MULTIELEMENT ULTRASOUND AND EDDY CURRENT INTEGRATED PROBE FOR NON-DESTRUCTIVE EVALUATION OF NUCLEAR REACTOR PRESSURE VESSEL HEAD PENETRATIONS

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ABSTRACT

An integrated combined UT (ultrasound testing) and ECT (eddy current testing) multielement probe prototype for inspection of gaps in nuclear reactor pressure vessel head penetrations (RVHPs) was numerically modelled, designed, assembled and tested in this work. The probe prototype consists of an acoustically active head and an acoustically passive body. The active part consists of an axial and a circumferential UT TOFD (time of flight diffraction) configuration pairs of central frequency of 6.2 MHz, of a normal beam 0° single element disc shape UT probe of central frequency of 2.25 MHz and a cross wound ECT probe. All these elements have been integrated in the polymer probe head of dimensions 29mm x 24.4 mm x 2.8 mm, with the OD (outer diameter) of 69.85 mm. The head is mounted on a flexible stainless steel probe body, able to follow the complicated structure of narrow gaps between penetration pipes and thermal sleeves. The prototype was assembled according to numerical optimizations results, and its electromechanical properties were tested on a stainless steel calibration block. The modelled and experimental results of electromechanical probe signals showed excellent agreement and all the artificially made indications on the calibration block were successfully detected and sized.

INTRODUCTION

Among compulsory activities for nuclear power plants inspections during regular and periodic outages prescribed by the standards, codes and regulations [1-3], it is of great importance to inspect the RVHPs. The penetration stainless steel pipes are mechanically expanded into the head and welded at the bottom (J-weld), see Figure 1.

A crack may appear in the heat affected zone of the weld and the space between the penetration pipe and the vessel head can, in such cases, be filled with water. Within the expanded penetration pipe, there is a thermal sleeve that protects the safety rods that control the nuclear reaction. Such a geometrical configuration creates a complex inspection environment, with a very narrow gap (3 mm – 9 mm) between the thermal sleeve and the penetration pipe, and the thin gap (filled with air, or with water in a case of a failure) between the penetration pipe, with the wall thickness of 15.9mm, and the reactor pressure vessel head. It is thus important to have a tool capable of inspecting the welds, the heat affected zones for cracks and the thin air gap for water leakage.

Figure 1. INETEC Lab RVHPs mock-up (welds, pipes and thermal sleeves configuration).
An inspection solution for such a configuration is proposed in this work – an integrated multielement probe consisting of a polymer probe head, a flexible probe body made of stainless steel and the probe connector with coaxial cables. The probe head contains two TOFD pairs of central frequency of 6.2 MHz, a normal beam probe of central frequency of 2.25 MHz, and a cross wound EC element. The flexible probe body houses the thin coaxial cables and the couplant, in this case water, supply. The design and construction procedure of this probe consisted of several steps: finite element modelling and theoretical optimization of the probe design, engineering of the acoustically active and passive materials, assembly, electronics engineering and the probe testing on a standard calibration block.

**FINITE ELEMENT MODELLING OF THE PROBE PERFORMANCE**

The theoretical modelling and optimization was performed within the PZFlex software package [4]. The software uses a finite element and wave – propagation analysis algorithms that are designed specifically for piezoelectric and ultrasound applications. In this work, the software was used for modelling of 6.2 MHz TOFD and 0° normal beam 2.25 MHz ultrasound probes with different designs and material properties in order to find the optimal configuration. The analysis model in this software package could be imported from a CAD format (Figure 2) or written in the PZFlex code. The second approach was finally applied in this work as it provided more options for user to configure different scenarios.

![Figure 2. CAD model of the integrated multielement NDE probe for testing of the penetration gaps: a) the polymer probe head containing active testing parts (piezoelectric elements in TOFD and normal beam configurations and an ECT element); b) the probe head mounted on a probe body made of a flexible stainless steel strip, able to bend and to follow the complex thermal sleeve-penetration pipe gap geometrical configurations.](image)

To perform the complete analysis of both axial and circumferential configurations of TOFD and of an additional zero degree probe, three separate models were created. Figure 3 shows the initial models of axial and circumferential ultrasound TOFD configurations, while Figure 4 presents the zero degree UT single element in the normal beam pulse-echo configuration. All three models are individual 2D projections in the same material body.

![Figure 3. 2D model of piezoelectric pairs in axial (a) and circumferential (b) TOFD UT configuration together with the pipe material (coloured in yellow) to inspect. The models were made by taking two perpendicular planar cross sections of the prototype probe head (Figure 2a). The blue areas are the polymer head housing cross sections.](image)
The model was set to run with different number of finite elements, excitation functions, boundary conditions etc. Setting all the input parameters correctly was generally the key to have comparable results with ones in real applications. Also, adding different electronic components in serial or parallel connections made the obtained simulation results significantly differ among themselves. Figure 6 shows a caption of a video in the user interface during a simulation. The video clips can greatly facilitate understanding of wave propagation in material and determine if the simulation procedure is converging in a desired direction.

In the PZFlex software package, the output results of the simulations can be specified by the user. In this work, the wanted output was the voltage amplitude as a function of time on the receive port of the TOFD pairs. In that way, the simulation results could be compared with the assembled probe measured signals in the experimental phase of the work. Another advantage of this theoretical approach is the modelling of different flaw indications in the inspected material and comparison of the results. In that way, the optimization of the probe for certain specific flaw indications is possible. Figure 6 shows the voltage resulting from an inspection of a healthy material, and Figure 7 shows the response of the probe positioned in front of an OD indication – in the latter case an additional reflection is visible if compared with the result in the Figure 6.

Figure 6. Receive port voltage signal of axial TOFD 6.2 MHz resulting from an inspection simulation by using a healthy testing material (no defects).
Figure 7. Receive port voltage signal of axial TOFD 6.2 MHz resulting from an inspection simulation by using a testing material with a small OD defect.

The goal of numerous simulations performed in this work was to determine the optimal materials for ultrasound wave’s excitation and for the backing material. Also, the angles and positions of the piezoelectric material were set to have better voltage responses regarding to different indication positions in the inspected material. The later experimental results showed very little difference from the simulated results. This modelling procedure has pointed to the main benefit of such an approach – reducing the invested time and resources during the development phase and speeding up to the final stage of probes construction and assembly.

PROBE ASSEMBLY

Several prototypes have been assembled in this work, as shown in Figure 8. Prior to the final assembly, the electrical and acoustical properties of the building parts, comprising piezoelectric elements, eddy current coils, backing materials, and polymer housing, were characterized. Figure 9 shows, as an example, the frequency dependence of the electrical impedance of the coils in the cross wound ECT element. It can be seen that the properties of both the element coils tested were identical, which is a confirmation of the precision of the construction of the ECT element in the probe. The spring system holding the polymer head to the stainless steel housing was specially designed to cover the testing in the gaps of 2 mm to 9 mm width. In this interval the spring holds the polymer head tightly adjusted to the wall of the penetration pipe – there is no lift-off. The water supply was made by a polymer tube to be used as an ultrasonic couplant. The stainless steel body of the probe was made to be flexible enough to bend and to follow the configuration of the thermal sleeve and the penetration pipe system, see Figure 1.

Figure 8. Assembled prototypes of the integrated multielement UT/ECT probe.
PROBE PERFORMANCE TESTING

A common procedure for testing ultrasound and eddy current NDE transducers is performed by using standard calibration blocks. A CAD design of such a calibration block is shown in Figure 10. One can see the axial and circumferential artificially made cracks that are suitable for testing of the UT TOFD and ECT techniques, as well as the abrupt block thickness change, that is convenient for the testing of the normal beam 0° UT transducer.

The experiments were performed on the block by using a ZETEC Tomoscan III commercial NDE pulser-receiver, accompanied by TomoView 2.29 software package for the pulser-receiver control and signal acquisition and analysis. Figure 11 shows representative A and B scans for axial TOFD, circular TOFD and 0° normal beam scanning of the calibration block, that were chosen from the set of the experimentally obtained results. The comparison of the measured results with those obtained by modelling in the PZFlex showed excellent agreement (see Table 1).

![Figure 9. Measured frequency dependence of the electrical impedance for the two coils used in the cross-wound eddy current element.](image)

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Table 1. Comparison of the notches and thickness sizing results, obtained by modelling in the PZFlex software package (“modelled size” column) and measurements by a fully assembled probe prototype (“measured size” column), with the real sizes on the calibration block (“actual size” column). The “shooting direction” column displays the direction of the testing ultrasound beam for each measurement.

CONCLUSIONS

NDE inspections in nuclear power plants can get really challenging when it comes to testing of complex geometrical configurations such as the gap between the thermal sleeve and the penetration pipe in the nuclear reactor pressure vessel head, as discussed here. Such places call for somewhat non-orthodox NDE tools. Such a tool has been presented in this work – an integrated combined UT and ECT multielement probe prototype was modelled, designed, assembled and tested. The probe prototype acoustically and electrically active part consists of several important and independent elements: an axial and a circumferential UT TOFD configuration pairs, a normal beam disc shape UT probe and a cross wound EC probe.
Those elements have been integrated in the acoustically and electromagnetically transparent polymer probe head and mounted on a flexible stainless steel probe body that is able to follow the complicated geometrical structure in question. The UT TOFD elements were designed by using specifically made composite piezoelectric elements utilized as ultrasound signal generators and receivers, additionally backed with special acoustic polymer-metal powder mixtures in order to produce the ultrasound testing signals of high quality. The pulse duration of the signal for the TOFD pairs was measured to be 0.5 µs, the bandwidth 71% and signal-to-noise ratio 40:1. For the normal beam single element, a classic commercial PZT piezoelectric disc was used, together with the specially made backing to reduce the ringing, and the pulse duration of the signal was measured to be 1.6 µs, the bandwidth 48% and signal-to-noise ratio 8:1, which was more than enough to have high quality testing signals. The modelled and the experimental results of electromechanical probe signals, when finally compared, showed an excellent agreement and all the artificially made indications on the testing calibration stainless steel block were successfully detected and sized. This probe has a very high commercial potential.

REFERENCES

2) ASTM Guidelines for Evaluating Characteristics of Ultrasonic Search Units, Designation: E 1065-08
3) EN 12668-2, Non-destructive testing – Characterization and verification of ultrasonic examination equipment – Part 2: Probes