REVIEW OF LESSONS LEARNED FROM 10 YEARS OF ULTRASONIC INSPECTIONS IN GAS PIPELINES

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1. ABSTRACT

In the early 21st century, a team of researchers in DNV (Norway) developed an ultrasonic technology for the inline inspection of gas pipelines without using a liquid batch. The technology has subsequently been used to inspect more than 15,000 kilometres of operational gas and liquid pipelines around the world.

The authors are presenting a review of lessons learned during the deployment of this new technology and reflecting on the advantages and limitations.

A summary is presented of validation work completed, both through pull testing and field excavations.

Several different use cases are considered; one being deployment of acoustic resonance ILI for the base line inspection of newly constructed gas pipelines. In particular, the others will highlight a number of long-distance gas transmission pipelines that have been inspected using acoustic resonance ILI, and highlight the benefits of ultrasonic baseline for pipelines.

Furthermore, the tools have shown notable flexibility in the field of difficult-to-inspect gas and liquid pipelines. Notably, large diameter variations have been traversed, and bidirectional inspections have been performed, as well as extremely long duration runs.

A summary of completed work will be of value to all pipeline operators of challenging pipelines, in particular offshore, demonstrating challenging pipeline inspection projects which have been completed successfully.

2. INTRODUCTION

10 Years after the successful qualification of Acoustic Resonance Technology (ART) for inline inspection, the authors look back on its achievements. Amongst the major milestones are 15,000 km of inspected pipelines, the longest ultrasonic inline inspections ever completed, and fleet expansion from 10" to 56" in diameter. The authors present a summary of achievements, combined with a brief description of the technology. This is followed by an overview of feature detection and identification capabilities. Finally, the authors will demonstrate how the tool can manage varying pigging and inspection challenges, and lessons learned on pipeline medium.

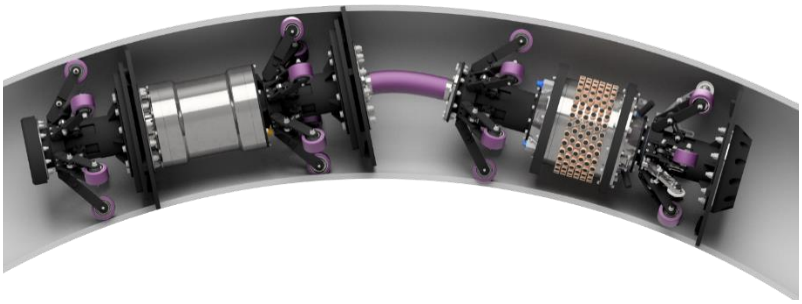

Figure 1 Typical In line Inspection tool, showing batter vessel to the left, and sensor vessel to the right.

3. HISTORICAL BACKGROUND

Acoustic Resonance Technology was the common method for wall thickness measurement in the age of analog electronics. Before the onset of digital electronics and low-cost digital timers, it was easier and more cost-effective to detect resonance than time-of-flight. As a result, many of our great engineering achievements were completed with the support of acoustic resonance NDE equipment, such as the Vidigage shown on the image below:

Figure 2 Branson Instruments Vidigage device, image taken from their brochure

Please note the three resonance peaks in the frequency spectrum, which we will discuss below. Since the 1970's, time-of-flight ultrasound became the method of choice for wall thickness measurements, a change that was largely driven by the cost-efficiency of the electrical circuitry.

The basis for the acoustic resonance technology inline inspection technology was developed at DNV, while developing a shallow seismic technology for shipwreck inspection. Initially, the application was launched as a hull inspection technology for vessels. The application for inspection of pipelines was developed once it was confirmed that compressed gas is a suitable coupling medium for ART.

With the support of a large Norwegian gas pipeline operator, the acoustic resonance technology was deployed on an inline inspection tool and validated through in-service qualification runs. The process followed standard TRL qualification steps, from limited prototype, bench-top testing and deployment of a full tool in operational pipelines. The first ART Scan^{TM} tool was successfully qualified in 2014, driving the authors to review 10 years of commercial deployment, lessons learned and a summary of achievements.

4. TECHNOLOGY DESCRIPTION

The first step of acoustic resonance measurement of the wall thickness is the emission of a wide-band acoustic waveform towards the target, as shown in the figure below. The waveform excites numerous standing compressional waves between the two surfaces of the pipe wall. All oscillations can be characterized by the integer number of half wavelengths per plate. For the fundamental, or first oscillation, the plate thickness corresponds to one half wavelength [1].

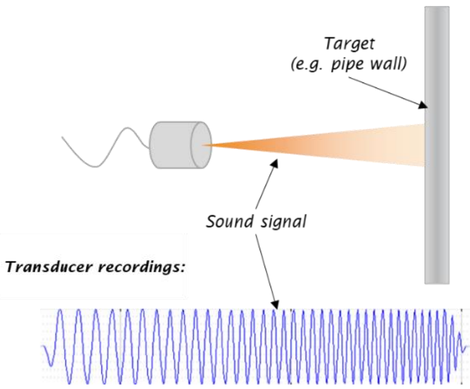

Figure 3 Emission of Wide Band Ultrasound Wave

The second step in the process is the detection of the returning signal. This returning acoustic energy signal is generated by the standing compressional waves inside the pipe wall, which acts as a source of acoustic energy after the initial wide-band waveform has passed. The resonance pattern emitted from the pipe wall (see figure below) is referred to as the resonance tail.

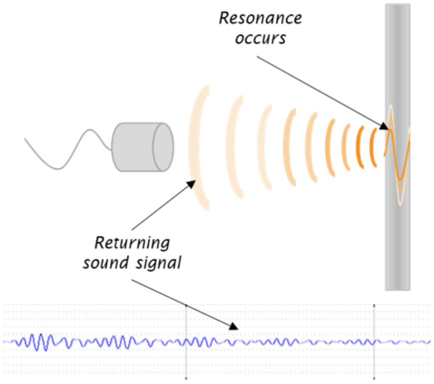

Figure 4 Emission of Resonance Tail

Recording the entire resonance tail allows for identification of the resonance frequencies. Through the estimated compressional speed of sound in the pipe material, the half wave resonance frequency provides an accurate measurement of local pipe wall thickness. Furthermore, additional higher order harmonics of the half-wave resonance frequency provide additional confidence in the initial measurement.

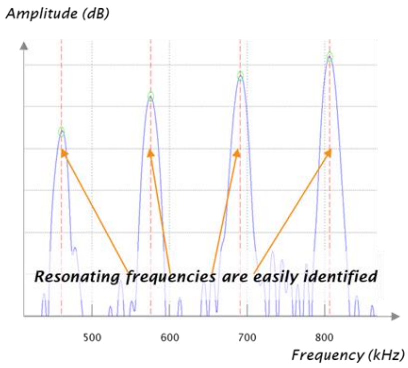

Figure 5 Identification of Resonance Frequencies

In the ILI application, the ART transducers are positioned away from the pipe wall, sending a wavefront to the pipe wall using the pressurized gas as a coupling medium. Amplification of the signal inside the pipe wall (as result of the resonance phenomenon) allows for sufficient signal strength to use ultrasound with gas a coupling medium.

5. CAPABILITIES OF ACOUSTIC RESONANCE TECHNOLOGY

The most obvious advantage of acoustic resonance in the pipeline inspection is the ability to perform an ultrasonic wall thickness measurement in gas pipelines.

Acoustic resonance, when deployed on an ILI platform, allows for the direct measurement of wall thickness of gas pipelines. The accuracy of the wall thickness measurement is ±0.4 mm (at 90% confidence), which is the same accuracy achieved with typical ultrasonic ILI tools in liquid pipelines.

When compared to typical MFL specification (depth sizing ±10%), it should be noted that ART is significantly more accurate in higher wall thickness spools, which are commonly used in the construction of offshore pipelines. The below chart shows a comparison in accuracy:

Wall Thickness	20 mm	25 mm	35 mm	40 mm
MFL Depth Sizing Accuracy (10% WT)	± 2.0 mm	± 2.5 mm	± 3.5 mm	± 4.0 mm
ART Depth Sizing Accuracy	± 0.4 mm	± 0.4 mm	± 0.4 mm	± 0.4 mm

Figure 6 Comparison of Depth sizing accuracy of ART vs MFL

The accuracy in feature depth sizing is beneficial to estimate corrosion growth rates, allowing for increased intervals between inspections, and ultimately leading to improved pipeline safety.

Moreover, the above depth sizing accuracy is not related to tool speed, so acoustic resonance can be used to inspect heavy wall gas lines at much higher velocities than MFL, reducing the need to reduce production.

5.1 Mid Wall Features / Laminations

Besides the improved accuracy of ultrasonics, ART detects mid-wall features which are not visible to magnetic ILI tools. One example would be laminations, which are attracting increased attention in gas lines given their integrity challenges with emerging fuels. Below screenshots show c-scan data of wall thickness (top) where the indicated area shows (sloping) laminations. The wall thickness reading indicates the offset between inner pipe surface and the location of the lamination.

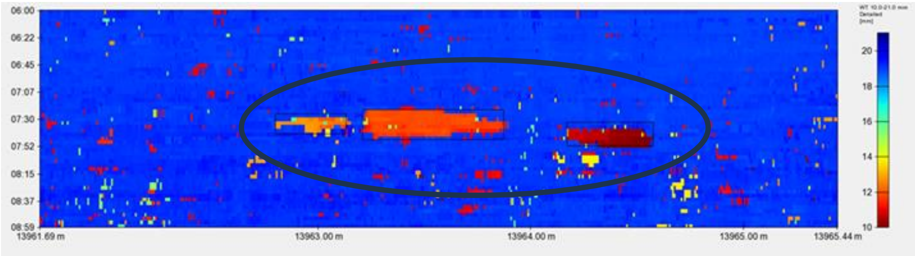

Figure 7 Lamination Example A

The above example 'A' shows a very abrupt change in a wall thickness, being typical for laminations, and not common for corrosion features. Of the three features, a change in wall thickness readings can be observed (from left to right), indicating these laminations are sloping. Positive identification of lamination features is possible through analysis attenuation of resonances, which is much lower in the case of laminations. A clear example of this identification is shown below in Example B.

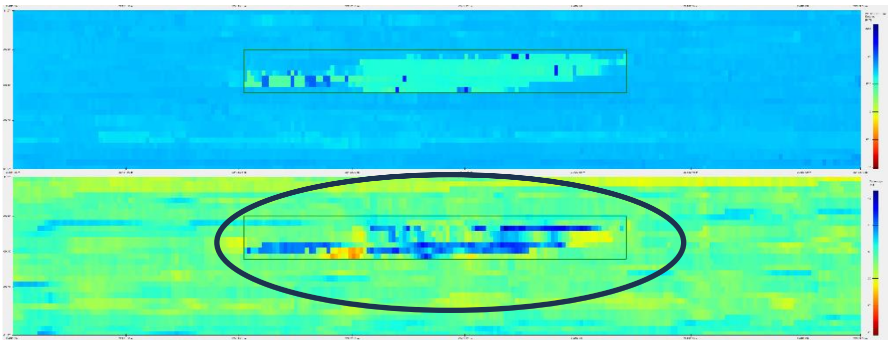

Figure 8 Lamination Example B

The lamination shown above includes 2 screenshots. The above c-scan shows wall thickness, the lower c-scan shows signal attenuation. Clearly seen in the feature area is a reduction in attenuation, which is typical for laminations. This characteristic is very distinctive for laminations and used to positively classify laminations from other features.

5.2 Corrosion Resistant Alloy (CRA)

Inspection of gas pipelines with corrosion resistant alloy (CRA) liners has become much easier with ART. Where the CRA is metallurgically bonded (hot roll-bonded) the tool measures the combined wall thickness of the carbon steel and the CRA liner. The c-scan below shows data captured in a live gas pipeline. The confirmed wall thickness of the line is about 37 mm.

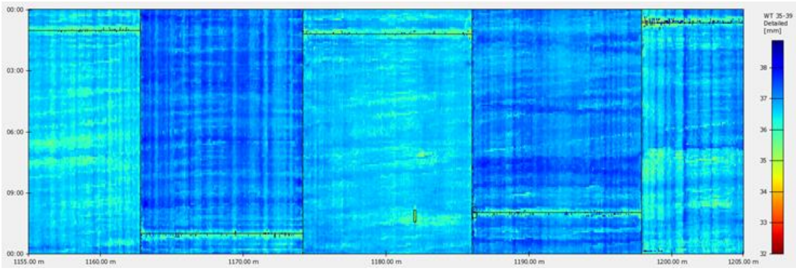

Figure 9 C-scan of Carbon Steel Pipeline with CRA Liner

When operating CRA lines, usage of ultrasonic inline inspection tools is the clear choice to get detailed information about the integrity of the line. With acoustic resonance, this can now be done in liquid as well as gas pipelines.

Materials used on the ART Scan ILI application are very suitable to CRA, since the contact points on the pipeline (cups, discs, wheels) are all non-metallic, thereby avoiding any risk of galvanic corrosion.

5.3 Paraffin and wax

ART Scan is often used to inspect crude oil pipelines, particularly those that have a high wax-content, due to the absorption spectrum of paraffin, shown below.

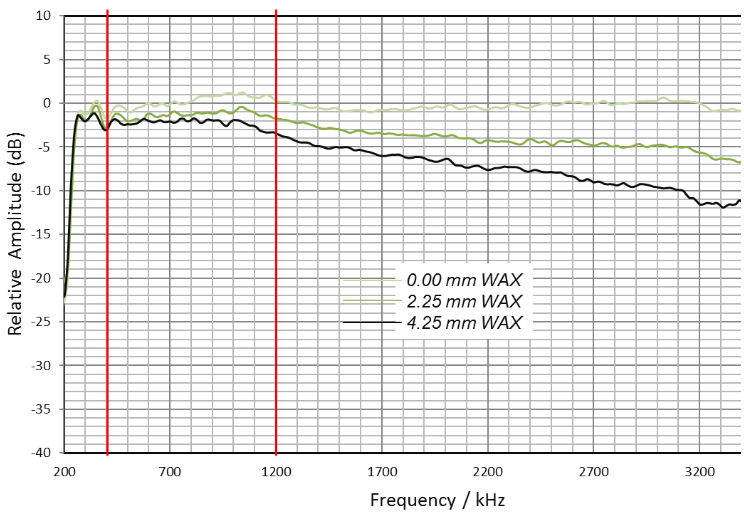

Figure 10 Absorption Spectrum of Ultrasound in Paraffin

The red bars indicate the operational range of Acoustic Resonance Technology, which ranges from 400 kHz to 1.2 MHz. These relatively low frequencies experience very low attenuation in paraffin. As such, ART Scan tools can record wall thickness even through layers of paraffin (wax) on the pipe wall. The images below show a test piece with 3 machined features, covered in a layer of paraffin. The deepest feature is covered with 17 mm of paraffin (wax).

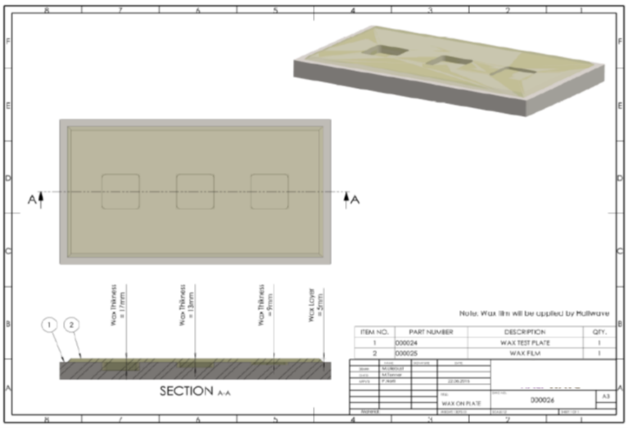

Figure 11 Test Plate with Paraffin Layer Applied

The c-scan below indicates that wall thickness is recorded continuously throughout the area covered with wax, even through 17 mm of paraffin:

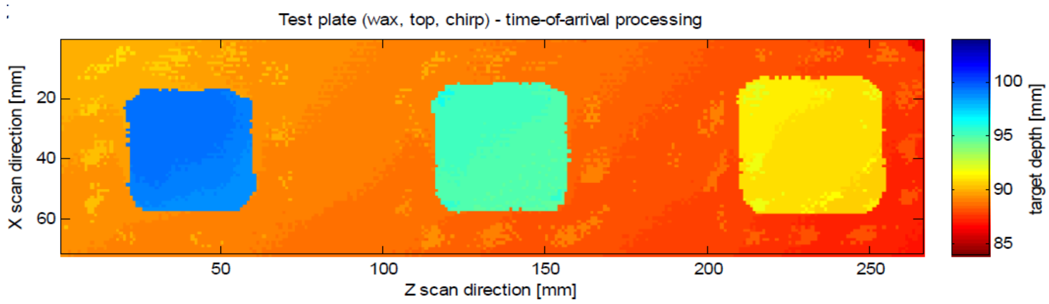

Figure 12 Feature Depth Sizing through layer of Paraffin

Multiple inspections have been completed in crude oil lines with various levels of paraffin (wax) deposition on the pipe wall. These inspections have shown that ART Scan tools can read wall thickness with some level of wax on the inside of the pipe wall. A screenshot from collected data is included below:

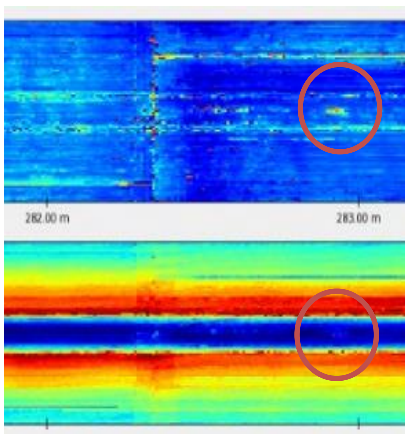

Figure 13 C-scan of Wall Thickness (top) and Depositions (bottom)

As seen in the screenshot data in the figure above, wall thickness data (top c-scan) is collected through a layer of deposits (bottom c-scan) shown in blue. Please note the ART tool has detected corrosion under this wax deposit (shown in the circle).

6. ACOUSTIC RESONANCE VALIDATION

The acoustic resonance ILI tools have been extensively validated through the years. Validation typically includes pull-testing the tools through pipe spools with machined features. A comparison is made of the measured and as-built feature sizes. Measurement specifications for the acoustic resonance technique have been derived through these validations.

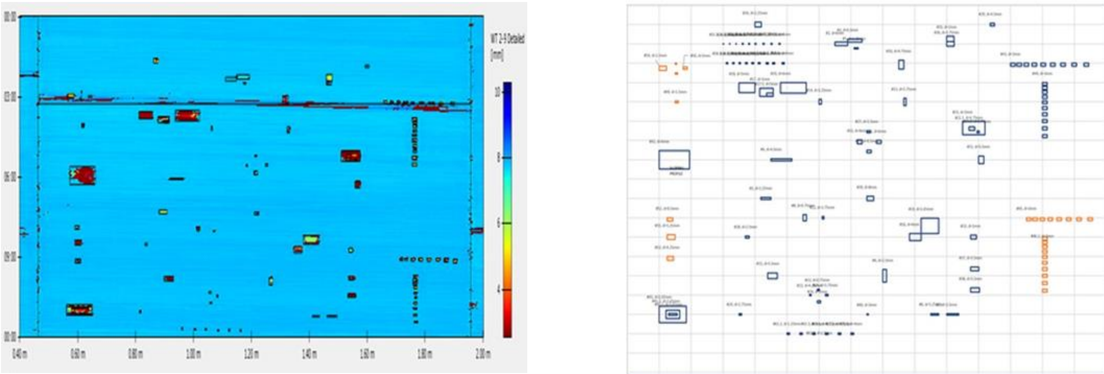

Figure 14 C-scan (left) and As-Built Drawing (right)

The feature spools shown above show a relatively large number of features, including feature-in-feature examples, and a sloping lamination. All are clearly detected and sized, both for internal and external features.

7. PIGGING CHALLENGES

Pipelines are typically designed and constructed with pigging in mind, although exceptions occur. Fortunately, acoustic resonance ILI tools can overcome many of the pigging challenges due to a combination of low tool drag and superior bore passing.

7.1 CHALLENGING FEATURES

Wye's, Tee's and non-return valves have been successfully navigated with ART Scan. Beyond this, the technology has been applied in multi-diameter pipelines (20x24, 24x30, 18x26, 16x24 and more). In multi-diameter pipelines, maintaining drive in all sections is crucial. For this reason, the tools are designed to run on centralizing wheel sets, shown below:

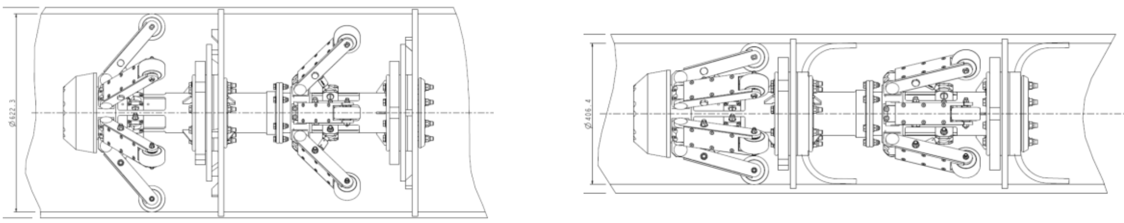

Figure 15 ART Tow section in 24" (left) and 16" (right) sections

The wheels carry the weight of the tool, reducing wear on the polyurethane package, and allowing for lighter discs. Care must be taken for the over-size discs not to wear excessively in the smaller bore sections. For this reason, buckle inducers can be used. Pull and pump trials confirm collapsibility and sealing throughout the line. An example of a pump-trial setup is shown below:

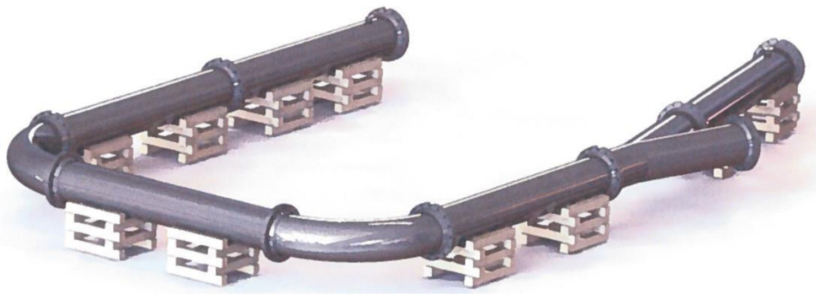

Figure 16 Pump Trial Setup including diameter change and Wye passage

Pump trials are completed for all challenging pig runs, including multi-diameter pigging and wye crossings, as well as bidirectional runs.

7.2 Managing Polyurethane Wear

Running the tools on wheels also allows for very long-distance runs. The photograph below shows an acoustic resonance ILI tool at the receiver site, after completing a 900+ kilometre run in Europe. The overall wear on the discs is extremely low.

Figure 17 ART Tool at receiver site following 900+ kilometre run

As a result of exceptionally low power consumption for the ART electronics, a 900 km run is completed with a single battery unit, in one single pass.

What also helps in reducing the wear is tool rotation, since discs are likely to wear more at the 6 o-clock position, even with centralizing wheels. To achieve constant rotation, the wheels are mounted on the tool at an angle, resulting a constant rotation as the tool passes through the line. This rotation is recorded with the inertial measurement unit, and reviewed to prove functionality of this design. A rotation chart is included below, where the tool makes one full rotation in less than 200 meters:

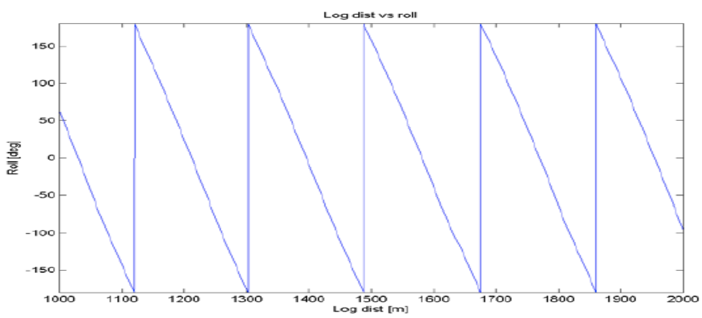

Figure 18 Tool Rotation Plot

7.3 Managing Elevation Changes

Low differential pressure and drag also ensure constant velocity when traversing elevation changes. In one of the ART Scan qualification runs, the tool passed under 3 fjords, shown in the elevation chart below:

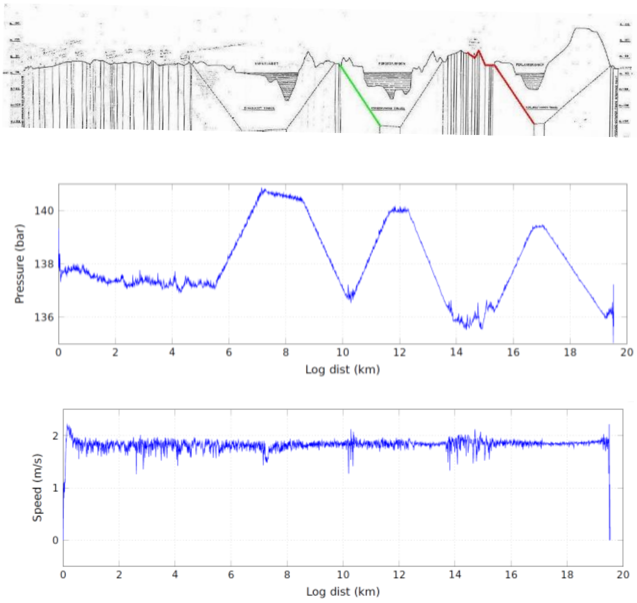

Figure 19 Elevation changes and speed profile

Each of the fjord crossings represent an elevation change of about 400 meters in about 1,000 meters horizontal travel (40% slope). The elevation change results in about 4 Bar increase in line pressure as a result of the static head. The third and lowest chart shows the ILI tool speed during this entire crossing which remains nearly constant at 2 m/s.

Similar tool run behaviour is observed at mountain crossings (no speed excursions) as well as offshore inspections when passing through fixed risers as well as steel catenary risers.

7.4 Variable Bypass Speed Control Unit

For lines that run at high velocities (above 3 m/s) the ART Scan tools can be combined with a speed control unit. This unit uses a variable bypass valve to maintain a constant tool speed. This unit can be combined with an ART Scan tool, but is also capable of running stand-alone. Following common industry practice, the units have 2 individually controlled valves to maximize reliability. The unit shown below is built for 24" lines and currently going through a qualification program. It will be released for commercial services in 2024, while other sizes will be made available soon.

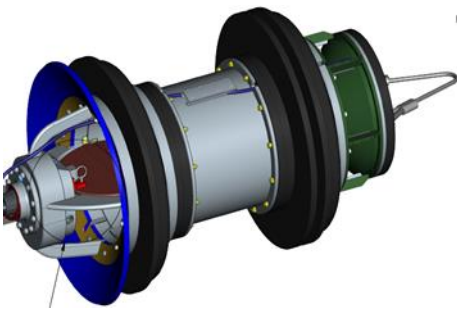

Figure 20 Variable Bypass Speed Control Unit for Gas Pipeline ILI

7.5 Bidirectional inspections

Bidirectional operation can be challenging for inline inspection tools, we note that several projects have been completed successfully, using ART Scan tools modified for bidirectional operation. One tool is shown below, which was used for a bidirectional inspection of the beach crossing of a 42" pipeline. Another bidirectional application is the inline inspection of risers of pipelines not designed for receiving pigs subsea.

Figure 21 Acoustic Resonance ILI Tool for 42" Bidirectional Inspection

7.6 Tool Sizes

Meanwhile acoustic resonance ILI tools have been constructed for various diameters, from small to large. Two examples are included below. On top: the smallest ART Scan tool built to date, a single-body in-line 14" inspection tool at just over 700 mm long. In the lower image: the largest tool in operation today, for the inspection of 48" pipelines.

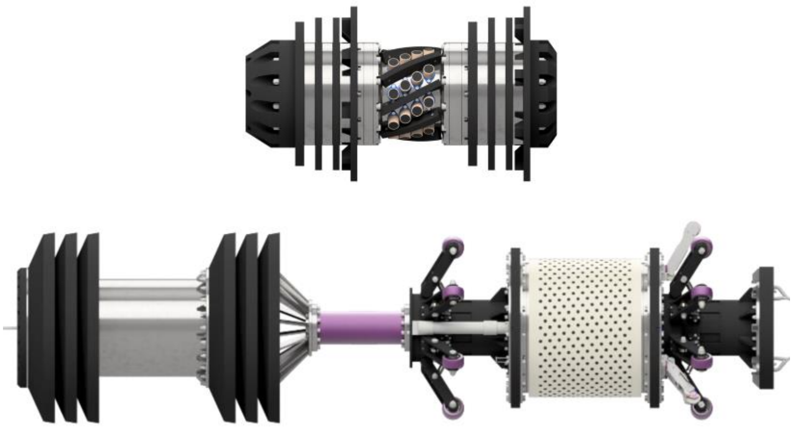

Figure 22 Smallest (top) and Largest (bottom) ART Scan Tools

8. PIPELINE MEDIUM

Pipeline medium is a critical parameter for all ultrasonic ILI tools, and acoustic resonance tools form no exception to this rule. Using resonance, ART can overcome the large acoustic impedance mismatch between the pipeline medium and pipe wall, but the tools are not immune to medium influences.

Several parameters are analysed to confirm pipelines are within the operational envelope of the ART Scan tools. Gas pressure is the leading parameter, a minimum pressure of 50 Bar is needed to couple sound into the pipe wall, if all other conditions are ideal. All tools are rated to 250 Bar operating pressure by default, some tools have been modified to run in higher pressures of 300 or even 500 Bar.

Gas composition plays a role, so this is carefully analysed during the initial assessment of each project. In this assessment ratio between lighter (C1) and heavier molecules (C2, C3, C4) is a key driver, trace elements of other molecules are also included in the assessment.

Other parameters to review are internal flow coating and external pipeline coating. Internal FBE flow coating improves the acoustic signal strength. Typical modern pipeline coatings (3LPP, 3LPE, CWC) are ideal for ART Scan, since they cause very low levels of signal attenuation.

Sour service can be managed by ART Scan, H_2S levels of 5% (50,000 PPM) have been seen and do not cause issues, although springs are replaced between runs.

Sometimes analysis shows the line conditions are not suitable to generate resonances in the pipe wall. In those cases, it will be possible to report all internal corrosion features based on the time-of-flight signal. This application has proven popular with offshore pipeline operators to inspect low pressure gas pipelines (5 – 25 Bar). Offshore pipelines are known to have a very low likelihood of external corrosion features. ART Scan tools will run at constant speeds even with very low back pressure, whereas MFL tools would experience speed excursions due to high drag caused by the magnets. This is another example of the wide operational envelope of ART Scan.

9. CONCLUSION

Acoustic resonance has become the go-to technology for long-distance gas transmission pipelines, for which the technology was initially developed. Operators of major gas pipelines have consistently used ART Scan for baseline services as well as in-service inspections, replacing magnetic flux leakage.

In parallel, we note that the tools have been adopted by operators of multi-diameter pipelines, especially for offshore applications. The safe and reliable navigation of diameter changes, wyes, and the ability to inspect through paraffin (wax) proves ART is the preferred and low-risk option for these lines.

Meanwhile we note a large number of inspections performed for underground gas storage facilities, both in Europe and North America. These lines are typically designed to handle the maximum reservoir pressure, leading to high wall thickness, and pushing them beyond the operational envelope of magnetic technologies.

Given this wide range of applications, it can be concluded that ART Scan has grown to be the key technology for challenging pipeline inspections around the world. The technology has earned a place in the market in the first 10 years of operations and will continue to deliver value to operators.

10. REFERENCES

[1] Vos et al, "Application Of Wide-Band Ultrasound For The Detection Of Angled Crack Features In Oil And Gas Pipelines", IPC 2018, Calgary, Canada