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Ultrasonic detection of stress corrosion cracks in pipe samples in gaseous atmosphere

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***Abstract*—Stress corrosion cracking (SCC) is a serious threat to gas pipelines. Current in-line inspection tools have issues with the detection and sizing of small cracks. Advances in gas-coupled broadband ultrasound enable new detection methods based on Guided Ultrasonic Waves (GUW). Recently, the potential to detect SCC using Halfwave's ART Scan® tool was successfully demonstrated on real pipe samples with SCC, submerged in water [1]. In this study, the ultrasonic detection of SCC is experimentally demonstrated, using pressurized gas at 60 bar as acoustic coupling medium. A custom-made test scanner with 32 transmit/receive channels was developed to perform circumferential scans of 425 mm $\times$ 60° from the inside of pipe samples of diameters close to 36 inches. The gaseous atmosphere of 60 bar (nitrogen) required the experiments to be conducted inside a pressure tank that contained both the test scanner and pipe samples. Broad-band pulses were transmitted, and signals were received from all scan positions. Processed parameters like spectral power and wall thickness estimates were calculated. 2D plots of processed parameters and reconstructed image results demonstrated the detection and sizing potential for real cracks, crack fields, and other surface irregularities.**

***Index Terms*—ultrasonic inspection, guided waves, crack detection, pipeline inspection, NDT**

I. Introduction

Most gas pipelines are buried and thus subject to underground conditions. The combination of a corrosive environment and tensile or hoop stress may develop stress corrosion cracking (SCC) in carbon steel pipes. SCC is a challenge in integrity management of underground gas pipelines.

Current in-line inspection technologies that are used for crack detection in gas have the requirement that the sensor is adjacent to the pipe wall and have limited sensitivity and sizing capabilities for small cracks. Therefore, there is a demand for a more sensitive, precise, robust and cost effective in-line inspection crack detection method.

Advances in gas-coupled ultrasound provide a potential method based on GWU, which have proven useful in NDT. Recently, the potential to detect SCC based on Halfwave's ART Scan® tool was successfully demonstrated on pipe samples with real corrosion cracks, submerged in water [1]. Processing resulted in 2D plots from a circumferential scan, which displayed the location of crack and pitting corrosion areas. The objective of this work is to experimentally demonstrate the ultrasonic detection of real SCC in pipe samples using pressurized gas at 60 bar as acoustic coupling medium, based on Halfwave's ART Scan® tool [2].

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II. Methods

The experimental test set-up has been designed to investigate the detection potential of SCC from inside 36" and 38" pipe samples in gas (nitrogen) at 60 bar. For this purpose, a custom-made scanner was manufactured to allow mechanical scanning inside a high-pressure chamber. The scanner head consists of 32 broadband ART Scan® gas transducers; 2 transmit (Tx) transducers and 30 receive (Rx) transducers. In this work only one Tx channel (13) is used. Fig. 1 displays a picture of the scanner head.

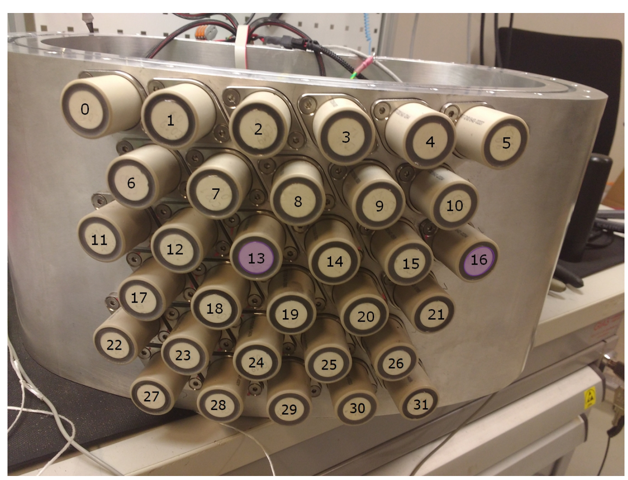

Fig. 1. Scanner head containing 32 broadband gas transducers, of which two dedicated transmit channels (13 and 16).

The scanner head could mechanically translate and rotate to perform circumferential scans of 425 mm × 60°. Scans were performed internally in the pipe with a stand-off distance between the transducers and the pipe wall of approximately 60 mm. Maximum scan resolution was 0.5 mm × 0.2°. The experiments at pressures of 60 bar were conducted inside a pressure tank that contained both the test scanner and pipe sample (see Fig. 2). Pictures of the experimental set-up in the pressure chamber at the Norwegian Underwater Institute are depicted in Fig. 3.

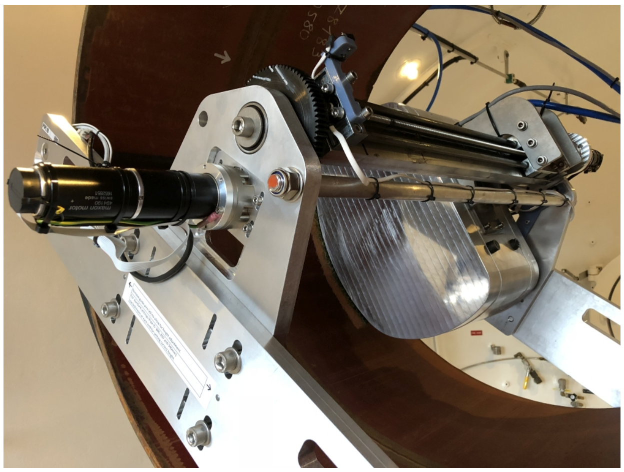

Fig. 2. Set-up of the test scanner inside a pipe sample.

The test subjects consist of two pipe samples with different diameters and different defect types, including SCC. Crack areas were identified prior to the experiments and the maximum depths of some cracks had been measured using time-of-flight diffraction (TOFD) before the scans. Table I summarizes some pipe sample characteristics and states the maximum measured crack depths. The 38" pipe sample has a spiral weld. The crack area of interest of this pipe is near the girth weld.

Fig. 3. Picture of the set-up inside the pressure chamber (left) and of the pressure chamber at the Norwegian Underwater Institute (right).

At all scan positions, broad-band chirp pulses were transmitted from channel 13, covering the 400–1100 kHz frequency range. Acoustic waves propagated through the pressurized

TABLE I
TEST SPOOL SAMPLE CHARACTERISTICS AND DIMENSIONS

Test sample	**Inner diameter**	**Wall thickness**	**Maximum crack depth**
36" pipe sample	889 mm	12.7 mm	4.6 mm (∼36%)
38" pipe sample	940 mm	13.0 mm	2.8 mm (∼22%)

gas to the pipe wall, partly propagated along the pipe wall as GUW, and leaking back into the gas, where they were detected by multiple receive transducer. Signal processing was applied to extract different parameters; wall thickness estimates, summed RF power, and spectral power. The spectral power is a power sum within a specified time window and over a narrow frequency range (<100 kHz) around the center frequency of a GUW of interest. These different processed parameters were then displayed as a function of their scan position. This type of processing of individual received signals is here referred to as point-wise processing.

The other processing type we used is image formation processing using a tomographic reconstruction algorithm. This represents an attempt to reconstruct higher resolution images from point-wise processed data. Details of the used approach are reported in [3].

III. RESULTS

A. *Point-wise processed parameter plots and detected defects*

Different processing methods were applied to find sensitive and specific parameters that could lead to robust detection of crack-like defects. A comparison of two processed parameters of a scanned area of the 36" pipe sample that includes stress corrosion cracks, is presented in Fig. 4. The left plot depicts the outer surface of the pipe section where SCC areas have been made visible by powder treatment. The dashed lines mark cracks and crack fields, and a solid ellipse marks a pitting corrosion. The maximum depths of the two isolated cracks below the girth weld is 4.3 mm, corresponding to approximately 35% of the pipe wall thickness. Fig. 4 plots the spectral power (center) and the thickness estimates (right) from Rx channel 19. The horizontal structure centered around $x \approx 170$ mm corresponds to the location of the girth weld. The areas with reduced power (center) and reduced wall thickness estimates (right) on the right side of the scan (around $y \approx 25°$) correspond to locations of cracks, crack fields and pitting corrosion. The spectral power shows up to 20 dB lower signal levels for SCC affected regions.

B. *Pressurized gas versus water*

In a previous study [1], where water was used as the acoustic coupling medium, the same 36" pipe was scanned. Fig. 5 displays the summed RF power as acquired in gas (left) and of an overlapping area in water (right). The scan parameters were not identical, however, the observed similarities are evident. This result suggests good reproducibility and increased confidence in the experimental results in pressurized gas.

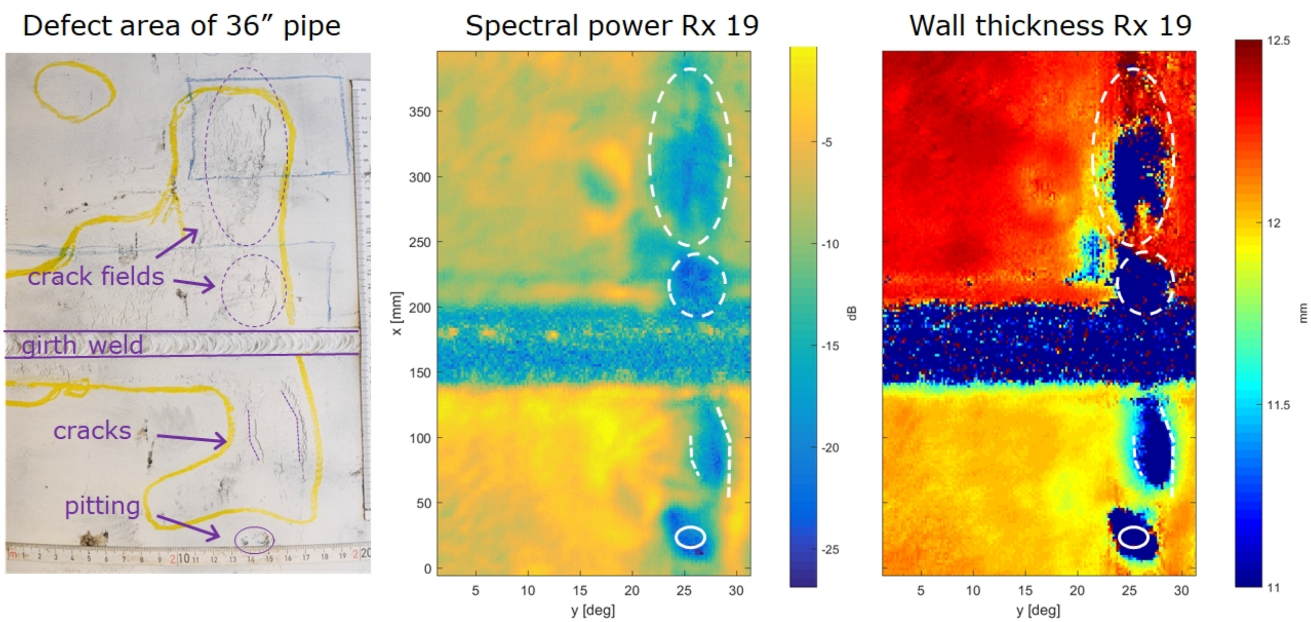

Fig. 4. Side-by-side comparison of a picture of the scanned are of the 36” pipe sample with marked defects (left) and processed spectral power (center) and wall thickness estimates (right) from channel 19 from the same area.

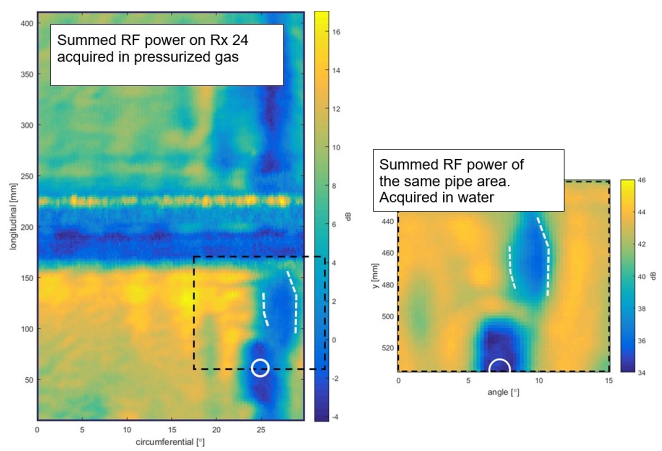

Fig. 5. Summed RF power plots from the 36” spool acquired in pressurized gas (left) and in water (right). The scan area in water has been smaller than in gas and is approximately marked by the dashed rectangle. The approximate locations of the 4.3-mm-deep crack and pitting corrosion dent are marked in white.

C. *Defect sizing using a tomographic inversion algorithm*

Initial sizing of detected defects inside the scanned area of the 36” pipe is based on tomographic inversion [3], applied to point-wise processed spectral power plots. The inversion algorithm converged on the result shown in Fig. 6 and combined information from eight transducer pairs with different relative orientations. Bright yellow parts of the image indicate high attenuation, while dark blue indicate no attenuation. The pitting and the crack below the girth weld match particularly well with the observed defects. Furthermore, the resulting image indicates that there is a noticeable improvement in spatial resolution over the point-wise processed source images (see e.g. center plot of Fig. 4). This can be expected since the inversion result compensates for the effects of the finite acoustic beam width and the projected distance between the Tx-Rx transducer pairs, which makes reconstructed defects look smaller than in point-wise processed plots.

TABLE II
COMPARISON OF REAL AND ESTIMATED DEFECT CHARACTERISTICS OF THREE SELECTED DEFECT AREAS

	Measured		**Estimated**	
defect type	**max depth**	**size**	**relative attenuation**	**size**
two cracks	4.3 mm	15 and 37 mm	86%	34×8 mm
pitting	–	14×9 mm	100%	10×8 mm
crack field	3.7 mm	60×40 mm	73%	88×28 mm

The estimated dimensions of three selected defect areas are based on a threshold set at 60% of the maximum reconstructed attenuation value from Fig. 6, and are displayed in Table II. These estimates based on tomographic inversion are within reasonable accuracy as compared to the measured dimensions.

D. *Cracks near the girth weld*

SCC close to the girth weld of the 38” pipe sample is shown in Fig. 7 with a photo of the spiral welds (top) and the corresponding spectral power plot (bottom). Some areas with low power around the girth weld that could be marked as suspicious areas are indicated with white arrows. These areas correspond to regions with both circumferential and small axial cracks. Fig. 7 therefore suggests the potential to detect significant cracks near a girth weld.

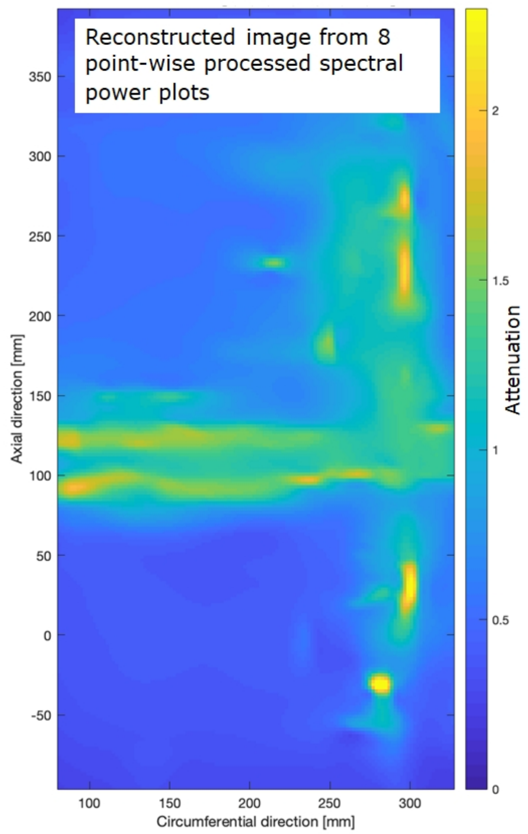

Fig. 6. Tomographic inversion result of combining spectral power plots from 8 receive channels surrounding 1 transmit channel.

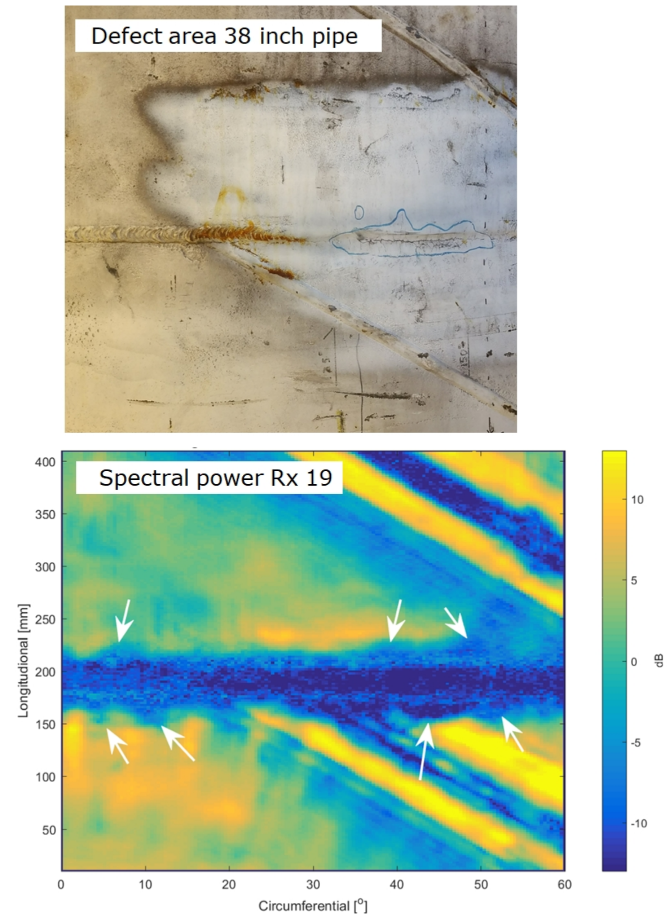

Fig. 7. Side-by-side comparison of the scan area of the 38" pipe (top) and the corresponding time windowed spectral power (bottom).

IV. Discussion

Despite a more challenging acoustic propagation in gas as compared to water [1] these results demonstrate the crack detection feasibility in gas using perpendicularly oriented transducers with respect to the pipe interior. Moreover, all 30 Rx channels were able to detect acoustic signals from GUW propagation well above the noise level.

The combination of GUW theory and experimental data analysis resulted in the use of narrow band spectral power analysis around a resonance frequency of interest. The time windowed power of these resonance modes appeared to be a promising parameter to detect cracks. Although we only showed spectral power plots around a single resonance mode, the spectral power of other modes are of interest too. Relative amplitude differences between these modes might be exploited in future work to distinguish between different defect types such as cracks, corrosion, and welds.

The size of cracks, in particular depth and length, can be expected to proportionally affect the propagation of guided waves. Therefore, it is expected that point-wise processed parameters (e.g. wall thickness estimates, spectral processing) will contain quantitative results that can be used to size defects. Initial tomographic image inversion results with point-wise processed data as input demonstrated the defect detection and crack sizing potential.

V. Conclusion

Experiments in pressurized nitrogen at 60 bar on pipe samples with real cracks demonstrated the potential to ultrasonically detect SCC using GUW with an ART Scan® based test set-up. Processed parameter plots showed significant differences at scan locations with isolated surface defects. Data from some Rx channels suggest to even detect suspicious regions near a weld. Initial image reconstruction results demonstrate the potential for the tested tomographic inversion approach for crack detection and sizing.

Acknowledgment

We thank our industry partners TransCanada, Fluxys, Open Grid Europe, and TENP for supplying relevant pipe samples.

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