RESEARCH PAPER

Cost-effective ultrasonic inspection of large diameter pipelines

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ABSTRACT

To be successful in the ILI business, organization require the right mix of technological capabilities, operational agility and quality standards. The business is fairly competitive, and often technological capabilities are pivotal in the customer proposition of the company. However, the best technologies are not solely required for successful ILI companies. Robustness of the system, operability by the ILI inspector, fitness of the product with commercial route to the market all contribute to a rapid return on investment. Providing a robust, versatile, high-resolution and cost-effective method to inspect large diameter pipelines was recognized as a challenge and opportunity. For that, a Large Diameter Ultrasonic Inspection tool capable of inspecting pipelines of 20 inch to 64 inch with high resolution was developed. The tool is always bi-directional and capable of mitigating 1.5D bends. Gathered data can be reviewed real-time during the inspection. The operating envelope of the tool is such that it can cope with various products in the pipeline, varying from (high salinity) water, crude oil and a multitude of refined products. Despite the fact that product properties (e.g. speed of sound, attenuation, temperature, etc) vary, the tool is designed such that this is not a limiting factor for the operating envelope. The application of advanced ultrasonic beam forming methodologies and signal generation and -processing ensure that the system is versatile and robust for these types of real-life operating conditions. This presentation will provide an overview of the utilization of these technologies, the validation program that has been used to demonstrate tool specifications and the experiences gained at successful projects.

Key words: Inline inspection, pigging, ultrasonic testing, signal processing, phased array.

INTRODUCTION

Pipeline infrastructures play an important role in our today's society. Economically and politically, the dependency of our community strongly depends on pipeline networks. Operating pipelines introduce risks to health, safety, environment and economics. Hence, managing these risks is essential.

Managing these risks comprises various activities, of which inspection and Non-Destructive-Testing (NDT) is a significant part.

A wide range of inspection tools is available in the market, deploying various technologies, in different ways. Among others the deployment of "Intelligent Pigs", allow to use advanced electronics and sensorics to assess the pipeline integrity, Various NDT methods and techniques can be utilized, among others Ultrasonic Testing.

The cost-effective ultrasonic inspection of large diameter pipelines has been a challenge for decades in our industry.

Problem statement and System Requirements

Scope

In the range of services provided, the inspection of large pipelines presents several technical and operational challenges.

To enable inspection of these pipelines, clients frequently require the inspection to be conducted without exposing their pipelines to a different product. This presents several challenges as these large pipelines may contain multiple liquid products at different temperatures, and frequently their acoustic properties cannot be characterized prior to inspection.

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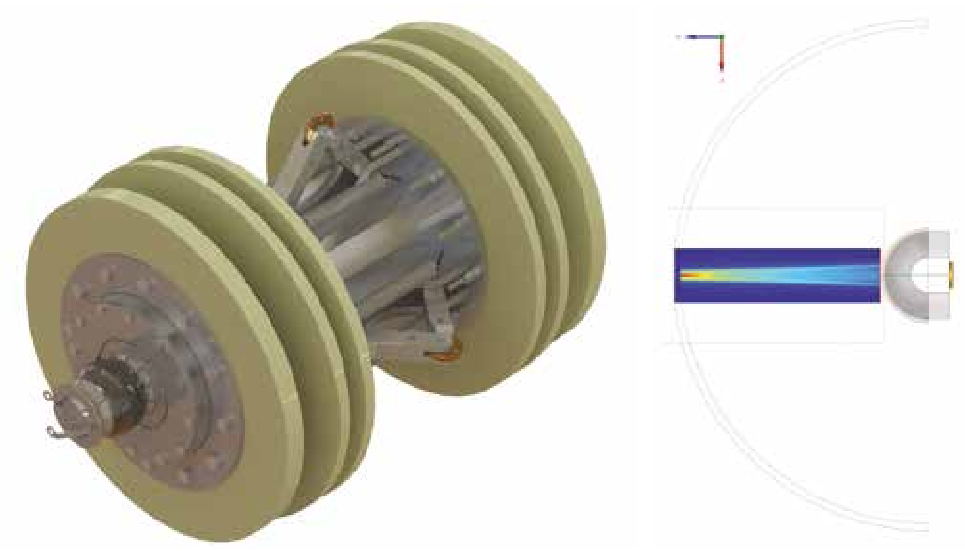

Figure 1. *LDUT Piglet®.*

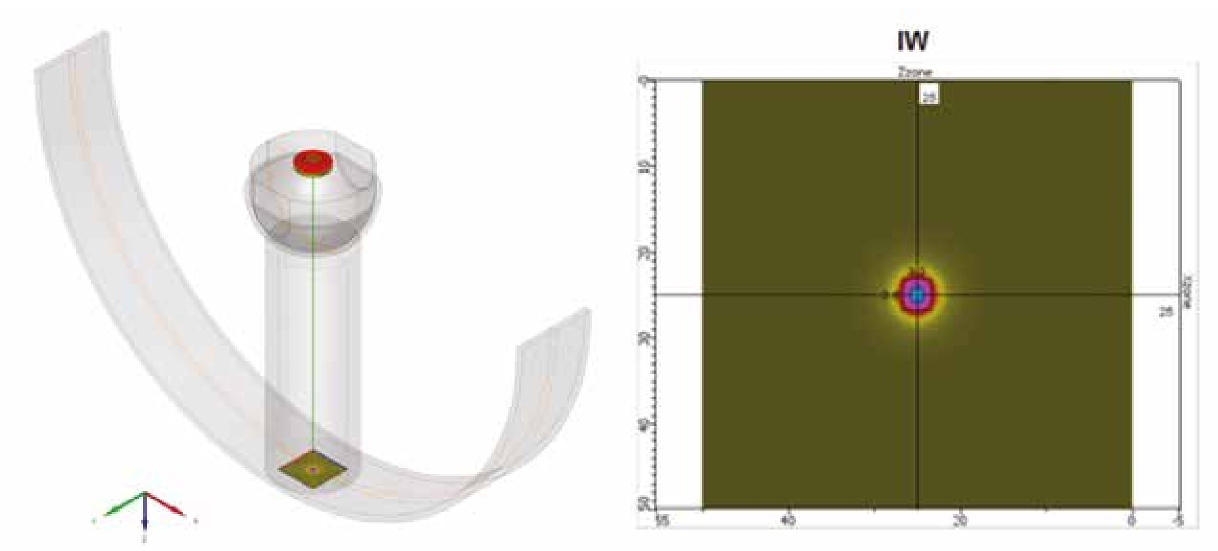

Figure 2. *Example of computational areas (IW plane).*

Characterizing the acoustic properties beforehand is typically only possible for some pure refined products, while in other, e.g. crude oils, it is not possible because of the wide variation produced from different oilfields or various blends available and furthermore their properties can vary significantly due to the temperature of the inspection medium.

Objective

The main objective was to develop a flexible, safe and cost-effective system based on Ultrasonic Testing, that could work in various inspection media (products) and increase the sensitivity and resolution of existing tools and be capable of inspecting pipelines ranging from 20 inches up to 64 inches with a formfactor of a typical bidi cleaning pig.

System Description

This inspection system relates to thickness measurement through the Phased Array Ultrasonic Testing (PAUT); enabling corrosion mapping of pipelines.

The concept is based on the standard Intero Piglet® system, deploying an autonomous pigging system, with an optional optical fiber tether to allow for real-time data review during the inspection. However, it is improved with an annular ultrasonic Phased Array transducer enclosed in a spherical housing.

The rotatable mirror arrangement based on the Internal Rotating Mirror Principle (IRIS) allows the pipe to be investigated 360° with an adjustable measuring grid. Some of the benefits of phased array technology over conventional UT

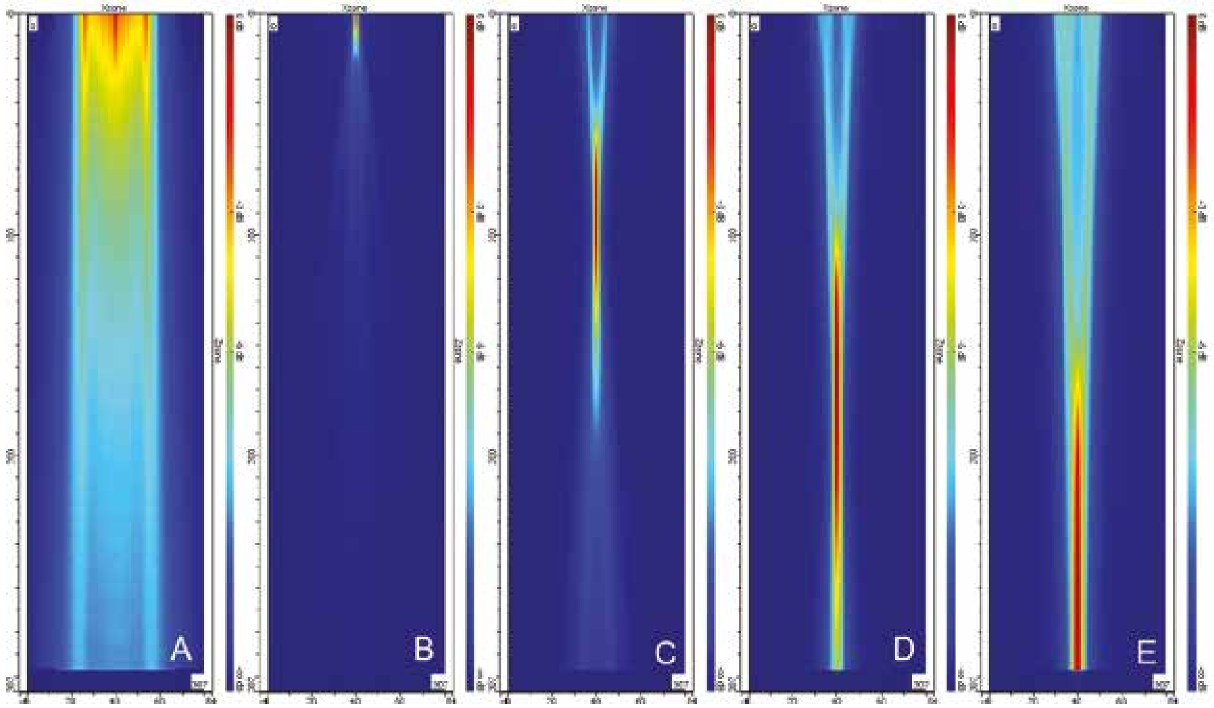

Figure 3. *Ultrasonic Field (L-Wave); (A) - Null delay (unfocused); (B) - 100 mm focal point; (C) - 200 mm focal point; (D) - 300 mm focal point; (E) - 411 mm focal point (BW) 30 inches.*

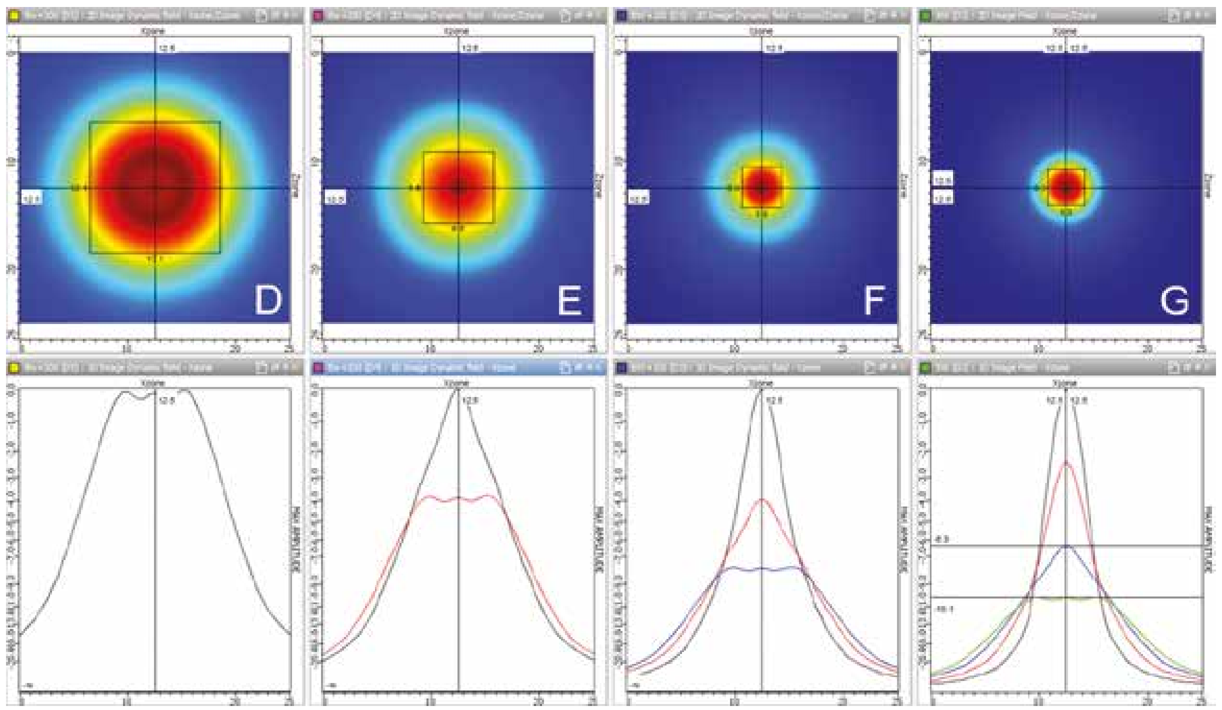

Figure 4. *Computational plane placed on the BW of a 28 inches pipe (Beam profile at -6dB), in this example the focal point is placed on the back-wall (I); +100mm from the back-wall (H); +200mm from the back-wall (G); and +300mm from the back-wall (F).*

Pipe	Nominal wall thickness [mm]	Defect ID	Type of Defect	POF defect Class	Defect Geometry	Diameter (Length = With) [mm]	Flaw depth [mm]	Metal loss [%]	Percent detected [%]
28 inches Sch STD	7.9	A-1	External Metal Loss	Pinhole	FBH	6.4	4.1	51.6	100
	7.9	A-2	External Metal Loss	Pinhole	FBH	8.9	**4.0**	**49.8**	**100**
	7.9	A-3	External Metal Loss	Pitting	FBH	10.5	**4.1**	**50.8**	**100**
	7.9	A-4	External Metal Loss	Pitting	FBH	12.9	**4.0**	**49.6**	**100**
	7.9	A-5	External Metal Loss	Pitting	FBH	15.4	**3.9**	**48.1**	**100**
	7.9	A-6	External Metal Loss	Pitting	FBH	18.2	**4.5**	**55.9**	**100**
	7.9	A-7	External Metal Loss	Pitting	FBH	28.4	**5.2**	**64.4**	**100**
	7.9	B-7	Internal Metal Loss	Pinhole	FBH	6.8	**3.5**	**43.8**	**100**
	7.9	B-6	Internal Metal Loss	Pinhole	FBH	8.5	**4.4**	**54.4**	**100**
	7.9	B-5	Internal Metal Loss	Pitting	FBH	10.8	**3.8**	**47.5**	**100**
	7.9	B-4	Internal Metal Loss	Pitting	FBH	12.6	**3.6**	**45.4**	**100**
	7.9	B-3	Internal Metal Loss	Pitting	FBH	15.3	**3.8**	**47.5**	**100**
	7.9	B-2	Internal Metal Loss	Pitting	FBH	18.5	**3.8**	**47.1**	**100**
	7.9	B-1	Internal Metal Loss	Pitting	FBH	25.7	**4.0**	**50.3**	**100**
	7.9	C-1	External Metal Loss	Pinhole	HBH	6.3	**4.1**	**50.6**	**0**
	7.9	C-2	External Metal Loss	Pinhole	HBH	8.2	**3.7**	**46.8**	**50**
	7.9	C-3	External Metal Loss	Pinhole	HBH	9.9	**3.8**	**47.0**	**75**
	7.9	C-4	External Metal Loss	Pitting	HBH	11.3	**3.8**	**48.0**	**100**
	7.9	C-5	External Metal Loss	Pitting	HBH	13.3	**3.8**	**47.6**	**100**
	7.9	C-6	External Metal Loss	Pitting	HBH	16.7	**4.2**	**52.3**	**100**
	7.9	C-7	External Metal Loss	Pitting	HBH	19.8	**4.9**	**61.5**	**100**
	7.9	D-7	Internal Metal Loss	Pinhole	HBH	6.2	**3.2**	**39.4**	**0**
	7.9	D-6	Internal Metal Loss	Pinhole	HBH	8.1	**4.1**	**51.6**	**17**
	7.9	D-5	Internal Metal Loss	Pinhole	HBH	9.7	**3.7**	**46.0**	**83**
	7.9	D-4	Internal Metal Loss	Pitting	HBH	11.0	**3.6**	**44.6**	**100**
	7.9	D-3	Internal Metal Loss	Pitting	HBH	12.8	**3.6**	**45.4**	**100**
	7.9	D-2	Internal Metal Loss	Pitting	HBH	15.4	**3.5**	**43.9**	**100**
	7.9	D-1	Internal Metal Loss	Pitting	HBH	17.7	**3.6**	**45.3**	**100**

Table 1. *A 28 inch test pipe overview.*

	a_{90}	$a_{90/95}$	# samples	# detected
Flat Bottomed Holes	n/a	n/a	168	168
Hemispherical Bottomed Holes	10.1	10.5	123	78

Table 2. *POD (a_{90} and $a_{90/95}$)*

Figure 5. *Pull-through test setup.*

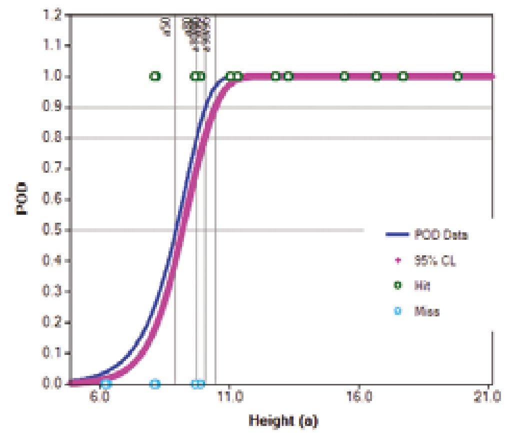

Figure 7. *POD curve for HBHs.*

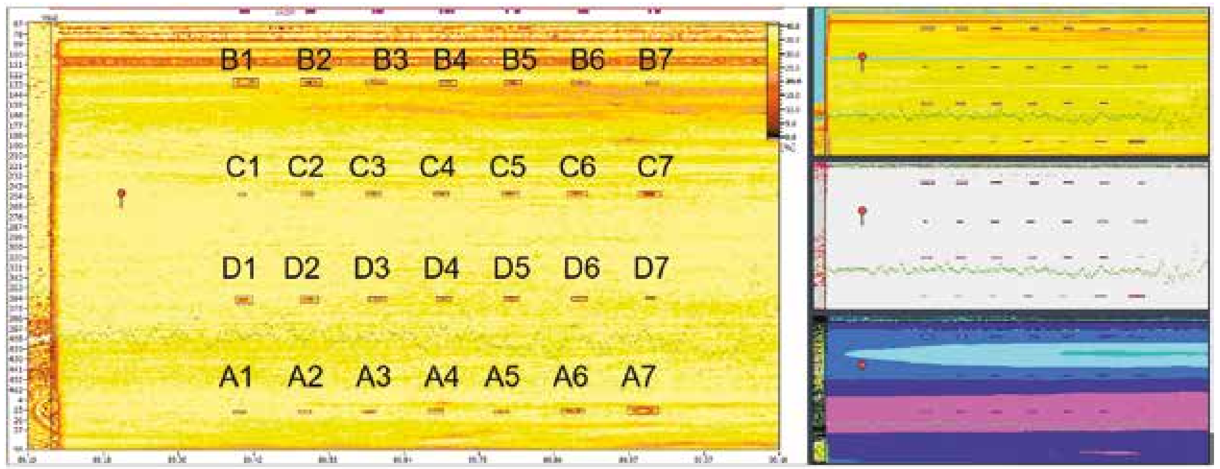

Figure 6. *Data acquisition C-scans.*

derive from the ability control beam shape on transmission and increase the sensitivity on reception. Annular array transducers have unique characteristics which make them superior for this application as they can focus at a predetermined distance producing a symmetric and circular beam profile.

Crude oils however are typically attenuative media which exhibit a natural high frequency filtering effect. Conventionally, overcoming the frequency dependent attenuation effects was done by outputting more energy, lowering the inspection frequency and transmitting a longer pulse at the cost of lowering the axial resolution.

Traditional single-pulse excitation can be replaced by long coded pulse excitation, which can extend the pulse duration instead of increasing the signal pulse amplitude. In this way, the average transmitting energy can be increased, overcoming severe attenuation by the inspection medium.

The application of frequency modulation signals, also

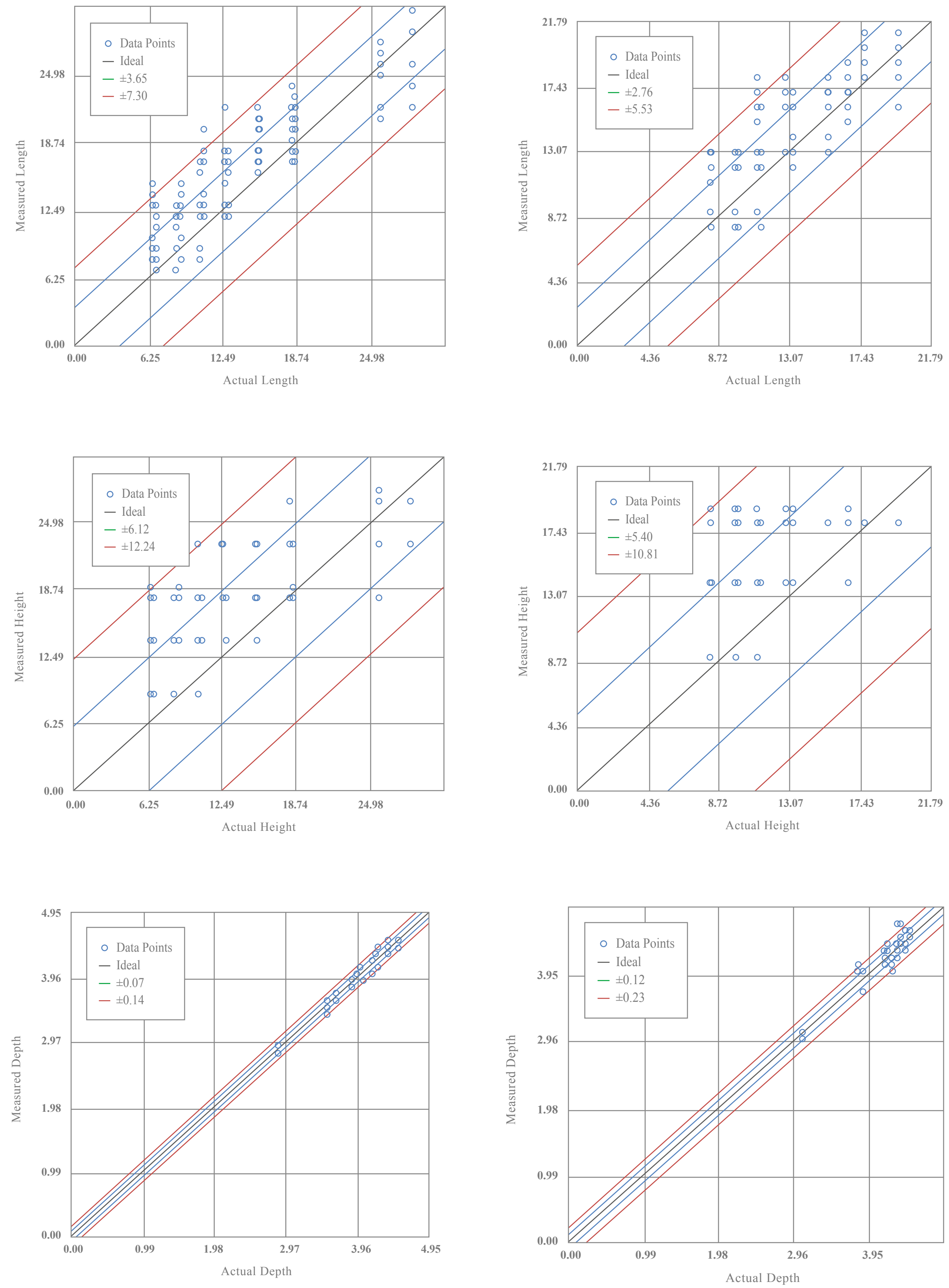

Figure 8. *Sizing accuracies for FBH (left) and HBH (right).*

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		# samples	Tolerance
Flat Bottomed Holes	Length	168	7.3
	Height		12.2
	Depth		0.2
Hemispherical Bottomed Holes	Length	123	5.4
	Height		10.8
	Depth		0.2

Table 3. *Sizing accuracy for all (FBH and HBH) defects at 95% confidence level.*

known as "chirps", consist of transmitting a wide band frequency modulated signal that is cross-correlated with a reference in order to be able to resolve in time the returned echoes. The correlation process restores axial resolution and increasing SNR.

The "chirp" signals are also less susceptible to the influences of coatings, contaminants, debris or impurities in the product. The signals applied are dependent on the application and the transducer used. In some applications the broadband electrical signal applied to the transducer includes energy up to 10MHz, for other applications, the energy may be restricted to 3.5MHz or less.

Performance specifications (POF 2016)

The Pipeline Operators Forum (POF) 2016 and the API1163 standard provide guidelines for defining the basis of performance specification of ILI systems. The performance specification was made by modelling and pull through tests. Statistical analysis of the data was done with STATUS 5 Eclipse Scientific software.

Modelling

Simulations in CIVA software were performed to provide constructive delay laws and beam computations to enable to cope with the multiple materials and the complex geometry of the prototype concept.

Beam computations were performed for different media and pipelines diameters and the correspondent beam profile was assessed in pre-defined computational areas (Fig. 2).

In Fig. 3 we can visualize the radiated ultrasonic field by the developed tool in a low velocity medium, i.e. Naphtha at 1130 m/s.

This beam energy mapping shows the zones of maximum energy of the beam within the defined computational area (Naphtha at 1130 m/s).

The developed system can extend the operating envelope to lower velocity media. Therefore, the diameter of the UT beam at pipe surface can be established according to the inspection requirements, Fig. 4 shows an example through a computation plane placed on the back-wall of a 28 inch pipeline, with Light Crude Oil at 1350m/s.

Pull-through tests

In March of 2018, pull through tests were performed in order to establish the performance specification on a 28 inches carbon-steel test pipe spool with artificial manufactured pinhole and pitting type of defects, having medium density crude oil, API gravity 26, as an inspection medium. Metal losses are represented by two types of geometries: flat bottomed holes (FBH) and hemispherical bottomed holes (HBH) (Table 1).

The Fig. 5, shows the test setup for the pull-through tests. Twelve runs were performed at an inspection speed of 100 m/h; 470 measurements per revolution enabling a measuring grid of approximately 4.6 x 4.2 mm, circumferential and axial, respectively. Sizing of the detected flaws was performed by Data Analysts. Fig. 6 shows the C-scan images of one of the pull-through runs performed.

POD and sizing curves

The probability of detection, POD, is the probability that a feature with size a will be detected by the ILI tool. According to the POF "Specifications and requirements for inline inspection of pipelines" version 2016, two features can be extracted:

- a 90/50 (a90) is the feature size at which the average POD is 90%
- a 90/95 (a90/95 is the feature size at which the lower 95% confidence limit of the POD is 90%).

All metal losses, represented by FBH's, were detected in all the runs. These are not taken into account in the below graph. The two smallest hemispherical bottom holes were not detected both internal and external (Fig. 7).

Sizing accuracies

The sizing accuracy results are depicted in Fig. 8.

Regarding metal losses, for FBH, the tool has a depth sizing accuracy of ±0.1mm, length sizing accuracy of ±7.3 mm and height of ±12.2 mm with a 95% confidence level. For HBH, is has a depth sizing accuracy of ±0.2mm, length sizing accuracy of ±5.4 mm and height of ±10.8 mm with a 95% confidence level.

Case study

The tool developed has been deployed over several projects. One of these projects was for a European pipeline owner.

Pipeline characteristics

The pipeline had the following characteristics:

- Diameter: 28 inches
- Nominal wall thickness: 7.9; 9.5 and 12.7 mm
- Length: 110 m
- Operational product: crude oil
- Inspection medium: crude oil.

As a part of the pig launcher, a validation spool is installed. The spool contains artificial metal-loss defects, with known dimensions. This allows additional performance, verification of system performance prior to the inspection, and to compare the tool performance historic results.

Results

The inspection of the pipeline, covering a total length of 112 m, was completed successfully in approximately 1.4 hours. The average velocity during inspection was 96 m/h.

A total of 226 anomalies were reported, of which 216 were classified as lamination. The remaining 10 anomalies are related to metal loss. All metal loss anomalies have been further analyzed, calculating Psafe and ERF (Emergency Repair Factor), based on ASME B31G.

The results (POD and sizing accuracy) from the validation piece inspection, reflect the tool performance characteristics as described in chapter 3

Benefits of the large diameter phased array tool

In previous inspections, labor intensive preparations were required to tune the system to the specific product properties, which were not always known beforehand. This resulted in significant project complexity and cost, related to cleaning, drying, water supply, water treatment, etcetera. Due to the improved and flexible acoustic design of the phased array tool, this is not required anymore, because the acoustic properties of the tool can be calibrated and tuned to the specifics of the product in the pipe on-site.

Safety, flexibility and reduced operational risk

- For any pipeline of 20 inch ID and up, the system can be integrated in a single bidi body, similar to a cleaning pig.
- The system can be deployed as a bi-directional tool: a single access point can be used for deployment and retrieval.
- The small sensor head makes it possible to cope with tight bends, tees, reductions, etcetera.
- Simple, small pig launcher suffice.
- Phased array technology increases flexibility to multitude of products and product types (heavy and light crude, diesel, naphtha, etc.)
- Optional availability of optical fiber for data communication during the inspection run: the data can be reviewed for position information and quality assurance: inspection parameters can be fine-tuned.

Time efficiency

- Inspection in product is a significant time-saver for the out-of-service period of the pipeline.
- The tethered data collection allows for instant feedback on the inspection quality, which allows for swift insight in the success of an inspection run.

Cost effectiveness

- Intero LDUT makes it economically feasible to even pig short and difficult to pig pipelines.
- Due to the capabilities of the tool to inspect in product, cost are reduced significantly.

Environmental

- No water usage, less cleaning, waste water (treatment), etc.

Quality

- Despite the fact that the inspection was executed in crude oil, the inspection performance on the validation spools was improved, compared to historic verification runs with a conventional tool in water.

Findings

A large diameter inspection tool has been developed based on the internal rotating mirror principle that allows the pipe to be investigated 360° enabling to establish both the measuring grid and beam profile according to the inspection requirements.

The tool brings many benefits, robustness, flexibility (short-radius bends, offtakes) and versatility (product independency: any fluid). A tool with bi-directional capabilities in a cleaning-pig formfactor which can be deployed in a cost-effective manner for short and difficult to pig pipelines.

The probability of detection and sizing accuracy has been validated, both by simulations and pull-tests. This has been confirmed on a real-life project.

All metal losses, represented by FBH's, were detected in all the runs. The a90/95 is established at 10.5 mm for hemispherical bottom holes.

Competing interests

The authors declare that there is no competing interest regarding the publication of this paper.

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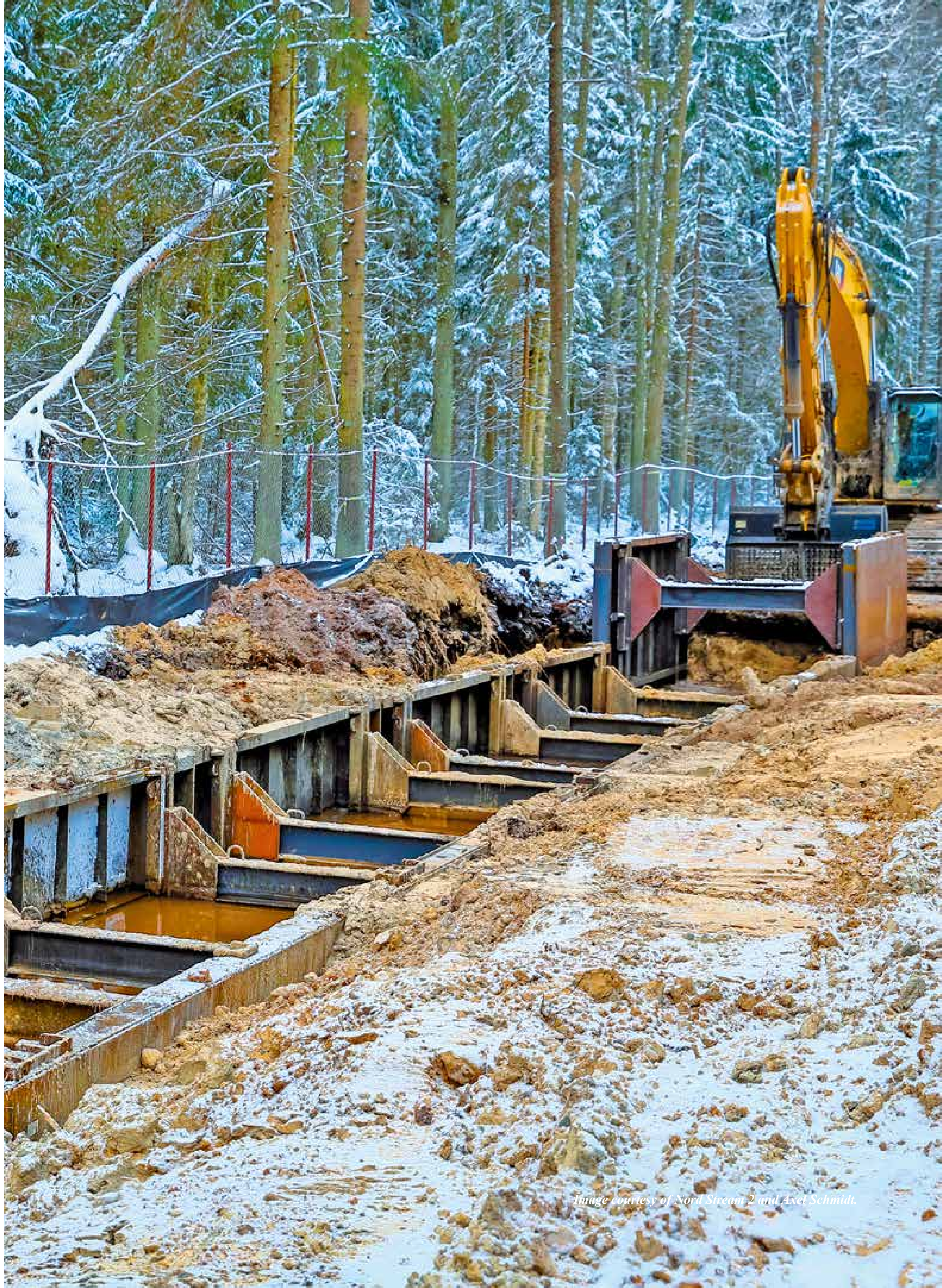

Image courtesy of Nord Stream 2 and Axel Schmidt.