Ultrasonic Pipe Inspection with Conventional Transducers or Phased-Arrays? A Comparison Based on POD-Analysis Can Help

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Abstract
For automated online inspection systems used in industrial applications the inspection speed is one of the major parameters to focus on. Phased-array applications, compared to conventional transducer arrangements, are quite promising, because it is possible to substitute the information obtained via a set of different incidence angles by one sector scan. However, possible advantages in view of inspection time obtained by using more recent inspection techniques have to be crosschecked with regard to the performance of these techniques to detect certain types of defects and defect sizes, respectively.

In this contribution, the results of a POD-analysis comparing conventional transducer arrangement versus a phased-array set-up will be presented. For the experimental part, a test pipe (ferritic steel) with a series of artificial defects with varying dimensions has been prepared. Ultrasonic data has been recorded with an automated scanning system for both applications, conventional and phased-array. The maximum indication amplitudes are used to calculate the Probability of Detection (POD) via an “a versus a”-analysis. This paper provides examples of the POD-calculations, where not only the “mh1823”-software according to MIL-HDBK-1823 has been used, but also POD evaluation software specifically developed at Fraunhofer ITWM. The results for both ultrasonic techniques are compared and are discussed with regard to the practical industrial application.

Keywords: Probability of detection (POD), phased array, large diameter line pipes, pipe end inspection, steel pipe

1. Introduction

Large diameter longitudinally welded line pipes have to follow increasing technical requirements in order to guarantee best performance during usage in oil and gas industry. Quality control incorporates several automated NDT systems. At our pipe mill EUROPIPE in Mülheim, Germany, the pipe end is inspected by an automated ultrasonic inspection system for the detection of laminations and longitudinal defects in combination with a magnetic particle (MP) testing of the bevel. Figure 1 shows the situation in the mill, Figure 2 the probe holder of the UT system. Two inspection cabins, each of them comprising the two inspection techniques are applied to the pipe, which is rotating in a fixed position, while UT and MP data are recorded simultaneously.

Figure 1. Location of pipe end inspection at EUROPIPE pipe mill in Mülheim, Germany
The complete ultrasonic module of the system has been recently exchanged by a new system provided by Salzgitter Mannesmann Research in Duisburg, Germany [1]. The former system was based on conventional single-element transducers, while the new system incorporates multi-element transducers with overlapping triggering for longitudinal defect testing and a 128 element phased-array transducer for lamination testing. For the contents of this paper, we will concentrate on the phased-array part of the UT system. By using the Probability of Detection analysis based on an “a versus â” representation the performance of the old and new system will be compared quantitatively.

2. Probability of Detection

The experimental determination of POD curves requires well-defined inspection of appropriate test specimens. Here, not only the defect size to be detected is of importance, but also the material properties and the geometry of the components to be inspected. The POD curve (in this study determined as a function of defect size a) together with the relevant confidence intervals provides the defect size, which can be detected with a ‘reasonable’ probability. The principal shape of the POD curve shows that the Probability of Detection increases with defect size. At the size $a_{90/95}$ the lower 95% confidence bound hits the 90% POD level. The size $a_{90/95}$ is usually considered to be the securely detectable defect size in view of the requirements of component integrity [2].

For POD determination using an ‘a versus â’-analysis test specimens supplied with model defects of different size are employed. In the inspection, a defect of size ‘a’ generates a signal of amplitude ‘â’, which is interpreted as a ‘hit’, if it exceeds the decision threshold value $\hat{\alpha}_{\text{dec}}$ (e.g. 6 dB above noise). Assuming a specific statistical distribution of the measured data the resulting ‘a versus â’ diagram can be transferred into a POD curve. The procedure described in MIL-HDBK-1823 uses the assumption that the signal amplitudes show a statistical normal distribution with constant variance. Also, a linear functional relation between amplitude â and defect size a is assumed [2]. To overcome those limiting assumptions, at Fraunhofer ITWM a model has been employed and modified which does not have to rely on these two assumptions [3]. In this model, the initially ‘undisturbed’ defect signal amplitude $S_0$ finally results in the measured signal amplitude $S(=a)$ by being overlaid with a Rayleigh-type noise distribution,
thus the signal distribution being of Ricean type (Figure 3). The variance $\sigma_0$ will be extracted from experimental data, see Chapter 4.

![figure 3](image)

**Figure 3.** Schematic representation of the calculation procedure for POD and PFI in the ITWM-model. The threshold $T$ corresponds to $\tilde{a}_{de}$.  

### 3. Experimental Setup

A test ring cut from an original pipe of dimension $1066 \times 29.6$ mm (Figure 4) has been prepared with a series of flat-bottom holes (FBHs) of different diameters (10, 7, 5, 4, 3, 2, 1 mm) in three different depth positions (25%, 50% and 75% of wall thickness). The variation of the diameter represents the defect size parameter variation for the POD analysis. As a consequence, three different POD curves can be calculated for the different depth positions. The wall thickness of the test ring has been chosen so that it represents a typical mid-wall region of the possible production range. The resulting 21 flat-bottom holes have been prepared as accurate as possible (diameter and orientation). The final results have been checked afterwards with tactile measurements.

![figure 4](image)

**Figure 4.** Series of FBHs in depth positions 25/50/75% of wall thickness and diameters 10, 7, 5, 4, 3, 2, 1 mm.

Figure 5 shows the experimental setup in the laboratory to perform the multiple runs of the test ring. It is important to note that the hardware components correspond to the mill situation.
The phased-array electronics, the mechanics of the probe holder, the transducers as well as the inspection configuration (inspection speed, prf etc.) are exactly the same as in the original mill application. The fulfilment of those boundary conditions is essential for the transferability of the results from lab to mill. The phased-array electronics additionally are equipped with conventional channels, which are used for the conventional transducer. Therefore, any differences between the performances of the conventional and PA-configuration can be related to the transducer characteristics and the inspection configuration.

The former conventional single element transducer (used in new condition) and the actual phased-array transducer are sketched in Figure 6. The conventional transducer consists of one transmitter element with a length of approximately 100 mm and three receiver elements summing up to the same length. The lower diagram on the left hand side shows the sensitivity drop-offs between the receiver elements measured with a small steel sphere in water.

Figure 5. Laboratory setup for performing the ‘a versus â’ analysis

Figure 6. General setup of the conventional transducer (left) and the actual PA-transducer (right) to be compared.
The PA-transducer exhibits 128 elements with a pitch of 0.75 mm. For the measurements, electronic scanning with a virtual transducer of 16 elements and a step size of 2 elements has been performed. Both transducers coincide with regard to the driving frequency of 4 MHz. In order to consider an eventual non-optimal position of the conventional transducer with regard to the position of the FBHs, the transducer position has been shifted from optimal central position of one element by two additional shifts of 5 mm each.

A typical result for one rotation of the pipe ring is given in Figure 7. For the recordings, a depth focusing algorithm for the PA has been applied. The calibration was done using the amplitude responses of the 3 mm FBH, which exhibit similar amplitudes in the echodynamic scan. The electronic scanning of the virtual transducer provides a C-scan which is given in the lower part of Figure 7.

![Figure 7. Typical echodynamic curve (upper part) and C-scan (lower part) recorded with the PA-configuration.](image)

4. Probability of Detection Results

4.1 Data characteristics

In terms of the ‘$a$ versus $\bar{a}$’ analysis the defect responses have been recorded for 30 rotations of the test ring in case of the PA and 90 rotations for the conventional transducer (3 x 30 including transducer shifts, see last chapter). The amplitude variations in dependence on the diameter of the FBH are given in Figure 8. For a depth of 75% (close to the back wall), both transducers exhibit a comparable dependence, which can be well approximated to be linear. For the mid-wall results (50%), the slope for the PA dependence decreases due to the sound beam characteristics. The conventional transducer follows this behaviour for a depth of 25% (close to the surface). As far as the detectability is concerned, the conventional transducer detects the 2 mm FBH very close to the decision threshold, while the PA is at least able to detect the 1 mm FBH, however also below the decision threshold.
Figure 8. Variation of amplitude data in dependence on the FBH diameter for the conventional (left) and PA (right) transducer in the three different depth positions (top to bottom). The dotted line indicates the decision threshold.

4.2 POD Evaluation

A first typical step in the mh1823-software is to represent the raw experimental data and to decide which representation of the data is most suitable for a linear fit. For the case here, it turns out that the linear-linear representation is the best choice. For the ITWM-model, the variances for the conventional as well as the PA-case have been set to the same value of $\sigma=120$, which practically means that the PA data are treated rather conservative in order not to force the results into an advantageous view of the actual PA-system. The decision threshold, according to the calibration of a 3 mm FBH, could be determined to be 11 dB above the noise level.
Figure 9 shows exemplarily the calculated POD curves as an output of mh1823 and the ITWM-software, respectively. Since the differences in data evaluations in both software approaches have not been forced by the input data used, it is not expected that the results differ significantly. The calculated values for the $a_{90/95}$ are very similar, while differences in the evaluation of the confidence bounds are becoming quite obvious.

![Figure 9](image)

Figure 9. POD curves calculated for 75% depth position with mh1823-software (left) and the ITWM-software (right). The upper part gives the result for the conventional transducer, the lower part for the PA.

In the remaining course of this publication, only the ITWM-software will be used further. Figure 10 shows the corresponding POD curves for both transducer configurations in all 3 depth positions. In all cases the conventional transducer leads to a significantly worse result as compared to the PA. Depending on the depth position, differences up to approximately 1 mm have been obtained. The width of the confidence bounds is quite comparable.
Looking at the center diagrams (50% depth position) of Figure 10, it can be seen that for PA the POD curve does not drop down to zero probability towards small defect sizes. Here, a Probability of False Indication (PFI) rate of about 5% can be seen. This fact can be explained by looking at the data shown in Figure 8 (center diagrams). By calibrating to the amplitudes of the 3 mm FBH, the 2 mm FBHs are detected as well, however at the expense of also registering noise signals and identifying them erroneously as indications. By calibrating with respect to the 5 mm FBH the PFI can be reduced, while of course the size $a_{90\%95}$ increases accordingly. This illustrates the importance of the applied calibration procedures in view of the defect sizes to be detected and the tolerable PFI rates.
Figure 11. ITWM-software based POD curves for the conventional (left) and PA (right) transducer for the depth position 50% (compare to center of Figure 10), but now with a calibration on a 5 mm FBH.

5. Conclusion

This paper has shown that a POD analysis is a powerful tool to quantitatively compare the performance of NDT inspection methods. For the investigations here, the recently installed phased-array application showed an improved POD in the order of magnitude of 0.5 mm to 1 mm, depending on the depth position of the circular reflector. The relation between POD and PFI could be shown by varying the level of the decision threshold (3 mm and 5 mm FBH as a reference reflector). Since all the POD evaluations provide real quantitative measures, the determination of additional sensitivity offsets becomes much more reliable. It turns out, that the choice of appropriate reference reflectors and their proper manufacturing is decisive for a representative POD result. However, the experimental efforts for an ‘a versus â’ analysis, especially in case the data is recorded under mill conditions, are quite high. In an upcoming investigation the potential to support those analyses by simulation (model-assisted POD, MAPOD) will be sorted out for practical application cases.

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References

