Design, Development and Irradiation Testing of 3-Channel Preamplifier for Ultrasonic NDT

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Abstract

An automated inspection system for in-service inspection of Reactor Pressure Vessel (RPV) of boiling water reactors has been indigenously designed and developed. The system comprises of three major components: an automated mechanical manipulator carrying the ultrasonic probes, multi-channel ultrasonic data acquisition system and data analysis software. During scanning, the B-scan and C-scan images are acquired from multiple UT transducers and the data is analyzed for detection and characterization of the flaws. Some of the significant flaws are required to be characterized using Time of Flight Diffraction (TOFD) technique.

In TOFD, the echo signals received from tips of the flaw are generally weak requiring significant amplification. It is desirable that the pre-amplifier is located very close to the receiver transducer so that the amplified signal can then be transferred to the data acquisition system. During RPV inspection, the pre-amplifier is carried by the probe holder and as a result it is exposed to a high dose of gamma radiation. A 3-channel preamplifier has been designed & developed at Electronics Division, BARC for use under radiation environment. Each channel of the preamplifier is a two stage architecture, which has been designed to meet the requirements of UT front end using commercial grade COTS components. It has 40dB large signal gain at about 10MHz bandwidth when operated with +/-5V power supply. The preamplifier has been successfully tested up to 500 krad(Si) Total Ionization Dose (TID) for intended performance. Co-60 based Gamma chamber with dose rate of about 36 rad(Si)/s has been used for this purpose. Irradiation has been carried out in seven steps. After each step, system parameters such as gain, supply current and 3-dB bandwidth were measured as per the guidelines of MIL-HDBK-814 standard. Design features and results of performance of the preamplifier with incremental irradiation are presented in this paper.

Keywords: TOFD, ultrasonic NDT, preamplifier, irradiation, ISI, RPV, DAQ.

1. Introduction

An automated inspection system for in-service inspection of RPV of boiling water reactors has been indigenously designed, developed and deployed at TAPS-1&2. The system comprises of three major components: an automated mechanical manipulator carrying the ultrasonic probes, multi-channel ultrasonic data acquisition system [1] and data analysis software. Up to 4MHz transducers are used for scanning. During scanning, the B-scan and C-scan images are acquired from multiple UT transducers and the data is analyzed for detection and characterization of the flaws. Flaw sizing is generally done using conventional 6dB drop technique, but some of the significant flaws are required to be characterized using TOFD technique for accurate flaw sizing. The TOFD offers great accuracy for measuring the critical through-wall size of crack-like-defects. The accuracy of the order of ±1mm or even better can be obtained in a wide range of material thickness from which pressurized components are constructed [2]. TOFD was initially developed as a method of accurate monitoring and sizing of through-wall height of in-service discontinuities in the nuclear industry. It has now been independently validated as one of the most effective techniques for locating and sizing discontinuities in ferritic welds [2]. In TOFD, the echo signals received from tips of the flaw are generally weak requiring significant amplification. It is desirable that the pre-amplifier is
located very close to the receiver transducer so that the amplified signal can then be transferred to the data acquisition system. During RPV inspection, the preamplifier is carried by the probe holder and as a result it is exposed to a high dose of gamma radiation. Life time of such preamplifier is limited due to degradation of characteristic parameters of semiconductor components with TID. Radiation hard semiconductor components remain unavailable in open market with their availability to user at sole discretion of manufacturer and suppliers. This criterion makes the certified radiation hard components inaccessible to most users. A 3-channel preamplifier has been designed & developed at Electronics Division, BARC for use under radiation environment. The preamplifier has been successfully tested up to 500krad (Si) TID for intended performance as per the guidelines in MIL-HDBK-814 standard [3][4].

2. Principle of TOFD

TOFD employs a pair of ultrasonic transducers for data acquisition, one acting as a transmitter and the other as receiver. For weld examination, these transducers are placed on either side of the weld joint. For thicker weld joints, more than one pair is used so that the data is available for the complete thickness of the weld joint. The separation between the transmitter and the receiver is determined by the beam angle and the depth range for which the data is being acquired. During data acquisition, the transmitter-receiver pair is moved along the length of the weld joint and an encoded B-scan image is generated. The transmitter sends an ultrasonic beam, which travels across the thickness of the weld joint. A small portion of this beam also travels along the surface and reaches the receiver. This wave is called as a lateral wave and has the shortest travel path. The beam travelling in the thickness direction interacts with the flaw(s) and its extremities before it reaches the back surface. At the back surface, the beam is reflected towards the receiver. During its travel through the material, the sound beam gets diffracted from extremities of the flaw, such as crack, lack-of-fusion, slag inclusion etc. These diffracted signals also reach the receiver, although earlier than the backwall signals. The typical A-scan signal for any position comprises of a signal from a lateral wave, the backwall signal and diffracted signals from the flaw(s), if any. By measuring the difference in the travel time of the diffracted signals from the upper and lower extremity of the flaw, the through-wall dimension of the flaw is determined accurately. Since the diffracted signals are very weak, more often than not, inspection using TOFD technique uses pre-amplifier. The pre-amplifier is placed closer to the receiver transducer so that the diffracted signal is not de-graded before it is processed for the purpose of imaging. TOFD is more reliable than traditional radiographic, pulse echo manual UT and automated UT weld testing methods [2][5].

3. Circuit Description

A 3-channel preamplifier board has been designed and developed at Electronics Division-BARC. Each channel of the preamplifier is 2-stage architecture. Figure 1a shows circuit schematic of one channel and figure 1b shows the photograph of PCB with one channel populated (Channel-2 for irradiation). Salient features of the preamplifier design are:

- Gain: up to 40dB at 20MHz bandwidth (Resistive load)
- Single or dual supply operation
- AC or DC coupling of input signal
- Input over-voltage protection
- Passive HP filter
PCB layout design accommodates three types of op-amps having different packages (2 types radhard and 1 commercial) on the same location

- Compact, low power design
- PCB size: 57mm x 72mm.

4. Irradiation Testing

Three preamplifier boards were assembled with gain of 40 dB and bandwidth of 10 MHz without load using commercial grade op-amps. Input and intermediate stages of preamplifier has been A.C. coupled with gain of 20dB at each stage. All passive components used were of commercial grade. Rechargeable commercial 12V/1.2AH battery has been used as power source to generate dual bias voltage (±5V) for circuit during irradiation.

4.1 Functional & Burn-in Testing before Irradiation

Pre-irradiation characterization was performed on each preamplifier board for functional testing and parameter variation. Verification with respect to design parameters with six hours of burn-in testing were carried out before start of irradiation. Preamplifier has also been tested to drive equivalent load of cable intended to be driven for the application.

4.2 Irradiation Procedure

Three units of preamplifier were irradiated to a maximum TID level of 500 krad(Si) with incremental readings at 50 krad(Si), 100 krad(Si), 200 krad(Si), 300 krad(Si), 400 krad(Si) and 500 krad(Si) under biased condition. Steps for irradiations have been selected in order to fulfill the criterion as per the ASTM-1892 and MIL–STD–750 test procedure [6] [7]. Irradiation was carried out in two batches, first batch with one preamplifier and second batch with two preamplifier boards, at different times.

4.3 Test Parameters
a) Supply Current from +5V & -5V.
b) Voltage gain with no load.
c) 3dB-Bandwidth with no load.

4.4 Irradiation Setup

Irradiation of all the boards was performed under biased condition (±5V) with system input grounded (A.C. coupled). The Co-60 radiation TID source used was a gamma chamber, GAMMA 5000. In the gamma chamber, Co-60 rods are held at the base of the chamber, shielded by lead. During radiation exposure the shaft with central cavity holding the preamplifier along with the battery was lowered in the gamma field. Time of exposure was controlled by electronic timer. Dose rate in the Gamma chamber was 36.11rad/sec, as determined by the initial strength of Co-60 rods and half life of Co-60. Preamplifier board’s power supply was connected in star topology while irradiating more than one preamplifier simultaneously.

4.5 Characterization Setup

Figure 2 shows the characterization setup used during the irradiation testing of the preamplifier boards. Signal generator was used to generate CW sinusoidal input of variable frequency and amplitude as test waveforms. Power supply circuit and battery, used during irradiation, were utilized for characterization as well. CRO was used to measure peak to peak voltage, using the same settings throughout the experiments. Current was measured using a multimeter with measurement resolution of 1mA. Measurements were carried out and completed with-in one hour at each characterization step to meet the applicable standards.

5. Results

5.1 Power Supply Current

Figure 3 shows the variation in supply current with increasing TID for all the preamplifier boards. Figure 3a shows the current taken from positive supply (+5V) and Figure 3b shows the current taken from negative supply (-5V). Solid blue diamond & blue line (dashed) present the results for the first preamplifier board; while the red square & red line (dotted) and green triangle & green line (dotted) present the results for the second and third preamplifier board, respectively. It is observed that there is no significant change in the power consumption by the preamplifier up to TID of 500 krad(Si).
5.2 Voltage Gain

Voltage gain was measured using 1MHz continuous sine wave input having peak to peak amplitude of 20mV. Figure 4 shows the voltage gain v/s TID graph for the preamplifier boards. It is observed that there is no significant change in the gain up-to TID of 500 krad(Si).

5.3 3-dB bandwidth

3-dB bandwidth has been calculated by measuring the frequency response of the system with 20mv peak-peak sinusoidal input with varying frequency of excitation from 500 kHz to 20MHz. Figure 5 shows the 3-dB bandwidth v/s TID graph for the preamplifier boards with no load. Significant change, about 40% reduction, in 3-dB bandwidth is observed at TID of 50 krad(Si) and no significant change thereafter up-to TID of 500 krad(Si).

6. Conclusion

A three channel preamplifier has been designed and developed at Electronics Division-BARC for ultrasonic NDT. Preamplifier has been tested for irradiation effects up-to TID of 500 krad(Si). Irradiation methodology and test setup to meet the inter irradiation delay as per applicable standard have been presented. Preamplifier has been irradiated with ionizing radiation inside gamma chamber and characterized for parameters of interest. Test parameters have been successfully measured for both output floating and load that preamplifier is intended to drive. Results obtained successfully represent the suitability of the designed preamplifier for intended application.
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8. References


[5] TOFD - The emerging ultrasonic computerized technique, for heavy wall Pressure Vessel welds examination By F. Betti, A. Guidi, B. Raffarta - NUM PIGNONE - Massa (Italy), G.Nardoni, P. Nardoni, D. Nardoni - I&T Brescia (Italy) and L. Nottingham – Structural Integrity - U.S.A.
