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Finite Element Simulations to Predict Probability of Detection (PoD) Curves for Ultrasonic Inspection of Nuclear Components

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Abstract

Nondestructive evaluation (NDE) methods for the qualification of structures in the nuclear industry are required to perform to very high standards of reliability, and hence, establishing the performance capabilities of inspection techniques is of utmost importance. The Probability of Detection (PoD) curve method has emerged as an important tool for the assessment of the performance of NDE techniques, in general. However, the conventional experimental means of generating PoD curves is very expensive, requiring large experimental data sets covering different defects as well as a range of test conditions, plant shut-down and also operator time. Several methods of achieving faster estimates for PoD curves using physics-based modelling have emerged to address this problem. However, most theoretical models remain limited to a small number of materials or defect types: thus numerical modelling techniques are very attractive, especially given the ever increasing computational power available to scientists today.

This paper reports the feasibility of using Finite Element (FE) simulations to augment sparse measurements made using experiments, and predict PoD curves for ultrasonic inspection of stainless steel plates and welds. PoD curves are obtained for the case of conventional (bulk P and SV wave) ultrasonic pulse-echo inspection of surface-breaking longitudinal notches in Stainless Steel plates. The main parameters affecting the uncertainty in practical ultrasonic inspection are identified and combinations are achieved, assuming each of them varies according to a normal distribution. FE simulations are performed for each combination of parameters, viz. frequencies, wedge angles, notch dimensions, and the amplitudes of scattered UT signals so predicted are used to generate the PoD curves. The results are compared against trial experimental measurements. Approach towards generating the POD curves for ultrasonic inspection of thick austenitic stainless steel welds will be discussed.

Peer-review under responsibility of the Indira Gandhi Centre for Atomic Research

Keywords: Ultrasonic testing, Stainless Steel plates, FE simulations, Reliability, Probability of Detection (PoD)

1. Introduction

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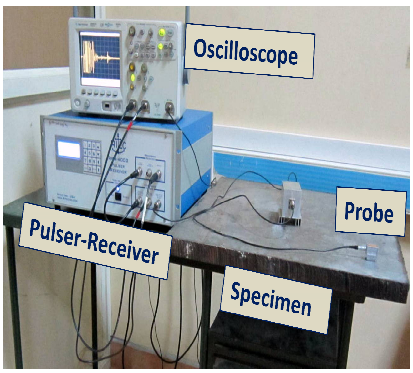
Robust and reliable Nondestructive Testing (NDT) procedures are crucial for ensuring the structural integrity of components in the nuclear industry, where safety is of paramount importance [1]. Thus, many techniques for the estimation of the reliability of NDT methods have been developed over the years, and the Probability of detection (PoD) curve method is today widely used. The PoD capability of a given NDT method is defined as the probability of the method in detecting a flaw of specific type and size [2]. PoD curves are plotted in terms of characteristic dimensions of the defect (depth, length, orientation, etc.) and are dependent on a number of factors including material, geometry, defect type, operator and environmental effects [3]. The generation of PoD curves requires a large amount of experimental data which in turn is often expensive, as experimentation requires plant shut-down and operator time. In this respect the use of simulation to reduce experiments is attractive. The work reported here seeks to study the feasibility of using finite element (FE) simulations to generate PoD curves for ultrasonic pulse-echo inspection of surface breaking notches in thick Stainless Steel plates.

In the work presented here, the angle beam technique (using a 45° L-wave probe in pulse-echo mode) widely used in conventional ultrasonic NDT is considered. For the simulations, the commercial FE package ABAQUS (v6.9, [4]) is used. This paper is organized as follows. Firstly, Description and details of the specimen used and the trial experiments to acquire the parameters for simulation are given, followed by a presentation of simulation results and the process for PoD curve generation. After a discussion on results of the simulation and comments upon the PoD curve generated through simulations, experimentally obtained PoD curves are used for validation. The results are discussed after which the paper concludes with directions for further work.

2. Trial Experiments

The considered material is an AISI 430 Stainless Steel with measured longitudinal wave speed V_L=5725m/s and shear wave speed V_T=3165m/s. The photograph of the experimental setup and schematic diagram of the specimen are shown in the Figure1 (a) and (b) respectively.

(a)



(b)

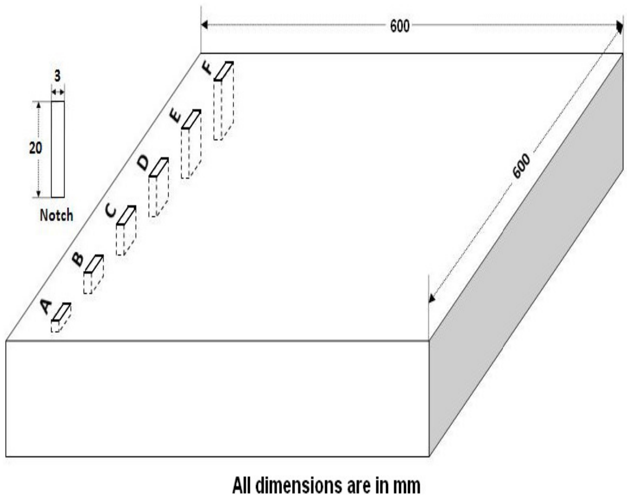


Fig.1: (a) Photograph showing the experimental set-up.; and (b) Schematic diagram of the Specimen

Rectangular notches of six different heights (10%,20%,30%,40%,50% and 60% of the plate thickness, respectively) were machined on the bottom surface of the plate using the Electric Discharge Machining (EDM) technique. The notches were each of 20 mm length and 3 mm width. The notches were located 50 mm away from one end of the plate. The dimensions of the notches are highlighted in Table 1 below.

TABLE 1. Dimensions of the notches machined in the specimen sample

Notch No.	Height [mm]	Length [mm]	Orientation
A	2.8	20	Vertical Surface breaking
B	5.6	20	Vertical Surface breaking
C	8.4	20	Vertical Surface breaking
D	11.2	20	Vertical Surface breaking
E	14.0	20	Vertical Surface breaking
F	16.8	20	Vertical Surface breaking

Trial experiments were performed on the maximum height notch (Notch F) using 45° L-wave probe with center frequency of 2 MHz. The probe was coupled to the plate by using a commercial ultrasonic couplant gel. Based on the maximum amplitude of the defect response signal, the probe position from the notch was noted. A maximum of 25 trials of testing were performed and the corresponding probe positions from the notch were noted. All the experimental tests were carried out by the same operator, and in the same environmental conditions.

3. Finite Element Simulations

3.1 Modelling

The commercial Finite element (FE) analysis package ABAQUS [4] was used to model the wave propagation in the specimen. 2D plane strain models were created for the analysis and the plate was modeled with the properties of AISI 430 Stainless Steel. Linear quadrilateral elements were used and the mesh size was taken as λ/20, sufficiently fine to satisfy the convergence criterion for wave propagation problems [5]. A 5-cycle Hanning windowed toneburst with center frequency 2 MHz was given as a nodal force to achieve wave excitation. The time step was used as $\Delta t=0.8\Delta x/C_{max}$ where Δx is the size of the smallest element in the model and C_{max} is the fastest mode velocity in the model [5]. In addition to this, Absorbing Layers with Increasing Damping (ALID) were incorporated in the side walls of the model to minimize side wall reflections [5]. The absorbing region is divided in to sub-layers with one-element thickness. These sub-layers are made of materials with the same material properties as the model region, except from having a gradually increasing material damping.

3.2 Distribution in Parameters

PoD curves are based on the statistical distribution of defect responses which is controlled by many factors such as material, geometry, defect type, instrumentation, operator, etc. related to the NDT procedure. Simulations usually do not provide information about such variabilities in experimental results, because they are performed considering ideal conditions. To simulate the effect of variability factors in the models, the possible sources of variability have to be considered. Here for simplicity, the sources of variability considered are: probe position relative to the notches, the angle between the incident wave and notch, and the center frequency of the incident signal. All three parameters are assumed to be independently normally distributed. The probe position is assumed to have a mean value where maximum signal response is obtained for each notch case, with standard deviation of 1 mm. The wave angle is assumed to be normally distributed with mean equal to the ideal value of the wave angle i.e. 45° with standard deviation of 1°. The center frequency is assumed to be normally distributed with mean equal to ideal value of the probe frequency i.e. 2 MHz with standard deviation of 0.2 MHz. Appropriate random numbers were generated for several combinations of these parameters using the MATLAB software package (vR2009a, [6]). Thus 10 combinations of sources of variability were achieved, with 10 simulations for each notch configuration leading to 60 simulations in total. The resulting large number of simulations was performed with the help of a script created using the Python platform [7]. This script completely automates the simulations including post processing operations such as accessing the output data base and saving the results in separate folders, etc. At the end of all the simulations, the obtained scatter plot of defect responses is used to derive the PoD curve. The parameters and the properties used in the FE simulation are shown in Table 2. The vertical displacement at the monitoring point is taken as the signal output. The snapshots from the FE simulation at different time instances are presented in Figure 2.

TABLE 2. Parameters used for plate model

Sl No	FE Parameter	Plate
1	Length of the plate model	75 [mm]
2	Thickness of plate model	28 [mm]
3	Material density	7800 [kg/m$^{3]}$
4	Young's modulus	200 [Gpa]
5	Poisson's ratio	0.28
6	Element type	Linear quadrilateral
7	Element size	λ/20 (20 elements per shear wave length)
8	Center frequency	Mean = 2 [MHz] Standard Deviation = [0.2 MHz]
9	Wave angle	Mean = 45° Standard Deviation = 1°
10	Probe position	Mean = 22 [mm] Standard Deviation = 1 [mm]
11	No of simulations	10 per notch

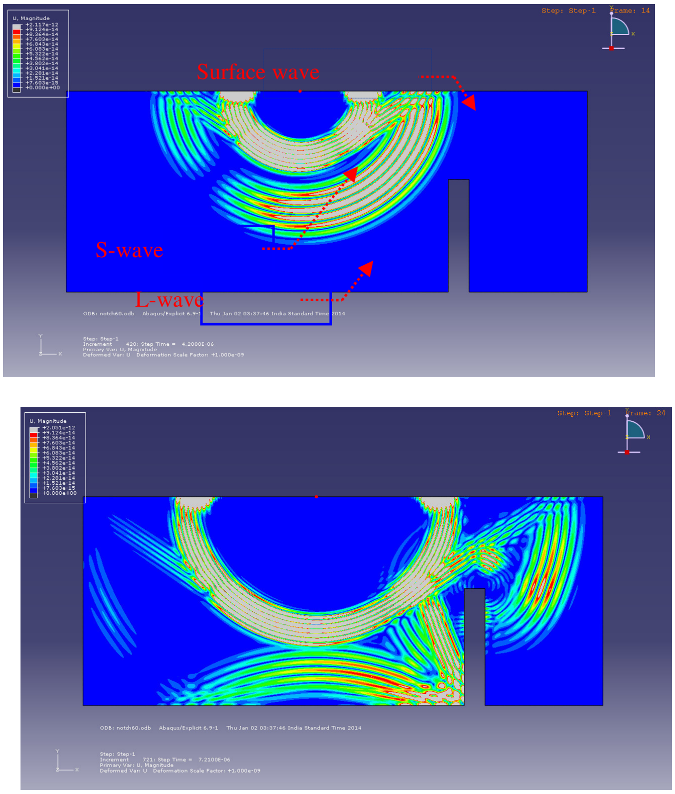


Fig.2 Snapshots of the contour of displacement magnitude at different time instances from the FE simulation:
(a) Shows the various components of wave. (b) Shows the diffracted lateral wave signal from notch tip and the interaction of ultrasonic wave with the notch corner.

4. Experiments

Experiments were performed on the six bottom surface breaking notches by using ultrasonic pulse-echo technique. A 2 MHz Plexi-glass wedge probe excited by a Hanning windowed toneburst is placed over the top surface of the Stainless Steel plate on a perpendicular line bisecting the notches. The signals reflected from the notches were averaged using 512 ensembles for each measurement. Also, ten measurements were taken for each notch height case, in order to account for the uncertainties. The amplitudes of the Hilbert envelopes over the defect response signals were taken with the help of MATLAB [6] and used for the PoD curve generation.

5. Generation of PoD Curve

The PoD is formally represented as a function of the flaw size. The most commonly used function is a cumulative log-normal distribution function [8]. A typical POD curve, as observed in previous work, is shown in Figure 3(a). As discussed in literature [8,9], the signal response ($\hat{a}$ versus *a,* where $\hat{a}$ is the response from the defect and *a* is defect size) analysis method uses a measured value $\hat{a}$ to correlate with real defect size *a* quantitatively as shown in Figure 3(b).

The relation between '$\hat{a}$' and defect length (or depth) '*a*' is correlated as [9]:

$$\ln(\hat{a}) = \beta_0 + \beta_1 \ln(a) + \delta \tag{1}$$

where, $\ln(\hat{a})$ is the relative measured value of the defect signal response, $\ln(a)$ is the relative value of the defect size, and δ is the random error and it follows a normal distribution with zero mean and constant standard deviation σ_δ. Based on the log-log plot of the defect response scatter, the values of β_0, β_1 and δ are determined by means of linear regression.

In signal response analysis, the defect is detected if the $\hat{a}$ exceeds the predefined decision threshold $\hat{a}_{th}$. The PoD can be generated, for each notch, calculating the probability of the signal response exceeds the decision threshold. It can be written as (see [8,9] for more details),

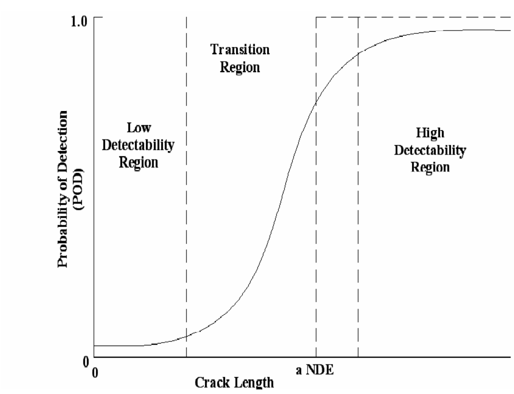
$$\text{PoD}(a) = \text{Probability}\left[\ln(\hat{a}) > \ln(\hat{a}_{th})\right] \tag{2}$$

$$\text{PoD}(a) = 1-\Phi\left[\frac{\ln(\hat{a}_{th}) - (\beta_0+\beta_1\ln(a))}{\sigma_\delta}\right] = \Phi\left[\frac{\ln(a) - \frac{(\ln(\hat{a}_{th}) - \beta_0)}{\beta_1}}{\frac{\sigma_\delta}{\beta_1}}\right] \tag{3}$$

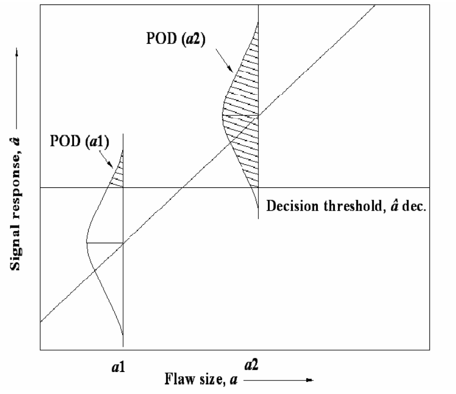
Equation (3) is acumulative log normal distribution function with mean μ and standard deviation σ given by:

$$\mu = \frac{(\ln(\hat{a}_{th}) - \beta_0)}{\beta_1} \tag{4}$$

$$\sigma = \frac{\sigma_\delta}{\beta_1} \tag{5}$$



(a)



(b)

Fig.3 (a) Typical POD curve for conventional amplitude based ultrasound inspection [10].
(b)Typical Schematic of POD (a) calculation from $\hat{a}$ versus a relation [10].

6. Results

The results of the FE simulations contain the reflected signals from the notch corner, diffracted signals from notch tip and bottom surface reflections. Typical output signal from the simulations is shown in Figure 4. The lateral wave reflection from the notch corner was considered for PoD curve generation. The linear regression analysis on the log-log scatter plot of the defect response signals from both simulations and experiments were performed by using MATLAB [6], and are shown in Figures 5 and Figure 6 respectively. The values of β_0, β_1 and δ were determined from the regression analysis. Determination of the decision threshold plays a vital role in PoD curve generation, which will greatly affect the PoD values. In this present work, the lowest of the mean of defect response signals was taken as the decision threshold. The obtained PoD curves through simulations and experiments are shown in Figure 7.

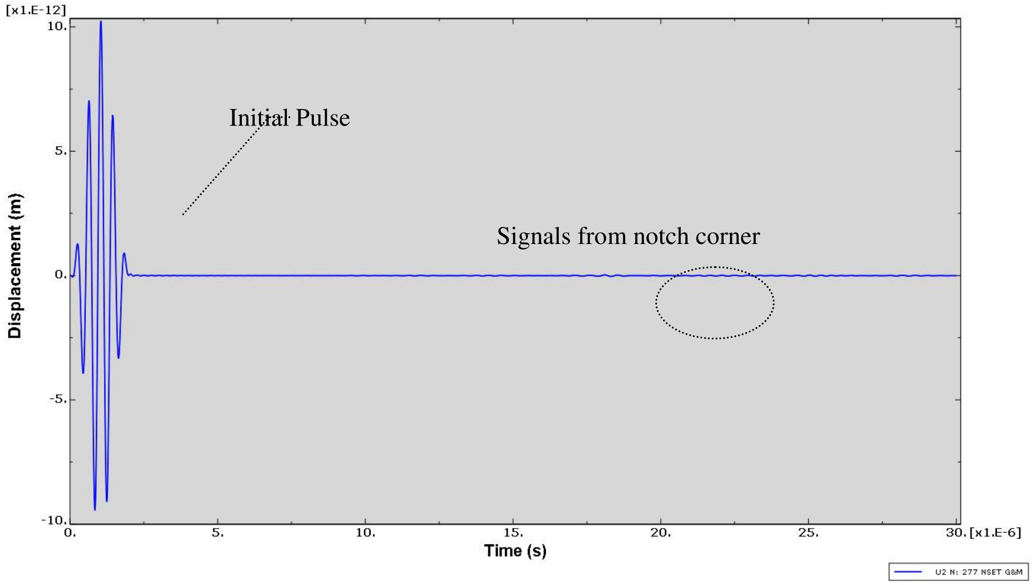


Fig.4 Time-trace (A scan) plots monitored at the excitation position.

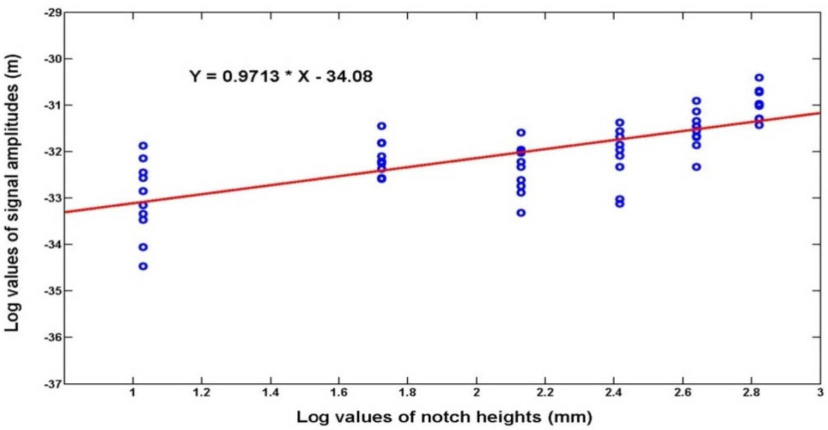


Fig.5 Linear regression plot over the defect response signals from simulations.

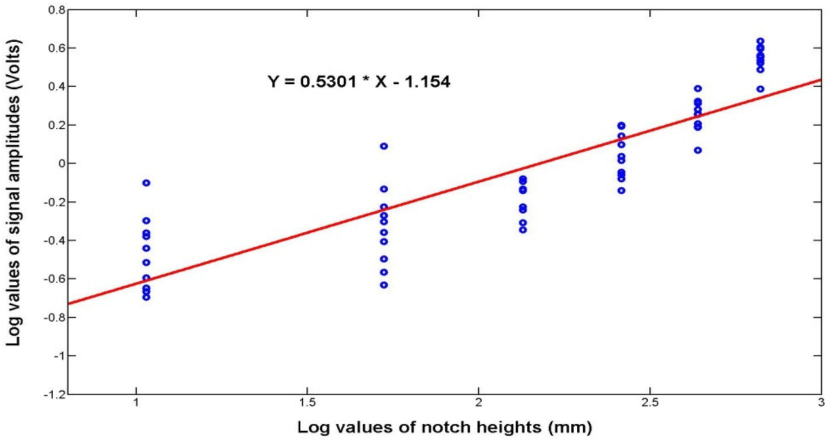


Fig.6 Linear regression plot over the defect response signals from experiments.

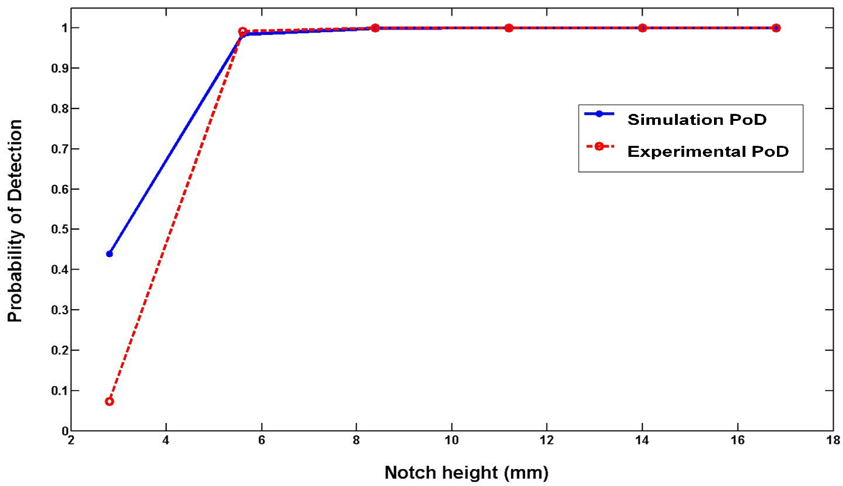


Fig.7 PoD curves generated through simulations and experiments.

7. Discussion

It is observed from Figure 7, that as to expected, the probability of detection increases with an increase in notch height. The PoD curves predicted by the FE simulations agrees well with those from experiments for notches having height more than 20% of the specimen thickness, thus demonstrating the promise of simulations for PoD characterization. However in the crucial defect height range of 0-20% there is a mismatch in the predictions. This is perhaps because the uncertainties for the parameters assumed in the FE simulation are not able to capture those in the experiments, for smaller notches. Moreover, some finer details such as noise sources which reduce the amplitude of measured reflection, and wave generation and reception conditions in experiments need to be incorporated in simulations. Further work for obtaining more accurate representation and bounds for parameter uncertainties is ongoing, and this will help in improving the FE-based PoD predictions.

8. Conclusions & Future work

Conventional pulse-echo inspection of Stainless Steel plates having surface breaking notches on the bottom surface was simulated using 2-D finite element analysis. By considering the sources of variability to include the effects of real time variations in the experiments, the PoD curve was generated through the simulation results, and comparison also made with the experimentally obtained PoD curve. The results demonstrate the potential for simulations as important tools for complete practical PoD characterization of NDT techniques and defect types. Further work is necessary to fully clarify on the choice and bounds for uncertainties assumed in the simulations.

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