Characterization of 1.5-D Ultrasound Transducer Arrays

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Abstract—The objective of this work was twofold. The first was to investigate theoretically and experimentally the acoustical and electrical characteristics of 1.5-D ultrasound transducer arrays for 3-D imaging applications. Modeling and simulations of arrays of various geometry, center frequencies, and materials were performed, analyzed and optimized. The optimization criteria was the best achievable lateral and elevation imaging resolution. The second objective was to fabricate several optimally designed prototypes of 1.5-D arrays and characterize their performance. Investigated were such vitally important performance issues such as spatial resolution, acoustical and electrical crosstalk, matching techniques, electrical impedance and element size, pulse-echo bandwidth and sensitivity.

INTRODUCTION

The "1.5-D" notation is commonly given to small two-dimensional arrays with a limited number of elements along the elevation dimension, as shown in Fig. 1. 1.5-D and 2-D transducer arrays allow dynamic control of the elevation beamwidth via apodization and electronic focusing. 2-D arrays could provide the ultrasound industry with long awaited 3-D imaging capabilities, characterized by symmetrical spatial resolution throughout the imaging field and superior image quality [1]. Unfortunately, several factors have limited development of 2-D array technology, including the large number of elements, small size, electrical interconnect, and demanding system requirements, among others [1,2,3]. The 1.5-D approach provides an important link between conventional 1-D arrays and 2-D arrays due to significant cost and implementation advantages. However, a relatively small body of published work has focused on 1.5-D arrays [2,3]. The objective of this research was to optimize the design of 1.5-D ultrasound transducer arrays through theoretical and experimental investigations of their performance. Transducers based on mechanically scanned 1.5-D arrays could efficiently acquire three-dimensional information for medical diagnosis. Small, hand-held 2-D scanheads would become feasible and affordable, thus creating opportunities for 3-D scanners with improved image quality.

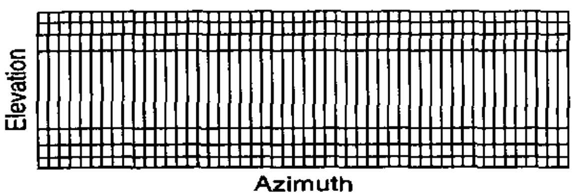

Figure 1: 1.5-D array, illustrating small number of elements along the elevation dimension relative to the azimuth.

METHODS

The scope of this research effort was divided into four main areas. The first was based on transducer simulations and characterization. The second on acoustic field simulations and characterization. The third on fabricating prototype 1.5-D arrays, and the fourth, on measuring and characterizing the arrays. The results provided valuable information for producing an optimal 1.5-D design. Topics studied were as follows.

1. Transducer simulation and characterization. The dispersion in 1.5-D transducer arrays was analyzed. A 1.5-D array will typically have its elevation height diced into a variety of sub-lengths. These parallelpipeds may have length resonances close to the thickness mode resonance if the aspect ratio is not controlled properly [4]. Such coupled resonances and dispersive effects could decrease the pulse-echo sensitivity as well as cause different sections of the array to have different frequency responses (bandwith and center frequency). Dispersion was measured in PZT-5A ceramic by extracting material constants [5] from electrical impedance measurements of parallelpipeds with a fixed thickness/width aspect ratio of 2:1 and elevation height/azimuthal width aspect ratios of 1:1 to 10:1. It is shown that conventional techniques may be used for aspect ratios greater than 4:1 or those for rods at 1:1. Material properties of D-1900 ceramic (5A equivalent) were also measured and used in pulse-echo simulations of several transducers using Mason's model. Acoustic matching and backing, and electrical matching was studied. The variation in sensitivity and bandwidth with element size was investigated. The result of the transducer analysis was a well-characterized element response that could be used as input to acoustic field calculations.

2. Acoustic field simulation and characterization. Simulations of acoustic fields in three dimensions was performed using a broadband, Fourier-based, numerical solution of Rayleigh's integral via the point-source method with the "soft-baffle" radiation condition. The transducer's simulated pulse-echo impulse response was used

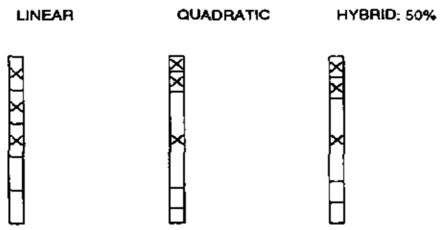

Figure 2: Elevation focusing geometries analyzed, illustrating a five (5) elevation element array. Exploiting symmetry, consecutive outer pairs of elements are electrically connected for on-axis focusing, resulting in less hardware.

in the simulations, and a rubber lens was included. It is shown that a lens or mechanical focus remains beneficial for a 1.5-D array, due to the small number of elevation elements, as has been found in [2,3], and also because it reduces the required electronic delay. Acoustic beamprofiles revealed the spatial resolution of various 1.5-D scanheads. The elevation focusing properties were isolated when desired by setting the azimuth acoustically small such that the radiation is essentially isotropic in the azimuthal plane. The effect of various elevational element geometries was studied. Linear (equally-spaced), quadratic, and hybrid-spaced elements were examined, as shown in Fig. 2. Quadratic spacing varied the elevation sizes in proportion to the square root of the number of elements. The hybrid array has linearly spaced outer element pairs, and a single central element with a size on the order of the quadratically-spaced array or less. Acoustic sidelobe levels and beamwidths were investigated versus the number of elevation elements. The varied transducer element sizes encountered in 1.5-D arrays creates a natural apodization. The improvements in elevation beamprofiles resulting from this apodization was analyzed.

3. Prototype fabrication. Based on the results of the transducer and field studies, several 5 MHz prototype 1.5-D arrays were fabricated for measurements. Prototypes had 15 mm elevation height, one to five elevational elements, and up to 128 azimuthal elements. The large elevational and azimuthal apertures are desirable for maximum resolution. Quadratic and hybrid geometries were constructed. Lenses were also included to augment the elevational focusing properties of the arrays. The prototypes had double matching layers made by the "cast and grind" technique, and the transducer was diced to a pitch of 0.167 mm. Three elements were bussed together for an azimuthal pitch of 0.5 mm (1.66λ). The elevation pitch was defined by dicing into the ceramic thickness to 80%, which preserved the ground contact while isolating the elements.

4. Array measurement and characterization. The prototypes were tested for acoustical and electrical parameters, including electrical impedance, cross-coupling, pulse-echo sensitivity, center frequency, fractional bandwidth and pulse ringdown time, as well as their variation with element size. The experimental measurements were analyzed and compared to simulations. A 1.5-D array design method was derived which takes into account all of the performance issues and results.

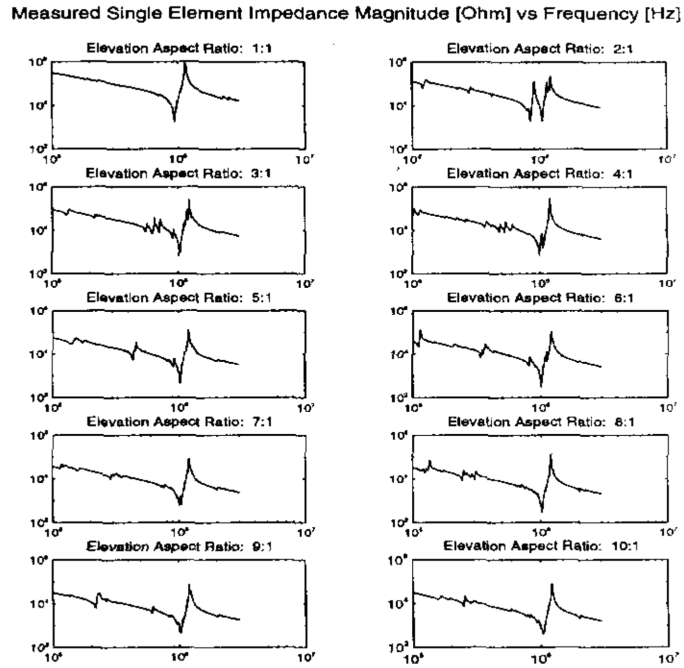

Figure 3: Measured electrical impedance magnitude of parallelpipeds of elevation height to azimuthal width aspect ratios of 1:1 to 10:1, showing asymptotic single mode for 1:1 and 10:1 ratios. The thickness to width aspect ratio in each case is 2:1.

RESULTS

Impedance plots from the dispersion study are shown in Fig. 3. It is clear that elevation height to azimuthal width aspect ratios near two (2) should be avoided due to strong height/width mode coupling. This may be accomplished by either sub-dicing along the elevation, to produce subelements with aspect ratios of 1:1, or by using elements with aspect ratios greater than about 5:1. Measurements and characterization of the effective material constants of such arrays has been conducted and results tabulated. Experimental measurements and analysis showed that the same thickness mode transducer constants and models used for bar shaped array elements can be used for the shorter elevation elements. However, at elevation height to azimuthal width aspect ratios less then 5:1, parasitic lateral modes are present in practice which a 1-D model will not represent. Elements subdiced into 1:1

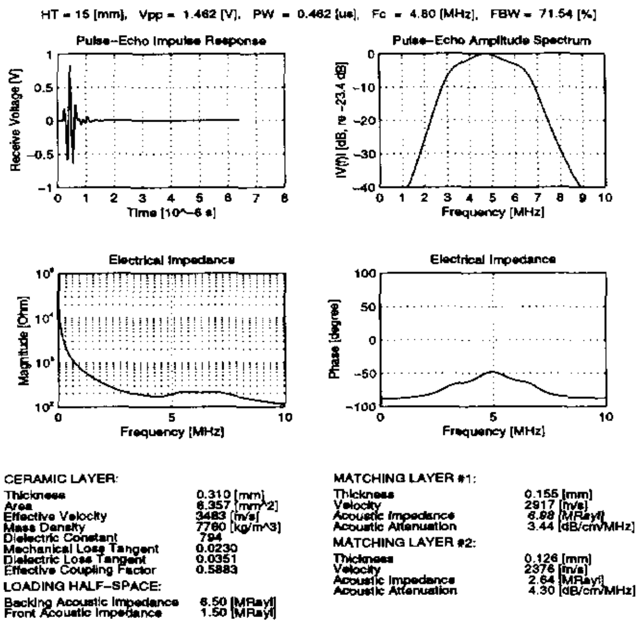

Figure 4: Pulse-echo simulation of a 5 MHz 1.5-D transducer element, using an elevation height of 15 mm.

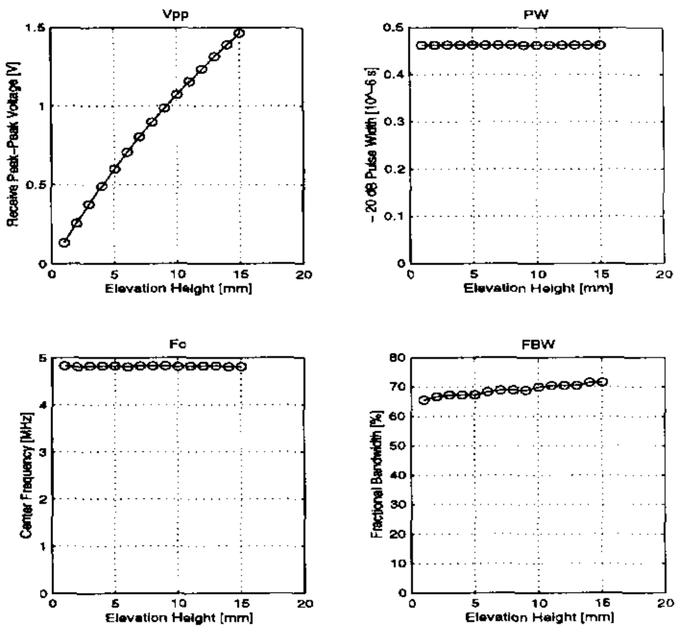

Figure 5: Variation of transducer parameters with elevation height simulated for D-1900 (PZT-5A equivalent) ceramic material.

aspect ratio pillars can be represented with unique material constants which represent this unimodal vibrational mode. For the large-aperture arrays of interest, with a modest number of elevation elements, elevational aspect ratios greater than 5:1 are achievable in practice.

Simulation of 3.5 MHz, 5 MHz, and 7.5 MHz 1.5-D arrays showed bandwidths and sensitivity comparable to 1-D arrays, as shown in Fig. 4. A drop in sensitivity occurs that is approximately proportional to elevation height when the element is small (element impedance is much greater than the pulser/receiver impedance). This effect is illustrated in Fig. 5. This was the case for both conventional and high dielectric constant ceramic material. An electric matching transformer can transform the impedance of the smaller elements, with the result that the sensitivities are matched. A change in height from 15 mm down to 1 mm in a 5 MHz array produced a sensitivity drop of about 21 dB, and a decrease in fractional bandwith of approximately 8%. Both were overcome with a 1:4 turns ratio matching transformer. In a typical 5 MHz array, where the center element was about 7 mm and the smallest on the order of 4 mm total, the sensitivity change was only 3 – 4 dB, which was acceptable for elevational apodization. These transducer simulation and characterization results were used to fabricate prototypes, and were employed in the acoustic field studies.

The acoustic field simulations had the objective of optimizing the 1.5-D array beamprofiles for imaging. Prefocusing the elevation dimension of a 1.5-D array with a curved ceramic or lens reduces the required electronic delay significantly. This reduction is beneficial since each of the elevation elements requires its own receiver delay and associated electronics. An analysis of the focal delay requirements of a linear, quadratic, and hybrid 1.5-D array with five (5) elevation elements operating at 5 MHz, and mechanically focused at 50 mm was undertaken. This corresponds to a fifty (50) wavelengths total elevation height. Fig. 6 shows that a one wavelength electronic time delay could focus such an array over a range from about 2.5 to 20 cm. Specific geometries used for simulation and prototype fabrication are listed in Table 1.

Table 1: Array Prototype Parameters.

Type	Number of Elements	Elevation Sizes [mm]
1-D	128 × 1	15
1.5-D Quad.	128 × 5	1.38,1.8,8.66,1.8,1.38
1.5-D Hybr.	128 × 5	2,2,7,2,2

Elevation element spacing was simulated. Acoustic field analysis of linear, quadratic, and hybrid-spacing revealed such arrays produced main lobes of equal beamwidth in the focal plane of the lens, but that the hybrid geometry produced lower sidelobe levels, which results in increased image contrast resolution. The -6 dB FWHM azimuthal and elevation resolutions followed the general $\lambda\times$f-number beamwidth of a focused radiator. Sidelobes at 3 cm electronic focus were approximately -25 dB below the main

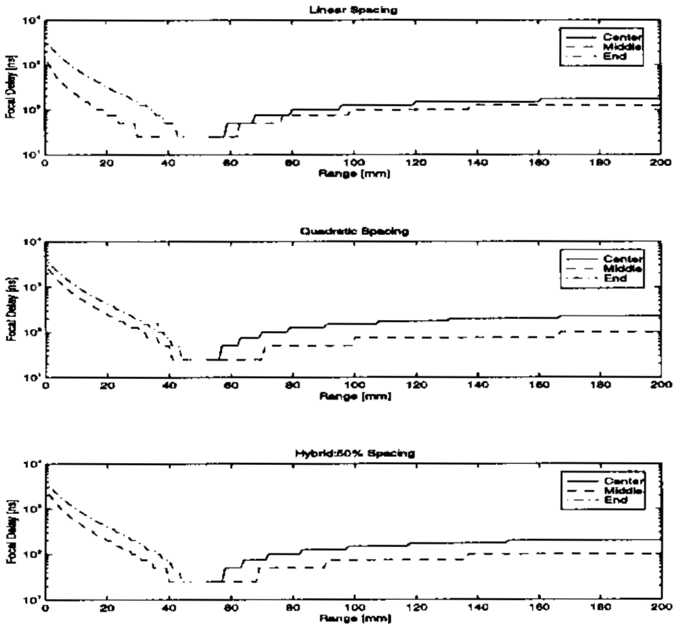

Figure 6: Quantized elevation focal delay versus range for a 15 mm height, 5-element (3 electrical) 1.5-D array. Delay taps are spaced at 25 ns, yet judicious selection of elevation focal zones yields only ±5 ns delay quantization error.

lobe for an aperture of 15 mm (F-number of 2).

The effect of the number of elevation elements on sidelobe levels of a hybrid geometry array, with a central element size of 47% of the elevation height is shown in Figs. 7. A five or seven element hybrid array yields better performance than the quadratically or linearly spaced arrays. The intrinsic area-based elevational apodization further lowered sidelobes in the hybrid array as shown in Fig. 8. Apodization dropped sidelobes about 4 dB at 3 cm and about 10 dB at 75 mm. The electronic focusing resulted in a significant reduction in the main lobe beamwidth compared to a 1-D array. At 3 cm the 1-D array had a -6 dB FWHM of 4 mm versus 0.7 mm for the 1.5-D hybrid array.

Several array prototypes were fabricated. Experimental measurements yielded results that agreed with simulations. Typical results are shown in Fig. 9, and are partially summarized in Table 2.

The pulse-shape and amplitude, fractional bandwidth, -20 dB ringdown time, and electrical impedance were measured. Representative values for a 5 element quadratically-spaced prototype yielded 69% bandwidth for all elements, 62% for the center, 63% for the inner, and 64% for the outer elements. Thus the fractional bandwidth decreased only slightly at the outer elements, maintaining the pulse shape as in simulations, and as is desirable for high axial resolution imaging. The highest

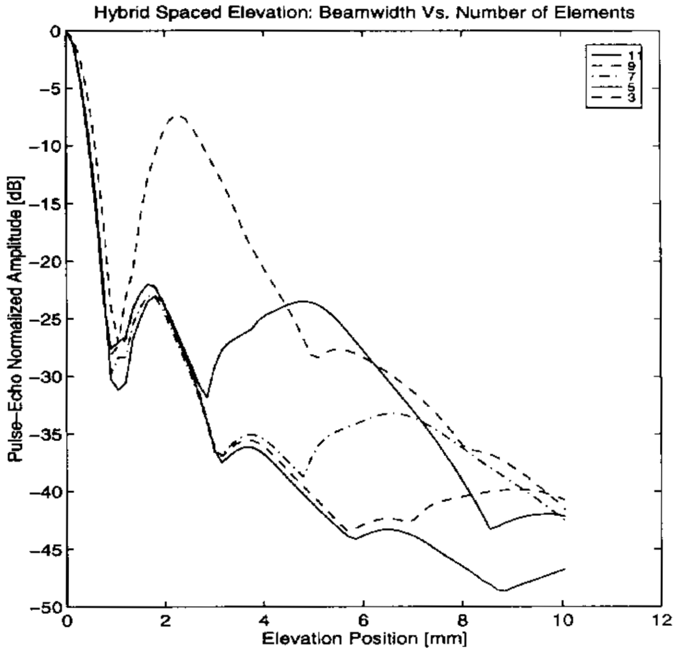

Figure 7: Beamprofile versus element count for hybrid spaced array focused at 3 cm.

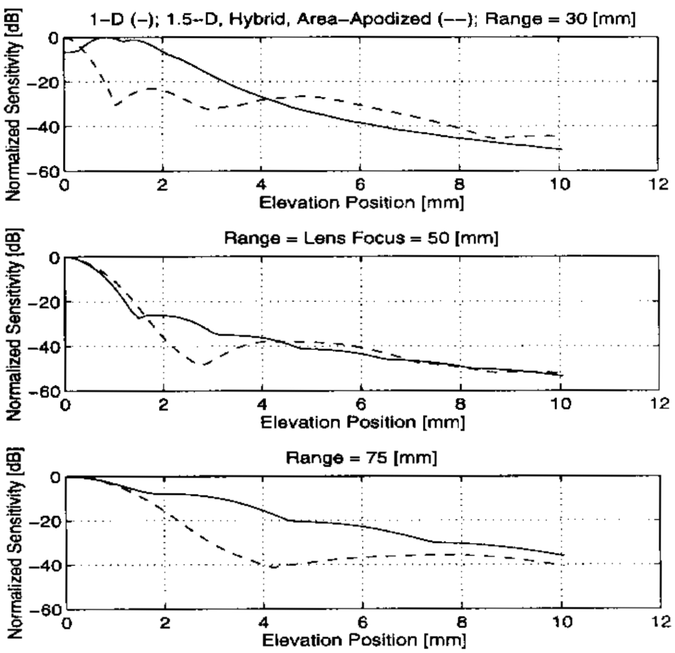

Figure 8: Comparison of elevation beamprofiles of a conventional 1-D array with that of a five element, hybrid spaced, 1.5-D array. The natural apodization resulting from the different transducer element sizes is included. The 1.5-D array is electronically focused at 30, 50, and 75 mm.

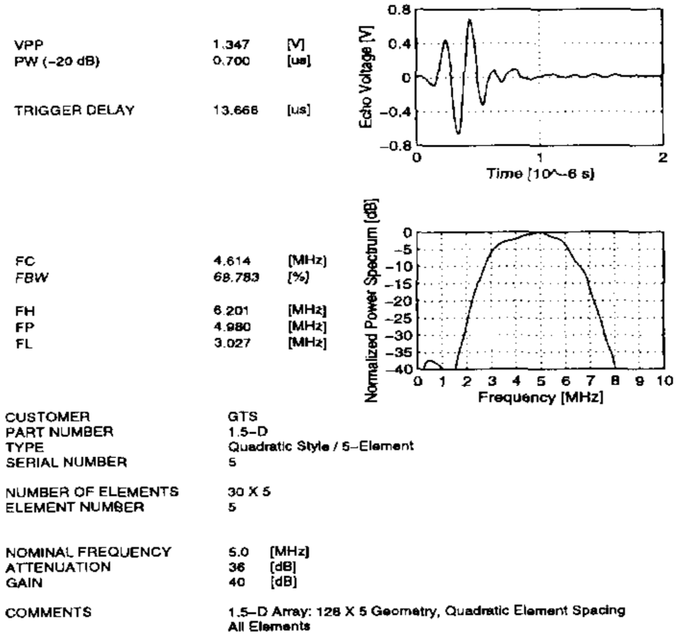

Figure 9: Pulse-echo test results of a 1.5-D array prototype with quadratically spaced elevation. All elements along elevation driven together.

Table 2: Additional Array Prototype Geometry and Pulse-Echo Test Results. †Abbreviations: A=All, C=center, I=inner, O=outer element, L=lensed.

Array Size	Element Tested†	Gain [dB]	Vpp [V]	PW [μs]	F_C [MHz]	FBW [%]
24×5	C	20	1.14	0.720	4.50	67.8
24×5	C+I	16	0.95	0.720	4.50	63.4
24×5	A	16	1.00	0.720	4.42	70.7
30×5	A	4	1.35	0.700	4.61	68.8
30×5	C	6	1.07	0.670	4.81	61.9
30×5	I	16	1.08	0.530	4.76	63.6
30×5	O	26	1.16	0.810	4.31	64.0
128×3	C	12	1.15	0.660	4.90	75.3
128×3	C+O	12	0.990	0.680	4.86	75.4
128×3	C	16	1.03	0.730	4.43	75.8
128×3	C+O	16	1.14	0.730	4.39	77.8
128×3	L+C	18	1.07	0.660	4.32	80.2
128×3	L+C+O	12	1.16	0.710	4.41	75.9

fractional bandwidth measured of 71% compares to 72% in simulations. The measured drop-off in sensitivity compared to the whole elevation (0 dB reference) was -5.2 dB center, -14 dB inner, -23 dB outer. This compares to a simulated drop off (if purely area-based, which is the approximate characteristic) of 0 dB, -4.8 dB, -12 dB and -15 dB. The simulation was for a 50 ohm pulser/receiver with a fixed -150V impulse, which is slightly different than the reactive loading of the commercial unit used for tests. The crosstalk measured in the quadratic array along the elevation was small compared to typical azimuthal crosstalk. A 20 volt peak-peak one cycle sinusoidal pulse on the center element produced only a 54 mV pulse on the adjacent inner-element pair (-51 dB). Azimuthal crosstalk measured was on the order of -40 dB. The electrical impedance closely followed simulations also. In summary, the optimized prototype arrays had performance comparable to or better than 1-D array elements A general set of guidelines and methods for fabricating 1.5-D arrays was developed. These results will be used in 3-D scanhead development and optimization.

CONCLUSION

In conclusion, array element dispersion, pulse-echo simulations, element sensitivity, pre-focusing, element spacing and count, and prototype fabrication and measurement have been discussed and their effect on 1.5-D arrays analyzed. This work can be used to optimize the design of 1.5-D transducer arrays.

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