples for a given bandwidth as in the conventional approach, and it therefore can handle more patients.

D. INTERPOLATION

There are a number of cases where a continuous analog signal needs to be recovered from a sampled data system. This is usually done by holding each sample for the duration of each clock period and passing the resulting staircase waveform through a low pass filter. If this output signal has to be sampled a second time, and if the clock frequency of the first sample rate gets through the low pass filter, the clock frequency components may be folded back by the second sampling operation and cause alias distortion. Although this problem is usually not severe, it can be a problem when the signals represent video images. In this case, phase distortion is not acceptable, and conventional low pass filters cannot be used. Two examples where this problem has appeared are:

1. A sampled data video transmission system in which the clock frequencies of the camera, the transmission link and the display are all asynchronous.

2. The generation of rectilinear raster data from raw ERTS data. In this case, the direction of the scan lines from the satellite data do not conform to the raster direction, and the spacing of the scan lines does not conform to the spacing of the raster lines. One approach toward generating the interpolated data for the output raster is to reconstruct a band limited continuous signal from the samples of raw data and to resample this continuous signal at the points corresponding to the pixel locations along the raster.

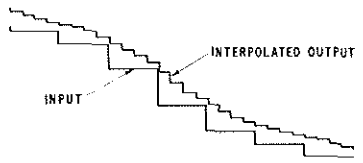


Fig. 7-An example of interpolation.

This approach can be conveniently implemented with CCD low pass filters of the type described above followed by a simple analog filter.

The function of the CCD is to provide a large number of interpolated sample values at a higher sample rate than that of the input samples as shown in Fig. 7. The output sample stream can be filtered by a much simpler analog filter than would have otherwise been required because the clock frequency has now been moved much farther away from the signal pass band.

IV. ACKNOWLEDGMENTS

The CCD transversal filter has involved the participation of a number of people. W. E. Engeler was responsible for the initial design concepts. H. S. Goldberg has performed device evaluation and circuit development. C. M. Puckette was responsible for the tap weight design and has been concerned with tap weight error. O. M. Mueller of GE Telecommunications Products Dept. has evaluated the devices in a communications application. R. C. Sherick has evaluated CCD's in the Weaver demodulator. D. Meyer and J. F. Richotte have been responsible for device fabrication, and L. J. Petrucco for circuit fabrication. Finally the authors would like to thank J. O. Quesnel for preparing this manuscript.

V. REFERENCES

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