

# Construction and validation of a novel phased array borehole probe for ultrasonic investigations at sealing structures in radioactive repositories

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## Extended Abstract

### Abstract

A new type of ultrasonic borehole probe is currently under development for the quality assurance of sealing structures in radioactive waste repositories using existing research boreholes. The goal is to examine the sealing structures made of salt concrete for possible cracks, delamination, and embedded objects. Earlier prototype probes use 12 or 16 individual dry point contact (DPC) horizontal shear wave transducers grouped into a transmitter and a receiver array, each made up of six or eight individual transducers. They are operated with a commercially available portable ultrasonic flaw detector used in the civil engineering industry. To increase the generated sound pressure of the borehole probe, the number of transducers in the novel probe is increased to 32. In addition, timed excitation of each probe is used to direct a focused sound beam to a specific angle and distance based on calculated time delays. Hence, the sensitive test volume is limited, and the signal-to-noise ratio of the received signals is improved. This paper presents the validation of the newly developed phased array borehole probe by beam computation in CIVA software and experimental investigations on a semi-cylindrical test specimen to investigate the directional characteristics. In combination with geophysical reconstruction techniques, an optimised radiation pattern of the probe is expected to improve the signal quality and thus increase the reliability of the imaging results. This is of great importance for the construction of safe sealing structures needed for the disposal of radioactive or toxic waste.

**Keywords:** *Borehole probe; Engineered barrier; Monitoring; Phased array technique; SealWasteSafe*

## 1 Introduction

The borehole probes developed at BAM are ultrasonic echo devices designed to investigate the close structures of radioactive waste repositories from within existing boreholes [1]. By using these probes, which consists of a large number of individual coupling agent-free dry point contact probes, the crack-free condition of the sealing structures is checked. The measured data is analysed using SAFT (Synthetic Aperture Focusing Technique) to locate cracks, delamination, and built-in parts. A first prototype consists of 12 individual dry contact shear wave transducers, six of which were connected in parallel as transmitters and six as receivers (Figure 1a), is operated by a commercially available flaw detector used in non-destructive testing in the civil engineering industry [1]. The probe is pushed to the required depth of the borehole and coupled pneumatically using air pressure. In order to increase the generated sound pressure and to adapt the phased array system, a 2nd generation borehole probe was developed which consists of 16 shear wave transducers (Figure 1b). Each row of transducers in the 2nd generation probe functions separately as a transmitter and receiver [1].



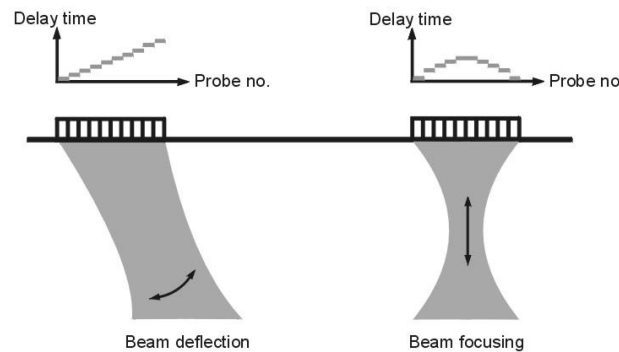


**Figure 1:** a) Earlier prototype, b) 2<sup>nd</sup> generation borehole probe c) New phased array borehole probe

In order to further increase the generated sound pressure and to integrate a phased array system, a 3<sup>rd</sup> generation borehole probe has been developed (Figure 1c). The 3<sup>rd</sup> generation borehole probe consists of 32 elements of a dry point contact shear wave transducer operating at 50 kHz. Each row of the array consists of 16 transducers that act individually as transmitters and receivers, penetrating the sound field up to 2m. The construction and validation of this novel 3<sup>rd</sup> generation phased array borehole probe is the goal of the current research.

## 2 Methods

### 2.1 Phased Array Technique



**Figure 2:** Schematic representation of phased array technique [2]

The development of the borehole probe with dynamic adjustment of the probe aperture and focusing of the sound field is to be carried out using the phased array technique. With the help of a controlled excitation function, the sound field can be focused and swivelled to a desired angle depending on the pre-calculated delay time for the individual transducers [2]. This limits the sensitive test volume and improves the signal to-noise ratio of the received signal. Figure 2 shows a schematic representation of the possible time-controlled ultrasound phased array technique.

### 2.2 Directivity measurement

The validation of the newly developed borehole probe (Figure 1c) with a larger aperture is carried out using a half-cylindrical test specimen. This specimen has a radius of 750 mm and a length of 800 mm and is made of concrete (Figure 3). A fixture was constructed to attach the borehole probe to the flat surface of this large semi-cylinder and a single point receiver is manually placed on the circular surface from 10° to 170° with a step of 1° with constant pressure. The maximum amplitude of each measurement signal is then plotted in polar coordinates to get the radiation pattern of the probe.



**Figure 3:** a) Half-cylinder test specimen b) measurement setup

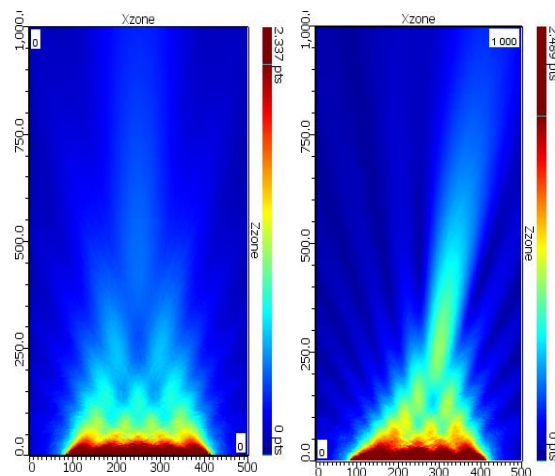
### 2.3 Simulation

A semi-analytical approach is implemented in the CIVA software [3]. CIVA is widely used in the industry as it is known for its efficient approach to modelling and simulating test problems. To validate the phased array system of the new borehole probe, beam computation is used. The most important parameters are the geometry and material properties (density and shear wave velocity) of the test specimen. The borehole probe array is represented using a point source with 16 elements (distance 20 mm) and a polarisation perpendicular to the test plane. The signal parameters are taken from the transducer datasheet and the array is used to determine a calculated delay time to sweep the beam to a required angle.

## 3 Results

### 3.1 Nearfield distance simulation

Figure 4 shows the sound field modelling for the new borehole probe with larger aperture by taking material properties of concrete test specimen. Figure 4a shows the harmonic simulation of unfocused borehole probe condition gives the near field distance of 0.43 m which is very good agreement with the calculated near field distance. In Figure 4b, the beam is swivelled to  $10^\circ$  for the calculated delay time, and a designed focusing distance up to 0.5 m. The simulations showed the near field distance to be:



**Figure 4:** a) Unfocused beam b)  $10^\circ$  focus beam

$$\text{Near Field } (N) = \frac{fD^2}{4V} = \frac{50000 \text{ Hz} * (0.3 \text{ m})^2}{4 * \frac{2656 \text{ m}}{\text{s}}} \approx 0.424 \text{ m}$$

$f$  - frequency  
 $D$  - aperture of probe  
 $V$  - velocity

### 3.2 Directivity measurement result

For the new phased array probe, homogeneous beam simulation is performed based on the material properties of the concrete specimen and calculated delay time for the  $45^\circ$ -focused beam. The simulation result (Figure 5a) shows the uniform beam with  $45^\circ$ -focus in the concrete material. Figure 5b shows the measurement result of the 3rd generation borehole probe for the focused beam, based on the delay time determined in the simulation. In the polar diagram, the main lobe at  $45^\circ$  clearly shows the focused beam, while the peaks at other angles could be due to attenuation by heterogeneous concrete material. The measurement result agrees very well with the simulation for the calculated delay time.

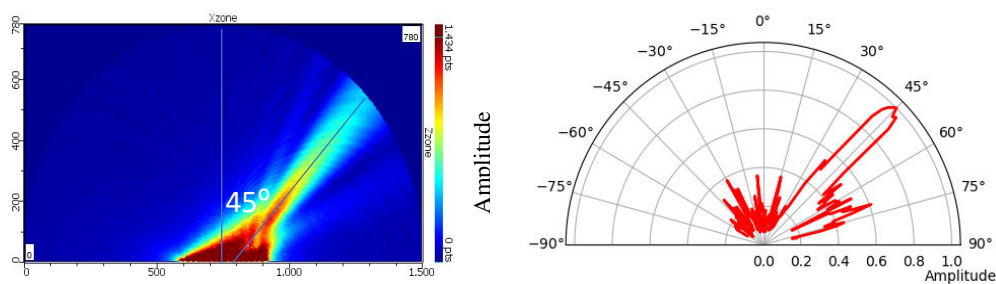


Figure 5: a) Beam simulation b) Measurement result of new borehole probe for  $45^\circ$  focus beam

## 4 Outlook and Summary

This paper first presents the design and construction of a novel 32-element phased array borehole probe that directs and focuses the beam to the desired angle using the calculated delay time. To validate the borehole probe, a half-cylindrical concrete specimen was built at BAM to investigate the directional characteristics. The calculated near-field distance for the new borehole probe and the simulation resulted in a distance of about 430 mm for the 16-element transmitter. The result of the directivity measurement and beam simulation for the new phased array probe agrees well with the calculated delay time for the  $45^\circ$  focus beam. Further investigations will be carried out on newly constructed borehole concrete specimen to identify the dead zone of the new probe and implement the image reconstruction techniques for this new phased array borehole probe.

## References

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