Design and Development of Automated Ultrasonic Instrumentation for Detection of Growth and Bowing of Under-Sodium Fuel Subassemblies of FBR

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ABSTRACT
Indian Fast Breeder Reactor (FBR) which is being commissioned at Kalpakkam, Tamilnadu is a sodium-pool type 500MW e nuclear reactor. The core of FBR is submerged under liquid sodium and has more than 1000 subassemblies consisting of fuel subassemblies (FSAs), blanket subassemblies, neutron reflectors, and control/ shut-down rods. Subassemblies are placed in honeycomb pattern over a grid plate where the primary coolant sodium enters from the bottom of the subassemblies and gushes out from their tops. Due to prolonged exposure to pressure differential, flow of high temperature sodium (at around 550°C) and radiation, stresses are generated in these subassemblies. These stresses can cause the subassemblies to grow, bow or protrude above the core-plenum, where core-plenum is the nominal elevation at which tops of all the subassemblies are aligned. Safety regulations have made it mandatory to inspect the core for detection of such anomalies before every fuel handling operation. Electronics Division, BARC has designed and developed an automated ultrasonic imaging system for the detection of growth and bowing of FSAs for FBR. The ultrasonic imaging system called as 4-Channel Downward Viewing System (DVS) along with a 2-axes automated Under Sodium Ultrasonic Scanner (USUSS) was successfully deployed at IGCAR, Kalpakkam. The complete system has been used to successfully carry out detection of growth of 5mm and bowing of 0.8° in FSAs. This paper describes the design considerations, components and constituent sub-systems, and experimental results obtained by the system. Results of under-sodium imaging campaigns at 170°C have also been discussed in the paper.

Keywords: Ultrasonic Imaging, growth, bowing, fuel subassemblies, fast breeder reactor, liquid sodium, under sodium, ultrasonic scanner, C-Scan, A-Scan

1. Introduction

In Prototype Fast Breeder Reactor (PFBR), all the 180+ Fuel Sub-Assemblies (FSAs) are submerged into a pool of liquid sodium. Under normal operational conditions, FSAs are subjected to high temperature (~550°C), irradiation, and pressure differential between the top and the bottom. These stresses can cause growth, bowing, or protrusion in the FSAs which can interfere with the fuel handling (FH) operations [1]. Safety regulations have made it mandatory to detect the presence of such anomalies before the FH campaigns. During FH operations, the temperature of the sodium would be around 200°C. Under the opaque liquid sodium inside the reactor vessel at such a high temperature, ultrasonic inspection technique is the only modality which can work satisfactorily for the detection of these anomalies. Electronics Division, BARC has designed and developed a 4-Channel DVS suitable for the Under Sodium Ultrasonic Scanner (USUSS) of PFBR. For the two under-water and two under-sodium imaging campaigns conducted at IGCAR, DVS has produced reliable results with a high degree of repeatability.

Four Downward Viewing Transducers (DVTs) of 5MHz are located at the bottom of a 400mm diameter conical shaped transducer holder. They are used to inspect the FSAs from the top and provide the plan-view of FSA top-heads in the form of ultrasonic C-Scan image. Four ultrasonic Side Viewing Transducers (SVTs) of 1MHz each and mounted with specific angular separation, have been used for detection of protrusion of FSAs. The Time-of-flight (TOF) in sodium between the top surface of the FSA top-head and the transducer is measured using the Pulse-Echo (PE) technique with an accuracy of 0.5mm. The transducer holder is attached to a spinner tube which is rotated by 360° and thus the loci of four DVTs generate the C-Scan image that covers 19 FSAs (Fig.4.2). Software analysis and visual inspection of the acquired ultrasonic image is carried out to detect the presence of growth or bowing in them [3].

2. System Description

4-Channel DVS of USUSS has been used for the detection of growth and bowing in the FSAs. The following sub-sections enlist the constituent sub-systems, the topology (Fig.1) and components of the system, and describe the experimental setup that has been used for under-water and under-sodium imaging.

Note: (1) Fig. 4.2 is referenced in beginning itself; (2) Fig. 7.1 is not given but mentioned in text
2.1 Sub-systems of DVS

**Mechanical Scanner** of USUSS is a slender structure (Fig.2) consisting of two detachable parts known as the lower and the upper part. The lower part of the scanner consists of shield plug, guide tube, spinner tube, and transducer holder. The upper part of the scanner contains a casing that houses the automation assembly having two servomotors for rotational and linear movements, two slip ring-units, and an intermediate piece which couples the spinner tube to the theta-axis servomotor. The lower part of the scanner is housed inside the test-vessel and is partly immersed into the liquid Sodium. Transducer holder and the bottom one-third of the guide-tube and the spinner tube are submerged inside sodium while the remaining parts remain in Argon. USUSS has been designed and developed by IGCAR, Kalpakkam.

**Electronic Instrumentation** of USUSS consists of Ultrasonic Pulser-Receiver (UPR) panel, Fibre-optic (FO) Transmitter-Receiver units, an Industrial PC (IPC) panel, and the Control & Drive (C&D) Automation panel. The UPR panel contains the following components: (a) Ultrasonic Pulser-Receiver (UPR) unit (Fig.3a) for excitation of transducers and amplification of received ultrasonic echo signals, (b) 870nm Multimode Fiber-Optic Instrumentation for carrying TTL trigger signals required by UPR unit over a distance of 100m, (c) Light Interface unit for FO interface, and (d) Isolation Transformer for mains power supply with separate ground paths for power, safety and instrumentation purposes. The IPC panel contains the Industrial PC and the FO Transmitter-Receiver unit (Fig.3b). PCI bus based Digitizer and Digital IO cards are installed inside the IPC.

Four downward viewing transducers (DVTs) are connected to the UPR via four 8m long MI cables followed by 20m co-ax cables. The ultrasonic echo signals from four DVTs are amplified and multiplexed in the UPR unit. The composite signal is routed via 100m shielded co-ax cable to a digitizer card located inside the IPC. IPC is also interfaced to the lower part of the scanner via proprietary cables.

**System Software** provides an integrated user interface for automated scanning and imaging. It generates timing and control signals for UPR and C&D panels. Synchronous to the trigger signals received from I/O board of IPC, UPR energises the ultrasonic transducers and the received echo signals are amplified and routed back to IPC for digitization and display. System software controls the motion and positioning of servomotors over the Ethernet interface between IPC and C&D panels.

2.2 Topology

Figure 1 shows the block diagram of various sub-systems of the 4-Channel DVS along with the components and their interconnections.

2.3 Components of DVS

**Hardware components** of the 4-channel DVS are installed in two 19" industrial panels based on their functions and location in the experimental setup namely the UPR panel and the IPC panel. The UPR panel contains the following components: (a) Ultrasonic Pulser-Receiver (UPR) unit (Fig.3a) for excitation of transducers and amplification of received ultrasonic echo signals, (b) 870nm Multimode Fiber-Optic Instrumentation for carrying TTL trigger signals required by UPR unit over a distance of 100m, (c) Light Interface unit for FO interface, and (d) Isolation Transformer for mains power supply with separate ground paths for power, safety and instrumentation purposes. The IPC panel contains the Industrial PC and the FO Transmitter-Receiver unit (Fig.3b). PCI bus based Digitizer and Digital IO cards are installed inside the IPC.
to the control and driver panel via 10m long Cat 5 100Mbps Ethernet cable. The C&D panel is connected to the servo motor drives by proprietary cables which carry motor power signals, feedback & control signals. K-type thermocouple (installed at the center of the transducer holder) provides the temperature of the sodium at the core of the test vessel. Ultrasonic Pulser-Receiver unit and FO instrumentation has been designed and developed by ED, BARC.

**System Software** of DVS is installed in the IPC and consists of modules for data acquisition, display, automation control, and an integrated graphical user interface (GUI) for system operation and ultrasonic image visualization. The software modules are implemented using a combination of languages and tools. For the parts related to computation and visualization, Visual Basic has been used. For the interface to third-party hardware, OEM APIs have been referenced inside callable routines (DLL) which are coded in C. Third-party software has also been used to carry out frequency domain analysis of transducer response. DVS software acquires the digitized data and provides visualization of A-Scan waveforms (Fig.4.1) and amplitude-and depth-based C-Scan imaging (Fig.4.2). GUI is used to set data acquisition parameters like the sampling frequency, depth of memory, and temporal averages. It also has provisions for post-acquisition analysis and log-generation. The software incorporates online temperature compensation for acoustic velocity of sodium and computes the TOF/Distance values in accordance with the current temperature value.

![Fig. 3](image1.jpg)

**Fig. 3** : (a) 4-Channel Ultrasonic Pulser-Receiver Unit : (b) Fiber-Optic 4-Channel Transmitter-Receiver Units

![Fig. 4.1](image2.jpg)

**Fig. 4.1** : A-Scan Waveforms for 4 DVTs with On-line Distance Readouts
The diameter of the transducer holder is 400mm and it houses the four DVTs (DVT1-DVT4) for downward viewing of FSAs. DVTs are mounted in a single line in the radial direction at defined distances from the centre. These distances are chosen so as to cover maximum 19 numbers of FSAs located underneath the transducer holder [1], [2].

For under sodium experiments, the experimental setup (Fig. 6) was installed inside a test vessel which was connected to sodium loop at IGCAR. The diameter of the vessel used was 1m and sodium was filled in the vessel to

2.4 Experimental Setup for under-sodium imaging

In PFBR, FSAs of 4.5m length are assembled in a honeycomb pattern. FSAs are assigned unique identifiers based on their locations. FSA top-head of 150mm length from the top of the full-length FSA is manufactured for the purpose of under-sodium imaging trials of DVS. 19 such FSA top-heads (Fig. 5) are assembled on a support plate. The assembly and numbering scheme for FSAs are exactly followed similar to PFBR for the experiments. The support plate is suspended inside the pool of liquid sodium by the means of four tie-rods. The transducer holder is lowered from the top (Fig. 6) and is held above the core-plenum.

The diameter of the transducer holder is 400mm and it houses the four DVTs (DVT1-DVT4) for downward viewing of FSAs. DVTs are mounted in a single line in the radial direction at defined distances from the centre. These distances are chosen so as to cover maximum 19 numbers of FSAs located underneath the transducer holder [1], [2].
3. Ultrasonic Imaging

DVS software is used to control the operations of all the electronic instrumentation and C&D automation. It controls trigger signals which are routed to UPR which in turn excites the DVTs in sequential manner. The amplified echo signals are multiplexed and fed to the digitizer for display of A-Scan waveforms. DVS software also controls the position and motion of Z- and θ-motors and acquires the plan-view (C-Scan image) of the FSA top-heads by synchronizing acquisition and motor movements.

3.1 Scanning Methodology

The Ultrasonic Scanner works on the pulse-echo principle. A short pulse of ultra sound is emitted from a transmitting transducer, and after some time, it hits the target reflector, and the same transducer works as a receiver which receives the echo signals. By providing the velocity value of ultrasound, TOF is measured, which also provides distance of the target from the transducer. With the position of the transducer fixed, the location of the target is estimated. With every ultrasonic pulse, one point on the target is interrogated. In order to obtain the complete profile, the ultrasonic beam of the transducer is moved over the FSA top-head assembly (Fig. 6). This process is called Scanning. In order to reduce the scanning time, a group of four transducers are operated in a sequential manner. The echo signals collected by scanning are used to build an image of the FSA assemblies (Fig.7.1 and Fig.7.2).
3.2 C-Scan Imaging

For imaging, the motors are brought to reference positions above the core-plenum and the motor is rotated with 1° angular steps. One rotation of 360° makes the 4 DVTs move over 19 FSAs. By synchronously operating the acquisition and motor movements, C-Scan image data is plotted along the loci of the DVTs (Fig.4.2) to construct the ultrasonic image. DVS software can acquire two different C-Scan visualizations. Amplitude-based C-Scan assigns a single color to the plot, depending only on the presence or absence of echo signal. Depth-based C-Scan image computes the TOF/Distance of the echo in on-line manner and assigns a color based on the depth of echo signal. Amplitude-based C-Scan image provides the plan-view of FSA top-head assembly and is used to detect bowing in the FSA. By analyzing (measuring center-to-center distances between the FSA top-heads) or by inspection (for missing/partial or absent echo signals), bowing type of anomaly can be detected. Depth-based C-Scan image provides a direct visual indication of the growth in FSA. The FSA which has grown above the core-plenum will be visible in a different color as against the plots corresponding to the normal FSAs at core-plenum.

3.3 Post-acquisition Analysis

The DVS software has provision for generating a wire-mesh corresponding to the actual geometry and placement of the FSAs on the support plate (Fig.6, Fig.7.1 and Fig.7.2). Each hexagon in the wire-mesh corresponds to a particular FSA top-head and is labeled with the unique identifier. The wire-mesh can be panned and rotated using the user interface. For the detection of anomalies, the wire-mesh is overlaid on the acquired C-Scan image and after the suitable placement; direct visualization of growth/bowing of the FSA is available.

4. Results

Using the DVS and the under-sodium experimental setup, growth and bowing types of anomalies have been successfully detected in various campaigns. The imaging results obtained under liquid sodium have shown high repeatability. A growth of ~5mm and bowing of ~0.8° introduced in two different FSA top-heads have been successfully detected for the under-sodium setup as shown in Fig. 7.1.

With the present ultrasonic instrumentation, it is possible to detect growth of more than or equal to 1mm and bowing of more than or equal to 0.8°. By reducing the angular step-size, high resolution C-Scan image can be obtained at the cost of increased scan-time (Table 1). Temporal averaging enhances the SNR of echo signals and thus provides noise-free C-Scan image but increases the acquisition and processing time. It has been observed that the angular resolution of 1° and 64 averages are optimal in terms of imaging conformity and scan-time requirements.

<table>
<thead>
<tr>
<th>Angular Resolution</th>
<th>Under-Water Scan Time</th>
<th>Under-Sodium Scan Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1°</td>
<td>5 min 9 sec</td>
<td>6 min 14 sec</td>
</tr>
<tr>
<td>0.5°</td>
<td>9 min 40 sec</td>
<td>11 min 39 sec</td>
</tr>
</tbody>
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The noise generated by sodium pumps and heaters necessitated more number of temporal averages and hence the scanning time for under-sodium imaging (Fig 7.2) was more compared to similar imaging results obtained in under-water setup (Fig 7.1).

5. Conclusion

The 4-Channel DVS and automated under sodium scanner have been successfully deployed for detection of growth and bowing of FSAs and overall system has produced repeatable and reliable results for under-sodium test setup.

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