LINEARISATION OF THE CHARGE COUPLED DEVICE TRANSFER FUNCTION

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ABSTRACT

The adoption of charge-coupled devices in analogue signal processing applications is dependent on several performance parameters being achieved such as:

(a) Low charge transfer inefficiency,

(b) High sampling rate,

(c) High signal to noise ratio, and

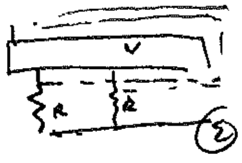
(d) Low harmonic distortion.

The first three parameters have been studied in some detail and are at the stage where most applications can be satisfied. Parameter (d) however, is not easily achieved, and currently only one technique has been developed which yields overall ccd distortion lower than 40 dB without seriously degrading dynamic range. The limitations of this technique are outlined and a potentially powerful technique for obtaining low harmonic distortion coupled with optimum dynamic range is discussed in detail. The technique utilises a sensing structure positioned adjacent to the ccd input gate in order to sense the quantity of charge being injected into the ccd; the signal from this circuit being used as feedback to control the quantity of charge entering the ccd. Assuming low loss transfer, this technique may be utilised to obtain a highly linear transfer function from many of the ccd devices likely to be used in signal processing applications.

INTRODUCTION

The operational parameters of charge-coupled devices in signal processing applications can be clearly specified for many applications. High transfer efficiency, bandwidth and signal to noise ratios can be achieved, and in some cases these are obtainable with low harmonic distortion. In many situations however, low distortion and high dynamic range are difficult to achieve simultaneously unless some method is used to linearise the charge injection and detection. It is thus extremely important to produce ccd's for signal processing applications, which have a low harmonic distortion, independent of dynamic range.

Many different schemes exist for injecting charge into ccd's. Their basis is to inject a quantity of charge which is proportional to the input signal voltage level. The most commonly used linearisation technique, potential equilibration[1,2], involves injecting a quantity of charge in such a manner as to produce a linear relationship between the surface potential under the collecting well and the surface potential under an input gate. The technique relies on the assumptions that:



(a) No distortion is introduced during transfer

(b) A detection circuit is available which can transform surface potential linearly to an output signal.

The latter assumption proves to be an important limitation in the fabrication of delay lines and programmable matched filters when a floating-gate sensing technique is utilised[3]. This limitation has led to the development of a technique which overcomes the problems of sensing and input circuit non-linearities and thus provides a linear ccd transfer function.

FEEDBACK LINEARISATION

The principles of operation of the linearisation technique are demonstrated in Figure 1. The input signal is applied to a differential amplifier, the output of which is connected to a diode diffusion at the ccd input. Adjacent to this diffusion is a gate, the potential of which is pulsed high after the commencement of the second-phase pulse and is returned to a low potential prior to the termination of the succeeding third-phase pulse. During the period when this gate potential is high, minority carriers flow from the input diffusion to the potential well below the first tap electrode. The quantity of charge residing in this well is sensed using a floating-gate reset technique and the output of the sense amplifier is used as feedback to the differential amplifier. As a result of the feedback, the charge injected into the ccd is controlled in such a manner as to give an output voltage from the sense amplifier which follows the input voltage according to the equation:

$$V_{out} = V_{in}/(1 + 1/(A_1 \times A_2)),$$

where A_1 is the gain of the differential amplifier stage and A_2 is the variable loss between the input diode and the sense amplifier output. From this equation, when $A_1 \times A_2$ is much greater than unity, the transfer function of the device is linear. For reasonable amplifier gains, this inequality is valid over virtually the entire signal charge range; A_2 only tending to zero for zero charge and as saturation of the tap potential well is reached.

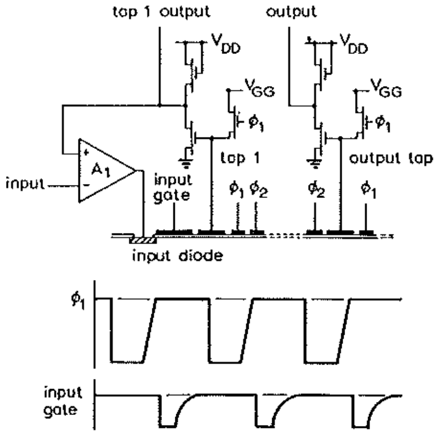


Fig.1. Circuit and timing diagram for feedback linearisation technique

The technique was implemented using a single-level metal ccd fabricated on 10 Ω cm, <100> orientation n-type silicon. The tap electrodes and the transfer electrodes were 8 and 4 μm long respectively with 2 μm gaps. The gain of the differential amplifier was 100 giving an overall open loop gain ($A_1 \times A_2$) of approximately 25.

Figure 2 demonstrates the open loop response of the device to a triangular waveform and Figure 3, the response with feedback applied. The improvement in linearity can clearly be seen, even for the relatively low open loop gain used. The only curvature visible on the corrected waveform occurs just prior to saturation being reached as predicted above.

A spectral analysis of the output of the first tap sense amplifier was performed. A low frequency sinusoidal signal was applied to give a 95% of maximum output voltage swing and the following results were obtained:

Fundamental	0 dB
2nd harmonic	< -40 dB
3rd harmonic	≪ -50 dB
4th harmonic	-50 dB
5th harmonic	≪ -50 dB

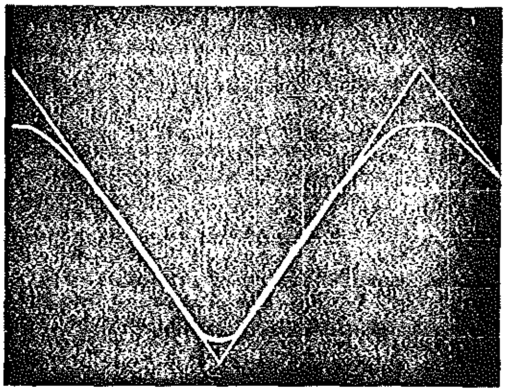


Fig.2. Input and output waveforms without linearisation

Input: 10 mV/division
Output: approximately 200 mV/division
Horizontal: 5 ms/division

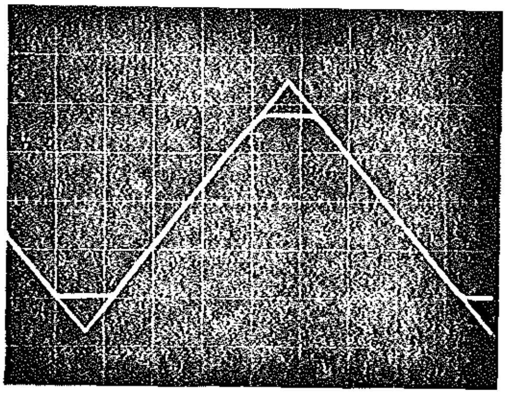


Fig.3. Input and output waveforms with linearisation

Input: 200 mV/division
Output: approximately 200 mV/division
Horizontal: 5 ms/division

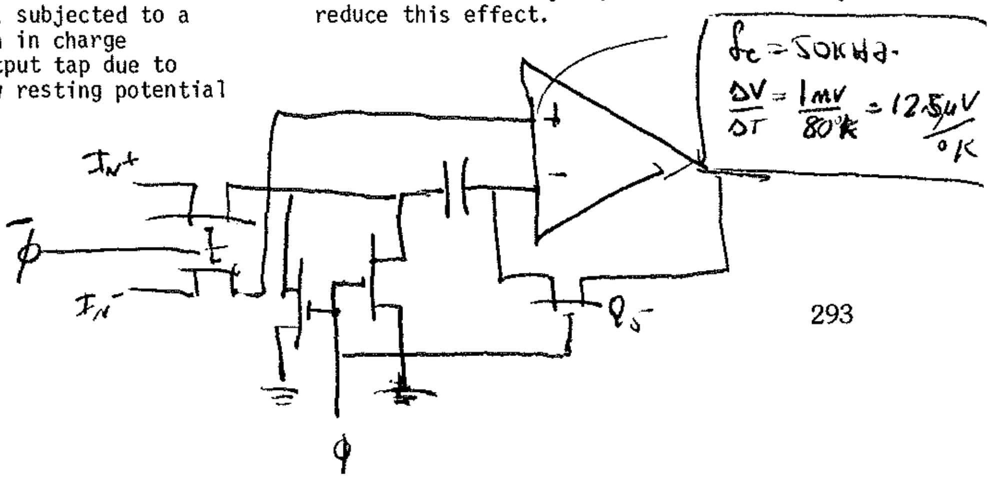
A measurement of charge residual after 127 transfers gave a residual inefficiency of less than 3×10^{-4} per transfer and the signal to noise ratio at both input and output taps was much greater than 50 dB. The signal was, however, subjected to a 20% of maximum reduction in charge magnitude at the ccd output tap due to recombination at the low resting potential used. This resulted in the output sensing circuitry being operated in a different part of its non-linear transfer curve from the input. Using the measurement technique outlined by Sequin and Mohsen[2], the 2nd and 3rd harmonics at the ccd output tap were less than -35 and -45 dB respectively, even for the highly unacceptable loss of signal experienced.

AMPLIFIER CONSIDERATIONS

The design of the differential amplifier used in the feedback loop is of fundamental importance to the stability and frequency performance of the technique. A wideband bipolar operational amplifier was used in the prototype system described above, but for frequencies up to several MHz there appears to be no fundamental reason why a MOS amplifier could not be used. In many of the signal processing applications utilising this type of linearisation, an operational amplifier could prove to be a useful device to have integrated with the ccd and for this reason a MOS operational amplifier is considered to be particularly desirable.

The open loop response of the circuit with the input gate in the on condition should, for stability, contain a dominant pole at frequency ω_c producing a 20 dB/decade roll-off until below unity gain, Figure 3. As the input gate is switched off, however, the series resistance associated with the channel directly below it increases in value, introducing a constantly reducing pole in the loop response. Hence, from the time that this pole reaches unity gain frequency ω_u until it is lower than ω_c^2/ω_u, the closed loop is potentially unstable. However, since the time taken for this to occur is much less than the loop delay, there appears to be no deleterious effect on the closed loop stability.

The equivalent input drift of a MOS operational amplifier could also prove to be a problem. However, since the amplifier is active for somewhat less than 50% of the time, it should be possible to incorporate a stabilisation circuit similar to that discussed by Fry[4] and substantially reduce this effect.



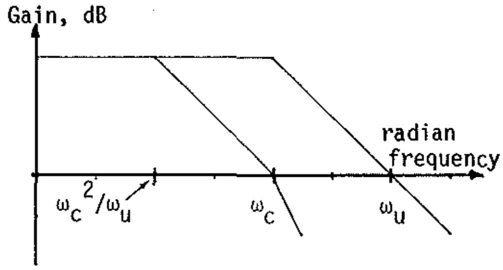


Fig.4. Change in open loop response during input gate switch off

CONCLUSIONS

In conclusion, a technique has been developed for electronically controlling the quantity of charge introduced into a ccd in such a manner as to produce an output signal from a non-linear sensing circuit, which is a near replica of the input signal. The advantages of the technique may be summarised as follows:

(a) It produces a linear, ccd transfer function,

(b) May be used with any non-linear, non-destructive sensing technique,

(c) May be applied to buried channel and peristaltic ccd's,

(d) Provides a designable, fixed gain transfer function,

(e) Allows the designer to choose the degree of linearity desired by varying the open loop gain, and

(f) May be used with multiplexed ccd's to overcome input threshold voltage variations.

The requirement for an operational amplifier at the ccd input may initially appear to be a major disadvantage. However, some form of buffer amplifier is likely to be necessary in virtually all applications. In recursive filters for example, such an amplifier is essential for the summation process, and if combined with ccd's allows other signal processing functions such as multiplication to be performed. Hence, the amplifier should ideally be produced in a technology compatible with the ccd in order that a high level of integration, and thus low unit cost, may be achieved in signal processing devices.

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