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Original Article

Simulation Based Investigation of Focusing Phased Array Ultrasound in Dissimilar Metal Welds

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ABSTRACT

Flaws at dissimilar metal welds (DMWs), such as reactor coolant systems components, Control Rod Drive Mechanism (CRDM), Bottom Mounted Instrumentation (BMI) etc., in nuclear power plants have been found. Notably, primary water stress corrosion cracking (PWSCC) in the DMWs could cause significant reliability problems at nuclear power plants. Therefore, phased array ultrasound is widely used for inspecting surface break cracks and stress corrosion cracks in DMWs. However, inspection of DMWs using phased array ultrasound has a relatively low probability of detection of cracks, because the crystalline structure of welds causes distortion and splitting of the ultrasonic beams which propagates anisotropic medium. Therefore, advanced evaluation techniques of phased array ultrasound are needed for improvement in the probability of detection of flaws in DMWs. Thus, in this study, an investigation of focusing and steering phased array ultrasound in DMWs was carried out using a time reversal technique, and an adaptive focusing technique based on finite element method (FEM) simulation. Also, evaluation of focusing performance of three different focusing techniques was performed by comparing amplitude of phased array ultrasonic signals scattered from the targeted flaw with three different time delays.

1. Introduction

Dissimilar metal welding (DMW) is used to join stainless steel components to steel tubes in power plants. In particular, in nuclear power plants, DMWs are used in major components such as CRDM, BMI, and inlet and outlet nozzles, etc. However, primary water stress corrosion cracks (PWSCCs) have been found in DMW areas of major components in nuclear power plants. Also, Bamford and Hall [1] reviewed and compared the behavior of weldings as opposed to base metal, from the

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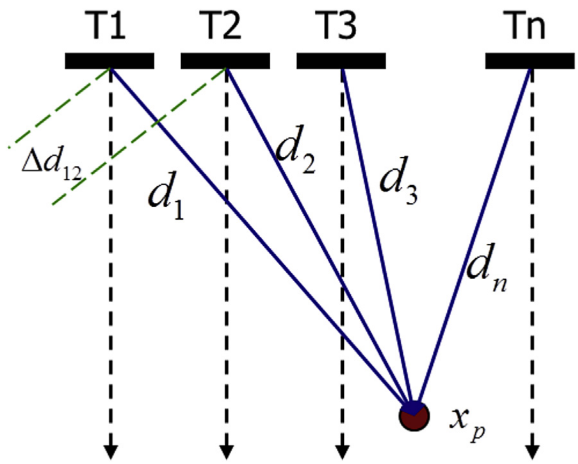

Fig. 1 – Geometry of the phased array used in deriving the focusing formula.

standpoint of time to crack initiation, growth rate of cracks, and their impact on structural integrity of nuclear power plants. Other researchers indicated that under some conditions the flaws found may lead to rupture before detectable leakage [2]. Thus, detection of PWSCC in DMWs is one of the major issues for ensuring safety of nuclear power plants. Currently, phased array ultrasound is widely used for PWSCCs and surface breaking cracks in the nuclear power plants. However, inspection of DMW using phased array ultrasound has a relatively low probability of detection of cracks, because the crystalline structure of welds causes distortion and splitting of the ultrasonic beams which propagates anisotropic medium [3]. Therefore, advanced evaluation techniques of phased array ultrasound are needed to improve the probability of detection of flaws in DMWs. Many studies have therefore been reported on DMW modeling and phased array focusing techniques to improve flaw detectability. Several studies have simulated the ultrasonic beam propagation in DMWs using an analytical method called the Athena and Mina code [4–8]. Also, Ye et al [6,7] present a model for predicting the ultrasonic beam propagation in DMWs using a modified Ogilvy's model. Other studies have simulated the ultrasonic beam propagation in DMWs using a numerical method which utilizes finite element method (FEM) software [9–11]. In order to have precise inspection of a DMW, focusing techniques of phased array ultrasound are needed to improve the probability of detection of flaws in DMWs. Recently; many studies have investigated focusing techniques using phased array ultrasonic testing. Among focusing techniques, adaptive focusing techniques and time reversal techniques are widely used to calculate time delay for focusing in anisotropic inhomogeneous materials. But these studies are limited by relative results only. Thus, in this study, a FEM model based investigation of focusing and steering ultrasonic beams in DMWs through understanding of propagation of ultrasonic waves in anisotropic inhomogeneous medium was performed. Also, the focusing performance of adaptive focusing, time reversal, and conventional techniques in the DMWs are compared.

2. Methods

2.1. *Focusing techniques*

2.1.1. *Conventional focusing techniques*

A phased array transducer consists of individual elements that are composed of piezoelectric crystals. To focus the phased array ultrasonic beam, time delays are applied to the array elements. In order to determine the time delay, the distance of each element to the focal spot should be identified. Fig. 1 shows a schematic diagram of the conventional focusing technique. T_1, T_2 and T_n in Fig. 1 indicate phased array elements which generate an ultrasonic beam. Then, the time delay can be determined using Equations 1 and 2.

$$P_{t_n} = Ae^{ikd_n}e^{-i\omega t} \tag{1}$$

where, P_{t1}, P_{t2}, and P_{tn} are radiated sound pressure by the n-th phased array elements (T_1, T_2 and T_n) at the interrogation point (x_p), as shown in Fig. 1. A is the input amplitude from the phased array elements; d_1, d_2 and d_n are the distances between the phased array element and the inspection point. For phase matching at point x_p, sound pressure which is T_1 and T_2 need to match using Equation 2. Δd_{12} is the gap between d_1 and d_2, C is the sound velocity of the material, and Δt_{12} is the time delay. Then, radiated sound pressure can be matched by adding a time delay, defined in Equation 3.

$$\exp[ikd_1] = \exp[ikd_2]\exp[ik\Delta d_{12}] = \exp[ikd_2]\exp[i\omega\Delta t_{12}] \tag{2}$$

$$\Delta t_{12} = \frac{\Delta d_{12}}{C} \tag{3}$$

2.1.2. *Adaptive focusing techniques*

The adaptive focusing technique is a time delay estimation method based on cross correlation. Cross correlation is widely used to determine the time delay through various received signals. One can calculate time delay using cross correlation between two signals acquired by two elements. Time delay can be rapidly detected and quantified using a cross correlation between each received signal, where the cross correlation function between received signals S_1 and S_2 is

$$\Delta t_n = \sum_{n=1}^{N} \max\left(\sum_{0}^{t} S_{n+1}(t-\tau)S_n(t)\right) \tag{4}$$

From each correlation function, we estimate the time delay that is obtained from the conventional cross correlation method.

For calculating the cross correlation between each received signal shown in Fig. 2A, the maximum value of the cross-correlation function indicates the point in time where the signals as best aligned, as shown in Fig. 2B.

2.1.3. *Time reversal focusing techniques*

The time reversal technique is a time delay estimation method that can be used in ultrasonic testing to improve flaw detection through anisotropy and inhomogeneous material such as DMWs. Among the techniques, the DORT method (French acronym for decomposition of the time reversal operator) is applied in this study. First, received signals are measured by