Cylindrical ultrasonic array for borehole applications

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Abstract A cylindrical ultrasonic array has been developed for operating environments that can reach extremes of $175°C$ and 20,000 psi. The array is a key component of the PharUSIT (Phased Array Ultrasonic Transducer for Inspec-tion of Tubing), a research demonstrator developed for borehole applications. The full array consists of 800 elements (10 rings of 80 elements each) and can provide a whole range of beam-forming versatilities and capabilities in 3D, such as variable focusing, beam steering, electronic scanning, etc, all accomplished without mechanical movements. Special piezocomposites have been developed for the transduction layer, and new polymeric composites have been formulated for the backing material. The center frequency was chosen to be about 500 kHz to accommodate attenuation of the propagation media. A novel technique utilizing custom flexible circuit provides electrical connections between the array and the front-end electronics. Special fabrication processes have been developed to construct the array in a cylindrical geometry. A customized testing protocol has been implemented to demonstrate the survivability of the array technology and to evaluate the performance characteristics of individual elements under high-temperature/high-pressure conditions. Data from electroacoustic measurements such as electrical impedance, bandwidth, sensitivity, angular directivity, and inter-element cross-talks will be shown.

1 Introduction

The objective of the "Phased Array Ultrasonic Transducer for Inspection of Tubing" Project (PharUSIT) is to develop a new ultrasonic transducer array with the associated electronics to provide full 3-D beam-forming versatility so that scanning and focusing can be carried out electronically in real-time. The system is intended for non-destructive testing in oil wells, performing measurements ranging from imaging the open borehole wall to evaluation of the steel casing and the quality of the cement behind it. The entire tool has to be packaged in a size and form-factor consistent with the borehole geometry. The operating environment is typified by unusual and harsh conditions, with temperature of up to $175°C$, pressure up to 1400 bars, and attenuative propagating medium loaded with mud particles. The transducer array is the key front-end component of the system and is exposed to both high-temperature and high-pressure (HTHP) conditions [1-3]. The design, fabrication and qualification of such a transducer array that can survive and perform under HTHP conditions is the subject of this paper.

2 Array Design & Specifications

A typical oil-well logging tool is tethered to the end of a long spooled cable (24,000 ft) which provides electrical power to the tool and also serves as a communication link between the down-hole tool and the surface systems. Normal operation involves lowering the tool to the depth of interest and measurements typically are conducted as the tool is withdrawn at a controlled speed. Elevation scanning and depth registration are automatically provided by mechanical means. To achieve 360F azimuthal coverage for the cylindrical geometry of the borehole, it is desirable to have a full azimuthally sampled cylindrical aperture for the transducer array. To provide comparable spatial resolution and beam-forming capabilities in elevation as well as in azimuth, the cylindrical aperture needs to have a suitable height in the elevation direction, appropriately sampled. We therefore decided to develop a fully sampled 2D cylindrical array to enable 3D beam-forming versatility in borehole applications.

The borehole liquid varies in composition (water, brine, oil, etc) and are often loaded with heavy mineral particles to achieve specific mass densities, which can be as high as 2000 kg/m^3, thus presenting to the transducer array a wide range of acoustic impedances and more importantly, high ultrasonic attenuations. The attenuation in the propagation medium limits the maximum center frequency of operation to around 500 kHz.

Since the total element count dictates the eventual complexity of the overall imaging system, the spatial sampling of the transducer aperture is an optimal compromise of the following factors: (i) the quality of the synthesized beam (relatively free of spurious lobes), (ii) angular directivity of each array element (preferably omni-directional), (iii) electrical impedance of individual elements. These factors are seldom satisfied simultaneously to their respective best possible theoretical limits and are often traded off in realizing a practical design.

The cylindrical aperture of the prototype array has a diameter of 80 mm to accommodate a 7.5" diameter bore-hole, the most common size. The array is composed of 10 rings of 80 elements each, for a total of 800 elements, as shown in Fig. 1. The elevation pitch is 3.5 mm and the azimuthal pitch is 3.14 mm. At a center frequency of 500 kHz operating in water (1500 m/s), the element pitches correspond to 1.2λ and 1.0λ in elevation and azimuth respectively. These spacings are much bigger than the theoretical requirement of 0.5λ for total elimination of grating lobes. Nonetheless, with pulse excitation and moderate off-axis beam steering angles, finite-difference modeling indicated no serious grating-lobe problems.

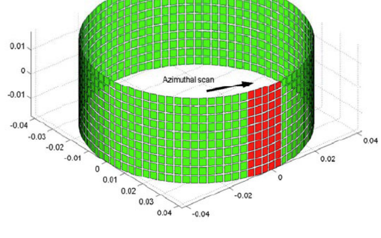

Figure 1. 2D cylindrical array of 80x10 elements with active aperture shown in red

Fig. 2 shows the structure of the transducer array. The active layer uses a 1-3 piezocomposite material developed by IMASONIC. Piezocomposite offers advantages over monolithic piezoceramic in that its inherently lower acoustic impedance allows higher coupling and broader bandwidth operating into a water-based propagation medium. The active layer is bonded to a backing block that ideally should have a matched acoustic impedance to give the transducer a broad bandwidth of operation (~100%). The backing block should have sufficient attenuation to absorb the unwanted acoustic energy radiated into it. The front of array is covered with a rubber layer to provide protection in the borehole environment. Appropriate choice of the rubber layer thickness and its acoustic impedance would further enhance the coupling efficiency and bandwidth characteristics. A 1 mm thick Viton boot is used as the front layer of the array. The size of the elements are maximized to 2.64 mm in azimuth and 3.0 mm in elevation to lower the electrical impedance for the benefit of the pulser-receiver electronics, with a 0.5 mm wide kerf defining the boundary between adjacent elements.

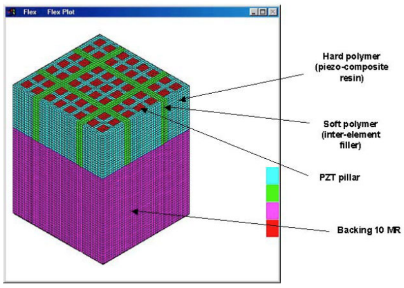

Figure 2. Structure of HTHP array

The selection of appropriate polymeric materials to form the matrix in the active layer and the backing block enables the transducer array to survive and perform satisfactorily up to the maximum HTHP conditions of 175°*C* and 1400 bars. IMASONIC employed a "hard" high-temperature polymer in the 1-3 piezocomposite layer. To withstanding high pressure, the kerfs that spatially define the individual elements need to be filled in. A "soft" polymer was used for that purpose. It is stiff enough to be subjected to the operating pressure but yet soft enough to maintain the acoustic isolation of the array elements. The most challenging polymer selection was that of the backing. The backing composite is loaded with high acoustic impedance particles made of tungsten and alumina to boost its effective impedance. The uncured polymer has to allow the easy introduction of large quantities of heavy particles and to suspend them uniformly throughout the curing process. In addition, the slurry mix has to be "injection-moldable" in order to be compatible with the fabrication process. We were able to achieve a backing impedance of 11 MRayl and an attenuation of ~12 dB/cm at 500 kHz.

Furthermore, to connect 800 individual array elements to the down-stream electronics, custom flex circuits were designed, fabricated and bonded to the front surface of the array elements to address them individually. The full array was essentially fabricated in 45° segments each consisting of 10×10 elements as shown in Fig. 3. The right picture in Fig. 3 shows a stand-alone (no electronics attached) array housed in a support fixture used for qualification testing.

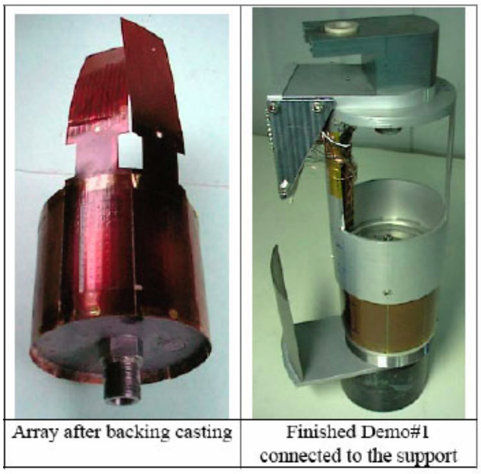

Figure 3. HTHP array fabrication steps

3 Array Testing & Results

The purpose of testing the transducer array is two-fold: (i) to characterize the electro-acoustic performance of the individual elements, (ii) to demonstrate the HTHP survivability of the array technology. We developed the following test procedure for qualifying HTHP ultrasonic phased arrays. Electrical impedance measurement in air provides a quick assessment of the "health" of each element through parameters such as the resonance frequency, capacitance and "peakiness " of the resonance. Before exposure to HTHP, each array element is characterized in a water-tank at room temperature and normal pressure. The characterization involved determining the angular response of individual elements. This initial data set establishes the baseline performance of the array. The water-tank setup is shown in Fig. 4. The array is held in a fixture that provided multiple degrees of adjustment so that each element can be precisely positioned in front of a large flat Plexiglas block reflector. The array element under test is rotated through a range of angles (±30°) with respect to the reflector at a constant distance of 75 mm and pulse-echo waveforms are collected and processed to assess the angular sensitivity, bandwidth, etc. A Panametrics 5077PR pulser-receiver is used. The excitation was a 300-volt unipolar pulse with a duration of one half-cycle at 500 kHz. The receiver gain is set to 26 dB. The array is then subjected to multiple HTHP cycles in a special pressure vessel system to assess its survivability. Pulse-echo waveforms are recorded throughout each HTHP cycle to monitor the behavior of the array. The test sequence is repeated to check for any significant changes before vs. after HTHP cycle, and from one test sequence to the next.

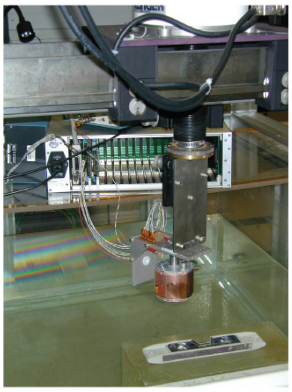

Figure 4. Water-tank test setup

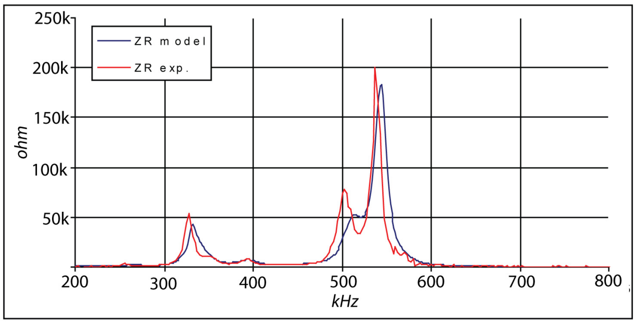

Figure 5. Comparison of theoretical vs. experimental electrical impedance of a 2.6x3.0 mm element

Fig. 5 is a comparison between the modeled (FEM) and the measured electrical impedance of an unloaded 2.6mm x 3.0 mm piezocomposite element in an early test sample fabricated by IMASONIC to show the good agreement. The thick-ness resonance occurs at 535 kHz. The weaker resonances at 500 kHz and 325 kHz are lateral modes related to the near cubic geometry and periodic layout of the array elements.

One of the later array prototypes, EXP#2, underwent the most thorough testing. EXP#2 was fabricated with 14 (column) $\times 10$ (row) elements. The measured capacitances and their distribution are illustrated in Fig. 6. There was initially only 1 dead element and 2 elements in Column 7 that were intermittently shorted together electrically. Parasitic capacitance due to the flex circuit interconnection contributes about 10 pF of the mean measured capacitance of 38.2 pF. The normal incidence pulse-echo amplitudes and their statistics are depicted in Fig. 7. The $\pm 3dB$ variation is comparable to the industry norm for medical ultrasound arrays. Fig. 8 shows a typical pulse-echo waveform and its frequency spectrum. The two-way -6 dB (or one-way -3 dB) bandwidth is about 43%, way below the specified target of 100%. The discrepancy is due to the large acoustic impedance mismatch between the backing and the piezocomposite layer. Fig. 9 depicts visually the inter-element crosstalk measurement. An element (Row 6) was excited with a 1-volt amplitude single-cycle 500 kHz pulse. Time-waveforms monitored at the neighbouring elements are displayed in a 2-D format to highlight the relevant crosstalk signals. The signal that registered simultaneously after $t = 0$ across the array corresponds to the electrical crosstalk, highest for the immediate neighbours at about -25 dB. The dominant acoustic crosstalk occurred in the backing and had a linear "move-out" indicated by progressively later arrivals for elements farther away. Acoustic crosstalk was strongest for the nearest neighbors at <-31 dB, and trailed off sharply for more distant elements. It can be inferred from the arrival times of the acoustic crosstalk signal that the compression velocity in the backing is about 2100 m/s.

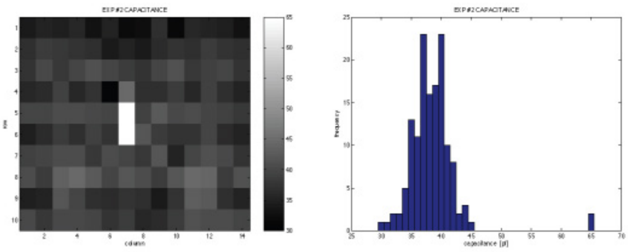

Figure 6. Element capacitances of EXP#2 before HTHP

Other experimental results of EXP#2 are summarized in Table I. Notably the 2-way -6 dB beam-width of the array elements is only about 37°, far from being omnidirec-tional. This is an expected consequence of maximizing the area of each element in order to reduce the electrical impedance.

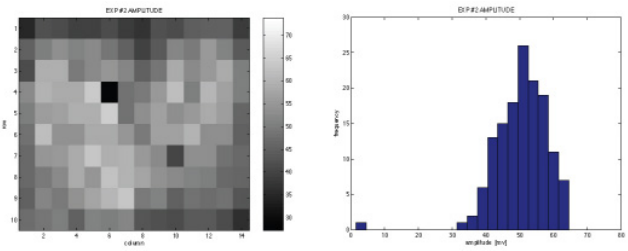

Figure 7. Pulse-echo amplitudes of elements before HTHP

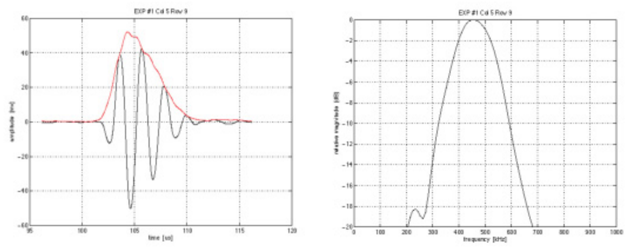

Figure 8. Typical pulse-echo waveform & spectrum

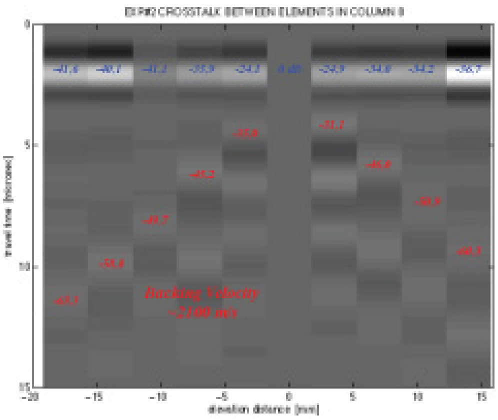

Figure 9. Inter-element crosstalk of EXP#2

Fig. 10 shows the evolution of the pulse-echo signal of an array element recorded in the pressure vessel system as the ambient condition was ramped up from normal to $345°F/15,757\,psi$. The data was recorded during the third HTHP cycle test. EXP#2 was subjected to 6 HTHP cycles in total. EXP#2 definitely survived and kept performing at maximum HTHP conditions. There was a progressive reduction in bandwidth with elevated temperature as evidenced by the increasing "ringiness" of the wave-form. This was primarily due to a significant reduction of the acoustic impedance of the backing material at high temperature, a behavior confirmed by an independent investigation.

All measurements in Table I were repeated after the HTHP cycling test. There were no significant changes except for the pulse-echo sensitivity, which dropped 20% after the HTHP test.

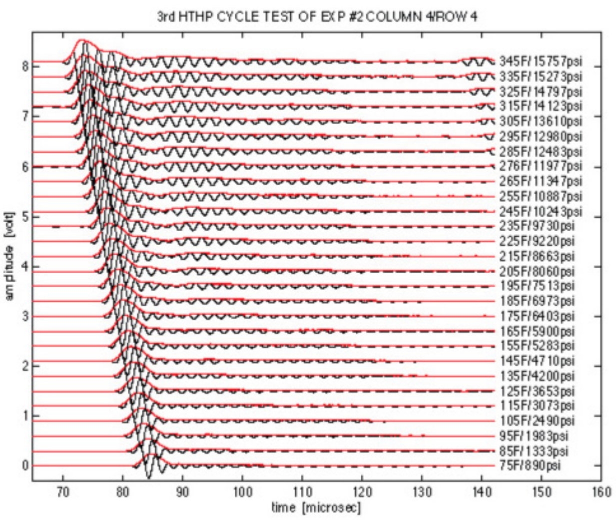

Figure 10. The third HTHP cycle test of EXP#2

4 Conclusion

We have demonstrated the feasibility of a 2D transducer array technology that can operate under HTHP conditions. Subsequent arrays with element counts up to 400 (40×10) fabricated after EXP#2 were able to maintain similarly good yield and were improved to have broader bandwidths (~60%). Further work remains to increase the acoustic impedance of the backing material to achieve 100% bandwidth. It is also desirable to increase the sensitivity of the array elements and to broaden their angular directivity.

TABLE I

	Before HTHP	After HTHP
Res. Freq. (kHz)	449.8 ±9.3	459.1 ±9.2
Capacitance (pF)	38.2 ±2.6	39.7 ±2.8
P-E Amplitude (mv)	50.9 ±6.6	41.6 ±5.0
Bandwidth	43%	43%
Azim. Beamwidth	37.3° ±3.0°	35.6° ±2.4°

Acknowledgments

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References

[1] A. J. Hayman, etal, *Development in Corrosion Logging Using Ultrasonic Imaging*, SPWLA Annual Symposium, Paris, France, June 1995

[2] A. J. Hayman, etal, *Quantitative Corrosion Evaluation in Wells Using Multi-Function Ultrasonic Imager*, Proc. 1995 IEEE Ultrasonics Symposium

[3] A. J. Hayman, etal, *High Resolution Cementation and Corrosion Imaging by Ultrasound*, SPWLA 32nd Annual Logging Symposium, Midland, Texas, USA, June 16-19, 1991