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Article · September 1999

Source: CiteSeer

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SUMMARY

The development of piezocomposites has been the main recent source for improved performance of transducers. This has given improved nearfield, higher bandwidths, and is about to give 1.5D probes with two-dimensional focusing, and eventually 2D arrays for steering and focusing of beams in 3D data volumes.

Due to the advent of digital beamformers implemented with custom VLSI chips, there has also been an improvement in image quality due to a more precise control over the beam, as well as provision for individual correction of transducer imperfections. In addition the reception of several beams in parallel is possible. New hybrid image formats such as steering of linear and curved arrays, and scanning of phased arrays in combination with steering, now emerge. Adaptive correction for phase aberrations due to tissue inhomogeneities may also become reality.

INTRODUCTION

Beamforming in ultrasound instruments for medical imaging has traditionally been implemented using analog delay lines. Typically 1D arrays with between 32 and 192 elements are used such as shown in Fig. 1, upper right-hand panel. The signal from each individual element is delayed in order to steer the beam in the desired direction. In addition focusing of the beam is performed. In the receive beamformer this gives rise to the concept of dynamic focusing. For each pulse which is transmitted from the array, the receive beamformer tracks the depth and focuses the receive beam as the depth increases. It is also important to let the receive aperture increase with depth. This gives a lateral resolution which is constant with depth, and decreases the sensitivity to aberrations in the imaged medium. This gives a requirement for dynamic control of the number of elements that are used. Since often a weighting function (apodization) is used for sidelobe reduction, the element weights also have to be dynamically updated with depth.

Optimization of image quality in medical ultrasound instruments requires a system's perspective on transducers and beamforming as there is an interaction between new developments in both fields. In this paper developments in transducers and beamformers and their relationship will be discussed.

COMPOSITE ARRAYS

The advent of piezocomposites has been the main recent development in transducer technology. A piezocomposite is a combination of a piezoelectric ceramic and a polymer which forms a new material with different piezoelectric properties. Piezocomposites have improved the performance of commonly used arrays such as the mechanically scanned annular array and the linear phased array of Fig. 1 upper panels, in the following ways [2]:

1. Acoustic impedance is reduced giving a better impedance match with tissue. This results in a reduction in reverberation level in the near field as the transducer surface to a less extent reflects back incident energy.
2. The composite materials make the radiators closer to the ideal of a vibrating piston. Primarily this is due to the suppression of unwanted surface waves propagating laterally over the transducer.
3. Piezocomposites make it possible to vary the electromechanical coupling constant, thus allowing more control over the trade-off between sensitivity and bandwidth. In general there is a trend towards transducers with large bandwidth, typically 60-80% relative bandwidth (-6 dB).

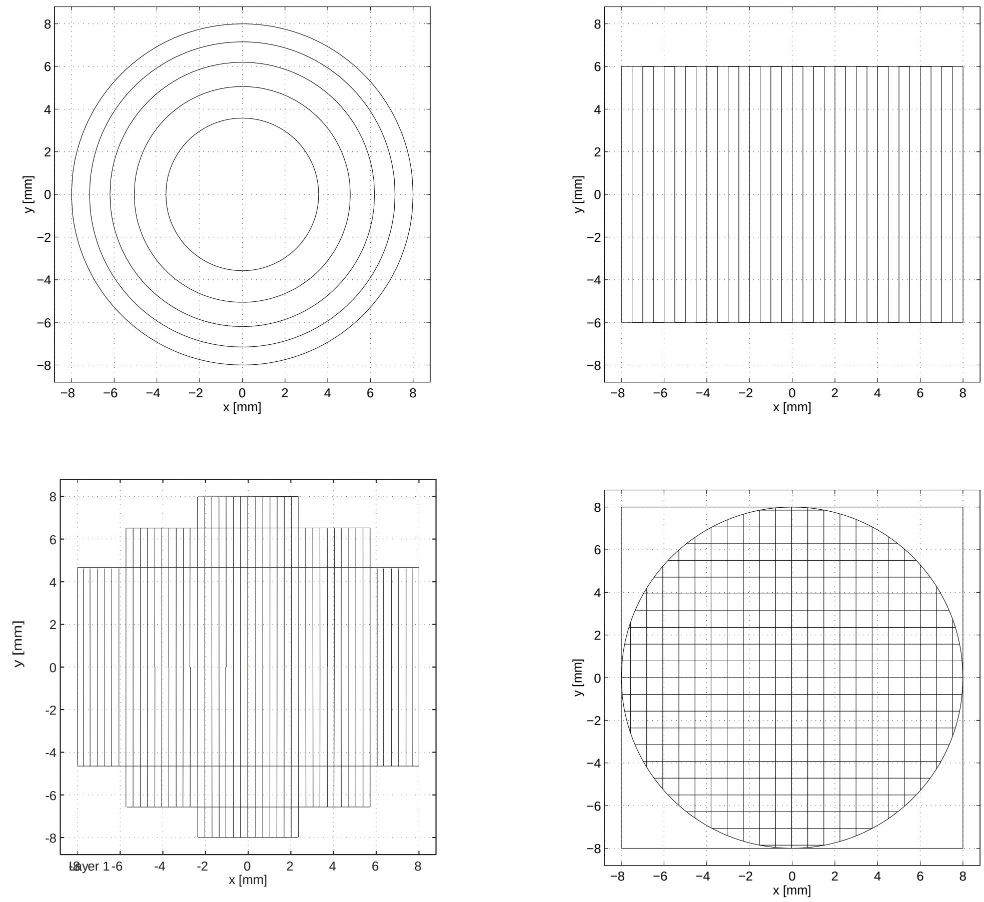

Fig. 1. Array types: Annular array, rectangular array, 1.5D array, and 2D array

New transducers that open up new possibilities are now possible:

1. Transducers that consist of two overlaid orthogonal linear phased arrays, resulting in a biplane transducer. The element patterns for the two arrays are defined on opposite sides of the ceramic. Grounding of one set of electrodes and scanning on the other gives an image in one plane, reversing the roles gives the other plane.
2. One of the advantages an annular phased array has over a linear phased array is variable focus in both dimensions. The 1.5D array shown in Fig. 1, lower left-hand panel, is designed to give variable focus in the short-axis direction also. The 5 elements shown are patterned according to a Fresnel lens. Typically such an array will require a doubling of beamformer channels. The figure shows a 32 element array where 22 + 10 elements are added on each side. Due to sym-

metry the side elements can be connected in parallel, resulting in 64 channels. A realistic array would have two to three times more elements than this [12].

3. Finally the composite technology makes it possible to consider true 2D arrays with square elements. This enables beam steering in 3D space [6]. Such arrays are a prerequisite for real time 3D imaging with transducers without moving parts. One of the challenges of such designs is the small size of each element, resulting in a high electrical impedance. One approach to overcome this is a multilayer composite where a layered structure of ceramic are connected electrically in parallel, but acoustically in series. Placing some of the scanner electronics in close vicinity to the transducer also helps overcome the problem of poor impedance match [10].

DIGITAL BEAMFORMING

Digital beamforming is now about to become feasible in beamformers for medical ultrasound. The concept has long been known, but availability of high-speed analog to digital converters, and VLSI technology improvements have now made digital beamformers feasible [4].

Digital beamforming first of all gives better control over time delay quantization errors. In analog beamformers, delay accuracy is typically in the order of 20 ns. For operation at frequencies at or even above 10 MHz, quantization noise will manifest itself as an increase in sidelobe level and thus reduce contrast resolution [7], [8]. In digital beamformers the delay accuracy can be greatly improved, thus allowing higher frequency operation.

A second advantage of digital beamformers is that it is possible to implement true time delay beamforming. This assures close-to-ideal operation over a wide bandwidth and is a necessity as transducer bandwidths have increased. Many analog beamformers have been implemented using a mixture between wide-band time-delay techniques and narrow-band phase-compensation techniques and will not allow true wideband operation.

The improved near-field of modern transducers also has an impact on design of beamformers. With analog beamformers the number of focal zones is related to size and cost, and therefore the number is kept as low as possible. A simple calculation of focal zone size in the near-field will give an indication of what is required to really take advantage of the clearer near-field of modern composite transducers. The depth of field is given by $6\lambda FN^2$ for an allowed 2 dB of defocusing loss [5]. In this expression λ is the wavelength, and FN is the f-number, i.e. the ratio of focal depth and aperture. A high frequency transducer at 10 MHz, operating at an f-number of 1.5 will give a depth of focus of about 2 mm. This necessitates continuous focus beamforming [9].

Even though transducers have been improved over the years, they are still not ideal. Sources of degraded image quality are found mainly in a time delay variation and in a variation in sensitivity from element to element. The time delay variation is caused by the surface not being exactly plane or curved. The variations can be measured and stored in the probe, and the beamformer can use the information to improve the image quality.

A more challenging effect to compensate is phase aberrations caused by for instance fat layers in the tissue. This requires adaptive compensation of time delays. So far only experimental systems have been demonstrated using this technique [3], but it may become reality in the future.

In addition to obtaining a more accurate realization of a beamformer, digital beamforming also opens up for new possibilities such as several parallel receive beams [1]. Although this has been around for a long time for instance in sonars, it is quite recent in medical ultrasound. This is primarily due to the high frequencies and high bandwidths involved. Front-ends with two to four parallel beams are now being introduced [9]. This can give a corresponding increase in frame rate, something which is of great importance in certain modes in cardiography, especially pediatric imaging and in color flow imaging. A 3D imaging system requires parallel beams over an area instead of along a line and thus may benefit from using four to sixteen parallel beams. This comes in addition to a vast increase in elements, typically from 64 for a phased linear array to $\pi 64^2/4 \approx 3200$

for a circular 2D array. Techniques for reducing this number, such as sparse array methods [11], are now being investigated in order to reduce the number of front-end channels.

Analog beamformers have traditionally been of two types: phased and sequentially scanned. The phased beamformers have enough delay to handle linear phased arrays and are used for sector formats such as required in cardiography. The less expensive sequentially scanned beamformers are used for focusing and slight steering of linear and curved arrays (i.e. about 20% of the delay of the phased beamformer). These probes are used in abdominal and obstetric applications, and are characterized by the same delay pattern sequentially repeated over the surface of the transducer. As beamformers become less expensive a larger proportion of the ultrasound scanners will contain a phased beamformer. This makes new hybrid image formats possible. Formats such as steering of linear and curved arrays that up till now only have been scanned, and scanning of linear phased arrays in combination with steering now emerge. Thus there is a tendency for the distinct transducer array categories to merge.

CONCLUSION

Piezocomposites have improved performance of transducers in common use today as well as made 2D arrays a possibility. On the other hand the development of the digital beamformer has meant that there is a shift in cost: analog channels including transmitters, preamplifiers, connectors, and cables are still expensive while digital capabilities such as increased accuracy and parallel beams will become less costly. This development gives increased image quality of today's scanners as well as opens the way for real-time 3D ultrasound systems in the near future.

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