Developing an Ultrasonic NDE System for a Research Reactor Tank

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Abstract. A special apparatus was developed for the ultrasonic inspection of a research reactor tank wall, from inside, without removal of the vessel top cover. The inspection is performed by the immersion technique using the coolant / moderator water as a medium for ultrasound transmission. A manipulator, carrying an ultrasonic search-unit is inserted into the tank through a central 70 mm diameter hole. The compact search unit carries up to 16 ultrasonic transducers, positioned at angular and straight orientations and operating both in pulse-echo and pitch-catch modes. The ultrasonic system is designed to scan the entire area of the tank wall with high resolution, to store the entire acquired data (full A-Scan) and to analyse it. It is capable of detecting 0.2 mm thickness variations, of corrosion pits of diameters greater than 3 mm and depths greater than 1 mm, and linear (crack-like) flaws in any orientation. The validation of the newly developed system, as well as of the inspection techniques, were carried out using a full-scale mock-up of a reactor tank, containing flaws unknown to the inspectors.

1. Introduction

Reactor vessels are required to sustain harsh service conditions including radiation, elevated temperature and contact with aqueous medium for prolonged periods. In case of nuclear power plants pressure vessels, these periodic non-destructive inspections are mandated by various codes[1]. However, for research reactors, there is less standardization. Significant differences between the construction of power-reactors and research reactors complicate the transfer of inspection technology from the former to the later reactors. For example, the inspection of power reactors generally requires the removal of the vessel top cover[2, 3] an extremely difficult task in some research reactors. The outer diameter surface of the vessel (OD) is inaccessible in many research reactors, unlike modern BWR[4]. In addition, reactors built according to standards require periodic inspections. An additionl problem in research reactors is the lack of periodic overall inspections. Thus, in the interpretation of results of inspections in research reactor vessels one usually cannot rely on comparison with past inspections.

With these difficulties in mind, the NRCN decided to develop a new ultrasonic NDE system, suitable for the inspection of a research reactor vessel from the inside, without removal of the vessel top cover. The goals set up for the sensitivity of the system were detection of 0.2 mm wall-thickness variation, corrosion pits of diameters greater than 3 mm and depths greater than 1 mm, and linear (crack-like) flaws in any orientation. It was required that all the data acquired in the inspection should be saved as a reference for future inspections. Any detected flaw is required to be located with ±1 mm precision, so that it can be approached again in the future.

The present report surveys the design and development of this new system. The system which was primarily intended for the IRR2 reactor tank, can probably fit for other closed tanks as well.

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2. System Design

The chosen inspection technique is immersion ultrasonic scanning. The inspection is being done without direct contact and without cleaning of the tank inner surface, so that the presence of an interfering sediment layer has to be taken into account. The inspection system scheme is presented in Figure 1.

The system consists of a computer controlled manipulator that carries the ultrasonic search-unit, motion control unit, drive motors, computerized ultrasonic instrumentation and a system of computers designed for data storage and processing.

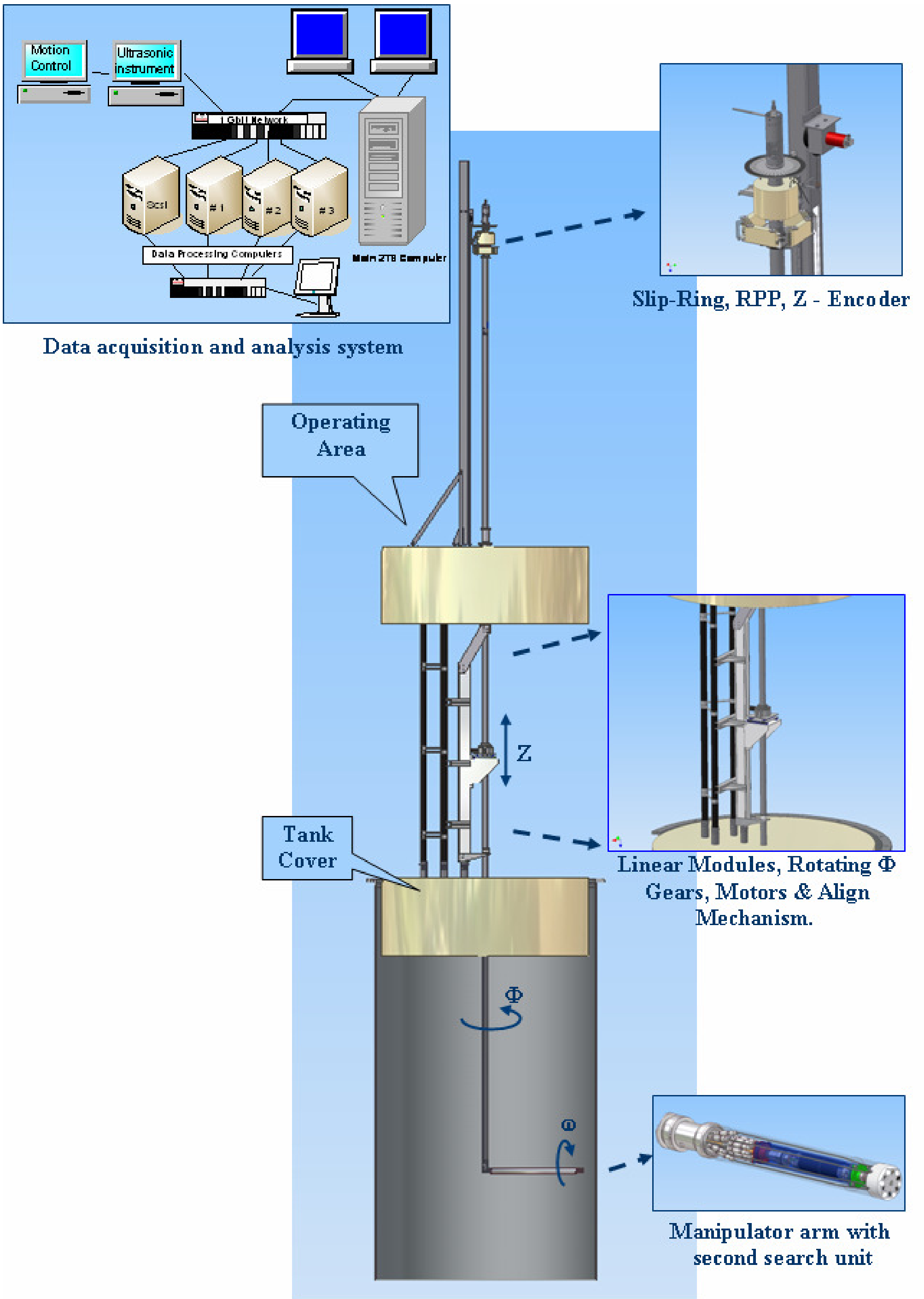

FIG. 1. Schematic drawing of the ultrasonic scan system.

2.1. Mechanics and Motion Control

The ultrasonic search-unit is carried by a custom-designed manipulator with three motion axes: the elevation Z, the rotations Φ along the perimeter and rotation ω of the transducers head, see schematic description on Figure 1.

At first the manipulator is inserted in parallel to the tank central axes. Then, the elbow folds up to a 90 degree position in order to place the transducers-head perpendicular to the tank wall. The folded arm length approximately 1.25 m is dictated by the geometry of the IRR2 tank, but it could be matched to other tank geometry by connecting different segments between the joints. The limited access into the tank and its dimensions impose a large ratio of manipulator length to manipulator diameter, which decreases the manipulator stiffness, and could cause a large deflection in the manipulator structures. In order to decrease the deflection of the main structure, the manipulator is supported by two Teflon sliding-bearings in a spherical housing which align the manipulator with the tank central axis. Furthermore, the arm was designed as a float unit in order to reduce the force act on the folding mechanism and drop off the bending moment of the main structure.

The manipulator is stirred by a three-motor drive governed by a computerized controller. The position of the manipulator in the Φ axis is monitored by a relative encoder that is attached to its motor and a home switch. The Z axis has, apart from the relative encoder, an absolute encoder. The system is programmed to stop if the disagreement between the relative and the absolute encoders exceeds 0.5 mm. The Z axis also has a home switch and two limit switches that are designed to prevent the manipulator from going out of the designed range of motion.

A small motor, located inside a sealed can at the front-end of the manipulator, enables the rotation of the search-unit around its central axis. This motor is controlled by an electromagnetic resolver and a limit switch and a homing switch.

2.2. Search Units

The ultrasonic search unit is designed to operate at a 40±5 mm distance from the tank wall and to achieve sufficient coverage of the whole wall thickness (8 mm in the IRR2). Two search-units are used as depicted in Figure 2:

(1) A detecting search-unit containing two 5 MHz straight transducers and six pairs of 2.25 MHz angular transducers, operated in both, Pulse-Echo and the Pitch-Catch modes. Two additional straight transducers are also mounted for backup. The straight transducers are intended for detection of thickness variations, corrosion damage and internal flaws such as voids and inclusions in welds. Each one of the two operating straight transducers is connected to two recording channels with different gain, in order to provide enough dynamic range for both weak direct reflections from flaws and the strong back-wall reflection. The angular transducers are posed at an angle of 18° which corresponds to a 45° refracted shear-wave ultrasonic beam inside the wall. The angular transducers may detect linear (crack-like) flaws. The use of several pairs of these transducers enables the detection of such flaws in any orientation, since the pitch-catch technique is not sensitive to the direction in which ultrasound is scattered from a discontinuity.

(2) An evaluation search-unit containing a 10 MHz straight transducer and 3 pairs of 2.25 – 10 MHz angular transducers. This search-unit can be rotated around its axis. This additional degree of freedom enables the inspector to find the orientation at which the reflected amplitude is maximal.

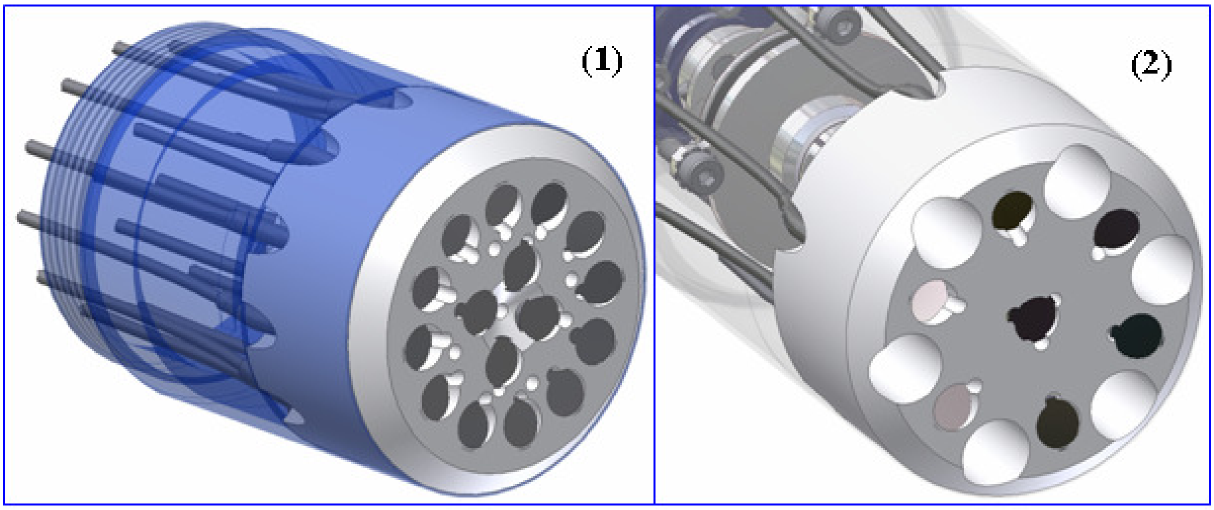

FIG. 2. A drawing of the search-units.

2.3. Ultrasonic Instrumentation

The ultrasonic instrument is based on a 16-channel industrial ultrasonic scanner. The scan parameters, i.e. velocity, range and resolution, are also set up using the programming interface of the ultrasonic scanner. The electrical pulses needed for the generation of ultrasound and initial amplification of the RF signals coming from the transducers, are done by four RPP (Remote Pulser Preamplifier). These RPPs are rotating with the manipulator, thus the connection between them and the main ultrasonic system is done through a slip-ring. The idea of this design is that the signal going through the slip ring is already amplified so that it is not sensitive to the noise added by the slip-ring.

2.4. Data Storage and Processing System

The signals acquired by the ultrasonic scanner are saved in a computer with fast SCSI hard disk. The next stage is reformatting of the saved data to a convenient structure. This is done by three computers working in parallel. Custom software has been written in order to process the vast amount of acquired data and to analyze the defects, see Figure 3. The reformatted data is saved to a 2 TByte RAID storage device. All the subsequent processing is done off-line, using the recorded full A-Scan data. The stored signals display is done using primarily C-Scans. The basic analysis procedure involves the examination of five C-scan displays:

(1) Amplitude of back-wall reflection to straight transducer (shadow map).
(2) Amplitude of reflection from inside the tank wall to straight transducers (conventional pulse-echo).
(3) Wall thickness map (measured by transit-times between echoes reflected to straight transducers).
(4) Amplitude of transmitted signal to angular receiver-transducers (pitch-catch mode).
(5) Amplitude of reflections from inside the wall to angular transducers (conventional pulse-echo).

Although these C-scans are standard, the multi-transducer, multi-channel scan required some adaptation. For example, conventionally each amplitude record of the transmitted echo in a Pitch-Catch configuration would be displayed as an individual C-Scan. Here, all the Pitch-Catch records were condensed into a single C-Scan, in which for each pixel, the lowest recorded amplitude was displayed.

If some indication is detected in the C-Scan, it is further analyzed using standard B and A scans.

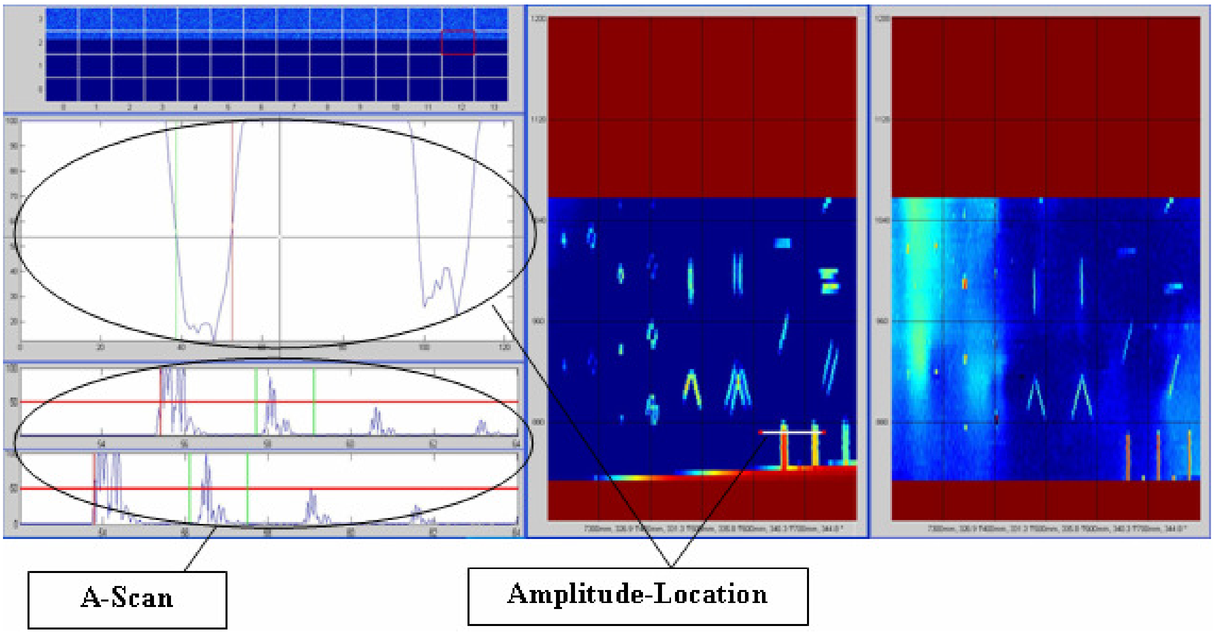

FIG. 3.The software display.

3. Scanning Procedure

Scanning will be done in three stages:

(1) Preliminary, low resolution (1 mm X 4 mm) scan of the whole tank wall using the first search-unit.
(2) High resolution (1 mm X 1 mm) scanning of suspect areas, detected in stage 1, using the same scan-head as in stage1.
(3) Local scan for evaluation of suspected flaws that may be detected in stages 1 and 2, using the second (evaluating) search-unit.

The scanning speed is around 35 mm/sec.

4. Validation Using Mock-Up

The design validation was carried out in two stages. First, the ultrasonic technique was calibrated on specimens with known flaws, using a laboratory-scale ultrasonic scanner. Some of these specimens were intentionally covered with stone by boiling them in tap-water, in order to simulate the sediment layer in the tank. In the second stage, the whole inspection system was tested in a full-sized mock-up, containing a full-scale segment of a tank wall. In this mock-up installation, critical procedures such as the insertion and the folding of the manipulator arm were practiced. The manipulator accuracy and the precision were examined. Furthermore, the overall integration of the various system components was tested. For example, an important issue faced in the mock-up experiments was the system sensitivity to electromagnetic noise.

The mock-up tank wall contained flaws that were unknown to the NDE inspector. The successful detection of these flaws, with no false alarms, was an important condition for the final approval of the design. In Figure 4, a sample C-scan (transmitted signal in pitch-catch mode) of an area containing such validation-flaws is shown. It is interesting to note how easily inner surface flaws are distinguished from outer surface flaws, even in the C-scan, without looking at more detailed information. This is because each inner-surface flaw produces a doubled image in this type of display, while only a single image is produced by the outer surface flaws.

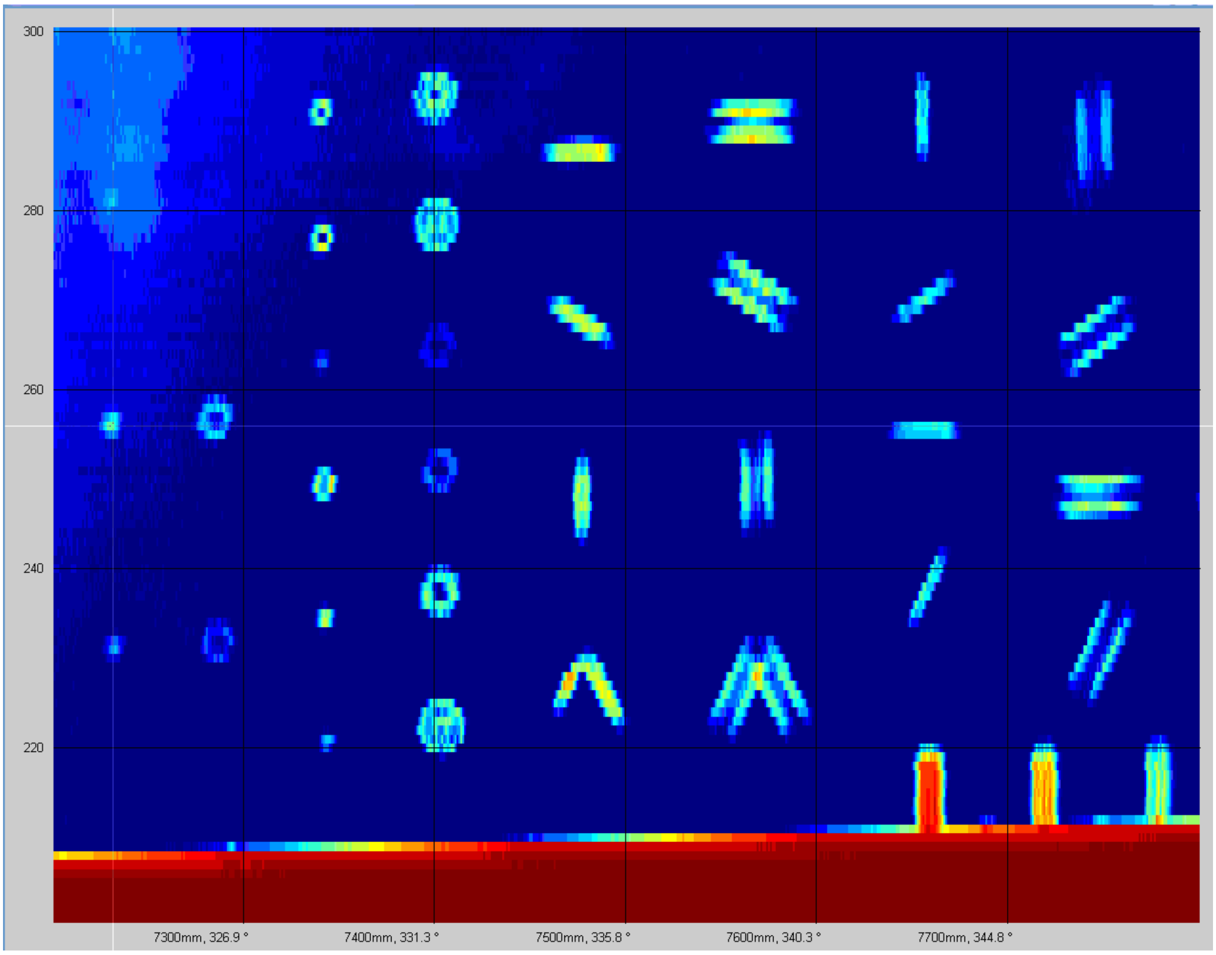

FIG. 4. C-scan of a flaw containing area in the mock-up installation (4 mm x 1mm resolution image produced by 6 pairs of angular 2.25 MHz transducers, in Pitch-Catch configuration). The colorbar on the left relates the colors in the image to the recorded amplitude (in arbitrary unite).

5. Conclusions

A special apparatus was developed for the ultrasonic scanning of a research reactor tank wall, without removal of the vessel top cover. The ultrasonic NDE system has been designed to scan the whole tank wall with fine resolution, store the whole acquired data (full A-scan) and analyse it.

The operation of the newly developed system was practiced using a full-scale mock-up. The inspection technique was validated using a variety of flaws that were unknown to the operators.

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