Eine modellunterstützte 3D-Darstellung von Ultraschallergebnissen

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Kurzfassung. Die Ultraschallprüfung von unter Pulver geschweißten Nähten wird in der automatisierten Prüfung sowohl konventionell als auch mit Phased-Array durchgeführt. Vielfältige Prüfanforderungen nach Detektion unterschiedlicher Fehlerorientierungen im gesamten Schweißnaht-Volumenbereich werden üblicherweise mit Mehrkopfsystemen bedient, deren Ergebnisse in Form von Linienaufzeichnungen und Amplituden über der Längenposition dargestellt werden. Die Interpretation der Ergebnisse und die Zuordnung von Anzeigen zu Volumenbereichen ist nicht anschaulich. Unter Zuhilfenahme von strahlentheoretischen Schallausbreitungsmodellen ist es gelungen, die Ergebnisse aller zur Prüfung beitragenden Ultraschallfunktionen in einer 3D-Darstellung zu vereinen. Der Vortrag diskutiert Details von mathematisch-physikalischen Modellen, die auf bestehende Aufzeichnungsdaten zurückgreifen ebenso wie die Validierung mit Hilfe von experimentellen Daten.

Introduction

Longitudinal seam welds for pipes are typically inspected using mechanized ultrasonic testing machines for their accuracy and high throughput. A combination of phased array and conventional probes are used to ensure coverage of the weld for a range of defects oriented in the longitudinal and traverse direction. Transducers are placed (normally) symmetrically on either side of the weld at a certain distance from the centre of the weld and operating at a certain wedge or refraction angle. Depending on the requirements, certain thick pipes are also inspected using a tandem configuration to detect appropriately oriented defects in the 30% to 70% of the thickness region. The inspection process is aided by the use of reference pipes with simulated notches and drilled holes to setup the inspection. Thus an inspection plan (skip distance, number of skips etc.) can be developed for a reference pipe that can be readily adapted to the inspection of production pipes with acceptable accuracy.

The typical output of these machines is a color-coded “2D” strip-chart that plots the ultrasonic amplitude against axial position. Indications above the threshold value are marked in a different color compared to the values recorded below the threshold. Depending on the need of inspection, the number of output strip-charts may vary and in some cases, be as high as 20 individual strip charts for a complete pipe scan. Not only does interpretation require significant UT expertise, the strip-chart itself offers little information such as the location of the indication within the geometry for further investigations. A typical probe configuration layout along with the output is shown in Figure-1.

In this paper, a mathematical 3D ray based model is developed to localize flagged indications to their actual location in the geometry of inspection. A number of numerical [1] as well as analytical [2] models have been developed previously to capture ultrasonic wave propagation in elastic and non-elastic media. While the numerical model attempts to capture accurate representations of transducers and defect interactions, analytical models have captured on-axis and off-axis ultrasonic beam profiles for a variety of inspection configurations.

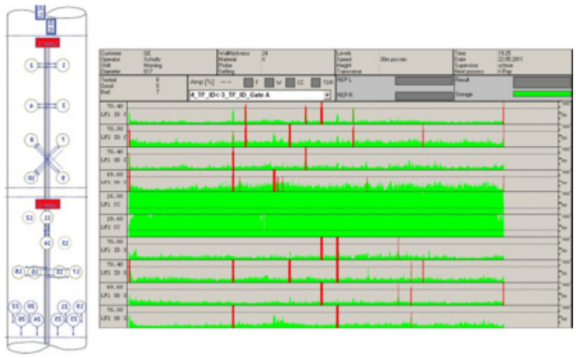
Figure 1: Typical Probe layout and strip chart output

Ray models have been used to capture effects of anisotropy on ultrasonic wave propagation and their effects on amplitude and propagation paths. Ogilvy in References [3-5] has discussed methods of using ray-theory for understanding and predicting ultrasonic behaviour in anisotropic materials. A layered approach to modelling ray propagation in anisotropic material was developed for understanding wave mode interaction to determine the optimal weld inspection through a numerical approach. An iterative approach to modelling ultrasonic energy propagation in anisotropic materials takes as inputs the slowness vector, a start and end point for the ray to iteratively converge at the end point for weld inspections. The model has been applied to size indications based on diffraction (ToF) and amplitude methods. These have also been incorporated into a commercial package RayTraim for simulating many applications.

While it is accepted that additional information related to the material properties such as slowness curves, weld properties etc. will enhance model accuracies, in many cases it is not possible/feasible to measure or get them directly under practical conditions especially when the production volume is very high. Here, an attempt is made to achieve acceptable accuracy of localization with the use of only inspection results and the geometry of inspection.

Description of the Ray-Model

Like all ray-models, there are two key inputs – the distance of the probe from a reference point and the angle of inspection that will serve as the direction vector. The material of the pipe along with the weld is assumed to be isotropic and the source is assumed to emanate from a single point. Because of the assumption the ray propagates along a straight line at the prescribed angle until an interface is encountered. The only known interfaces are the outer and the inner diameter of the pipe.

Accounting for the curvature of the geometry, the ray continues to travel until a terminating condition is reached. While no constraints are placed on the terminating condition, it can be made specific as the number of skips or can be generic to represent a geometrical feature such as the centre or the side of the weld. While the former allows simplification of the algorithm the latter allows for rigorous and a more generic implementation for handling weld coverage. This also means that a 'generic' number of multiple reflections within the sample can be captured. This is particularly useful to generalize the algorithm to capture both the outer diameter (OD) and the inner diameter (ID) defects. The terminating condition commences the inverse model that maps the beam traversal path onto a time-of-flight map based on an assumed speed of sound.

Although the model assumes the source from a point, the associated beam divergence is estimated as a function of the transducer property. Since the material is assumed isotropic, no ray-bending or additional beam divergence due to the material is computed. As this model is primarily targeted for an existing inspection setup it is assumed that the inspection process itself has been sufficiently optimized and hence no attempts are made to model the amplitude of the received ultrasonic signal.

The model implements in and out-of-plane ultrasonic propagation. In-plane propagation refers to the probe and the defect in the same axial location and is used for localizing longitudinal flaws. The out-of-plane model refers to the probe and the defect in different axial locations for flaws oriented in the transverse direction.

Results and Discussion

A 6-channel semi-automatic inspection system was used to test the localization algorithm. The system was fitted with 4 conventional shear wave probes (60^{o} and 70^{o}) and two 16-element phased array probes. Reference pipes with N5 simulated notches were used as test specimen. Table 1 captures the details of the test specimen used in the tests. Results for longitudinal and transverse flaw configurations are presented here. The results presented here are only from the conventional probes although the models are capable of handling phased array probes as well.

The following inputs are used:

1. Geometrical information (Pipe and weld details)
2. Inspection parameters related to the probe
3. The inspection results - amplitude and time-of-flight

Test Pipe	OD (mm)	Thickness (mm)	Weld Bead (mm)	
			Height	Width
1	665	18	24	22
2	714	18	24	22

Table 1: Test Pipe configuration

Longitudinal Flaws

The notch configuration for test pipe 1 is shown in Figure 2. The horizontal section represents the weld with notches in the centre and on either side of it. An equal number of notches are placed both on the OD and the ID of the weld. Distinction is made between the centre notches placed on the weld cap and by grinding the weld cap (notch placed between two vertical solid lines).

The conventional 60^{o} shear probe was placed at a distance of 60mm from the centre of the weld for inspecting the outer diameter (Probe 1 & 2) and at about 90 mm to inspect the inner diameter (Probe 1 & 2) in two separate runs as shown in Figure 3.

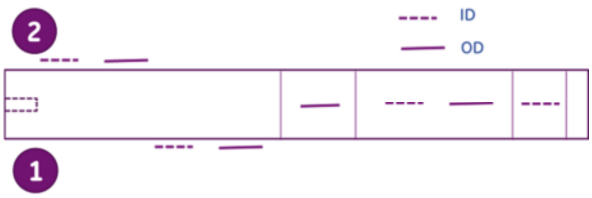

Figure 2: Defect Configuration of Test-Pipe 1

Both the probes were placed facing each other at the same axial location. The scan direction runs from right to left so that the first indications on the strip-chart represent the centre notches depending on ID or OD.

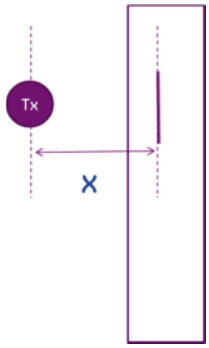

Figure 3: Inspection distance of the probe from the center of the weld

The scan generates two separate strip charts; one for each probe placed on either side of the weld. We will discuss the OD and the ID runs separately. For the sake of clarity and ease of understanding only one strip chart is presented while the 3D geometry contains both the channels localized. The strip chart along with the top view of the test-pipe is shown in Figure 4. The four indications from the strip-chart are as follows: The first indication is from the center OD notch, the second from the center OD notch with the ground weld cap. The third indication is from the notch on the other side of the weld while the fourth is from the notch on the side of the weld as the inspecting transducer. While detecting flaws on the other side of the weld is uncommon, their occurrence cannot be completely ignored either, especially at lower wall thicknesses (under 12mm). However, it provides an interesting opportunity to test the assumptions used within the model.

Using parameters of the test pipe listed in Table 1, coupled with the inspection parameters, the forward ray-model is computed until each ray has crossed the center of the weld. The over-design ensures that the weld coverage is complete and no indications are missed out due to lack of information from the forward model. The time of flight for the peak signal obtained between the gates is also recorded separately. Based on the forward model, a TOF map over the weld-region is generated so that each indication in the stripchart is mapped to a possible location in world-coordinates.

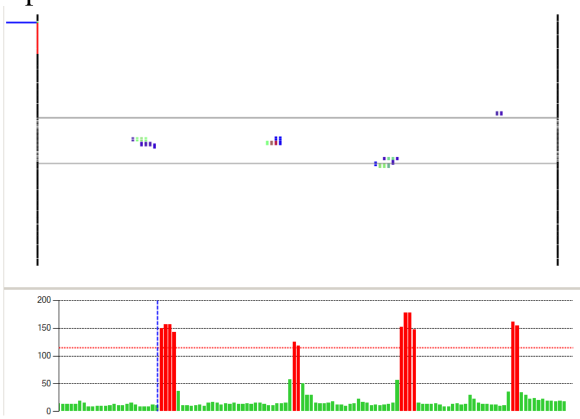

Figure 4: 3D localization of Longitudinal OD flaws – Stripchart and Top View

The top view resolves the lateral resolution of the algorithm. The 2 center notches are localized at the center, 2 more flaws are localized on either side of the weld.

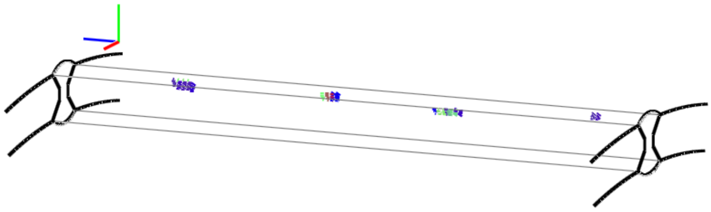

Figure 5: 3D localization of Longitudinal OD flaws – a perspective view

From Figure 5 the depth resolution of the localization is evident. All the indications are localized on the outer diameter. While there is distinction on the reference pipe between the two center notches, it is difficult to resolve them in the 3D localization. The intersection of the indications from the probes facing each other can possibly be used for resolving these two flaws in the depth direction, however it has been noticed to be an inconsistent approach. It must be noted that the length of the representation is not an indication of the extent of the flaw but only elucidates the possible locations of the indications.

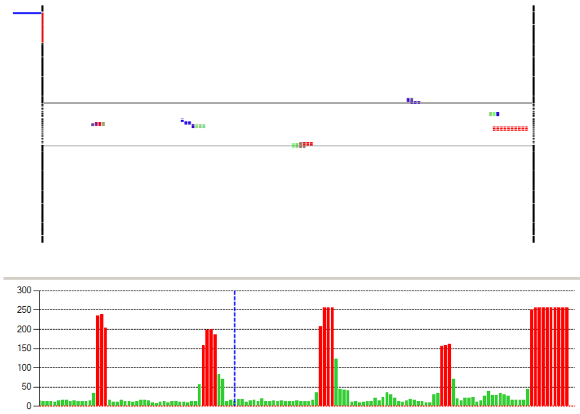

Figure 6: 3D localization of Longitudinal OD flaws – Stripchart and Top View

Figure 6 captures the results of the ID run in 3D. The strip-chart indications refer to the ID indications from right to left (in Figure 1) with a similar indication from the other side of the of the weld. The last indication in the stripchart refers to the End-drilled reference hole. Clear distinction can be made in the depth resolution as seen in Figure 7. All indications are localised in the inner diameter with clear distinction in the lateral resolution as well.

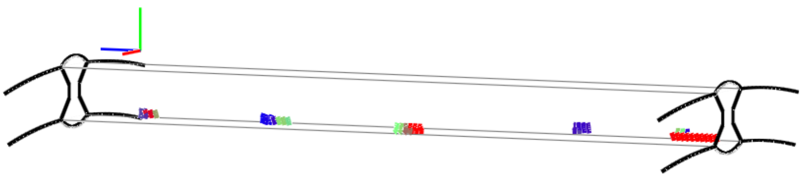

Figure 7: 3D localization of Longitudinal ID flaws – a perspective view

The EDH is a reference hole normally located either in the middle or the on-thirds, two-thirds location. Here the EDH has also been localised in the ID. Although, the travel paths are different for the flaws located in the middle of the thickness and the flaws in the OD or the ID, the resultant time of flight are very close for both cases as the resultant echoes roughly emanate at similar times from the surface of the pipe, probably with varying amplitudes.

Transverse Flaws

Transverse flaws are oriented perpendicular to the axis of the pipe. Pitch-catch method provides a reliable technique of capturing these flaws during automatic inspection runs. To enable them, the transducers are normally skewed at 45 degrees on the surface of the pipe so that the transmitter and the receiver can be placed on either side of the weld. The configuration is illustrated in Figure 8. Two probes on either side of the weld are skewed at a certain angle towards the weld. In addition to the transverse distance of the probe to the center of the weld, a second distance is measured (and used as input) which is the axial distance from the reference flaw to the centre of the probe. Typically, these two distances are similar values. This is normally measured after maximizing the defect response. Both the distances are used to measure the skew angle using trigonometric relationships. The process of setting up the initial skew of the transducer is not discussed here. The corresponding distances for the OD and ID configuration are shown in the inset in figure 8. The distances are symmetric on either side of the weld.

	X (mm)	Y (mm)
OD	48	55
ID	74	80

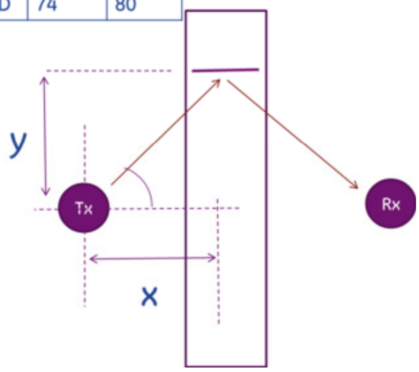

Figure 8: Pitch-catch configuration for transverse notches

A reference pipe with only transverse notches as shown in figure 9 was scanned in two separate scans for OD and ID. It consists of 3 through drilled holes (TDH) on both sides and centre of the weld. In addition it has 4 transverse notches, 2 on the OD and 2 on the ID. Similar to Plate-1, distinction in depth is made between the notch on the weld and after removing the weld bead or cap (represented by the notch between two solid vertical lines).

Figure 9: Transverse notches defect configuration

The configuration consisted of two symmetric setups as shown in Figure 8, appearing like an X. Hence two strip charts are produced. One strip-chart where the maximum number of indications was picked is displayed. In addition to the corresponding transverse notches picked by the respective configuration, the OD configuration picked an indication from the side TDH while the ID configuration picked a central TDH. To be able to localize the indication, the out-of plane model with the estimated skew angle is used to determine the time of flight map along the skewed plane. Since the transducers and the defect do not lie in the same plane, their position is axially corrected to place the indication correctly in the strip-chart.

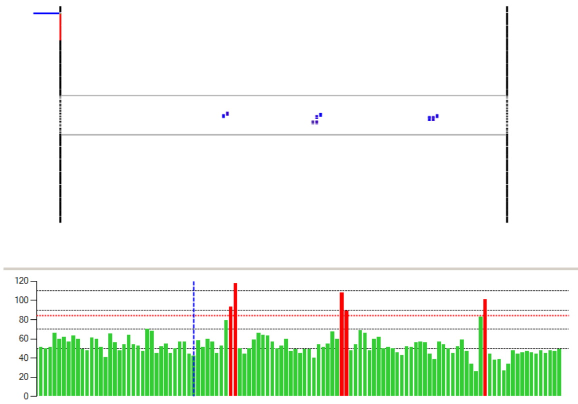

Figure 10: 3D localization of Transverse OD flaws – strip-chart and Top View

Figure 10 captures the top view of the 3D localization of the OD transverse notch along with the recorded strip-chart for one of the channels. The strip chart presents three indications – the first one from the Side-TDH (closer to the ID transverse notch) and the other two from the two OD transverse notches. When the localization is viewed from the top, all the indications have been placed along the centre of the weld including the side-TDH. This lateral artefact stems from axial misalignment between the probes resulting in slightly elongated travel paths. However, under the current experimental limitations, it seems to be the best possible localization that can be achieved. With further accuracy introduced in the beam-spread calculations it is hoped that the accuracy of the localization can further be increased.

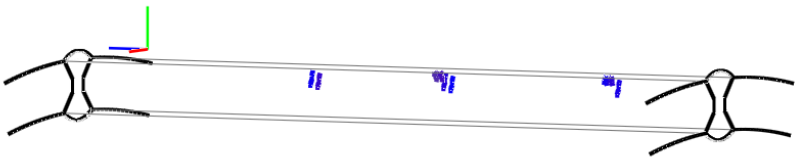

Figure 11: 3D localization of Transverse OD flaws – a perspective view

In the perspective view in Figure 11, it is observed that the indications have been correctly localized on the OD. Since the TDH runs through the thickness of the pipe, it will be localized based on the inspection configuration (OD or ID).

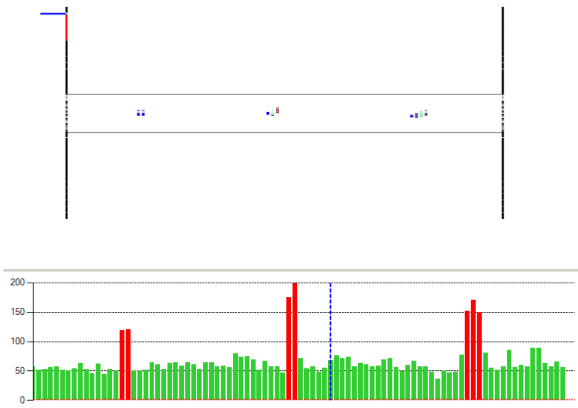

Figure 12: 3D localization of Transverse ID flaws – strip-chart and Top View

Figure 12 captures the localization of the ID transverse notch. As with the OD, the ID configuration also raised three indications in the strip-chart – one from the central TDH and the others from the ID transverse notches. The top view localizes all the indications at the centre of the weld which is their actual location in the reference pipe.

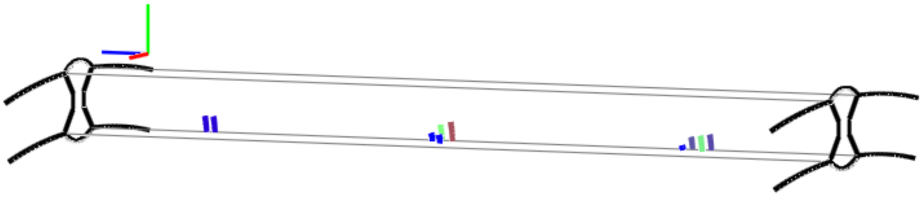

Figure 13: 3D localization of Transverse OD flaws – a perspective view

In the side view, all indications have been localized along the ID (Figure 13). In this particular setup, the individual channels were unable to pick up any of the through holes together. Under such situations it becomes evident that defects that run through the cross-sectional weld are easily visualized and decisions related to the setup are understood faster.

The localization algorithm can be used to gain an immediate reference about the location of the flaws in the geometry. This has the potential to reduce investigation time during other confirmatory inspection runs or for local repair of the pipes. In addition, multiple channels can be combined to look at the "complete" picture of the inspection. Coupled with the user experience the interpretation of the results can be more insightful as well as have the capacity to be more productive

Conclusion

An advanced and easily adaptable ray-model has been developed and demonstrated for the localization of defects. The model has been demonstrated for localizing simulated longitudinal and transverse notches in longitudinal seam weld reference pipes. Lateral resolution was shown to distinguish defects either in the center or the side of the weld. The depth resolution is restricted to localizing accurately either along the outer or the inner diameter of the pipe. At the current stage of development, with the limited data available from automatic inspection scans it is difficult to determine the exact depth of the indication. It was shown that the algorithm is robust to the extent of the accuracy of the provided inputs, namely, the distance and the angle of the probe. The current capability has the potential to be extended further into sizing and characterization of defects.

References

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