Design, Development & Feasibility Trials of Multi-channel Ultrasonic Instrumentation for Accurate Measurement of Internal Diameter and Wall Thickness of Pressure Tubes of PHWR

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Abstract. Accurate measurement of Internal Diameter (ID) and Wall Thickness (WT) of Pressure Tubes (PT) is very important for assessment of remaining life while in service as well as damage analysis after service in a nuclear reactor. An automated ultrasonic gauging system is under development at Electronics Division, BARC for post irradiation examination of pressure tubes. A prototype of multi-channel ultrasonic instrumentation has been designed and developed for carrying out feasibility trials for accurate measurement of PT-ID and WT. It comprises of in-house developed 5-channel ultrasonic pulser-receiver, USB digitizer and GUI based control/data acquisition/analysis software. The pulser-receiver is housed in a 6Ux19”x320mm bin with serial interface to PC and the digitizer is a standalone USB powered module. Each pulser channel provides spike type excitation for high frequency transducers with user selectable precise pulse width and amplitude control. Each receiver channel has user programmable gain 20-90dB with 25MHz bandwidth and the digitizer provides sampling rate up to 100MSPS. The prototype instrumentation has been tested with an under water test setup comprising of probe head inserted in a section of a Zircalloy pressure tube. The probe head has 2mm step block for measurement of reference sound velocity and 10MHz focus transducer for measurement of water path and WT. Distinct echoes were obtained from two faces of step reference block as well as inner and outer wall of the pressure tube. Reference velocity, water path and WT were computed by measuring accurate time of flight between two peaks in the acquired RF signal using cross correlation technique. Measurements were carried out and found to be in conformance with the actual values. This paper describes the indigenously designed & developed ultrasonic instrumentation, test setup and results of feasibility trials.

Introduction

In Indian Pressurized Heavy Water Reactors (PHWRs), the pressure tubes hold the fuel bundles. They are subjected to nuclear radiation, high pressure, temperature and flow of heavy water; due to which they tend to deform over a period of time. Mechanical deformation is in the form of increase in ID, reduction in WT and change in shape from circular to oval. Excessive deformation may cause operational difficulties of the nuclear reactor. Hence it is very essential to measure the PT-ID and WT to assess their remaining life while they are in service. These parameters are also measured after their service in the reactor, to analyze the causes of damage and subsequent improvement in the material design. An automated ultrasonic gauging system is under development at Electronics Division, BARC for post irradiation examination of pressure tubes. A prototype of multi-channel ultrasonic instrumentation has been designed and developed for carrying out feasibility trials for accurate measurement of PT-ID and WT. This paper describes the indigenously designed & developed ultrasonic instrumentation, test setup and results of feasibility trials.
Ultrasonic Instrumentation

The ultrasonic instrumentation comprising of multi-channel ultrasonic pulser receiver, USB digitizer and data acquisition/measurement/analysis software has been designed and developed at Electronics Division, BARC for carrying out feasibility trials for measurement of ID and WT of pressure tubes of PHWR. Following paragraphs describe different components of ultrasonic instrumentation:

Multi-channel Ultrasonic Pulser Receiver (UPR). Fig. 1 shows the photograph of the indigenously developed multi-channel UPR [1]. It is based on modular architecture and can have up to 8 channels of pulser-receivers. Each pulser-receiver channel can be configured for pulse-echo or through transmission mode. Through software control, each pulser channel can generate single negative pulse of variable width or burst of unipolar negative or bipolar high voltage square wave signal of desired frequency for excitation of ultrasonic transducers. Each receiver channel has independently controlled Programmable Gain Amplifier (PGA). Receiver outputs are multiplexed using 8:1 multiplexer. Multiplexed echo signal is passed through a band pass filter and additional gain is provided by using one more PGA before sending the RF signal out for interfacing to data acquisition cards. On board Complex Programmable Logic Devices (CPLDs) provide complete timing and control of the unit. Direct Digital Synthesizer (DDS) is used for generating the transducer excitation signal of desired frequency/width. Microcontroller interfaces the unit to host computer using RS485/ RS232 serial communication link. It interprets and executes various commands received from the computer. The UPR unit is a 19” rack mountable unit having 6U (267mm) height and 320mm depth. Eight ultrasonic pulser-receivers are contained in four modules of 10T width, each having two independent pulser-receiver channels. One multi channel sequencer module contains micro-controller, digital control logic and analog multiplexer etc. One high voltage supply module generates HV power supplies for the pulser-receiver modules. All the modules are interconnected using a double Euro backplane. Following are the major technical specifications of the UPR unit:

- No. of pulser-receiver channels : 1 to 8
- Pulse voltage : +/-35V to +/-250V (bipolar output)
  -35V to -250V (unipolar output)
- Pulse frequency : 20kHz – 15MHz in steps of 1Hz
- Pulse cycles : 1 – 20 complete cycles
- Trigger source : Internal PRF or software
- PRF : 30Hz – 5kHz in 1Hz increments
- Damping : 150 or 470 ohms (fixed)
- Channel firing : Sequential with user selectable sequence
- Receiver gain : 20dB – 90dB in 1dB steps
- Receiver bandwidth : 25MHz
- Receiver input protection : +/- 1kV
- LPF : 4 settings
- HPF : 4 settings
- Output : RF (+/- 3.8V maximum)
Serial Communication: RS485 or RS232 (Selectable)
Power supply: 12VD@550mA, 5VD@400mA, +5VA@350mA and -5VA@350mA
Dimensions: 19” x 6U x 320mm(D)

Fig. 2(a,b) show 1MHz and 5MHz bipolar pulse train output, having different number of cycles and about +/-200v amplitude into a 50 ohms load, at Tx terminal of the pulser. Fig. 2(c,d) show unipolar outputs into 50 ohms, suitable for 10MHz and 15MHz ultrasonic transducers.

Fig. 2: Pulser output at Tx terminal into 50 Ohms a) 1MHz, 5cycles, bipolar, b) 5MHz, 1cycle, bipolar, c) ~50ns width, unipolar for 10MHz and d) ~30ns width, unipolar for 15MHz transducer.

USB Digitizer. Fig. 3 shows the photograph of the in-house developed digitizer module [2]. This compact low cost, low power USB powered module incorporates three functionalities on single board. Main features of the digitizer section are:

a) Sampling rate:100/50/25/12.5 MSPS
b) Trigger: Internal PRF/ External/ Self
c) ADC resolution:8 bits
d) Programmable acquisition delay and number of samples
e) Buffer size: up to 128kB
f) Communication: USB 2.0 (Full/ High speed)
g) Power: USB or External 5V
h) Dimensions:170mm x 144mm x 30mm.

Other two features included on-board are receiver amplifier (with programmable gain, 1kv input protection & 50 ohms termination) and a tone burst generator to generate frequency/phase agile sine/square wave signal having user selected frequency, no. of cycles in burst, repetition rate and 1Vpp amplitude into 50 ohms. These features have been implemented so that this module can be used for other ultrasonic NDT applications.

Control and Data Acquisition/Measurement/Analysis Software. Dedicated GUI based interactive software has been developed with following main features, suitable for this application:

a) Acquisition mode: Single shot/ Continuous
b) On-line display of acquired data (V v/s. t) with time-base scrolling and scaling
c) Online averaging of acquired data: Running/ Simple (up to 256)
d) Online/offline FFT plot of user selected window of acquired data
e) Time of Flight (ToF) calculation based on correlation, threshold & peak value
f) Ultrasonic measurements: velocity, velocity profile, thickness, attenuation
g) file save/open operations in ASCII format
Feasibility Trials

Fig. 4 shows the test setup used for the feasibility trials carried out in the lab. The test setup comprised of probe head, with velocity reference 2mm step block and 10MHz point focused transducer (with 15m cable) mounted in it, and a section of dummy pressure tube. The probe head was inserted in the dummy pressure tube and assembly was immersed in water. The ultrasonic transducer was connected to in-house developed pulser-receiver and the receiver output was connected to CRO as well as USB bus based 100MSPS digitizer for data acquisition. Pulser on RS232 and digitizer on USB were connected to host PC where control and data acquisition software was installed. Fig. 5 shows the type of excitation pulse used for the 10MHz point focused probe. Pulse amplitude and receiver gain were adjusted during the trials for different measurements.

Measurement of Reference Sound Velocity. The transducer was adjusted such that roughly equal amplitude of the echo is obtained from the two steps of the reference step wedge. Fig. 6 shows the screen print of the two distinct RF echo signals received from the two steps of step wedge block for measuring the reference velocity. Time of flight was measured between these two echoes using cross correlation technique. Correlation plot is also seen in Fig. 6. It was observed that even if the shape of the RF echo signal is changed such that the position of the peak is interchanged, the measured time of flight does not change, because the position of peaks in the correlation plot remain same. An example to this effect is shown in Fig. 7.

Measurement of Water Path for ID measurement. The transducer was placed such that it faces the PT ID and the multiple interface echo signals from ID surface are maximized in amplitude. Fig. 8 shows first two interface echo signals from PT ID. Between these two interface signals, backwall reflections from PT OD are also seen in this figure. Water path was measured by measuring ToF between first two ID interface echoes using correlation technique and multiplying it with measured reference sound velocity. ID is measured by placing two transducers back to back along the
diameter of the PT, as depicted in Fig. 9, and adding the two measured water paths with the transducer face to face distance obtained during calibration

**Measurement of Pressure Tube Wall Thickness.** A-scan waveform shown in Fig. 8 was expanded as shown in Fig. 10. It shows the RF echo from 1st ID interface and first two backwall echoes from the OD of the tube. Gain was adjusted such that the backwall echoes have sufficient amplitude but not saturating. Wall thickness was measured by measuring ToF between first two backwall echoes using correlation technique.

**Accuracy of Measurements.** Measurement accuracy in the reference sound velocity in light water, achieved with the present setup is about 0.37%, which can be improved to 0.1% or better, using the combination of digital signal processing of the echo signals, increased step difference in the reference step wedge and/or more sampling rate. Similarly the measurement accuracy in wall thickness that could be achieved is about 24 microns, which is adequate for the purpose. Measurement accuracy in water path (for ID measurement) depends on two factors, accuracy of measured reference velocity and accuracy of ToF measurement. ToF measurement accuracy that can be achieved with 100MSPS sampling rate is about 7.5 microns for one probe at room temperature.

**Conclusion**

A prototype multichannel ultrasonic instrumentation has been indigenously designed and developed at Electronics Division, BARC for accurate measurement of internal diameter and wall thickness of pressure tubes of PHWR. Feasibility trials have been successfully carried out using an under-water test setup comprising of probe head inserted in a section of Zircalloy pressure tube and 15 m long...
signal cables. An automated system for measuring the PT ID and WT is under development for post irradiation examination of pressure tubes.

References

