CCD DYNAMICALLY FOCUSSED LENSES FOR ULTRASONIC IMAGING SYSTEMS

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ABSTRACT. Charge coupled device (CCD) delay lines offer many useful features when incorporated into multi-piezoelectric-element electronically focussed successors to the single element ultrasonic imaging systems currently in clinical use on humans and in non-destructive testing use on materials.

Two such electronically focussed systems are presented: (1) a microprocessor controlled delay line system and (2) a single chip C3D lens system.

INTRODUCTION

Ultrasonic imaging systems are currently in use: (1) on humans in a variety of medical imaging applications and (2) on materials in non-destructive testing applications. Single element piezoelectric transducers are used in these commercial instruments to obtain cross section scans using mechanical scanners and storage CRTs. Charge coupled device (CCD) delay lines offer many useful features when incorporated in multi-piezoelectric-element electronically focussed successor to these single transducer systems. Briefly stated the CCD acts as an electronically adjustable delay line performing the required delay-sum operation on the 1-5 MHz ultrasonic signals. This CCD capability makes economically feasible an ultrasonic imaging system with the following features:

1. High resolution
2. Dynamic focussing
3. Adjustable field of view

CCD ULTRASONIC IMAGING

The basic acoustic imaging problem being considered is shown in Fig. 1 along with a simple signal processing architecture. In operation a burst of ultrasound is transmitted from the "array" of piezoelectric transducers. Reflections from the "target" return to the array, arriving at the elements with a spherical time delay distribution associated with the target range (the farther away the target the smaller the time delay between elements in the spherical distribution). The basic signal processing task to be performed by the delay lines is to equalize the total propagation time from the target through the medium, piezoelectric transducers and individual channel electronics to the common signal output summing node. It is accomplished by spacing the input taps of the CCD delay line in a quadratic arrangement and dynamically sweeping the clock frequency to control the curvature of the quadratic delays to complement the curvature of the spherical wavefronts from targets T_1 through T_2 and beyond. It permits significant improvements in resolution at ranges less than ten times the aperture of the system.

One may consider a system as shown in Fig. 2 which utilizes a linear delay distribution (in cascade with the quadratic distribution) to steer the "focussed" beam providing two-dimensional display information. This is a simple steering technique which allows deflection of the formed beam in one direction from the perpendicular. Typical systems may be designed for thirty to fourty-five degrees deflection. In operation the linear array of delay lines "electronically rotates" the piezoelectric array thereby providing the quadratic delay line with focus task similar to the "on-axis" focussing just discussed. One minor difference in focussing is that the apparent range for focussing is larger than the range to the midline of the array due to the "elec-

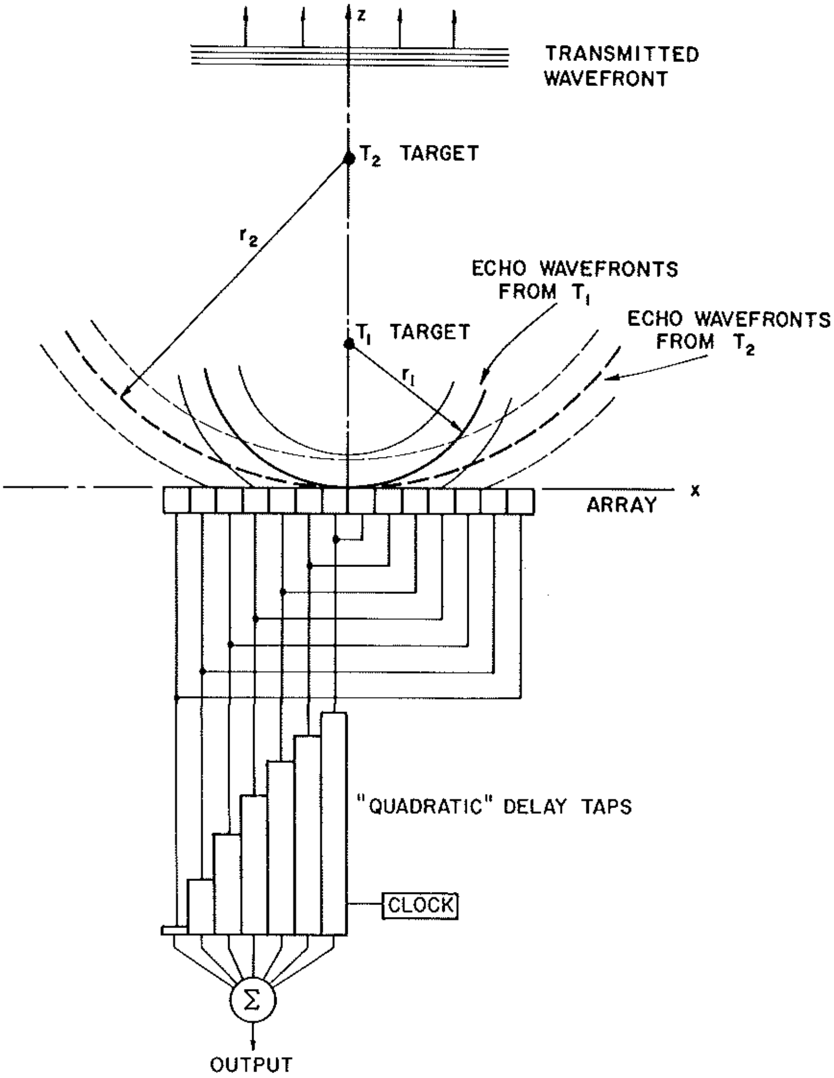

Fig. 1. Dynamic Focussing with Quadratically Tapped Variable Delay Line.

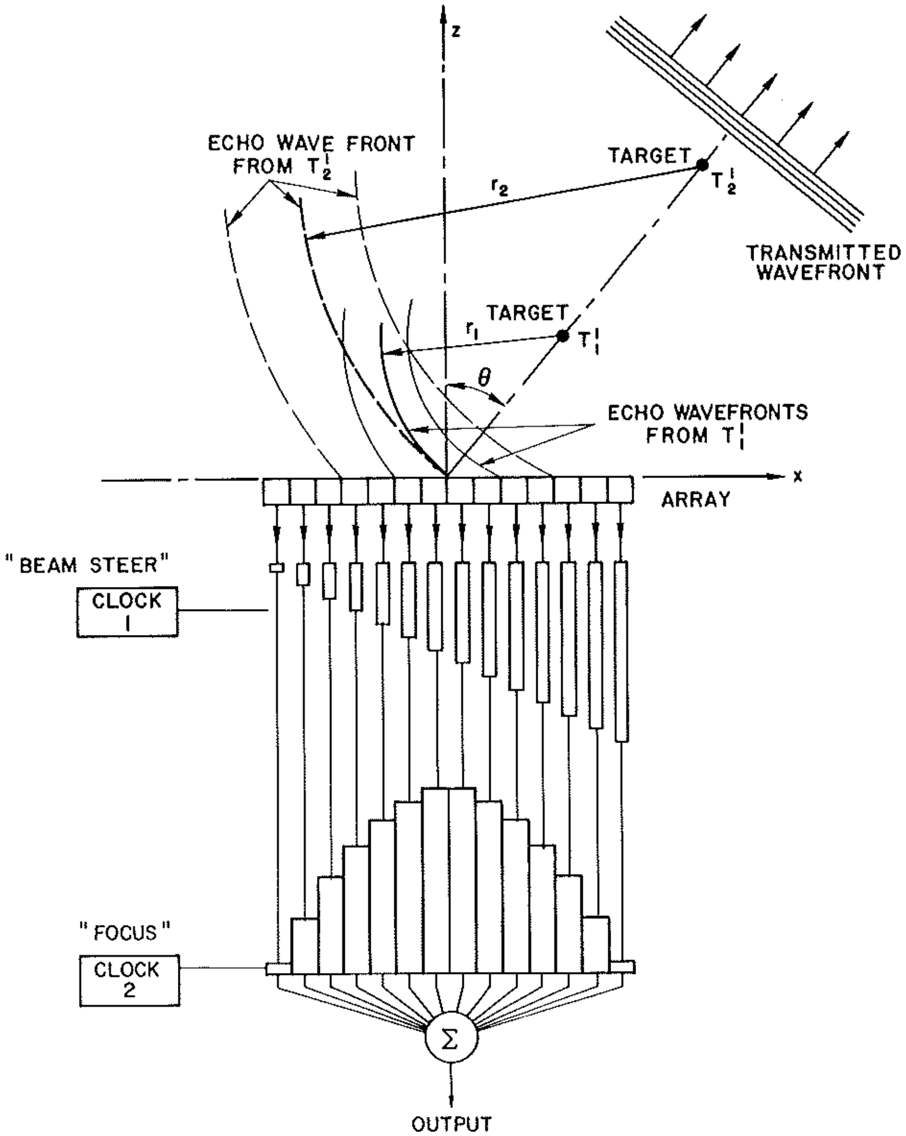

Fig. 2. Dynamic Focussing and Beam Steering with Variable Delay Lines.

tronic rotation" being about the point of zero (beam steer) time delay (i.e. the far end of the piezoelectric array from the target).

In actual practice two problems exist with implementing this system shown in Fig. 2. First it is desirable to have as large a field of view as possible, thus the formed beam should be capable of being swept in either direction from the perpendicular. Secondly the clock frequency variations should be kept to a minimum to reduce the variation of CCD parameters with clock rate.

The two systems concepts described in the following sections achieve this set of goals through two quite different approaches. The first to be discussed achieves each channel delay function using a single serial-in-serial-out (SISO) CCD delay line. Thirty-one channels (one for each transducer element) is required for this system. The clock frequency applied to each CCD channel is independently adjustable. The frequency applied to a specific channel is a multiplicative product of two functions: the beam steering frequency function and the focus frequency function. Each CCD clock is applied uniformly along the delay line but is time-varying in frequency. The second approach utilizes a single specially-designed C3D lens integrated circuit for the entire system time delay function. This single chip approach has the potential of realizing a complete focussed ultrasound probe in a hand held package.

A MICROPROCESSOR-CONTROLLED IMAGING SYSTEM

The delay lines of an ultrasonic imaging system thus may perform two forms of time delay equalization: (1) parabolic (focus) and (2) linear (beam steer). An experimental ultrasonic imaging system has been built using thirty-one 200 element serial-in-serial-out CCD delay lines to perform the quadratic and linear delay functions of a single piezoelectric element in one device [6]. As shown in Fig. 3 the delay time of each of the thirty-one channels is determined by the digital rate multiplier assigned to each channel.

A voltage controlled oscillator (VCO) and a sweep generator are used to dynamically control the time delay for focussing, and an 8080 microprocessor is used to control a rate multiplier for beam steering. This system is capable of ± 30 degrees deflection and dynamic focussing of echoes from ranges of 2 to 40 cm when using a 31 element 3.1 cm linear array (element dimensions are .1 x 1 cm). This system uses a multiplicative control algorithm for the CCD time delays which provides the separation of focus and beam steer functions into tasks which are amenable to microprocessor control and simple sweep generation circuitry.

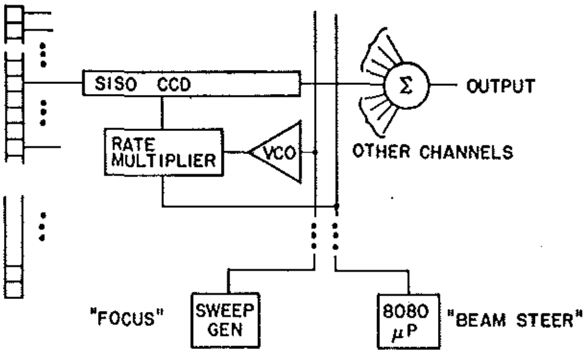

Fig. 3. Microprocessor Controlled System.

Unfortunately this system requires significant volume (1 cu.yd.) due to the large amount of electronics associated with each of the thirty-one channels. Over seven hundred integrated circuits and six thousand discrete components are used. There is little likelihood that with present technology this system will be configured in a hand-held probe.

THE C3D LENS ON A CHIP

The cascade charge coupled device (C3D) is a recent invention of the Stanford Integrated Circuits Laboratory [4] that has the potential of realizing a compact focus unit. This device is basically an array of charge coupled delay lines interconnected on a single integrated circuit substrate and having multiple sections of delay each clocked independently at a different frequency giving flexibility in design which can be utilized to realize sophisticated signal processing functions. Multiple input taps (first demonstrated in the Stanford Razorback CCD [5]) combined with multiple sections experiencing different clock rates yield devices capable of performing the high speed spatial Fourier transform required for the imaging task.

A simple form of C3D lens is a device which incorporates all of the delay electronics in Fig. 1b on one silicon chip. Signal charges injected by the transducers in the piezoelectric array undergo time delays determined by the frequency of clock 1, clock 2, and the number of bits transferred in the sections controlled by these two clocks.

The acoustic imaging system shown in Fig. 2 may be considered to have an optical equivalent of a wedge shaped lens for linear delay closely spaced with a spherically shaped lens for quadratic delay. The "thickness" of both lenses may be electronically varied to steer and focus the lens system on different target points.

Thus the C3D lens realizing this delay function may be considered as having two lens elements in one group on a single silicon chip. There is significant advantage in optics as well as in C3D lenses to have more than just two lens elements in an imaging system. The single parabolically shaped lens in Fig. 2, for instance, actually can be realized to advantage using multiple elements to correct for imaging and electronic aberrations. Fig. 4 shows photomicrographs of two element and three element C3D lens versions designed and fabricated at Stanford to perform the parabolic lens function shown in Fig. 2.

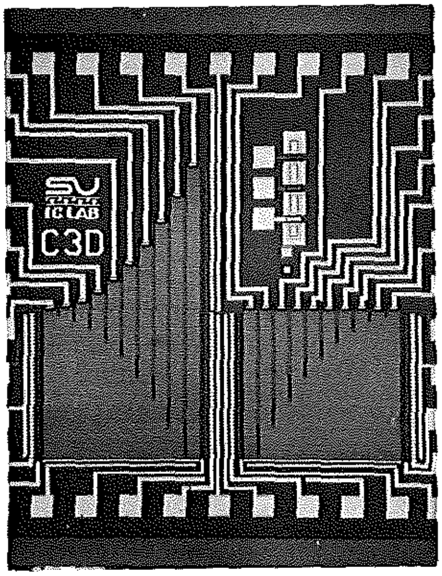

Fig. 4. C3D Prototype Devices.

The device on the right of this figure is the two element parabolic lens. This two element device uses the first element to increase the curvature of the arriving wavefront by a large constant amount (large in comparison to the curvature of the typical wavefronts being imaged). The second element in this two element lens focusses the highly curved wavefronts, i.e. decreases the curvature to a linear wavefront. The total curvature function focussed by the second element is a large constant curvature added to the curvature of the acoustic waves impinging upon the piezoelectric array. Thus the variations in the second element "thickness" (clock frequency) with changes in focussed range are small in comparison to the total second element thickness. This two element C3D lens requires significantly less clock frequency variation with focus range variation than single element equivalents. For an imaging system designed at Stanford this two element lens requires the 2 MHz variation of a 5 MHz clock while a single equivalent lens would require a 45 MHz variation (45 MHz variation is impractical for present day C3D lenses).

The three element lens shown on the left side of Fig. 4 can be used in several modes. The simplest is to simulate a two element lens by clocking the first two elements at an identical, time invariant frequency, and the third element at a frequency in keeping with the focus requirements. Since this two element lens has a first element with twice the number of sample storage positions as the previously described lens, this allows the clock frequency of this element to be twice that of the previously described two element lens. This design technique of allowing choice of clock frequencies provides a method for designing difference frequencies (cross modulation products) of the two clocks to be outside the passband of the ultrasonic channels used.

The goal of this C3D development program is to realize a device as shown in Fig. 5 which incorporates both the focus and beam steer functions on a single chip. As can be seen in this figure two wedge shaped "lens elements" are used to realize this beam steer function. Thus if clocks 1 and 2 are equal in frequency, there is no delay differ-

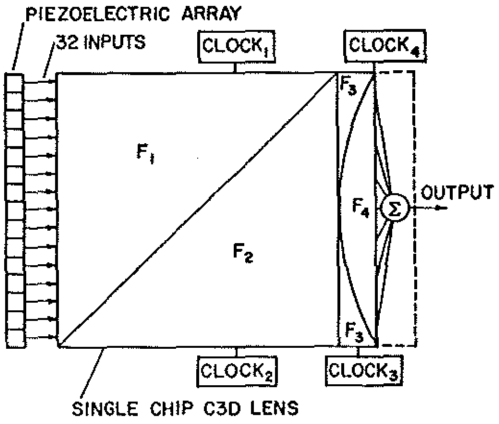

Fig. 5. C3D Lens with Beam Steer and Focus Elements.

ence between channels introduced by the two wedge-shaped delay functions. Beam steering off axis may then be accomplished by clocking the two lens elements at different clock frequencies (the larger the difference frequency the larger the formed beam deflection off axis).

Thus the C3D shown in Fig. 4 is comprised of isolated channels of delay (32 shown in the figure) experiencing different zones (F_1, F_2, F_3 and F_4) of signal propagation velocity determined by the clock frequency of the respective zone. Different channels experience different quantities of delay determined by the number of elements that channel has in each of the zones and the clock frequency of those zones.

There are three classes of focus aberrations associated with the C3D lens which must be considered in any practical system design. These are

1. Dynamic focus aberrations
2. Focus approximation aberrations
3. Electronic distortion aberrations

Dynamic focus aberrations result from "moving the lens" before all elements in the array have received a given wavefront. In the C3D lens design shown in Fig. 5 it is assumed that the lens will focus only at one depth during operation. In practice, the focus range is scanned in synchronism with the returning echoes. Initially after a transmit burst the lens is focussed close to the array to focus nearby targets, then is dynamically scanned in synchronism with the returning echoes from target at greater depths. Unfortunately the lens must be moved before the entire wavefront from a given depth arrives to every element in the array. The outer elements in the array are therefore focussed farther from the array than they should to be exactly focussed on the arriving wavefront. This focus error is called dynamic focus aberration. In the microprocessor controlled system shown in Fig. 3 there is no dynamic focus error for on-axis imaging. This system has the design flexibility to focus the outer elements at different depths than the inner elements due to the separate focus oscillator on each channel. In the C3D lens, however, extra lens elements (clock zones) may be added to connect for this form of abberation.

These are aberrations due to the focus approximation used in the device design shown in Fig. 5. This device uses parabolic delay equalization for a spherical wavefront. While a C3D lens could easily be designed to exactly equalize (except for truncation error) the delay for a specific spherical wavefront, it could not be scanned by varying the clock rate to equalize other spherical wavefronts. Thus the parabolic approximation which is fairly accurate at ranges greater than the aperature of the array is used to acomplish a generally useful focus function in a single device. As in the case of dynamic focus aberration, additional lens elements may be used to advantage in reducing this form of aberration.

Electronic aberrations encompass all of the imaging distortions due to the nonideal parameters of the C3D lens. Two significant sources of electronic aberrations in the C3D lens are (1) charge transfer efficiency (2) cross modulation distortion. The efficiency of charge transfer between storage electrodes determines the total number of storage elements permissible between device input and output. Large charge transfer losses result in a reduced delay line bandwidth. Typically transfer loss considerations limit the total number of storage elements in a channel to five hundred and the maximum clock frequency to fifteen megahertz. Intermodulation distortion results from the interaction of the four clock frequencies shown in Fig. 5 with nonlinearities at the C3D inputs, output and lens element interfaces. While the input and output cross modulation distortions may be eliminated in principal by shielding these points from the clocks, the lens element interface cross modulation distortion is primarily a function of the design of the lens interface and the respective clock frequencies of the lens elements on each side of the interface. This interface cross modulation distortion is the result of the asynchronous partitioning of charge packets which arrive at an interface with a propagation velocity different from the packets leaving the other side. In this case the packets are regrouped resulting in a difference frequency being generated. From a spectral point of view one may consider the signal packet as being resampled at each interface by a special type of sampler. If the resampling is not performed at frequencies large enough to encompass twice the highest frequency sampled, some aliasing will occur.

Unfortunately the spectrum to be sampled is very rich in harmonics so insuring twice that the largest frequency component be sampled is impractical. Fortunately some averaging (low pass filtering) occurs at the interface reducing the magnitudes of some of the aliased components. In a practical system design using C3D lenses the spectrum and magnitude of these difference frequencies relative to the desired signal passband should be considered. A detailed analysis of electronic distortion aberrations is beyond the scope of this paper.

SUMMARY

Two electronically focussed ultrasound imaging systems have been presented. Both systems offer significant improvement in resolution compared with single element systems for ranges from one to ten times the system aperature. The microprocessor controlled system offers fewer sources of imaging aberrations while the single chip C3D lens offers high performance in an extremely compact and potentially economical system configuration.

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