Semi-Annual Technical Report

September 30, 1977 through March 30, 1978

SINGLE CHIP LENSES FOR ULTRASONIC IMAGING:
EFFECTS OF TRANSFER EFFICIENCY ON LENS PERFORMANCE

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Sponsored by

Advanced Research Projects Agency (DOD)
ARPA Order No. 3448

Monitored by NE Under
Contract F49620-77-C-0133

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REPORT SUMMARY

Several of the theoretical fundamental limits of single chip lenses using charge coupled device technology have been analyzed at Stanford University. This report concentrates the effects of incomplete transfer on lens performance. It is the conclusion of this report that while transfer efficiency may have a pronounced effect on system performance in other applications for the lens being considered: (1) the attenuation effects of transfer efficiency are deterministic and insignificant, (2) the lateral resolution and sidelobe response are to first order not modified, and (3) for moderate values of charge-transfer inefficiency the spatial shifting of the beamsteering angle is minor. Thus the CCD lens is largely insensitive to the major limitation commonly encountered (transfer inefficiency) in charge coupled device applications today.

FUNDAMENTAL LIMITS OF C3D PERFORMANCE

Effects of Incomplete Charge Transfer

The time-delay accuracy of the cascade charge-coupled device will largely determine its ultimate utility as an electronic lens for an ultrasonic imaging system. Time-delay and amplitude errors reduce overall image quality by creating uncertainty as to the position of the focal point of the lens or by degrading the sidelobe level of the image. As a result, this report examines the aspects and effects of transfer efficiency of the C3D electronic lens that will inherently limit the time-delay and amplitude accuracy generated by this approach.

To assess the effects of incomplete charge transfer on the performance of the 20-input four-section C3D electronic lens, this device is modeled as a 4 x 20 array of individual CCD delay lines, each characterized by the number of bits in the delay-line section, the clock frequency applied to the section, and knowledge of incomplete charge transfer per transfer as a function of clock frequency. Because the cascade charge-coupled device (C3D) lens is fabricated on a single integrated-circuit die, good matching of incomplete charge transfer vs clock frequency across the entire array is expected. Consequently, it is assumed that a single transfer inefficiency vs clock-frequency relationship applies to all of the time-delay sections in the C3D electronic lens.

The position of each delay line within the C3D lens is identified by the subscripts i,j, where i = 1,2,3,4 refers to the four clocked sections and j = -9,-8,...,-0,+0,+1,...,+8,+9 refers to the transducer channel position numbered from left to right across the lens.† Based on this notation, the time delay applied to the j^{th} transducer channel (assuming ideal delay lines) is

$$\Delta T_j = \sum_{i=1}^{4} \Delta T_{i,j} = \sum_{i=1}^{4} \frac{N_{i,j}}{F_i} \tag{1}$$

where F_i is the clock frequency applied to the i^{th} delay section and $N_{i,j}$ is the number of bits in the i^{th} clock section of the j^{th} transducer.

Recalling the dispersion relations of Joyce and Bertram [1], attenuation A_j and time delay ΔT_j for each trasnducer channel can be defined as

$$A_j = \prod_{i=1}^{4} A_{i,j} = \prod_{i=1}^{4} \left(1 - \varepsilon_{F_i}\right)^{2N_{i,j}} \left\{\exp\left[2N_{i,j}\varepsilon_{F_i} \cos\left(\frac{2\pi\nu_{sig}}{F_i}\right)\right]\right\}. \tag{2}$$

and

$$\Delta T_j = \sum_{i=1}^{4} \Delta T_{i,j} = \sum_{i=1}^{4} \left\{\frac{N_{i,j}}{F_i} + \frac{N_{i,j}\varepsilon_{F_i}}{F_i} \left[\mathrm{sinc}\left(\frac{2\pi\nu_{sig}}{F_i}\right)\right]\right\} \tag{3}$$

where ε_{F_i} is charge-transfer inefficiency at the clock frequency applied to the i^{th} section of delay. Although these expressions for attenuation and time delay are significant, the variation of these quantities from transducer to transducer rather than their absolute magnitude will determine overall

†The subscripts j = -0 and j = 0 refer to the two center transducers of an array containing an even number of transducers. In this context, the "transducer at j + 1" is located next to the transducer at position j (if j = -0, then j + 1 = 0).

image quality. As a result, the following subsections will examine the effects of attenuation and time-delay variations across the array caused by incomplete charge transfer. Because beam steering and focusing are generally independent of one another, the impact of such a transfer on each of these functions is considered separately.

1. Beam Steering

For the beam-steering section, Eqs. (2) and (3) can be rewritten as

$$A_j = \left(1 - \varepsilon_{F_3}\right)^{2N_{3,j}} \left(1 - \varepsilon_{F_4}\right)^{2N_{4,j}} \exp\left[2N_{3,j}\varepsilon_{F_3} \cos\left(\frac{2\pi\nu_{sig}}{F_3}\right)\right]$$

$$\cdot \exp\left[2N_{4,j}\varepsilon_{F_4} \cos\left(\frac{2\pi\nu_{sig}}{F_4}\right)\right] \tag{4}$$

and

$$\Delta T_j = \frac{N_{3,j}}{F_3} + \frac{N_{4,j}}{F_4} + \frac{N_{3,j}\varepsilon_{F_3}}{F_3}\left[\operatorname{sinc}\left(\frac{2\pi\nu_{sig}}{F_3}\right)\right]$$

$$+ \frac{N_{4,j}\varepsilon_{F_4}}{F_4}\left[\operatorname{sinc}\left(\frac{2\pi\nu_{sig}}{F_4}\right)\right] \tag{5}$$

Maintaining the beam-steering convention (established in Chapter IV) that the number of bits in each of the beam-steering sections increases or decreases by an increment of n_3 bits per transducer channel, the recursive relations that express the attenuation and time delay of transducer channel $j + 1$ in terms of channel j are

$$A_{j+1} = A_j \left\{ \left(1 - \varepsilon_{F_3}\right)^{2n_3} \left(1 - \varepsilon_{F_4}\right)^{-2n_3} \right.$$

$$\left. \cdot \exp\left[2n_3\varepsilon_{F_3} \cos\left(\frac{2\pi\nu_{sig}}{F_3}\right) - 2n_3\varepsilon_{F_4} \cos\left(\frac{2\pi\nu_{sig}}{F_4}\right)\right] \right\} \tag{6}$$

and

$$\Delta T_{j+1} = \Delta T_j + \frac{n_3}{F_3} - \frac{n_3}{F_4} + \frac{n_3\varepsilon_{F_3}}{F_3} \left[\mathrm{sinc}\left(\frac{2\pi\nu_{sig}}{F_3}\right)\right]$$

$$- \frac{n_3\varepsilon_{F_4}}{F_4} \left[\mathrm{sinc}\left(\frac{2\pi\nu_{sig}}{F_4}\right)\right] \tag{7}$$

Equation (6) indicates that the attenuation at any two adjacent transducers will differ by a constant multiplicative factor that will be dependent on the clock frequencies and on the transfer inefficiencies at those frequencies but will be independen the absolute position along the transducer array. If the C3D lens is used to steer a 20-element 1.5 mm element 1.4 MHz array to 25° with F_3 = 5 MHz ($\varepsilon_5 \approx 0.002$) and F_4 = 30 MHz ($\varepsilon_{30} \approx 0.025$), the element-to-element attenuation coefficient is 0.995. This demonstrates that, even for broad differences in charge-transfer inefficiency caused by the large clock-frequency variation required to beam steer to the extremes of the field of view, the change in attenuation across the array resulting from incomplete charge transfer is substantially less than that resulting from acoustic path-length differences.

Comparison of Eq. (7) to the beam-steering angle/clock-frequency relation for ideal delay lines reveals that the beamsteering angle in the presence of incomplete charge transfer θ_ε is

$$\theta_\varepsilon = \sin^{-1}\left[\frac{cn_3}{d}\left(\frac{1}{F_3} - \frac{1}{F_4}\right) + \frac{cn_3}{d}\left(\frac{\varepsilon_{F_3}\ \mathrm{sinc}\ (2\pi\nu_{sig}/F_3)}{F_3} - \frac{\varepsilon_{F_4}\ \mathrm{sinc}\ (2\pi\nu_{sig}/F_4)}{F_4}\right)\right]$$

$$= \sin^{-1}\ (\sin\theta + \sin\Delta\theta) \qquad (8)$$

where $\sin\theta$ is the beam-steering angle expected for ideal delay lines and $\sin\Delta\theta$ denotes the small error caused by incomplete transfer. Continuing with the same clock frequencies and transfer inefficiencies as before results in $\theta = 24.62°$ ($\sin\theta = 0.417$), $\sin\Delta\theta = -0.0022$, and $\theta_\varepsilon = 24.48°$.

Equation (8) therefore indicates that, although incomplete charge transfer will alter the actual beam-steering angle slightly, the lateral resolution and sidelobe level of the image point will not be affected by such time-delay variations. Because transfer inefficiency is well matched at any given clock frequency on the single-chip lens, the device can be operated at clock frequencies much higher than would be normally expected, based on the completeness of charge transfer at these higher frequencies. As indicated in the left portion of Figure 1, the time delay error due to incomplete charge transfer is directly proportional to the number of bits clocked at each frequency, so good matching of transfer efficiency results in a net time delay error that varies linearly across the array for the beam steering section shown.

Implementation of electronic beam steering with a number of individual CCDs, as shown in the right portion of Figure 1, will not provide an assurance of well matched transfer efficiency between devices. As a result, the time delay errors developed across the array due to incomplete charge transfer will be randomly distributed and will tend to degrade the sidelobe supression afforded by the imaging system. Increased angular beam-steering accuracy and increased sidelobe suppression calls for CCDs with low transfer inefficiency at high clock frequencies if electronic beam steering is realized using individual CCD delay lines.

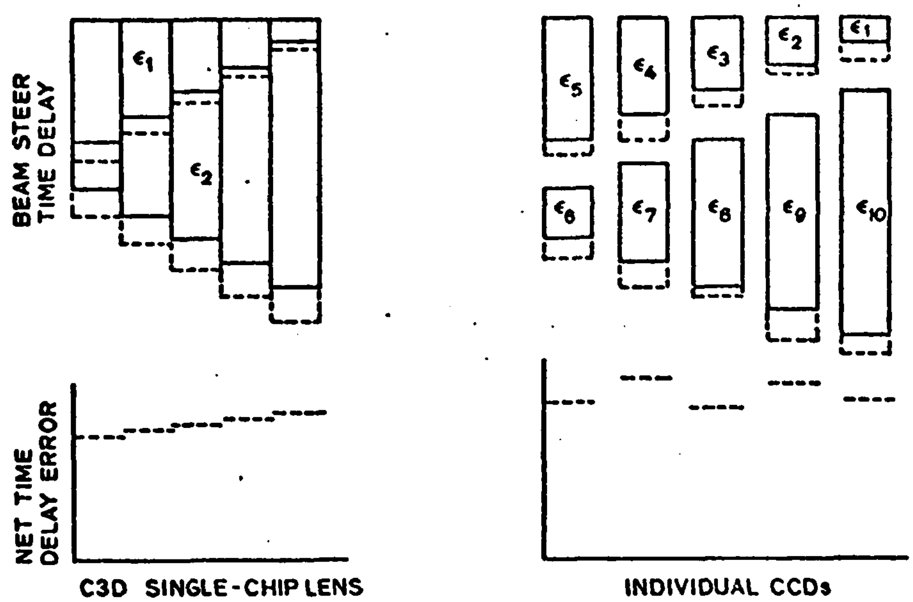

Fig. 1. C3D SINGLE-CHIP LENS VS INDIVIDUAL CCDs. (Ideal Time Delay ——; Including Transfer Inefficiency ---)

In addition to substantially reducing the delay line hardware required for electronically beam steered ultrasonic imaging, the C3D single-chip lens provides increased angular beam-steering accuracy because of improved matching of time delay between transducer channels. Furthermore, improved matching of the time delay should make it possible to achieve greater degrees of sidelobe suppression with the C3D single-chip lens as compared to individual CCD delay lines.

2. Focusing

Based on the above method, attenuation and time delay produced by the focusing rather than the beam-steering section can be written as

$$A_j = \left(1 - \varepsilon_{F_2}\right)^{n_2 j'} \left(1 - \varepsilon_{F_1}\right)^{n_1 (j'_{max} - j')} \exp\left[n_2 j' \varepsilon_{F_2} \cos\left(\frac{2\pi\nu_{sig}}{F_2}\right)\right]$$

$$\cdot \exp\left[n_1 (j'_{max} - j') \varepsilon_{F_1} \cos\left(\frac{2\pi\nu_{sig}}{F_1}\right)\right] \tag{9}$$

and

$$\Delta T_j = \frac{n_2 j'}{2F_2} + \frac{n_1 (j'_{max} - j')}{2F_1} + \frac{n_2 j'}{2F_2} \varepsilon_{F_2} \operatorname{sinc}\left(\frac{2\ \nu_{sig}}{F_2}\right)$$

$$+ \frac{n_1 (j'_{max} - j')}{2F_1} \varepsilon_{F_1} \operatorname{sinc}\left(\frac{2\ \nu_{sig}}{F_1}\right) \tag{10}$$

where

$$j' = |j|^2 + |j|$$

$$j'_{max} = |j_{max}|^2 + |j_{max}|$$

In contrast to the beam-steering section where large differences in frequency are required to steer the array to the extremes of the field of view, focusing over the entire range requires clock frequencies F_1 and

F_2 to differ only slightly. Because $\varepsilon_{F_1} \approx \varepsilon_{F_2}$ for $F_1 \approx F_2$, it is assumed that A_j will also vary by only a small amount across the transducer array and that ΔT_j will nearly equal those values expected for ideal delay-line performance. To verify this assumption, ΔT_j was calculated for the 20-element array of 1.5-mm, 1.5-MHz transducers using F_1 = 8 MHz (ε_{F_1} = 0.004) and F_2 = 10 MHz (ε_{F_2} = 0.006). Under these conditions, ideal delay lines would focus to a range of 12.0 cm; including the effects of incomp te charge transfer results in a focal point located at 12.05 cm.

The effects of incomplete charge transfer on the operati of the C3D demonstrate that the variation in attenuation across the a is deterministic and insignificant. Differences in time delay across the array resulting from incomplete charge transfer shift the focal point of the imaging system in both range and beam-steering angle but do not degrade the lateral resolution or sidelobe response of the focal point. Even at moderately high values of charge-trasnfer inefficiency, however, spatial shifting of the focal point is slight when compared to lateral resolution or depth of focus. This insensitivity to incomplete charge transfer is a direct result of good transfer-efficiency matching (at any clock frequency) across the array which, in turn, is due to the C3D single-chip lens approach.

References

[1] W.B. Joyce and W.J. Bertram, "Linearized Dispersion Relation and Green's Function for Discrete-Charge-Transfer Devices with Incomplete Transfer," Bell System Tech. J., 50, Jul-Aug 1971, pp. 1741-1759.