HIGH TEMPERATURE TRANSDUCERS SYSTEM FOR LONG RANGE ULTRASOUND NON-DESTRUCTIVE EVALUATION IN AGING POWER PLANTS

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ABSTRACT

Majority of the current nuclear plants reactors are either close to the end of their 40-years operating license, or already entering a granted extension period. Operators perform expensive refurbishments to address the security and economical soundness of keeping the plants running until they reach 80 or more years. It will most probably be essential to have preventive in-situ continuous structural health monitoring techniques for aging plants. A powerful such tool is high temperature ultrasonic guided waves (UGW) for monitoring the plants pipework. A high temperature lithium niobate piezoelectric shear mode UGW transducer operating at 600°C has been developed and tested in this work. The electromechanical parameters of the transducer have been experimentally investigated as functions of temperature. The flaws detection capability of UGW in steel pipes at elevated temperatures has been studied using finite element analysis. The decreased transducers signals at elevated temperatures have been tackled by advanced signal analysis that has been done through pre-processing techniques, such as pattern recognition, along with signal focusing algorithms.

Keywords: high temperature ultrasound, aging nuclear power plants

1. Introduction

The recent accident in the Fukushima nuclear power plant has made governments all over the world re-discuss and re-evaluate the safety procedures and regulations for their nuclear power plants. The outcome of those re-evaluations is not yet precisely defined – nevertheless the final solution should not neglect that there is a non-negligible amount of data showing that failures and accidents in NPPs become more probable as the plants age. A large portion of active NPPs in the world are close to the end of their operating license, which is generally 40 years. The economically sound solution seems to be granting the license extensions and increasing the safety levels by additional inspection and repair activities. A continuous online monitoring of the structural health monitoring of such facilities and incorporated logic for prediction (modelling) of transient failures/cracks behaviour turns out to be one of the most prospect tools [1]. For such a solution one has to have a system that is functional and resistant to harsh working environment of NPPs. For an ultrasound monitoring system the high operating temperatures are one of the key
obstacles to overcome, due to generally low Curie temperatures of commercially available piezoelectrics and to weak ultrasound reception capability of piezoelectrics at high temperatures. The work presented here is an on-going development of a long range ultrasound testing (LRUT) system for NDE of NPP piping at operating temperatures.

2. High-temperature UGW propagation modelling

The behaviour of the ultrasonic guided waves (UGW) for the LRUT at room temperature, 260°C and 595°C Celsius was modelled in this work. Frequencies varying between 10-200 kHz were investigated. Steel pipes are ideal for application of guided ultrasonic waves as they require an elongated medium to propagate – the wave propagation is not dependent only on the material from which the pipe has been manufactured but also on the size and thickness of the pipe. The pipe studied was 8 inches, ANSI Schedule 40. Calculation of dispersion curves for three temperatures (room temperature, 260°C and 595°C) has been carried by using literature available material data for steel. Three wave modes have been selected: L(0,1), identified as a candidate during the preliminary investigation, L(0,2) and the torsional vibration mode T(0,1) (Fig. 1). The transient analysis simulations were performed using the same pipe material and geometry as for the dispersion curves calculation. The crack was selected to be 1mm wide and for practical reasons covering 90 degrees of the circumference. Different frequencies have been investigated (60kHz, 100kHz, 150kHz, 200kHz). The excitation was applied axially on 32 points equally distributed in the circumference of the pipe (configuration of transducers in the UT collar).

Fig. 1: Dispersion curves generated for 8 inches pipe at 260°C and 595°C. Further material data for different Poisson’s ratio was also calculated to investigate impact of Poisson’s ratio to the dispersion curves.

The torsional (shear) mode T(0,1) was finally selected to be exploited in the transducers design due to its non-dispersive behaviour throughout the frequency range of interest.

3. High-temperature ultrasound shear wave piezoelectric transducers

Lithium niobate was selected for development of high temperature transducers. The high temperature piezoelectric properties of the LiNbO$_3$ were studied previously – it was observed that the samples retained its piezoelectric properties at up to 600°C [2,3]. Performance of the transducer was examined by pitch-catch experiments taken at ambient (20°C) and high temperatures (up to 600°C). The LiNbO$_3$ samples were used with dimensions of 13mm x 3mm x 0.5mm, and gold coated on both sides of the length-width plane. The samples were placed in a specially designed sample holder inside a furnace. The high temperature impedance measurements were sequentially performed in 50°C intervals beginning at 50°C up to 600°C.
The characteristic frequencies, capacitance, density and dimensions of samples were used to calculate the dielectric, elastic and piezoelectric coefficients. Subsequently, complete high-temperature prototype transducers were manufactured and tested ultrasonically up to 600°C. This was carried out on a steel rod at 70 kHz. Fig. 2a shows the temperature dependence of the piezoelectric coefficient $d_{15}$. The increase of $d_{15}$ from 350°C to 600°C means that the transmission quality of the material should improve. Fig. 2b shows the temperature dependence of the piezoelectric coefficient $g_{15}$. The decrease of $g_{15}$ from 350°C to 600°C means that the reception quality of the material should deteriorate.

The transmission and reception quality of the transducer up to 600°C was measured using a pitch-catch set-up. A 1.5m long square steel bar (12mm²) was used as the wave guide. On one end a PZT element was permanently fixed on to bar, and the other end was placed inside the furnace. The peak-to-peak amplitude value of the fastest arriving wave mode was used as an indication of transducer’s performance. Measurements were taken from room temperature (20°C) up to 600°C, at 50°C intervals (Fig. 3). Fig. 4 shows the average transmission and reception quality of lithium niobate LRUT transducer at up to 600°C. In reception mode, a significant decrease can be observed between 200°C to 400°C, but from 450°C it starts to improve and at 600°C it reaches a similar performance in reception quality as was observed at ambient temperatures. This behaviour could be due to the assembly procedure. The transmission quality is lower than the reception quality at ambient temperature, but between 250°C and 450°C the reception quality is lower than transmission quality. In the transmission mode the transducer is relatively stable between 20°C and 600°C.
Fig. 3: The measured reception and transmission transducer signals at 20°C and 600°C – the transducer is operational at 600°C, with an observable decrease in peak-to-peak amplitude.

Fig. 4: The average transmission and reception quality of lithium niobate LRUT transducer at up to 600°C.

4. **Signal analysis algorithms**

For the purposes of the demanding flaw detection task, advanced signal processing techniques were developed and integrated, such as normalization, signal smoothing, correlation, baseline subtraction, feature extraction, selection and classification based on Support Vector Machines. For the training and validation of the system, an extensive experimental investigation was carried out on different experimental setups. The results (Fig. 5) show that the proposed method is able to effectively detect flaws under various temperature conditions and experimental scenarios.
Fig. 5: The output of the proposed signal processing module for a pipe at 250°C with a 9% Cross Section Area (CSA) weld defect and a graph indicating the weld defect location in the pipe.

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