Simulation of the probability of detection of a flat-bottom hole within a pipe using ultrasounds

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Abstract
The probability of detection (POD), often calculated statistically from experimental data, represents the ability of an inspection to detect a given flaw. The object of this work is to simulate the POD of a reference flaw called “Flat-Bottom Hole” (FBH) present within a pipe wall during an ultrasonic inspection, which is a method commonly employed at Vallourec mills for controlling seamless steel pipes. The simulation is based on a simple concept: to detect the FBH, the ultrasonic wave must be reflected by it, which is only the case when the transducer and the FBH are in front of one another. This POD modelling is a function of the pulse repetition frequency of the electronics, the user-defined alarm filtering algorithm, as well as the dimensions, linear and rotational speed of the pipe. In addition, this model takes into account the intensity and shape of the emission field from the transducer as well as the ability of the FBH to reflect the ultrasounds to compute a theoretical signal amplitude as a function of the relative positions of the pipe and the transducer.

Keywords: pipe, probability of detection, flat-bottom hole, ultrasounds

1. Introduction

Pipes produced at Vallourec mills pass through a series of non-destructive evaluations aimed at detecting potential structural irregularities: wall-thickness out-of-range, surface-breaking flaws, delaminations, etc. Ultrasonic NDT benches are the ideal piece of equipment to make that kind of testing, as these remain operational at industrial speed: pipes can indeed be controlled while making several revolutions per second (rps) and with a linear speed of about 1m/s.

In order to be approved, the control process must be able to detect reference flaws, usually machined, whose dimensions are defined either by the industrial standard or the client specification. The most common reference flaws are internal and external notches, whose orientations are longitudinal, transversal or oblique. These usually measure 1” or more in length for a depth equal to 5% of the wall-thickness.

Sometimes, the detection of a Flat-Bottom Hole (FBH) is also required by the client, for example to assess the inspection of delaminations. A FBH is a circular hole pierced from the inner surface of the pipe, with specific diameter and depth. The diameter of the FBH varies with the level of severity of the standard or client specification. It is therefore necessary for Vallourec to know the probability of detection (POD) of the FBHs as a function of their diameter and the parameters of the NDT bench: dimensions and frequency of the transducer(s), pulse repetition frequency of the electronics, linear and rotational speed defining the shot distance, operating procedure that sets the reference gain, detection threshold, etc. The development of a numerical model to compute the POD by
simulating the physical processes and trajectories of the ultrasonic waves between the flaw and the transducer is an interesting approach to identify technical solutions in order to reach the aimed POD for a given FBH diameter.

2. **Numerical simulation**

   **2.1 Working principle**

We have developed a simple, 2-dimensional model, which is sufficient because FBH detection is achieved using a transducer oriented so as to make a wall-thickness measurement: the angle between the beam and the surface of the FBH is always equal to 90°. This model takes into account the mappings of the emission field of the transducer and the reflection coefficient of the FBH. The consecutive positions of the FBH with respect to the transducer are computed at the moments when the ultrasonic shots are triggered, as a function of the linear and rotational speed of the pipe, as well as the pulse repetition frequency, for one given helical trajectory. The signal amplitudes associated to these shots are computed and the alarm filtering algorithm (single or multiple thresholds, number of required consecutive shots above the threshold(s)) concludes as to whether the flaw is detected or not. The whole process is then repeated over all possible helical trajectories by spatial discretisation. The POD of the FBH is equal to the ratio of the number of trajectories leading to detection of the flaw, to the total number of computed helical trajectories.

The different stages of this process are detailed in paragraphs 2.2 to 2.7.

   **2.2 Emission field of the transducer**

The emission field of a Ø0.5" 5MHz non-focused Panametrics V309 transducer was measured in a water tank using a small steel bead as a reflector, with a spatial resolution of 5pixels/mm. The water path was 52mm. The emission field consists of a main spot surrounded with a ring. A simulation using CIVA confirmed this result. Still, it is the experimental mapping that was used within the model as this input impacts strongly the simulation result. In order for the model to be valid, one needs to work not with a mapping of the emission field, but with a mapping of the reception field of the transducer. It is indeed necessary to take into account the curvature of the outer surface of the pipe and the fact that the FBH will send back much less energy toward the transducer as soon as the active surfaces of those 2 elements are not situated on parallel planes. In Figure 1, the X axis corresponding to the pipe axis, these geometrical constraints were modelled by convoluting each column of the emission field mapping with a Gaussian. The resulting mapping consists of a main spot surrounded with 2 secondary, lower-intensity spots.
Figure 1. Left: emission field measured experimentally. Centre: CIVA simulation of the emission field. Right: reception field, obtained by convoluting each column of the emission field mapping with a Gaussian. Arbitrary units.

2.3 Flat-Bottom Hole

Flat-Bottom Holes are modelled in 2D with a simple circular shape. Since experimental mappings with a focused transducer have demonstrated there is an edge effect, the reflection coefficient of the FBH decreases near the border of the FBH.

Figure 2. Modelled mapping of the reflection coefficient of a Ø6mm FBH, including an edge effect.

2.4 Calculation of the trajectory of the FBH during the consecutive shots

The inspection parameters are the followings:

- $V_{\text{Rot}}$: pipe rotational speed in mm/s
- $V_{\text{Tra}}$: pipe linear speed in mm/s
- $\Phi_{\text{pipe}}$: pipe diameter in mm
- $F_R$: pulse repetition frequency in Hz

The spatial resolution of the calculation in pixels/mm, called Res, is an input of the simulation.
From those parameters, one can calculate:

- **Step**: the helical step of the inspection, in mm
  \[
  \text{Step} = V_{\text{Tra}} \times \Theta_{\text{pipe}} \times \pi / V_{\text{Rot}}
  \]

- **D_{\text{Step}}**: the number of pixels corresponding to one helical step
  \[
  D_{\text{Step}} = \text{Res} \times \text{Step}
  \]

- **D_{X}**: the displacement of the FBH between 2 consecutive shots along axis X, in pixels
  \[
  D_{X} = \text{Res} \times V_{\text{Tra}} / F_{R}
  \]

- **D_{Y}**: the displacement of the FBH between 2 consecutive shots along axis Y, in pixels
  \[
  D_{Y} = \text{Res} \times V_{\text{Rot}} / F_{R}
  \]

Figure 3. Left: image showing 10 consecutive positions of a Ø3.2mm FBH as it passes in front of the transducer, during 2 consecutive turns, for one helical trajectory. Right: the signal amplitudes associated with these 10 shots. Shot n°3 returns the highest signal amplitude.
2.5 Calculation of the signal amplitude

The calculation of the signal amplitude in percent is achieved by multiplying, pixel by pixel, the mappings of the FBH and the transducer when these are at least partly superimposed. The result is normalized by dividing it with the value obtained when the mapping of a Ø6.3mm FBH is right in front of the transducer, multiplied with 85%. This is equivalent to, in a real experiment, setting the gain so that the maximum signal amplitude of a Ø6.3mm FBH be equal to 85%.

2.6 Alarm filtering algorithm

The current alarm filtering algorithm allows the user to choose n, the number of consecutive shots required to trigger the detection. As n increases, the detection threshold needs to decrease to ensure the same POD. A practical example is given in Figure 4, which shows experimental data of an echo from a FBH. If n=1, the FBH will be detected when the threshold is ≤ 47%. If n=2, the FBH will be detected when the threshold is ≤ 44%. If n=3, the FBH will be detected when the threshold is ≤ 35%.

![Signal amplitude as a function of the shot number, as a FBH passes in front of the transducer](image)

Figure 4. Signal amplitude as a function of the shot number, as a FBH passes in front of the transducer

2.7 Calculation of the POD

At this point we can tell if the flaw is detected as it takes a given helical trajectory. The next step is to repeat this process for all existing helical trajectories, which is made by spatial discretisation, by moving the coordinates of the position of the starting FBH in increments I_X over a distance Step along axis X, and in increments I_Y over a distance D_Y along axis Y. The simulation is therefore made
over \((I_X+1)\times(I_Y+1)\) helical trajectories. Finally, the POD is equal to the ratio of the number of trajectories that achieved flaw detection to the total number of trajectories.

3. Experiments

A Ø114.8mm-pipe with a wall-thickness of 6.9mm, measuring 8m in length and containing 3 FBHs with diameters 3.2mm, 4.7mm and 6.35mm, pierced at a depth of 50\% of the wall-thickness, was placed on a lathe rotating at 35rpm. A Ø0.5″ 5MHz non-focused Panametrics V309 transducer controlled this pipe in lamination mode. The water path was 52mm. The transducer was moving along the pipe axis with a speed of 8mm/rotation - voluntarily high to make sure the signal amplitude varies strongly with the helical trajectory, at least for the smallest 2 FBHs. These parameters correspond, in the simulation, to \(V_{\text{Rot}} = 210\text{mm/s}\) and \(V_{\text{Tra}} = 4.66\text{ mm/s}\). The pulse repetition frequency was 200Hz, thus resulting in a circumferential shot distance \(\approx 1\text{mm}\). The gain was adjusted so the highest signal amplitude achievable by the Ø6.35mm FBH be equal to 85\%. 60 runs were made for the Ø3.2mm and Ø4.7mm FBHs. 30 runs were made for the Ø6.35mm FBH. The signal amplitudes of all shots for those 150 runs were recorded.

Figure 5. Left: experimental A-scan. The first gate (yellow) is used as an « echo start »: it locates the maximum of the interface echo. The second gate (red), located so as to detect FBHs situated at a depth of 50\% of the wall-thickness, moves automatically to stay at a constant distance of the maximum of the interface echo. This system makes sure the slight variation in water path due to the rotation of the pipe on the lathe does not impact the result. Right: experimental A-scan in the presence of a FBH – here the signal amplitude is 61\%.

4. Results and discussion

The experimental and simulation results are compared in Figures 6 and 7, corresponding to two different alarm filtering algorithms (respectively 1 shot and 2 consecutive shots above the threshold required to trigger the alarm).

The detection experiments of the Ø3.2mm and Ø4.7mm FBHs returned surprising results since these do not consist in Gaussians with one favoured signal amplitude, but rather double-Gaussians with 2 favoured signal amplitudes: 35\% and 50\% for the Ø3.2mm FBH; 60\% and 85\% for the Ø4.7mm FBH. This result, well reproduced by the simulation, is explained by the fact that the reception field
of the transducer consists in one main spot surrounded with two secondary ones. As for the Ø6.35mm FBH, the simulation results are more dispersed than the experimental ones. This is thought to be due to a mapping of the FBH whose edge effect has been overestimated. To be more accurate the model should include an experimental mapping of the FBH, because in practice no FBH has a reflection coefficient perfectly homogeneous over its surface and the slightest irregularity impacts the simulation result.

Logically, for a given threshold, the POD increases with the diameter of the FBH.

For n=1, the simulated POD of 100% is achieved for thresholds up to 28% for the Ø3.2mm FBH, 55% for the Ø4.7mm FBH and 78% for the Ø6.35mm FBH.

For n=2, the simulated POD of 100% is achieved for thresholds up to 22% for the Ø3.2mm FBH, 49% for the Ø4.7mm FBH and 66% for the Ø6.35mm FBH.

Figure 6. Results with a 1-shot alarm filtering (detection achieved if any 1 shot is above the defined threshold). Comparison of the simulation (left column, 205 simulations per FBH) and experimental
results (centre column, 30 or 60 runs per FBH) for the FBHs of diameter 3.2mm (top row), 4.7mm (centre row) and 6.35mm (bottom row). These 6 images represent normalised histograms of the probability of occurrence as a function of the highest signal amplitude recorded. Right column: simulated (blue) and experimental (red) PODs of the 3 FBHs.

Figure 7. Results with a 2-shot alarm filtering (detection achieved if 2 consecutive shots are above the defined threshold). Comparison of the simulation (left column, 205 simulations per FBH) and experimental results (centre column, 30 or 60 runs per FBH) for the FBHs of diameter 3.2mm (top row), 4.7mm (centre row) and 6.35mm (bottom row). These 6 images represent normalised histograms of the probability of occurrence as a function of the highest signal amplitude recorded. Right column: simulated (blue) and experimental (red) PODs of the 3 FBHs.
5. Conclusion

Although this is a relatively simple 2D model, the experimental and simulated PODs are remarkably similar. This approach is a useful tool to optimise the detection threshold and therefore the POD of the FBHs as a function of their diameter. The threshold should then be compared to the noise level. If these are too close from each other this will lead to false alarms; a decrease in inspection speed and/or a change in transducer will therefore be more appropriate. In the future, this model will be applied to phased-array transducers. One possible improvement of this model would be to use real mappings of the reflection coefficient of the FBHs instead of simulated ones. Another possibility would be to simulate these mappings with software such as CIVA.