CHAPTER-4
4.1 INTRODUCTION

As already explained in chapter-1, the core and the mechanical components which make up the primary sodium circuit are totally immersed in sodium, with the core being at ~5 m below the sodium surface. Examination of the internal structure is therefore a difficult task, visual techniques being impossible because of the opacity of the liquid metal. In the present study, ultrasound technique is explored for seeing through liquid sodium.

The use of ultrasound under sodium has been for two purposes. First is to detect any fuel subassembly projecting from its original location which may interfere with the fuel-handling operation. Another is to image and locate the top of some of the core assemblies so that estimates can be made of the bending or bowing caused by the fast neutron induced damage on the structural metal. These two purposes are called ‘ranging’ and ‘imaging’. During fuel handling, it is essential to ensure that the region between the core top and control plug structure is not obstructed. Failure to do so could result in components breaking or at the worst case, jamming. In the UK Prototype Fast Reactor, mechanical arms sweep the core to ensure that it is clear. In the French fast reactor a simple high frequency sonar like device performs the same task (Lions, 1974). Sweep arm devices have also been considered for German reactors. The Japanese have examined the use of ultrasonic viewing systems for improving fuel transfer efficiency (Usegi, 1980).

Core distortion is caused mainly by a phenomenon known as neutron-induced void. When components are irradiated in fast reactors, fast neutrons displace atoms in the structural metal, producing voids and causing the structure to expand. Uneven neutron flux produces uneven growth and bending. The problem is severe in the fuel wrappers in the core which tend to bow away from the core centre (Bishop, 1981). Uninhibited bowing would
lead to difficulties in fuel extraction and remedial action is therefore an important part of fuel management. The role of scanner is also to image and locate the heads of some of the core subassemblies so that estimates of bow could be made. In FFTF prototype reactor a device to image the core top was developed. Trials in sodium facility of FFTF have been reported (Day, 1974). Ultrasonic rigid under sodium viewer was also loaded into the PFR. Its main purpose is to assist in the assessment of core component distortion. The technique used in the Indian Prototype Fast Breeder Reactor for bow measurement is discussed by Swaminathan, (2012). The choice of ultrasonic transducer is PZT (lead zirconate titanate) and is encapsulated in Nickel casing (Bishop,1980 and Swaminathan 1990 ).

In the present study, two methods are envisaged for finding the presence of an object in the gap between subassembly head and thermowell sleeves. Figure 4.1 shows the schematic of gap between bottom of the thermowell sleeves mounted in lattice plate and top of the subassembly, known as above core plenum. Receiving the echo directly from the projected object is called direct imaging and other one is indirect imaging using shadowing effect of protruded object on peripheral subassemblies.

Fig. 4.1 Schematic of above core plenum (100 mm gap)
4.1.1 Principles of Ultrasonic Techniques

When sound waves travel through sodium or any other medium they are reflected and refracted by targets placed in their path. This occurs whenever the dimension of the target is large compared with the wavelength of sound, and the acoustic impedance of the target is significantly different from that of sodium. This principle is applicable for most reactor targets. The acoustic impedance mismatch between sodium and stainless steel results in about 83% of incident sound energy being reflected. When considering the choice of operating frequency, it is a compromise between resolution and attenuation. High frequencies are required for good resolution but attenuation increases as square of frequency. In ranging purposes, 1 MHz frequency is selected where attenuation is sufficiently low to allow transmission through several metres in sodium. Ultrasonic technique works on pulse echo principle. In this a single transducer acts both as a transmitter and receiver of sound. Good resolution is achieved by limiting the spread of sound, i.e. by ensuring that the ratio of transducer diameter to wavelength is large and the pulses are of short duration.

4.2 CONCEPT OF DETECTION METHOD

The core in the case of PFBR consists of 1758 subassemblies (Fig. 4.2). Out of these, about 40% of the subassemblies that are located in the centre are hexagonal in shape. The remaining 60% of the subassemblies that are positioned in the periphery of the core are cylindrical in shape. These cylindrical shielding subassemblies are permanent in the reactor, while the hexagonal subassemblies are frequently changed. There are 9 rows of shielding subassemblies. The last row of shielding subassemblies is projected by 100 mm above all the other subassemblies. These subassemblies are denoted as SSA. From the shielding subassemblies, echo will be obtained as shown in the first A-scan. If any reactor components or fuel subassemblies are protruded by a differential growth of 45 mm from the normal subassembly top, as shown in the Fig. 4.3, the echo received from SSA vanishes due to the
protrusion. If the object is favorably oriented, the echo is received from the object, as well as there will be decrease in echo amplitude from the SSA. From this, location of the protruded object can be directly inferred. This is referred as direct imaging technique. This is demonstrated in second B-scan. If the protrusion is not favorably oriented then, there will not be any echo received from the object. But, at the same time, there will be a reduction in echo amplitude received from the SSA. By detecting the decrease in signal strength from SSA, the protrusion can be detected. This method of protrusion detection is referred as indirect imaging technique.
4.3. ULTRASONIC IMAGING USING DIRECT IMAGING TECHNIQUE

For example, in the case of PFBR (Chetal et al., 2006), there are two types of absorber rods, namely Control and Safety Rods (CSR) and Diverse Safety Rods (DSR) which are part of reactor core. In the current generation fast reactors, two types of absorber rods are used. One set of primary rods are used for power regulation and shut down while the other set of secondary rods are used only for reactor shut down. Provision of two sets of absorber rods enhances the reliability of the shut down system. The respective drive mechanisms are Control and Safety Rod Drive Mechanism (CSRDM) and Diverse Safety Rod Drive Mechanism (DSRDM) housed in the upper core structure known as control plug (see, Fig. 1.2). In the reactor, nine CSRs gripped by the respective CSRDM are used for control as
well as shutdown of the reactor. Diverse Safety Rods (DSRs) are used only for reactor shutdown. DSR is attached to DSRDM. During fuel handling operation, CSRDM and DSRDM are lifted above the bottom of control plug so that there is a clear 100 mm gap in the plenum and the plug rotation can be performed safely. However, in case of any fault, CSR / DSR is not detached from CSRDM / DSRDM or if it is not lifted above the bottom of control plug, then it will hinder the plug rotation. Hence, it is necessary to detect and locate the projected object, if any before rotation of plug during fuel handling operation. The absorber rod drive mechanisms are located at fixed distance and hence gating is provided based on their location and image is constructed.

4.3.1 Simulation of Projected Component in Reactor

During reactor operating condition, gripper of CSRDM holds the head of CSR. During fuel handling operation, the CSRDM is positioned far away from the subassembly head after detaching the CSR into the core. In case of the condition in which, CSR is not detached from the CSRDM or the latter is not lifted to safe position, then it will project into the core cover plenum as shown in Fig. 4.4a. During reactor operating condition, an electromagnet of DSRDM holds the mobile DSR. In the case of reactor shutdown condition, the DSR is dropped inside the active core and DSRDM is taken out of the above core plenum. If DSRDM is not withdrawn properly, then it will be within the above core plenum as shown in Fig. 4.4b. The DSR will be within the subassembly and it will not come out along with the mechanism. Hence DSR simulation is not required. The projected components which need simulation are CSRDM gripper, DSRDM electromagnet and CSR. The portion of CSRDM gripper and DSRDM electromagnet within ~ 600 mm height can appear in the above core plenum as it moves into the SA for a distance of ~ 500 mm in addition to the 100 mm above core plenum. In order to simulate this condition in the water tank, the height of the cylindrical object is reduced to obtain overall height of ~ 230 mm by keeping the complex shapes of
same size, which is suitable to carry out experiments in the water tank. Prior to sodium testing, water testing is required, to validate the experiment as it has almost same acoustic properties as that of sodium and also handling the objects in water is easy. As the projected object has different shapes at different elevations, support rods with manual lifting arrangement are used to move the object up and down to get the image from different profiles within the 100 mm gap.

**Fig. 4.4a** Portion of CSR in 100 mm plenum
Fig. 4.4b Portion of DSRDM through 100 mm above Core Plenum

Fig. 4.5 Actual and Mockup CSRDM gripper with important dimensions
In the case of CSRDM gripper, the complex shapes are cone, cylinder, slot and taper portions. The actual size of CSRDM gripper and the mock up used for simulation are shown in Fig. 4.5. The CSR head has three different shapes, two cylindrical and a conical shape. The shapes in DSRDM are rectangular slot, conical portion and cylindrical surface. Geometric details of experimental CSR and DSRDM are shown in Figs. 4.6 and 4.7 respectively.

Fig. 4.6 Experimented CSR

Fig. 4.7 Experimented electromagnet of DSRDM with support rod
4.3.2. Orientation of CSRDM and DSRDM

Deployment of the scanner requires two openings in the top shield (Fig. 1.2). In the case of PFBR, the In-Vessel Transfer position (IVTP) access port and Observation port are used for this purpose as depicted in Fig. 4.8. Locations of CSRDM and DSRDM and distance from the transducer are depicted in this figure.

![Diagram showing orientation of CSRDM and DSRDM from IVTP access port and Observation port](image)

**Fig. 4.8** Orientation of CSRDM and DSRDM from IVTP access port and Observation port

The straight line shows the direct view of both CSRDM and DSRDM from IVTP access port and Observation port. The maximum distance for CSRDM from IVTP access port is 2814 mm. The same is simulated in the water experiments.

4.3.3 Experimental Setup

For construction of ultrasonic images the ultrasonic transducer should be scanned systematically over the object known as ‘scanning’. The experimental set up consists of mechanical scanner, ultrasonic transducer, ultrasonic equipment and the Personal Computer (PC) based automation system.
**Mechanical Setup**

To carry out the ultrasonic imaging experiments, a set up has been erected in conjunction with the 5 m water tank as shown in Fig. 4.9. The setup consists of ultrasonic scanner fitted with 1 MHz ultrasonic transducer, located at one extreme end of water tank. The mockup scanner consists of 6 m long 33 mm diameter stainless steel tube called the spinner located inside a 90mm diameter guide tube. The spinner tube is inserted through the guide tube which carries transducer holder at its bottom end. The guide tube serves to maintain the lengthy spinner tube vertical and without wobbling during it’s up /down and spinning movements. An ultrasonic transducer is mounted inside housing at the bottom of the spinner tube with its active face looking sideways. The liquid sodium proof transducer consists of piezoelectric crystal soldered on to the nickel casing to operate at high temperature. The spinner tube is allowed to move vertically by 300 mm and allowed to rotate about its axis. The spinner tube is attached with 2 stepper motors one for rotary movement and other for axial movement. The lattice plate of 2.25 m diameter is fixed using
tie rods at the centre of the tank. The lattice plate consists of thermowell sleeves and has the provision to locate the CSRDM and DSRDM. The simulated CSRDM gripper is fixed on the holder provided in the lattice plate (6 CSRDM + 3 DSRDM). The height of the water pool is 500 mm. The tank bottom is leveled by mounting thick S.S. plate. The water tank has the facility to fill and drain the water. The subassembly heads of 150 mm height have been fabricated and mounted in the tank. The lattice plate height is adjusted such that the gap between the bottom of the thermowell sleeves and subassembly top is maintained as 100 mm. The transducer centre is placed at 25 mm above the subassembly top and the remaining 75 mm is scanned by the ultrasonic transducer. The 25 mm length is known as the dead zone which is due to the dimension of the transducer.

- **PC based automation system**

  A PC based automatic ultrasonic scanning system is developed to carry out ultrasonic experiments in water. Fig.3.10 shows the schematic of the PC based automation system. The system consists of mechanical scanner, liquid-sodium proof transducer, stepper motor and drive system, Ultrasonic equipment, Industrial PC with digitizer card and the software for acquisition of ultrasonic data and C scan plotting.

- **Ultrasonic scanner**

  The scanner consists of 6 m long tube about 90 mm diameter called guide tube and smaller diameter tube called spinner tube which is kept inserted through the guide tube carrying transducer holder at its bottom end. The spinner tube is allowed to move vertically 300mm and allowed to rotate about its axis. The spinner tube is attached with 2 stepper motors
Ultrasonic Transducer

Ultrasonic experiments are carried out in water for ranging purposes. Therefore 1 MHz PZT plain-A crystal having curie temperature of 380°C is used for transducer design. The transducer is assembled in a nickel casing which is having good wettability at reactor shut down temperature of 180°C. The crystal is soldered to the diaphragm inner surface using high temperature solder alloy having melting point of 220°C. For sodium application, 3 mm dia. Mineral insulated cable with copper conductor along with contact plate serves the purpose of carrying electrical pulses to the crystal which is insulated from the body using alumina ceramic. For water application, co-axial cable is used. The transducer is used as transmitter as well as receiver.
• **Ultrasonic test instrument**

The ultrasonic test instrument is an important instrument in the PC-based automation system. The function of the instrument is to supply high voltage pulse in the form of ‘spike’/tone burst to the transducer which is then allowed to vibrate at its natural frequency of 1 MHZ. This ultrasonic echo travels back to the transducer which converts it back to a voltage pulse. The instrument has provision to give RF output. This is interfaced with the high speed digitizer card mounted inside the industrial PC. USB based external digitizer card is adopted for reliable long term application. Therefore the acquisition scheme was modified to acquire RF signal and view the distance of 5 m by suitably selecting 100 Hz pulse repetition rate. Analog amplification of the radio frequency ultrasonic signal is straightforward (Da Silva 2005; Pro-Wave 2005). The RF signal is digitized to permit real-time or post acquisition signal processing. Digitization permits signal averaging, frequency analysis, implementation of software filter and special algorithms to improve signal to noise ratio (Karasawa, 2000).

• **Stepper motor and its drive system**

A high performance micro stepping driver and a stepping motor (Alpha Step) with built-in-rotor-position sensor is used in the setup. The speed and the amount of rotation are constantly monitored during the operation, so that when an overload is about to cause the motor to misstep, any de-load in response is corrected and operation continues at maximum torque. In addition to the four-gear types ideal for low-speed high torque operation, a model equipped with an electromagnetic brake is used. This is suitable for holding the load in position during Z-axis or Θ-axis movement. The stepper motor is connected to a separate a DC power supply of 24V DC through a shielded cable separately connected to the electromagnetic brake.
The stepper motor drive system consists of a translator circuit (Photo Transistor) that receives a signal that includes the number of steps and direction. The translator circuit sends four individual control signals to the switch set circuit and the switch set circuit sends power signals to each of the two phases (windings) in the stepper motor. The signal for the number of steps is a series of square wave pulses (one for each step) which is used to move the rotor. The signal for the direction is constant-voltage signal that is either positive or negative. The translator receives the signal from a Programmable Logic Controller (PLC). The PLC sends a command signal that consists of the number of steps the motor should run and the direction signal indicates the direction. The LED in the PLC module can detect the steps signal.

There are 2 inputs connected to the driver, viz., Direction and step active signal

1. When the DIR input is ON, a rise of the “PLS input” from OFF to ON will rotate the motor one step in CW direction.

2. When the DIR input is OFF, a rise of the “PLS input” from ON to OFF will rotate the motor one step in CCW direction.

For carrying out the experiment, the scanner automated with 2 geared stepper motors with micro stepping drive for Z and Theta movements are used. The USIP-12 equipment/Ritec pulser receiver with spike/tone burst excitation is used in pulse echo mode. The in house developed ultrasonic transducer of 1 MHz frequency is connected to this equipment. The RF signal output from USIP-12/Ritec is interfaced to the PCI 5152 digitizer card with the following specification

- 300 MHz bandwidth
- 2 GS/s maximum sampling rate
- 2 simultaneously sampled channels
- onboard memory - 64 MB/ch
- 10 V input range
The digitizer card is located inside the Industrial PC and a software has been developed in Lab view for acquiring A scan data, B scan data, C scan data, offline analysis and movement of stepper motors. For controlling the stepper motor, controllers and drives are required. The controller is controlled by sending commands through RS232C communication port from PC. The MOXA make RS 232 multiport communication card is used in PC which provides additional communication ports for controlling the two stepper motors.

- **Software Architecture**

  The main user interface consists of buttons, from which one can navigate to different screens such as configuration panel, A-scan, B-scan, C-scan, offline analysis and exit. The Main panel consists of two main loops, viz., upper loop to handle the front panel buttons and lower loop to carry out the operation such as motor movement, then acquisition of ultrasonic data, finding out transit time based on gate settings, plotting of images based on menu driven commands from A-scan, B-scan, C-scan and offline analysis.

- **Commissioning of automation system**

  For carrying out water experiments, the scanner having 2 geared stepper motor with micro-stepping drive for Z and theta movement is successfully interfaced to the PC. The ultrasonic equipment with spike excitation is used in pulse echo mode. The in house developed ultrasonic transducer is connected to the equipment. The RF signal is interfaced to the digitizer board located in industrial PC. A software has been developed for acquiring A scan, B-Scan and C-Scan data. Software filters are provided to acquire noise-free signal. For constructing the images C-scan facility is used. Once the amplitude crosses the threshold limit, point is plotted on the screen corresponding to the motor movement.
The color of the point is based on the transit time data thereby constructing the pseudo 3D images.

4.3.4 Details of Experiments

Different experiments have been conducted by systematically moving the ultrasonic transducer (center beam) from 25 mm height (above the normal SA top surface) to 100 mm height in steps of 1 mm in the upward direction and $0.2^\circ$ steps in the $\theta$ direction. Based on different orientation and shapes of the components, criteria for the different case studies are selected.

- Case – 1

Fig.4.11a shows the plotted image of CSRDM and DSRDM with minimum amplitude threshold of 0.1V which is just above the noise level. It shows top view and side view of three CSRDMs and two DSRDMs. The different shapes and profiles of CSRDMs and DSRDMs have been simulated in the first case study.
Fig. 4.11a Case-1 objects and Ultrasonic image with threshold of 0.1V at 0 mm elevation
(i) Side view of objects (ii) Top view of objects (iii) C-scan image (iv) B-scan image

In CSRDM, taper, and stepped cylindrical portion with and without slot and in DSRDM, cylindrical portion with and without slot have been experimented. The shapes of the objects and their side and top views are tabulated in Table - 4.1.

Table-4.1 Shape of objects in case-1

<table>
<thead>
<tr>
<th>Object No.</th>
<th>Name of the object</th>
<th>Shape of the object in Side view</th>
<th>Shape of the object in Top view</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CSRDM</td>
<td>Tapered and cylindrical portion</td>
<td>Without slot</td>
</tr>
<tr>
<td>2</td>
<td>CSRDM</td>
<td>Cylindrical portion</td>
<td>With slot</td>
</tr>
<tr>
<td>3</td>
<td>DSRDM</td>
<td>Cylindrical portion</td>
<td>With rectangular slot</td>
</tr>
<tr>
<td>4</td>
<td>CSRDM</td>
<td>Two cylindrical portion of varying dimension</td>
<td>Without slot</td>
</tr>
<tr>
<td>5</td>
<td>DSRDM</td>
<td>Cylindrical portion</td>
<td>Without rectangular slot</td>
</tr>
</tbody>
</table>
The image is constructed with different colors for different depths. The image is very distinct with good echo strength irrespective of the tapered portion in Object No.1 which is CSRDM. Because the slot is in direct view to ultrasonic transducer, echo is not of sufficient strength and hence the image was not distinct in the second object. The third object is DSRDM cylindrical portion with rectangular slot in 100 mm plenum. The image is clear but not broader when compared with object No.5 due to the presence of slot in the cylindrical portion. The fourth object is CSRDM with slot slightly away from the direct view of transducer and two cylindrical surfaces of varying dimensions in 100 mm plenum. The variation in transit time due to difference in dimensions of the cylindrical portion is observed in the image by two different colours. In the case of fifth object, the echo strength is very good and broader image is obtained from the cylindrical portion of DSRDM.

![Ultrasonic image](image_url)

**Fig. 4.11b** Case-1 objects and Ultrasonic image with threshold of 0.15V at 0 mm elevation: (i) Side view of objects (ii) Top view of objects (iii) C-scan image (iv) B-scan image
The same data is analysed by varying the amplitude thresholding. Figure 4.11b shows the same image plotted with amplitude thresholding of 0.15V. The difference in images of the DSRDM objects 3 and 5 is clearly observed. The signal strength from the slot is less compared with cylindrical surface without rectangular slot. The B-scan image at 0 mm elevation gives the depth information of the objects. The objects 1 and 5 give better echo strength compared with 3 and 4 which are represented in darker lines in B-scan. Due to the sudden change in the dimension, discontinuity is observed in the image of object no.4. To confirm the discontinuity in image due to sudden dimensional change, experiment is repeated. Fig.4.11c shows the repeated trials of CSRDM object and its image.

Fig. 4.11c  Case-1 CSRDM object and its ultrasonic image
(i)  Side view of objects (ii)  C-scan image of CSRDM  (iii) C-scan image with higher amplitude thresholding

Difference in transit time is observed as two different colors in the image. The discontinuity is observed in the image with higher amplitude thresholding.
• Case – 2

In case -2, the ultrasonic imaging of conical portions of CSRDM and DSRDM are aimed at. The first and fourth objects are used as reference. In the case of second object (CSRDM), conical portion is in the 100 mm plenum, hence, reflected ultrasonic energy does not come back to the ultrasonic transducer and no echo is observed from the object. In the case of third object (DSRDM) also, conical portion is in the 100 mm plenum, hence image is not obtained. Fig. 4.12 shows ultrasonic imaging of conical portions of CSRDM/DSRDM.

![Ultrasonic imaging of conical portions of CSRDM/DSRDM](image)

Fig. 4.12 Case-2 Ultrasonic image of conical portions of CSRDM/DSRDM

(i) Side view of objects (ii) C-scan image of objects

• Case – 3

Figure 4.13 shows the object and its ultrasonic image. The first object is CSRDM in which the slot is in direct view to ultrasonic transducer with cone and cylindrical surfaces in
side view. A feeble echo is received from the cylindrical portion above the conical portion. But no echo is received from the conical portion. In the case of second object (DSRDM) with rectangular slot, the image is plotted in full strength but with a slight change in echo strength near the rectangular slot portion.

![Diagram of objects and their ultrasound images]

**Fig. 4.13 Case-3 Objects and its ultrasonic image**

(i) Side view of objects (ii) C-scan image

The third object is CSRDM with slot at slight deviation from the direct path and small conical portion with cylindrical surface in the above core plenum, No echo is received from conical portion and good image is obtained from the cylindrical portion.

- **Case – 4**

  Figure 4.14 shows the ultrasonic image of CSR object. In the first orientation, 16 mm cylindrical portion above the subassembly top contributes to good image and due to
beam divergence, the image is constructed for longer elevation. Also, at 75 mm height again, image is obtained from the starting point of cylindrical portion.

![Diagram of CSR at different orientations](image)

**Fig. 4.14 Case-4 Ultrasonic image of CSR at two different orientations**

(a) Side view of objects (b) C-scan image of object-1 (c) C-scan image of object-2

The echo started appearing from the top cylindrical portion also. In the second orientation, 5 mm cylindrical portion 84 mm conical portion and 11 mm cylindrical portion are viewed through above core plenum. No image is obtained from 5 mm cylindrical portion. But, 11 mm top cylindrical portion gives raise to sufficient echo. Due to beam divergence, at lower elevation onwards image is obtained.

### 4.3.5 DISCUSSION

From case-1, it is concluded that, if the CSRDM slot is not in direct view and cylindrical portion is in above core plenum, broad and distinct image can be obtained. The small tapered portion in between two cylindrical surfaces is not having any impact due to
beam divergence effect. If the slot is in direct view and cylindrical surface is with in the plenum, only feeble echo is received and the image is not distinct. For two different diameters of cylindrical portions with step change in CSRDM, different transit times are observed and are represented in two different colors. Due to sudden change in cylindrical portion, a small discontinuity is observed in the image for higher amplitude thresholding. In the case of DSRDM, the cylindrical portion without slot gives rise to broad and distinct image compared to the cylindrical portion with slot. However in both the cases, images are obtained.

From case-2, it is concluded that the conical portion of CSRDM and DSRDM at the end will not give back echo and hence image cannot be obtained. The images of the objects 1 and 2 are used as reference.

From case-3 it is concluded that if the CSRDM slot is in direct view to transducer, and also conical and cylindrical portion are in above core plenum, no echo is received from the conical portion and feeble echo is observed from the cylindrical portion. In the case of CSRDM, if the slot is in slight deviation from direct ultrasonic path, good images are obtained.

From case-4, it is concluded that the strong echo is received from the cylindrical portion of 16 mm of CSR and echo started appearing from the top cylindrical portion also. No echo is obtained from conical portion. Due to beam divergence, the image is plotted for longer distance. In the orientation-2, a strong echo is obtained from the top cylindrical portion of height 11 mm and no echo is received from the bottom cylindrical portion of 5 mm.

To summarise the result, in the case of CSRDM, the cylindrical portion gives rise to very good image provided the slot of the CSRDM is not in direct view of ultrasonic
transducer. The conical portion of DSRDM and CSRDM will not give back echo irrespective of position of the slot using direct imaging technique.

4.4 ULTRASONIC IMAGING USING INDIRECT IMAGING TECHNIQUE

In the case of PFBR, 30% of the hexagonal fuel subassemblies are oriented favorably to ultrasonic beam and remaining 70% are unfavorably oriented to ultrasonic beam. In indirect imaging technique, protrusion is detected by shadowing effect of protruded object on cylindrical peripheral shielding subassemblies (SSAs). The peripheral SSA has 100 mm extra projection above any other subassembly and located in the last row of the core. The possible protruded objects are hexagonal fuel subassembly head as shown in Fig. 4.15 and absorber rod drive mechanisms which are not geometrically favorable to ultrasonic beam in some orientation. In indirect imaging technique, there is a change in the echo pattern and reduction in amplitude received from the SSA due to the protruding object. The challenge is to analyse the data using specific methodology for protrusion detection. The ultrasonic scanner is deployed in two ports namely, In-vessel Transfer Position access port (IVTP) in large rotating plug and Observation Port.

![Fuel subassembly head](image)

Fig. 4.15 Fuel subassembly head
4.4.1 Simulation

The reactor core consists of different sectors. Each sector contains a group of subassembly arranged in specific patterns. These patterns are simulated in 5 m water tank and experiments were carried out using transducer having 0.6 MHz frequency to simulate the beam divergence effect equivalent to that in sodium for 1 MHz frequency. The beam spread half angle in water and sodium are given by the formula

\[ \sin \theta_1 = \frac{K \lambda_1}{D}, \quad \sin \theta_2 = \frac{K \lambda_2}{D} \]

\[ \text{(4.1)} \]

Where \( \theta_1 \) ---- beam spread half angle for water

\( \lambda_1 \) ---- wavelength of 1 MHz frequency transducer in m

D ---- distance of the object in m

\( \theta_2 \) ---- beam spread half angle in sodium in deg.

From the experiment, the half beam angle for 1MHz transducer is found out to be 3° in water. A cylindrical rod of 3 mm diameter is placed at various distances and the transducer was moved through an angle of 18 deg. and the intensity of the echo signal is plotted in Fig. 4.16.

![Fig. 4.16 Determination of beam spread in water using 1 MHz transducer](image-url)
From the peak value, the angular distance for 70% of the signal drop is obtained. The half beam angle obtained from the graph is 3°.

The half beam angle for sodium can be calculated using the formula

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{\lambda_1}{\lambda_2}$$

The wave length is calculated using the formula

$$V = n \lambda$$

For water $1500 = 1 \times 10^6 \times \lambda_1$ and for Sodium (Na) $2500 = 1 \times 10^6 \times \lambda_2$

$$\lambda_1 = 1.5 \times 10^{-3} \text{ m}$$

$$\lambda_2 = 2.5 \times 10^{-3} \text{ m}$$

Using eq. (4.2) half beam angle in sodium is found to be

$$\theta_2 = 5°$$

For the same medium, velocity of sound remains same. Therefore we have

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{f_2}{f_1}$$

The frequency required for the transducer to simulate the same beam angle in water equivalent to that of sodium is found to be

$$f = 0.6 \text{ MHz}$$

A water proof transducer with PZT crystal of 500 kHz resonant frequency has been fabricated and is excited using 0.6 MHz frequency sine wave. Experiments are carried out in water using this frequency. The two factors which vary in sodium and water are

1. Beam divergence
2. Beam attenuation

The beam divergence equivalent to that of sodium is simulated in water using 0.6 MHz frequency. The attenuation of the signal amplitude A can be described by the general law of attenuation $A = A_0 e^{-\alpha x}$. For two different sound paths $x_1$ and $x_2$ the following linearised form results: $2 \ln \left( \frac{A_2}{A_1} \right) = \alpha (x_1 - x_2)$. The attenuation coefficient ($\alpha$) of the liquid is determined experimentally. Based on the attenuation coefficient, Distance Amplitude
Correction (DAC) will be suitably applied in the electronics to compensate for the attenuation loss.

4.4.2 Algorithm

The signal strength from each cylindrical Blocking SA (BSA) varies due to its orientation. And also due to beam divergence effect, there will be bunch of echoes received from the BSAs. The reflections from the adjacent BSAs due to divergence effect arrive at different time of flight compared with reflections from BSA which are at direct line of sight. Therefore angle specific gating was provided and with in gating, summation algorithm was used for plotting the C-scan image. The algorithm with in gating was represented as

\[
\text{Intensity of signal within the gate} = \frac{\sum_{i=1}^{n} \left| A_i \right|}{n}
\]

Where, \( n \) is the no. of samples within gate and \( \text{mod } A \) is the amplitude of the rectified signal.

In case of protruding subassembly not being favorably oriented, scanning from one port will provide information about protrusion and to exactly locate the position, ultrasonic scanning is to be carried out from another port.

4.4.3 Details of Experiments

The reactor core is shown in Fig. 4.17 along with 6 retro reflectors. The details of sector-1 to sector-5 are marked in reactor core. The peripheral subassemblies are cylindrical in shape except 6 subassemblies. The reference targets (retro) are fixed over cylindrical subassembly at 6 different places. The reference target is used to assess the inclination of the transducer in the installed condition of the scanner. The following experiments have been performed in water tank simulating the retro reflector also.
The retro reflectors are corner cube reflectors used to measure the vertical orientation of the side viewing transducers. The complete core is simulated in 5 m water tank in different sectors with 40° scan angle. The scanning experiment is carried out with 1° step angle and 1 mm vertical height. Totally 9 experiments have been carried out with the above specific algorithm. Two representative results are presented along with the above experiments, viz.,

- Effect on inclination of objects with respect to ultrasonic beam and
- Effect of random protrusion of 20 mm

Table-4.2 Simulation of sector in clockwise direction

<table>
<thead>
<tr>
<th>Sector</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector 1 (Half)</td>
<td>Without Retro</td>
</tr>
<tr>
<td>Sector 3</td>
<td>Retro 1 (OP-R2)</td>
</tr>
<tr>
<td>Sector 4</td>
<td>Retro (IVTP-R2)</td>
</tr>
<tr>
<td>Sector 5</td>
<td>Retro (OP-R1)</td>
</tr>
</tbody>
</table>

Table-4.3 Simulation of sector in anti-clock wise direction

<table>
<thead>
<tr>
<th>Sector</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector 1 (Half)</td>
<td>Without Retro</td>
</tr>
<tr>
<td>Sector 3</td>
<td>Retro 2 (IVTP-R3)</td>
</tr>
<tr>
<td>Sector 4</td>
<td>Without Retro</td>
</tr>
<tr>
<td>Sector 5</td>
<td>Retro(OP-R3)</td>
</tr>
</tbody>
</table>
Experiments in Sector -1

Sector-1 is simulated at a distance of 4.3 m in water as in Fig. 4.18. The reactor conditions such as average fuel subassembly growth of 20 mm as shown in Fig. 4.19 and the above core plenum of 90 mm from normal subassembly top were simulated in water setup. Actual gap between normal subassembly top to bottom of thermowell sleeves is 90 mm. Due to the growth of fuel subassembly, the gap is considered as 70 mm which is conservative. The experiment is simulated for IVTP access port location, where dummy subassembly (i.e., no growth) is present beneath the transducer holder during scanning. The transducer is positioned
25 mm above the normal SA top. Therefore, the effective ultrasonic scan region is 65 mm from transducer position. The actual distance in the reactor is 5137 mm whereas in the simulation it is 4300 mm in sector -1 due to dimensional limitation of water tank. Overlap between sectors (3 SSAs) are made inorder to avoid missing information due to beam divergence effect.

![Sector-1 in Water Setup](image1)

**Fig. 4.18 Sector-1 in Water Setup**

![Simulation of 20mm growth of fuel subassembly](image2)

**Fig. 4.19 Simulation of 20mm growth of fuel subassembly**
As the signal strength is not uniform from all the cylindrical SSA, experiments are carried out at 3 different conditions. The photograph of sector-I is shown in Fig. 4.20

- Protrusion of objects at same angle at different distances
- Protrusion of objects at different angles at same distances
- Protrusion of conical portion of CSRDM from top of the thermowell (T/W) sleeves

![Photograph of Sector-I setup simulating protrusion at same angle at different distances from 1 m, 2 m & 3 m](image)

**Fig. 4.20** Photograph of Sector-I setup simulating protrusion at same angle at different distances from 1 m, 2m & 3m

- **Protrusion at same angle at different distances**

The ultrasonic data are collected using a PC based automatic scanning system for various conditions, such as without any protrusion which serves as a reference data and for 65 mm growth of fuel subassembly at various distances of 1 m, 2 m and 3 m leaving clear space of 25 mm from the top of the thermowell sleeve. Then protrusion is made at different distances 1 m, 2 m and 3 m at same angle. From the collected data, C-scan image is constructed using summation algorithm with angle specific gating as shown in Fig. 4.21. The dip in amplitude
shows the angle at which the object is protruded. In C-scan image, the protruded object is marked with an arrow. The C-scan image obtained shows that there is no useful data from 0 to 25 mm of ultrasonic scan region.

![C-scan images]

Fig. 4.21 Sector -1 C-Scan image by protruding the SA at same angle
(a) Background (b) protrusion at 1 m distance (c) @ 2 m (d) @ 3 m

It is found that there is a clear dip in echo signal strength at same angle (one subassembly left or right) at different distances. As the protrusion is nearer, the blocking effect is seen in wider angles compared with protrusion at longer distance. The same effect is seen in the C-scan images. The variable gating is selected in such a way that from the bunches of echo, the peak amplitude echo is targeted.
• **Protrusion at same distance at different angles**

The experiment has been carried out by protruding the object at same distance in different angles. The object simulation is shown in Fig. 4.22. The fuel subassembly is protruded at different angles at same distance of 2 m. The C-scan image is represented in Fig. 4.23. From the image, it is found that there is a clear decrease in the signal strength and was represented in arrow. The experimental results show that the protrusion is detectable at different angles at same distance through above core plenum.

![Protrusion at different angle 2 m distance](image)

**Fig. 4.22 Photograph of Sector-I setup simulating protrusion at different angle at same distances (2m)**
Fig. 4.23 C-Scan image of protruded SA at same distance (2 m) with different angles

(a) Background (b) protrusion @ right (c) @ left (d) @ centre

- Protrusion of CSRDM

As the CSR conical portion is not detectable by direct imaging technique, experiments have been carried out in Sector-1 by protruding the conical portion of CSR from the top of the core cover plate (Fig. 4.24). The CSR conical portion is adjusted in such a way that 60 mm of the conical portion is protruded from the bottom of the thermowell sleeves. The farthest CSRDM slot is selected to simulate longer distance of around 2.8 m distance. The C-scan image is taken first without protrusion which serve as a background reference data. Then with various protrusion of conical portion from 60 mm to 20 mm insteps of 20 mm, are simulated and the C-scan image is constructed as shown in Fig. 4.25. From the image it is found that, 60 mm conical portion is detected easily and for protrusion of 40 mm and 20 mm also, there is decrease in the signal strength.
Fig. 4.24 Photograph showing position of protruded CSR conical portion

Fig. 4.25 C-Scan image of protruded CSR conical portion at different lengths from top

(a) Background   (b) protrusion of 60 mm CSR conical portion
(c) 40 mm CSR conical portion   (d) 20 mm CSR Conical portion
• **Experiments in Sector-4**

The actual distance of sector-4 is 4281 mm and the simulation distance is 3857 mm. The simulation details of sector-4 are shown in Fig. 4.26. The fuel subassembly growth of 20 mm projection is simulated below the lattice plate. The scan is started in the clockwise direction. At the starting portion, the image construction is started from 20 mm elevation and after that, image construction is started even earlier and this is seen clearly in the image which represents the normal subassembly.

The photograph of Sector -4 is shown in Fig.4.27 with retro. The experiment is carried out with and without retro. The C-scan image without retro is shown in Fig. 4.28 (i). The protrusion is made on FSA beneath the core cover plate at different distance without retro. The C-scan image is plotted and found that protrusion is detectable and is represented by arrow in the figure. Again experiment is carried out with retro and projection is made at different angles other than fuel subassembly and the image is obtained. The protrusion is clearly visible in the image as shown in Fig. 4.28(ii).

![Simulation details of Sector-4](image-url)
Fig. 4.27 Photograph of Sector-4

Fig. 4.28 (i) C-scan image of protruded object at 1m, 2m, and 3m
(a) Background (b) protrusion @ 1 m distance (c) @ 2 m (d) @ 3 m
Fig. 4.28 (ii) C-scan image of protruded object at 1m, 2m distance

(a) Back ground (b) protrusion at 1 m (c) @ 2m

- **Study on effect of inclination of SSA**

A cylindrical blocking subassembly is kept at a distance of 4300 mm away from the transducer with ultrasonic beam passes through the above core plenum of 90 mm. Initially, the background data is obtained by taking 10° sweep in B-scan at 45 mm elevation. The A-scan data is obtained as shown in Fig. 4.29. Then the SSA is inclined to 0.22° using the shim. The signal strength is obtained from B-scan and A-scan data. With different inclination in steps of 0.22°, up to 0.86° is obtained. It is found from Fig. 4.29 that beyond 0.44°, the signal strength is weak and not detectable which shows that inclination up to 0.44° is tolerable to ultrasonic beam.
Study on Random protrusion

In the reactor, once in every ~8 months fuel handling operation is carried out and one third of the core will be handled. The freshly loaded fuel subassembly grows to a smaller extent than the old fuel subassemblies. The probable maximum growth of the fuel subassembly is ~20 mm which is due to neutron irradiation and differential expansion. Therefore, the experiments are carried out by providing equal protrusion of 20 mm growth and the random protrusion of partially 5 mm, 10 mm, 15 mm and 20 mm growth. This
experiment is carried out in sector-I and C- scan images are obtained. The result shows that some more information is available in random growth and it starts from 15 mm elevation onwards and for equal growth, information starts from 25 mm only. Therefore result obtained from simulation of equal fuel subassembly growth is conservative.

**BG- Equal 20mm growth of FSA**

**BG- random growth (5-20) mm**

![Useful scan region starts from 25mm](image)

![Useful scan region starts from 15mm](image)

(a) Background from 20mm equal growth of fuel subassembly

(b) Background from 5-20mm random growth of fuel subassembly

**Fig. 4.30 Effect on random and equal protrusion of SSA**

(a) Background from 20mm equal growth of fuel subassembly

(b) Background from 5-20mm random growth of fuel subassembly

**4.4.4 Discussion on Results**

Experiments have been carried out in water simulating the beam divergence effect equivalent to that of sodium. The core cover plate with thermowell sleeves is simulated and various experiments have been performed simulating the reactor sectors. Sufficient overlapping between sectors are provided to avoid loss of information. Beneath the core cover plate, Fuel subassemblies are located and which will undergo maximum growth of 20mm. Equal growth of fuel subassemblies are provided in the simulation experiments. The angle specific gating algorithm is selected for detecting the protruded object. The signal strengths from the SSA at different orientations are not the same and hence experiments have been carried out to detect the protrusion of object at different angles and also at different distances. From the results it is found that protrusion detection is possible up to 3 m distance at any angle. The detection capability is restricted to 3 m only. The conical portion of
CSRDM is also detectable using indirect imaging technique. The effect of inclination of SSA beyond 0.44° in vertical plane with respect to ultrasonic beam is not detectable.

4.5 CLOSURE

A PC based automatic scanning system has been designed and developed to carry out the experiments. Critical reactor components, namely, CSRDM/DSRDM/CSR have been simulated by keeping the complex shapes to true dimensions and cylindrical surface at reduced height to carry out the experiments. Ultrasonic imaging software with special offline features and different ways of representing the ultrasonic signals such as A-scan, B-Scan and C-Scan displays have been developed and utilized for imaging the reactor components. Different case studies have been carried out.

It is seen that, the cylindrical shapes are easily detectable while the conical shapes cannot be detected. However, conical shapes along with 10 mm cylindrical surface in the above core plenum are detectable. Two cylindrical surfaces of varying dimensions can be identified by the change in the transit time which is represented by two different colours in the C scan display. A sudden change in the dimension of cylindrical surface shows a slight discontinuity in the image when amplitude of thresholding is increased. A small taper portion within the cylindrical surface cannot be identified in the image due to beam divergence effect. The distances of various objects are obtained by the B-Scan data at that elevation.

The DSRDM has a rectangular slot and conical portion. The cylindrical portion of DSRDM without rectangular slot and DSRDM with rectangular slot are detected as they give strong echoes. Echo is not received from conical portion which is at the extreme end. In the case of CSRDM, the cylindrical portion gives rise to a good image, provided the slot of the CSRDM is not in direct view of ultrasonic transducer beam. The conical portion does not give back echo irrespective of position of the slot. The CSR consists of cylindrical
portion at both the ends with conical portion in the middle. Experiment shows that conical portion does not give back echo but the cylindrical portion at both the ends give sufficient amplitude echoes. Therefore CSR can be ultrasonically imaged using direct imaging technique in all possible conditions.

In the case of indirect imaging technique, protrusion of objects which is geometrically unfavorable to ultrasonic beam can be detectable using angle specific gating with summation algorithm. Initially, without any protrusion, the core is scanned and the C-scan image is constructed which serves as the reference data. The gating is set based on reference data targeting SSA. The objects such as hexagonal subassembly having differential growth of 45 mm can be detectable as observed in water experiments. The objects such as the conical shape or any irregular shape hanging from the top of the thermo well sleeves by 20 mm is also detectable. The inclination effect of peripheral SSA is also studied and found that 0.44º inclination in vertical plane with respect to ultrasonic beam is tolerable to ultrasonic beam.

The direct imaging method is efficient when the protruded objects are favorably oriented to ultrasonic beam (30%). In such cases, the protruded object can be easily localized using direct imaging method. But if the protruded objects are unfavorably oriented to ultrasonic beam (remaining 70%), indirect imaging method is used to find the angle at which the object is protruded. To localize the protrusion, the scanner will be deployed in Observation Port also and from the intersection point, the protrusion is localized. Therefore both the methods are required based on the need.