Advances in Ultrasonic Instrumentation for Non-Destructive Evaluation of Mechanical Components of Nuclear Reactors

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ABSTRACT
In the first and second stage nuclear program of Department of Atomic Energy (DAE), technologies are matured for Pressurised Heavy Water Reactors (PHWRs) and Sodium-Cooled Fast Breeder Reactors (FBRs). Pre-service-Inspection (PSI), In-Service-Inspection (ISI) and Post-Irradiation-Examination (PIE) procedures are carried out for mechanical components and structures/assemblies of these reactors, conforming to ASME, ASTM and IIW standards. Non-Destructive Evaluation (NDE) of vital components of nuclear reactors is carried out for pressure vessels, heat exchangers, storage tanks, turbines, coolant channels, primary and secondary cooling systems, nuclear Fuel and fuel handling mechanisms etc. Ultrasonic testing (UT) is one of the safest and renowned NDE techniques adopted worldwide for NDE of major components of nuclear reactors. Ultrasonic techniques with Pulse-Echo or pitch-catch angle-beam methods are utilised for contact and immersion modes of inspection, by using piezo-electric transducers of typically 1-25 MHz frequency. Conventional ultrasonic instrumentation for UT consists of a flaw detector and transducer(s) which are employed for flaw detection, thickness gauging and estimation of flaw sizes. The rapid advancements in the field of high speed semiconductor technologies and computational capabilities have made significant impact on the design and development of automated ultrasonic imaging required for PSI/ ISI and PIE applications in the nuclear industry. Automated ultrasonic C-Scan imaging technique is employed to generate high resolution cross-sectional images of the interiors of the mechanical components and thus enables flaw detection, flaw sizing and flaw characterization for - assessment of structural integrity, structural health monitoring and life expectancy. Automated, precision mechanical scanners, high speed digitizers, ultrasonic multichannel high speed pulsers and wide-band high-gain multichannel receivers, focused and damped single element transducers or linear/ phased array transducers and user-friendly GUI software for data/image acquisition-storage-display-measurement and analysis are major building blocks of modern C-Scan imaging systems.

This paper provides description of the building blocks required for an automated advanced C-Scan imaging system. Two case studies have been discussed in the paper namely inspection of pressure tubes which are vital components of coolant channels which contain fuel of PHWR and under-sodium viewing of core of a Prototype FBR (PFBR).

Keywords
Ultrasonic Testing, ultrasonic instrumentation, ultrasonic imaging, pulser, ultrasonic transducer, PHWR, PFBR.

1. INTRODUCTION
Advanced ultrasonic instrumentation is employed for flaw detection, flaw sizing and flaw characterisation of engineering components. Based on the actual application, ultrasonic instrumentation is broadly categorized into three groups viz. Flaw Detector, Thickness Gauge and Ultrasonic Imaging System. Primarily, the ultrasonic instrumentation is used to insonify the test-specimen by contact or immersion method. The ultrasonic signals received from the flaws or discontinuities are amplified, filtered and processed for digitization, storage, display, measurement and analysis. Ultrasonic inspection is carried out either manually or by using automation.

2. DESCRIPTION
For inspection of engineering components and materials, selection of the ultrasonic instrumentation is based on few vital parameters such as: Amplitude of reflected signal, Time of Flight (TOF) of reflected signal, inspection technique, scan-time and piezo-electric transducers. Conventional flaw detectors provide amplitude of received signal and TOF whereas ultrasonic imaging systems provide amplitude and phase of received signal, TOF and cross-sectional image of interiors of the component under test. Ultrasonic Imaging Systems acquire signals in three modes such as A-Scan (1D) waveform, B-Scan (2D) image and C-Scan (3D) image. The A-Scan waveform data indicates amplitude of the echo signal Vs TOF or Depth. Typical A-Scan waveforms acquired by multichannel instrumentation are shown in **Figure 1.** B-Scan image indicates depth of a discontinuity in cross-sectional front view and the C-Scan image is a discontinuity distribution in Plan view. *[10], [11]*

3. ULTRASONIC TESTING
Advanced ultrasonic testing is a tool which enables NDT expert to visualize depth, geometry and orientation of the flaw. Major components of the advanced ultrasonic imaging system are electronics H/W, GUI software, automation and ultrasonic imaging technique and they are described in brief in following sub-sections:

3.1 Ultrasonic Instrumentation H/W
Some of the conventional and advanced ultrasonic instrumentation have been discussed.

3.1.1 Thickness Gauge
Thickness gauges are widely employed in fabrication/manufacturing industries for accurate measurement of thickness of test objects or coatings. For contact type gauging, the thickness is computed by measuring TOF between the successive backwall echo signals and by knowing acoustic velocity of the material. For immersion type gauging, the TOF between interface echo signal and backwall is utilized to compute thickness. Thickness gauges are provided with built-in temperature compensation for variation in acoustic velocity over temperature. Thickness gauges also have built-in steel block of known thickness for on-line

calibration of acoustic velocity, in medium. Thickness gauging unit is frequently used to estimate pitting/wall thinning of pipes/tubes/ elbows due to corrosion/erosion. Modern thickness gauges have data logging & corrosion mapping and profiling s/w for inspection of long length/large size objects.

3.1.2 Flaw Detector

Ultrasonic flaw detector (UFD) is a general tool used by NDT experts for inspection of engineering components. The Flaw Detector displays 'A-Scan' waveform for interpretation of signal by the operator. This instrument contains a source of high voltage spike generator (called a pulser); 'echo signal' amplifier (called a receiver) and a display device to enable the operator to interpret received ultrasonic signals. All the functions of a 'Flaw Detector' are controlled by the operator and parameter settings are the 'setup' of an instrument.

3.1.3 Ultrasonic Imaging System [1]

The mechanical components, where stringent quality control requirements are mandatory, it is the Ultrasonic Imaging technique that provides maximum information about the integrity of the component under test. Ultrasonic imaging system based on PC is preferred for inspection and visualization of interiors of critical components, in the form of high resolution images. Such high resolution, cross-sectional (B-Scan and C-Scan) images serve as a reference for defect growth monitoring and are used for locating and sizing the defects. Advanced signal processing techniques such as FFT, Synthetic Aperture Focusing Technique (SAFT) or Time-of-Flight Diffraction (TOFD) technique, Digital Filtering techniques are analysis tools used for understanding and interpreting the flaws in an accurate manner.

For assessing the integrity of objects like Tubes, Pipes, Billets, pressure vessels etc. which have circular geometry, it is desirable to perform volumetric i.e. C-Scan imaging inspection, under contact/immersion mode over its entire volume, using automation. The main advantage of Ultrasonic imaging technique is its ability to visualize interiors of such objects during Pre-Service, In-Service or Post-Service stages. For objects with long length/large dimensions, multichannel and multi-probe Ultrasonic Imaging systems are extremely useful and they drastically reduce the inspection time. Major building blocks of an automated ultrasonic imaging system are:

1. Ultrasonic Spike or Square-wave Pulser (Schematic diagram of spike pulser is shown in **Figure 2**) *[2],[9]*
2. High gain and wideband Receiver (Typical-3dB Bw:50MHz or higher with Gain: 80dB or more)
3. High speed Digitizer for Data acquisition (Typical Sampling Rate: 50MSPS @ 8 Bits)
4. Multi-axes Automated precision Scanner
5. Piezo-electric Transducers (Typical frequency upto 25MHz for routine applications)
6. Contact, immersion or air-coupled scanning technique *[3]*
7. Computer for data/image storage, display, measurement and analysis

3.1.4 Ultrasonic Transducers

Ultrasonic transducers made of Lead-Zirconate-Titanate/ Bismuth Titanate/ Lead Metaniobate etc. are the frontend of ultrasonic instrumentation. Every application demands specific parameters of a transducer such as transducer frequency, mechanical & electrical damping, sensitivity, focusing and immersion or contact mode of the transducers etc. Several types of transducers are available for NDE of engineering components, and they have following types of configurations:

1. Single element, dual element or Linear/ Phased array transducers
2. Pulse-echo or pitch-catch mode
3. Spherical or cylindrical focusing
4. Light or heavy damping
5. Immersion, contact or air-coupled ultrasonic technique *[3]*
6. Room temperature or high temperature transducers
7. Radiation resistant transducers

3.2 Ultrasonic Imaging S/W

Using contact or immersion technique, automated ultrasonic imaging system provides digitized 1D A-Scan waveform data or 2D/3D B-Scan or C-Scan image data. Once the digital data is available in the computer, measurement and analysis is performed. Following are some of the essential software modules of the ultrasonic imaging system:

1. Acquisition, Storage and Display of ultrasonic signals
2. Control S/W for automated acquisition of B-Scan/ C-Scan image
3. Time gated signal acquisition
4. TOF and amplitude measurement for A-Scan data
5. Flaw detection, sizing and depth measurement
6. TOFD and SAFT S/W for flaw sizing and depth measurement of planar flaws
7. On-line correction of acoustic velocity with reference to variation in temperature
8. Use of temporal averaging and digital filters for enhancement of SNR
9. FFT technique for flaw characterization

3.3 Automation

Automated precision scanners of different types are required for acquisition of B-Scan and C-Scan images using PC based ultrasonic instrumentation. Typical scanners are as listed below:

1. X-Theta scanner for inspection from inside/ outside of tube/pipe using immersion technique
2. Pipe Inspection and Gauging (PIG) system for inspection of long length pipes carrying liquids, specifically utilized in petrochemical industry
3. Robotic Vehicle for inspection of large vessels
4. Crawlers for inspection of plates and sectors of tanks
5. X-Y scanner for under water inspection of critical components having odd-geometry

3.4 Ultrasonic Imaging Technique

For stringent quality control, ultrasonic imaging technique provides information about the integrity and defect growth of the component under test. Schematic block diagram of a typical ultrasonic multi-channel imaging system is shown in **Figure 3**. *[5], [14]*

4. CASE STUDY

4.1.1 Ultrasonic Gauging and Imaging of Tubes For PHWR *[8],[12],[13]*

Inspection of Tubes and Pipes is carried out using ultrasonic immersion technique as it is very accurate in measuring loss of wall thickness, variation in Inner Diameter (ID) and Outer Diameter (OD), ovality and is reliable for detecting planar cracks and volumetric defects in circumferential and axial directions. Automated image acquisition of sample pressure tube of 540MWe was carried out using Z-Theta mechanism using focused transducers. The automated scanner and assembly are shown in **Figure 4(a)**, **4(b)**, **4(c)** and **4(d)**. Ultrasonic data was analyzed to perform profilometry and results are shown in **Figure 5** and **Figure 6**. It is emphasized that, ultrasound is an important tool for detecting and accurately sizing defects in tubes and pipes. In addition, it can be used in production process where, automated inspection is necessary for high throughput. Using automation, the tubes and pipes can be inspected over the entire volume or at selective regions. A-Scan echo signal received from a pressure tube, when scanned from ID side is shown in **Figure 7**. B-Scan image of the tube is shown in **Figure 8**, where echo signals corresponding to ID and OD are shown.

4.1.2 Ultrasonic Viewing of Fuel Sub-Assemblies of PFBR *[4],[6],[7],[15],[16],[17]*

Under Sodium Ultrasonic Scanner (USUSS) is employed before every fuel handling (FH) campaign to view in-core sodium-submerged Fuel Sub-Assemblies (FSA) which contain fuel of FBR. Z-Theta mechanism of USUSS (as shown in **Figure 9)** is mounted onto the Viewing Port in-order to visualize in-core FSAs located in the core of PFBR, where, the sodium temperature is 180^0C during reactor shutdown. Main function of USUSS is to provide a clearance to perform safe FH operation and confirm absence of objectionable growth and protrusion of FSAs. The sodium-compatible and high temperature ultrasonic transducers of 1MHz and 5MHz frequencies are used for viewing inside the reactor vessel. System Hardware comprises of PC based 8-Channel ultrasonic Imaging system which is intend to detect growth and protrusion of FSAs. Photograph of 8-Channel ultrasonic imaging system is shown in **Figure 10** and photographs of test set-up are shown in **Figure 11(a)** and **Figure 11(b)**. Images acquired at 180 Deg.C. using this system to detect growth and protrusion of Fuel-Subassemblies are shown in **Figure 12(a)** and **Figure 12(b)**. Capabilities of USUSS of PFBR are comparable with similar systems available for Monju Nuclear Reactor (Japan) and Phenix and SuperPhenix Nuclear Reactors (France). Salient features of 8-Channel ultrasonic imaging system for USUSS of PFBR are:

- 8-Channel, Ultrasonic Pulser-Receiver
- Industrial PC with 100 MSPS, 8 Bits PCI Digitizer
- Fedora-8 compatible Data acquisition and Imaging Software
- 1MHz sodium-compatible four Transducers for detection of Protrusion of FSAs
- 5MHz sodium-compatible four Transducers for detection of growth in FSAs
- 2-Axes automated mechanical Scanner with 7.5mtr tall spinner tube and transducer holder assembly to mount 8 transducers (as shown in **Figure 11(b)**)
- H/W conforms to IEC 61000 and IS 9000 standards for EMI/EMC and Environmental compliances respectively

5. CONCLUSION

Ultrasonic NDE of vital engineering components of nuclear reactors, conforming to codal standards such as ASME, ASTM, ISO and IIW have become mandatory due to stringent safety requirements of nuclear industry for Pre-service, In-service and Post-service inspection. Conventional flaw detectors enable detection of flaws located inside the material with estimation of flaw size. Thickness gauges provide accurate thickness of plates, tubes and pipes. The computer based automated ultrasonic imaging systems, in conjunction with single/dual element transducers or linear/phased array transducers are extremely useful for flaw-detection, flaw-sizing and flaw-characterization of critical components. For gauging of pressure tube, accuracy of 50 microns was achieved for measurement of ~4.6mm wall thickness, using ultrasonic gauging instrument. Using 8-Channel ultrasonic imaging system and under sodium scanner, FSA growth of 2mm was detected. Electronics Division, BARC is engaged in the design and development of advanced ultrasonic instrumentation systems more than two decades and has enabled NDT procedures to preserve high quality standards of inspection of materials and mechanical components of Indian nuclear industry.

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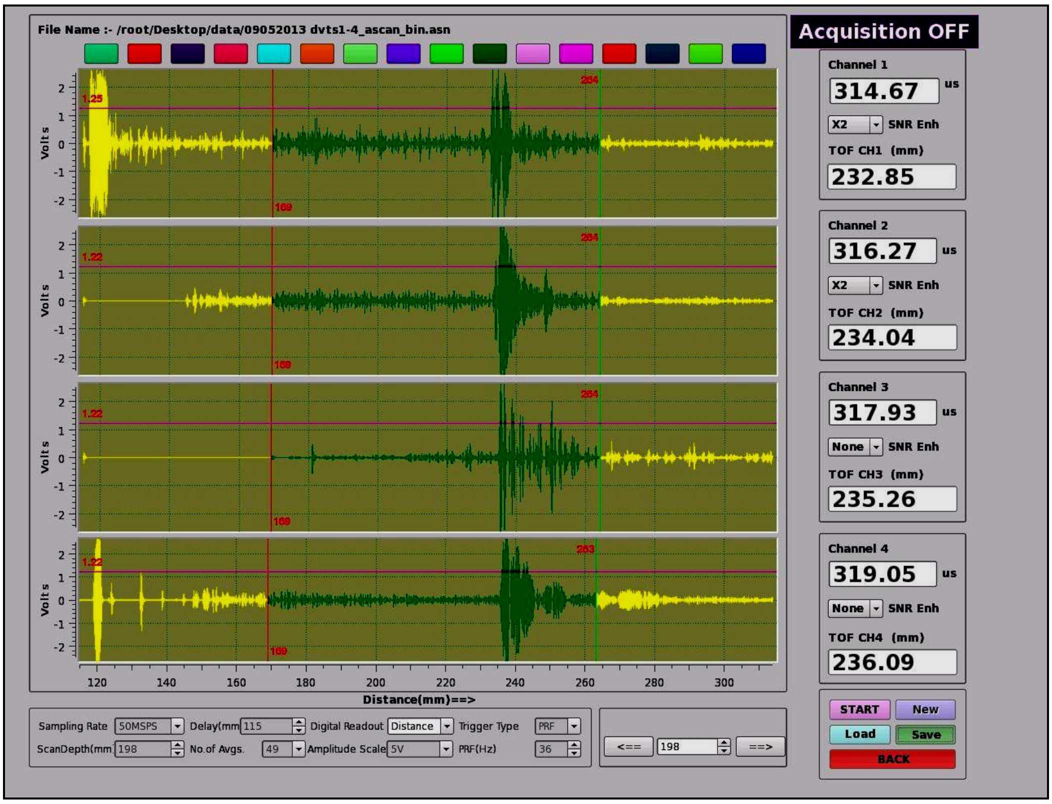


Figure 1: 4-Channel A-Scan Waveforms

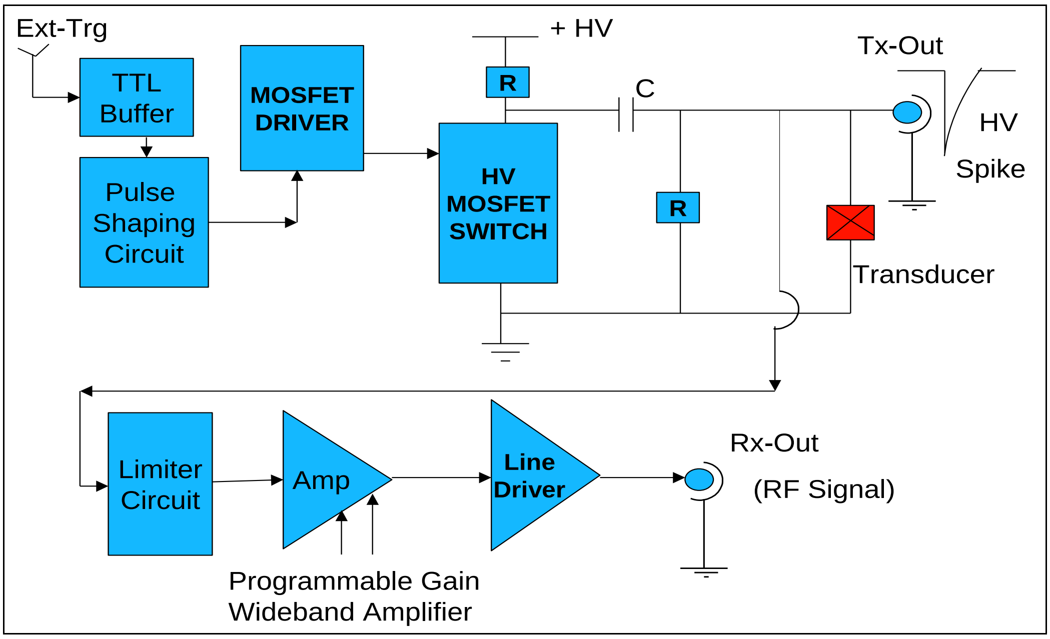


Figure 2: Block Diagram of Ultrasonic Spike Pulser and Receiver

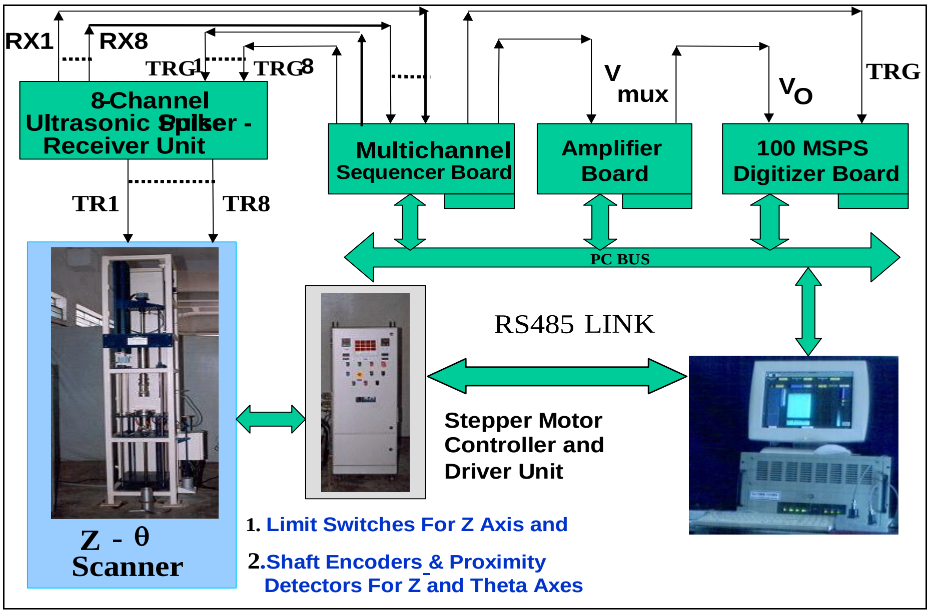


Figure 3: Block Diagram of Ultrasonic Multichannel Imaging System

(a)

(b)

(c)

(d)

Figure 4: (a) Automated Z-Theta Mechanical Scanning Assembly available at ED, BARC; (b), (c) and (d) - Tube Holding Assembly and Inspection Head with Ultrasonic Immersion Transducers.

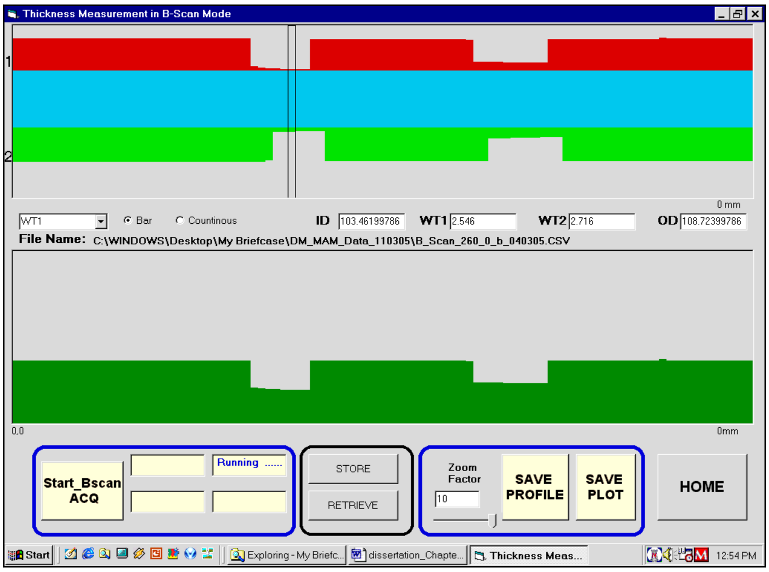


Figure 5: Profilometry Graph for a Sample Pressure Tube of PHWR showing Variation in Wall-Thickness

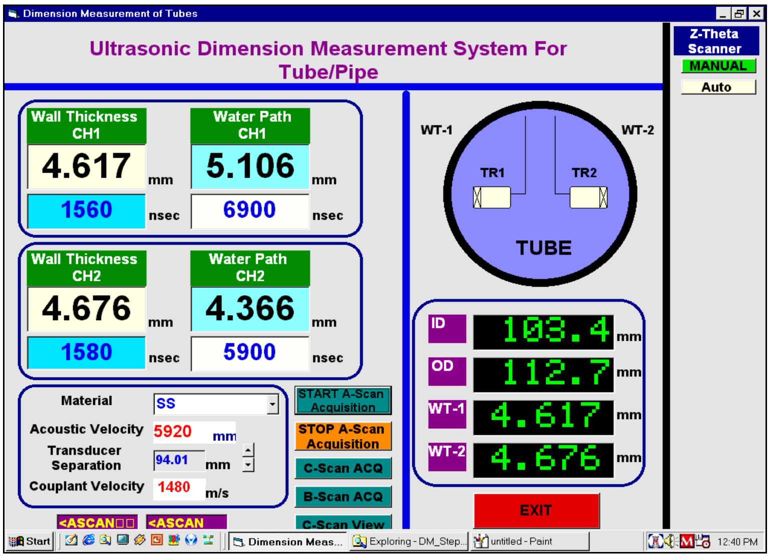


Figure 6: Ultrasonic Gauging of Sample Pressure Tube of PHWR

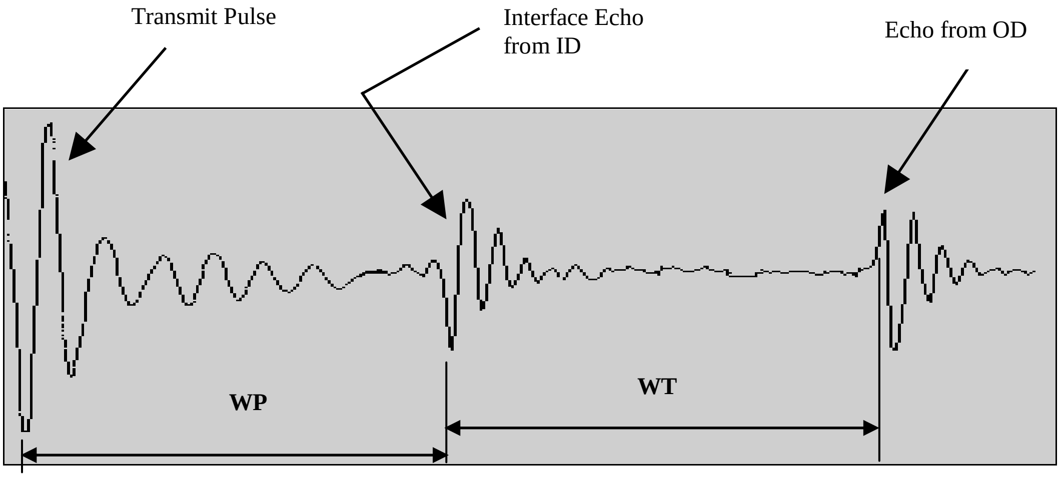
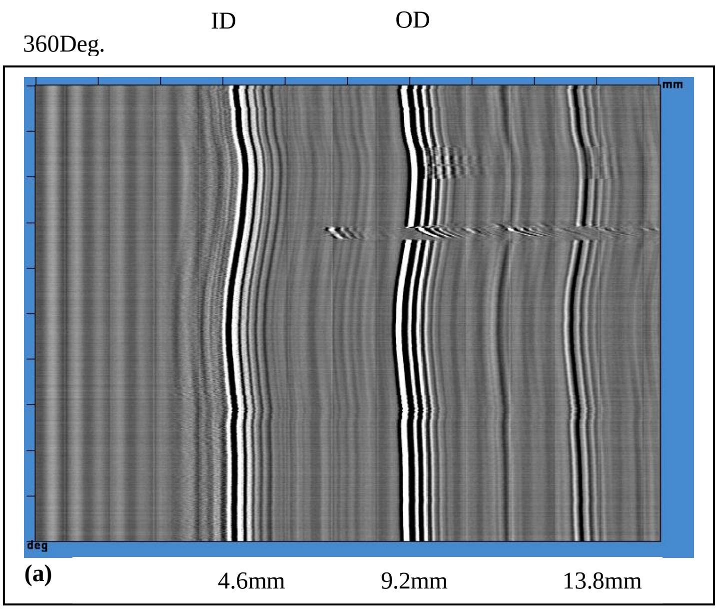


Figure 7: A-Scan waveform used for Gauging of a sample Tube
(Sample Pressure Tube was inspected from ID side using water immersion mode)



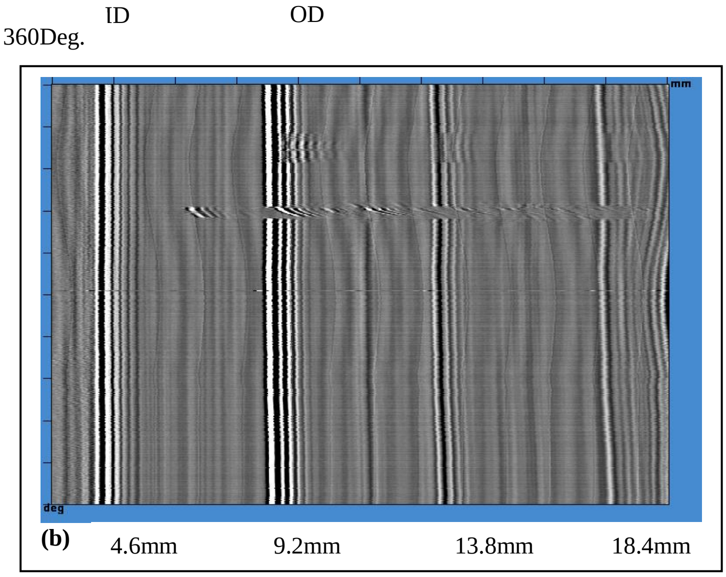


Figure 8: (a) B-Scan Image of a sample Pressure Tube without using Time Gating for Interface Echo Signal; (b) B-Scan Image of a Tube processed using Time Gating for Interface Echo Signal [This inspection was carried out from ID of tube using water immersion mode.]

Figure 9: Under Sodium Ultrasonic Scanner (USUSS)

Figure 10: 8-Channel Ultrasonic Imaging System

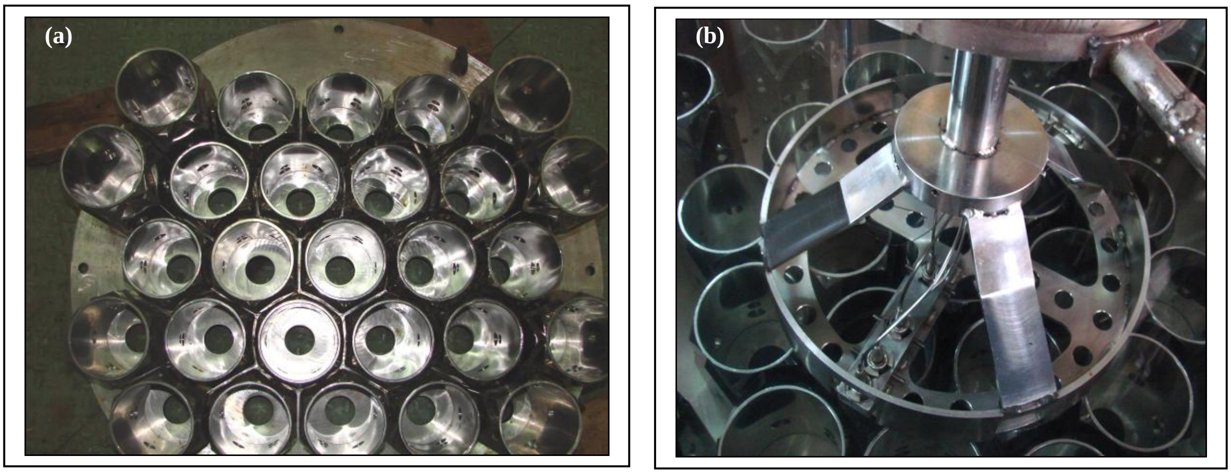


Figure 11 (a) and (b): Setup for water-submerged FSAs and Transducer Holder Assembly

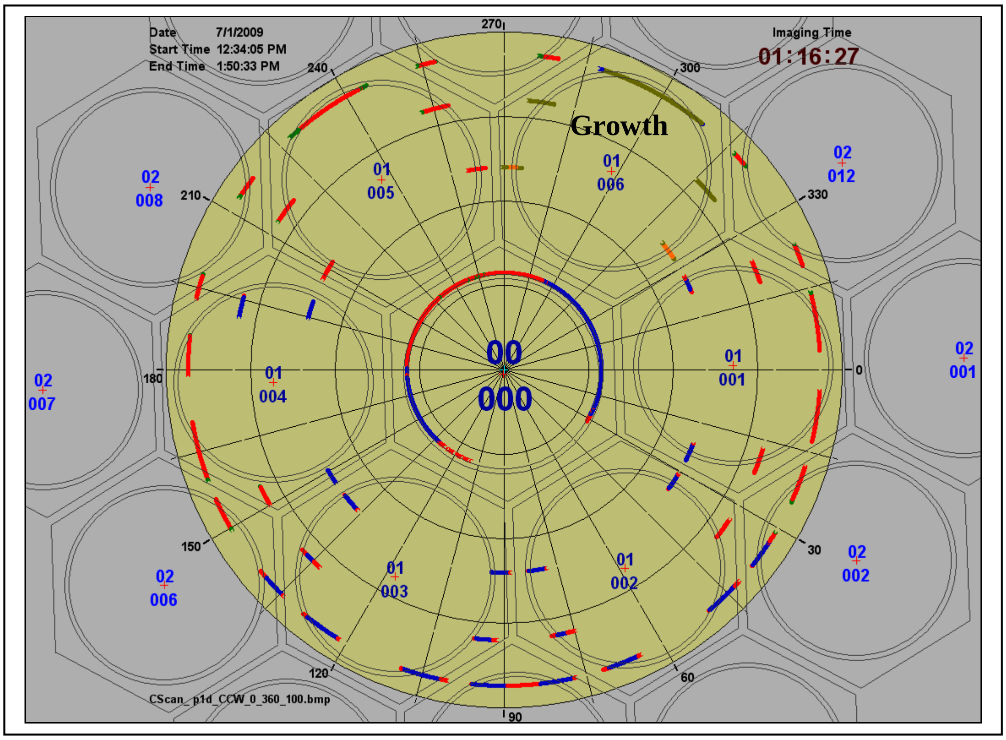


Figure 12(a): C-Scan Image of sodium-submerged FSAs acquired at 180 Deg.C., using 5MHz Sodium-compatible Transducers for Detection of 5mm Growth in one of the FSAs

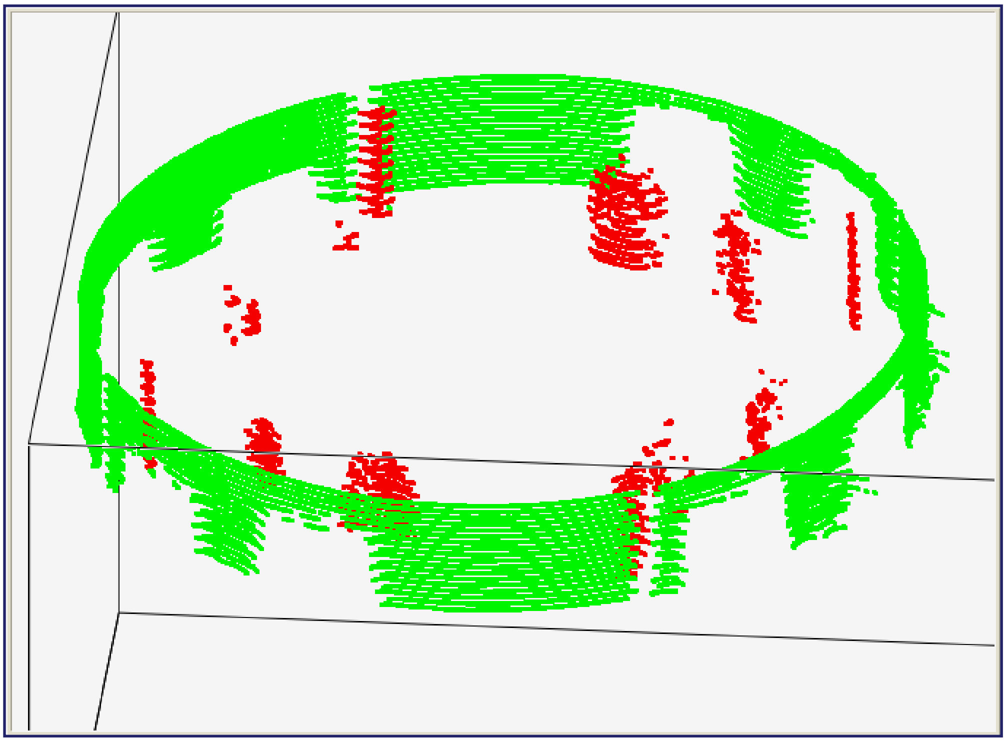


Figure 12(b): 3D Image of sodium-submerged FSAs, acquired at 180 Deg.C., using 1MHz Sodium-compatible Transducers for Detection of Protrusion of FSAs