Enhancing Subsea Pipeline Integrity: A Strategic Approach to Inspection and Management

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Abstract

Petrobras oversees more than 4,000 kilometers of subsea rigid pipelines across Brazilian offshore fields, where ensuring safe hydrocarbon transportation relies heavily on a robust integrity management (IM) program. This program involves periodic inspections, which pose significant challenges due to the insulating layers of these pipelines, obstructing external evaluations, and the random distribution of potential flaws along their length. Intelligent pigs remain the preferred inspection technology. However, approximately 50% of the global subsea pipeline network cannot accommodate in-line inspection (ILI) tools due to design constraints, including multi-diameter configurations, tight bends, and bifurcating Y-shaped junctions. Retrofitting these systems with pig launchers and receivers is frequently cost-prohibitive. This paper outlines Petrobras' inspection strategy aimed at advancing the IM of both piggable and unpiggable pipelines. Two categories of inspection tools—screening tools and localized tools—are currently being qualified for operations at water depths reaching 2,000 meters. Screening tools are engineered to scan entire pipeline lengths at speeds of at least 1 m/s, efficiently detecting and locating defects. Once potential anomalies are identified, localized tools are deployed to these specific areas to perform quantitative defect characterization, enabling precise fitness-for-service (FFS) assessments. For piggable pipelines, Petrobras integrates Direct Magnetic Resonance (DMR) technology into cost-effective cleaning pigs frequently deployed during routine maintenance. This approach allows deferral of intelligent pig runs when no defects are detected. For unpiggable pipelines, a distinct strategy is required. Remotely Operated Vehicles (ROVs) deploy external screening tools utilizing Metal Magnetic Memory (MMM) technology, capable of penetrating insulating layers to detect potential flaws. Localized inspection tools are further categorized based on defect type: corrosion defects or cracks. These tools are also applicable to piggable pipelines, enhancing defect characterization accuracy through cross-validation with intelligent pig data. This integrated inspection framework not only optimizes operational costs but also enhances diagnostic reliability, contributing significantly to the safe and efficient management of subsea asset integrity.

1. INTRODUCTION

Subsea pipelines are a cornerstone of offshore infrastructure, representing the most cost-effective and reliable method for transporting oil and gas across extensive distances [1]. In Brazil, offshore operations account for 96% of the country's total oil and gas production, with 5,909 km of subsea pipelines spread throughout its territorial waters [2]. This extensive network underscores the critical importance of pipeline integrity management (IM), given the potential consequences of failures, including production losses, explosions, human and environmental casualties, and pollution [4]. According to a DNV report [3], the failure frequency of pipelines can reach up to 4.8×10^{-4} per kilometer-year.

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Pipeline integrity can be defined as "the ability of a subsea pipeline system to operate safely while withstanding operational and environmental loads throughout its lifecycle." To achieve this, operators adhere to international standards, safety regulations, and industry best practices, developing tailored integrity management plans [1]. As highlighted by Amaechi et al. [5], IM systems are inherently complex and rely on multiple key components, including data gathering, risk assessment, integrity evaluation, and the implementation of mitigation measures. These plans must evolve continually to address unique operational and environmental conditions [5].

At Petrobras, the Pipeline Integrity and Inspection Plan for Rigid Pipelines (PIDR) serves as the foundation of its integrity management approach. However, inspecting subsea pipelines in deep and ultra-deep waters, where most of Petrobras' fields are located, poses significant technical challenges [6]. Pipelines vary widely in diameter, length, fluid type, operating pressure, wall thickness, manufacturing processes, coatings, and subsea environmental conditions. These variations introduce different failure mechanisms and life expectancy profiles, requiring a diverse range of inspection tools [1][5].

Traditional subsea pipeline inspections primarily rely on Remotely Operated Vehicles (ROVs) equipped with cameras for visual assessment and sonar-based tools for data acquisition. These inspections typically evaluate the cathodic protection system, anode consumption rate, external wall conditions, coating integrity, pipeline stability, displacement, and free spans [3][7][8].

While external damage can be assessed using ROVs, internal corrosion remains one of the most prevalent failure mechanisms [9]. Conversely, external corrosion is generally not a significant concern for subsea pipelines [3]. To monitor internal wall thickness losses, Intelligent Pipeline Inspection Gauges (PIGs) are employed. These devices, driven by fluid flow, enable rapid inspection over long distances. However, PIGs have limitations, including their inability to navigate tight bends, multi-diameter transitions, or Y-junctions, rendering certain pipelines unpiggable. In some cases, pipelines lack the required launchers and receivers, further complicating inspection [1].

Unpiggable pipelines also pose challenges for external inspection, as they often feature complex multi-layer coatings designed for corrosion resistance, abrasion protection, stabilization (e.g., concrete coatings), or thermal insulation. As the thickness and number of coating layers increase, inspection becomes more challenging. In many cases, coatings must be partially removed to enable external inspection, significantly increasing operational costs and vessel time. Consequently, there is a growing interest in developing external screening tools as viable alternatives for inspecting unpiggable pipelines [1][9].

Subsea pipelines are also susceptible to other failure mechanisms, including localized impacts (e.g., ship anchor strikes) and long-term issues such as buckling and fatigue [3]. Free spans—unsupported sections caused by soil erosion—are a notable fatigue risk. These free spans are prone to Vortex-Induced Vibrations (VIV), where ocean currents create cyclical vortex patterns, potentially causing

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periodic stress on the pipeline. Over time, this stress may result in fatigue cracking, which requires regular integrity assessments and inspections to prevent failures [10][11][12].
Fatigue damage typically progresses through crack initiation and propagation. Cracks may originate from material defects, welding processes, or operational conditions. Detecting cracks, especially those smaller than 1 mm in width, remains challenging with traditional inspection tools primarily designed for corrosion-related defects. As operational pressure demands increase, cracks pose a significant threat to pipeline integrity, highlighting the critical need for effective crack detection and quantification technologies [13].

This paper outlines Petrobras' two-step inspection strategy, designed to enhance the integrity management of rigid subsea pipelines. The strategy focuses on a combination of screening and localized inspections, enabling rapid assessment of pipeline conditions across extensive lengths. Screening tools identify potential defect zones, while localized tools perform detailed characterization, optimizing inspection time and operational efficiency.

The approach is categorized into two distinct strategies for piggable and unpiggable pipelines, each requiring specialized tools and technologies. A schematic representation of this strategy is shown in Figure 1, illustrating the integration of inspection techniques for improved integrity management outcomes.

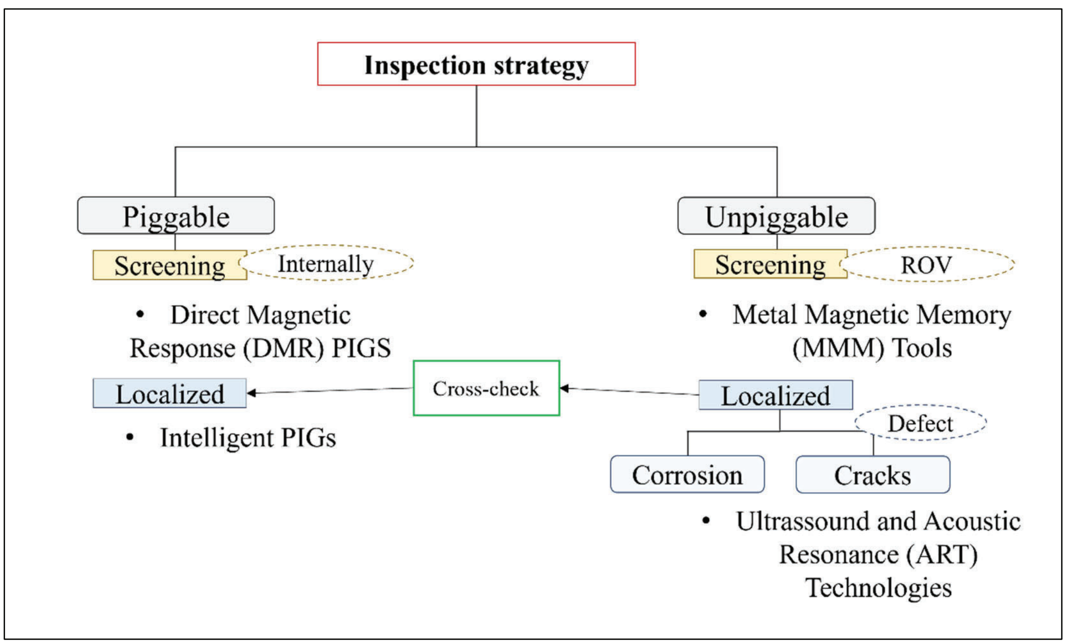

Figure 1. Schematic of Petrobras' inspection strategy for subsea pipeline integrity management

The pilot program includes pipelines from three different basins, encompassing 10 piggable and 10 unpiggable pipelines. It is expected that over 1,500 km of pipelines will be inspected using the

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qualified tools under this initiative. The selected pipelines feature various coatings, including concrete, HDPE, PP, and FBE, with coating thicknesses ranging from 3 mm to 50 mm. Pipeline diameters range from 6 inches to 18 inches, with operating depths reaching up to 2,000 meters.
The qualification of these inspection tools enables precise defect quantification, supporting accurate fitness-for-service (FFS) assessments and potential service life extensions for subsea pipelines.

2. PRE-QUALIFICATION PROCESS

Petrobras is leading a project aimed at qualifying inspection tools by inviting manufacturers to participate in a rigorous pre-qualification process. The primary objective is to assess whether each tool is capable of delivering reliable field services within Petrobras' subsea pipeline network. The pre-qualification process is divided into two distinct phases:

- **Phase 1 – Documentation Phase:**

In this initial phase, tool manufacturers are required to submit comprehensive documentation and detailed technical reports. These documents must provide evidence of the tool's previous operational performance, demonstrating its Technology Readiness Level (TRL) and overall suitability for subsea pipeline inspection tasks.

- **Phase 2 – Testing Phase:**

In the second phase, the tools undergo practical testing using specially prepared specimens provided by Petrobras. These tests aim to evaluate the tool's performance, reliability, and suitability for operational deployment in Petrobras' subsea pipelines.

Phase 2 Testing for PIGs

The testing process for Intelligent Pipeline Inspection Gauges (PIGs) consists of two primary assessments:

1. **PIG Loop Test:**
   - Testing takes place in a 14-inch PIG Loop provided by Petrobras, located in Pindamonhangaba, Brazil.
   - The test loop spans 100 meters in length and contains over 250 machined defects.
   - The system operates with freshwater and is equipped with controls for flow rate and fluid velocity.
   - The primary objectives of this test are to verify the Probability of Detection (PoD) and ensure the tool can maintain an inspection speed of at least 1 m/s.

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2. **Hyperbaric Chamber Test:**
    - The PIG is subjected to testing in a hyperbaric chamber located at Petrobras' Research and Development Center (CENPES).
    - The test simulates conditions equivalent to water depths of up to 2,000 meters, operating at 200 bar for 24 hours.
    - The goal is to confirm that the tool's sensors and electronic systems function effectively under high-pressure subsea conditions.

Phase 2 Testing for Localized Tools

Localized inspection tools, designed for corrosion and crack detection and typically deployed using Remotely Operated Vehicles (ROVs), were tested exclusively in the hyperbaric chamber under conditions mirroring 2,000-meter water depths (200 bar) for 24 hours.

- Petrobras provided two distinct test specimens, each tailored to simulate different operational scenarios.
- The crack detection tool was specifically tested using specimens with circumferential welds to evaluate its effectiveness in identifying and characterizing crack-like defects.

The strategies and technologies developed for inspecting piggable and unpiggable pipelines are elaborated in the following sections, detailing their implementation and expected outcomes.

Specimen	Nominal wall thickness (pol)	Length (mm)	Coating	Coating thickness (mm)
A	12	1200	3LPE	3
B	18	1010	PP	50

Figure 2. Properties of test specimens for localized tools testing.

PIGGABLE PIPELINES

According to Petrobras' standard N-1487 [14] for rigid pipeline inspection, each pipeline must have a well-defined inspection plan, specifying periodic inspection intervals and the most suitable inspection methods for each section. The standard emphasizes that Pipeline Inspection Gauges (PIGs) are the most effective tools for detecting and sizing defects in subsea pipelines.

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The Role of PIGs in Pipeline Integrity

PIGs are primarily employed for internal cleaning of pipelines, removing debris, wax, hydrates, and asphaltene deposits that can accumulate and obstruct fluid flow. These devices are launched into the pipeline at high speeds using hydraulic pressure from pig launchers. In addition to maintaining flow efficiency, regular cleaning PIG runs serve as an essential corrosion mitigation measure [8], aligning with Petrobras' integrity management protocols and NACE SP0106 guidelines [15].

Intelligent PIGs (Smart PIGs)

Beyond traditional cleaning tools, Intelligent PIGs (Smart PIGs) are advanced inspection devices equipped with sensors, data storage systems, and analytical capabilities [16]. These electronic tools gather and record critical data as they traverse the pipeline, detecting deformations, mapping pipeline positioning, assessing corrosion levels, and identifying cracks [7].

Smart PIGs enable a comprehensive integrity assessment by inspecting the entire pipeline length, offering greater precision than localized inspection tools, which can only evaluate specific pipeline sections. However, deploying Intelligent PIGs is generally more time-consuming and operationally complex compared to cleaning PIGs. Additionally, they often carry Non-Destructive Testing (NDT) technologies, such as Ultrasonic Testing (UT) and Magnetic Flux Leakage (MFL) sensors, which significantly increase operational costs [1][17].

Alternative Inspection Strategies

Petrobras' N-1487 standard [14] outlines alternative inspection methodologies to reduce dependency on full-scale Intelligent PIG runs. One such approach involves measuring pipeline wall thickness in specific subsea sections, prioritizing critical points such as the pipeline bottom axis.

To optimize costs and increase inspection frequency, this project explores simplified inspection techniques integrated into cleaning PIGs. These hybrid cleaning-inspection PIGs enable screening during routine cleaning runs, enhancing pipeline integrity assessments at a lower cost and higher frequency.

When potential damage is detected during these cleaning runs, Intelligent PIG deployments can be selectively triggered for more detailed and accurate assessments. This strategy ensures a balanced trade-off between operational cost, inspection precision, and safety assurance.

Low-Cost PIG Qualification Program

A low-cost inspection PIG has already undergone successful pre-qualification testing. This PIG features a metallic mandrel body combined with Direct Magnetic Response (DMR) sensors.

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DMR Technology Overview:

- The DMR technique relies on detecting magnetic flux distortions caused by defects on the pipeline wall [18].
- The DMR probe consists of a perpendicular magnet, a Hall-effect sensor, and a sacrificial plate.
- The magnet generates a constant magnetic flux, inducing eddy currents on the pipe wall.
- When a defect is encountered, it distorts the magnetic response, which is then detected by the Hall-effect sensor [18].

Pre-Qualification Testing Results:

- The low-cost PIG underwent four test runs in a 14-inch PIG loop located in Pindamonhangaba, Brazil.
- The average inspection speed achieved was 1.049 m/s.
- The tool successfully detected rectangular, oval, and grouped defects pre-existing in the test specimens.
- The PIG was also subjected to a 24-hour hyperbaric chamber test at 200 bar, simulating subsea conditions at 2,000 meters water depth.
- The sensors demonstrated stable performance and met the requirements specified in the Pipeline Operators Forum (POF) guidelines for In-Line Inspection (ILI) [19].

Outlook for PIG-Based Inspection Strategy

By integrating cost-effective screening tools into regular cleaning operations, Petrobras aims to enhance inspection coverage while maintaining operational efficiency. This hybrid approach leverages the strengths of both cleaning PIGs and Intelligent PIGs, ensuring cost optimization, frequent assessments, and enhanced pipeline safety.

UNPIGGABLE PIPELINES

When a pipeline is classified as unpiggable, external inspection tools become essential for integrity assessments. Unlike piggable pipelines, unpiggable ones require alternative movement methods, such as tools powered by motors, deployed by Remotely Operated Vehicles (ROVs), or manually operated by divers. Additionally, preparatory actions, such as the removal of marine growth or coatings, may be required before inspection, depending on the pipeline's condition.

Challenges in Unpiggable Pipeline Integrity Management

Managing the integrity of unpiggable pipelines is particularly challenging due to the limited availability of effective inspection tools capable of screening through thick coatings and insulation

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layers. This limitation increases the likelihood of undetected defects, often forcing operators to rely on localized direct assessment methods.

To overcome these challenges, Petrobras is actively qualifying external screening tools specifically designed for coated subsea pipelines. These tools primarily utilize technologies such as Metal Magnetic Memory (MMM) and other Non-Destructive Testing (NDT) techniques proven effective for insulated pipelines [20].

Metal Magnetic Memory (MMM) Technology

The MMM technique is a passive magnetic inspection method tailored for ferromagnetic materials [20]. It is a fast-screening technology capable of detecting magnetic anomalies caused by material defects with minimal surface preparation. Unlike other magnetic inspection methods, MMM does not require external magnetic field sources, specialized surface treatments, or additional equipment [21].

Operating Principle of MMM

- Magnetic Memory Effect: When defects are present in a ferromagnetic material, they create Stress Concentration Zones (SCZs).
- Due to the magneto-mechanical effect, these SCZs generate a Self-Magnetic Field Leakage (SMFL) [22][23].
- Sensor Detection: MMM sensors are capable of detecting these magnetic anomalies and identifying potential damage sites [24].
- Natural Magnetic Fields: One key advantage of MMM is its reliance on ambient magnetic fields, such as the Earth's magnetic field, eliminating the need for an artificial magnetic source [23].

This simplicity in setup and deployment makes MMM a highly effective and practical screening technology for inspecting unpiggable subsea pipelines.

Pre-Qualification Process for Localized Tools

The pre-qualification process for localized inspection tools designed for unpiggable pipelines is currently ongoing. Two companies are actively testing their tools in Petrobras' hyperbaric chamber to evaluate their effectiveness in detecting corrosion and cracks under simulated subsea conditions.

The tools under evaluation are based on different technologies:

1. Acoustic Resonance Technology (ART)
2. Ultrasound Techniques, including Phased Array Ultrasonic Testing (PAUT) and Time-of-Flight Diffraction (TOFD)
3. Gamma radiation (Computed Tomography)

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Acoustic Resonance Technology (ART)

- ART is based on the transient acoustic reflection phenomenon along the pipeline wall.
- A linear chirp wideband signal is emitted towards the pipeline surface, inducing oscillations and resonance in the target material.
- The resonance frequencies are directly related to the thickness and material properties of the pipeline wall.
- By analyzing these resonance frequencies, ART can accurately measure wall thickness and detect material inconsistencies [25].

Phased Array Ultrasonic Testing (PAUT)

- A phased array transducer consists of multiple piezoelectric elements, each individually controlled by a computer system.
- These elements can emit ultrasonic waves with precise control over phase, amplitude, angle, and focal distance.
- This control allows the creation of an inspection beam tailored to user-defined scan patterns, enabling detailed analysis of pipeline cross-sections [26].
- The resulting cross-sectional image provides high-resolution data for defect characterization and integrity assessment.

Time-of-Flight Diffraction (TOFD)

- TOFD is widely recognized as one of the most accurate ultrasonic techniques with a high Probability of Detection (PoD).
- It utilizes two ultrasonic transducers: one as a transmitter and the other as a receiver.
- When an ultrasonic wave encounters a defect, it generates diffracted echoes along the edges of the flaw.
- These echoes are captured by the receiver and analyzed to determine the location, size, and orientation of the defect [1][27].
- TOFD is particularly effective for weld crack detection, making it an industry-standard technique for offshore pipeline inspections.

Gamma radiation (Computed Tomography)

- Gamma ray computed tomography (CT) utilizes a radiation source and detectors arranged around the object to be inspected.
- The gamma rays penetrate the material, and the attenuation of the radiation is measured by detectors positioned at various angles.
- Advanced algorithms reconstruct the collected data into detailed cross-sectional images, providing insights into the internal structure of pipelines.
- These high-resolution images enable precise detection of wall thickness loss, material buildup, blockages, and structural anomalies, ensuring accurate integrity assessment.

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The combination of these different technologies represents a comprehensive approach to inspecting unpiggable pipelines. These methods address the challenges posed by coatings, operational depth, and structural complexity, enabling Petrobras to enhance the reliability and safety of its unpiggable pipeline network.

3. CONCLUSIONS

Petrobras' approach to optimizing the integrity management of rigid subsea pipelines relies on a two-step inspection strategy that combines screening and localized inspections to ensure comprehensive assessment, operational safety, and cost-effectiveness.

For piggable pipelines, a low-cost smart cleaning PIG utilizing Direct Magnetic Response (DMR) technology has successfully completed pre-qualification tests. Results from PIG Loop trials and hyperbaric chamber evaluations demonstrated its capability to operate at depths of up to 2,000 meters and maintain an adequate Probability of Detection (PoD). In this strategy, intelligent PIGs (Smart PIGs) are deployed as localized tools and are only run in critical segments identified during the initial screening phase, thereby optimizing inspection costs and operational time.

For unpiggable pipelines, efforts are ongoing to qualify a screening tool based on Metal Magnetic Memory (MMM) or equivalent Non-Destructive Testing (NDT) technologies. Although no MMM tool has completed pre-qualification, testing is underway. Additionally, localized tools for corrosion and crack detection are being evaluated using Ultrasound Technologies, including Phased Array Ultrasonic Testing (PAUT) and Time-of-Flight Diffraction (TOFD), as well as Acoustic Resonance Technology (ART) and Gamma Ray Computed Tomography. These tools are currently undergoing testing in a hyperbaric chamber under simulated subsea conditions. This two-step strategy significantly improves the Probability of Detection (PoD), ensuring that the entire pipeline length is efficiently screened while enabling precise defect characterization in critical areas through localized tools.

By focusing on targeted inspections, Petrobras enhances operational safety, reduces inspection-related disruptions, and potentially enables the service life extension of subsea pipelines. Furthermore, the ability to perform high-speed screening inspections reduces overall inspection times and associated costs, establishing a robust and efficient framework for managing the integrity of rigid subsea pipelines.

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REFERENCES

[1] M. Ho, S. El-Borgi, D. Patil, and G. Song, “Inspection and monitoring systems subsea pipelines: A review paper,” Struct. Heal. Monit., vol. 19, no. 2, pp. 606–645, 2020, doi: 10.1177/1475921719837718.

[2] A. Figueredo, D. Coelho, P. Miranda, M. Souza Junior, P. Melo, and C. Vaz Junior, “Subsea pipelines incidents prevention: A case study in Brazil,” Jounal Loss Prev. Process Ind., vol. 83, no. 105007, 2023, doi: https://doi.org/10.1016/j.jlp.2023.105007.

[3] DNV GL, “Recommended Failure Rates for Pipelines,” Energy Rep., 2017, [Online]. Available: www.dnvgl.com

[4] S. Vishnuvardhan, A. R. Murthy, and A. Choudhary, “A review on pipeline failures, defects in pipelines and their assessment and fatigue life prediction methods,” Int. J. Press. Vessel. Pip., vol. 201, p. 104853, Feb. 2023, doi: 10.1016/j.ijpvp.2022.104853.

[5] C. V. Amaechi, G. Hosie, and A. Reda, “Review on Subsea Pipeline Integrity Management: An Operator’s Perspective,” Energies, vol. 16, no. 1, pp. 1–12, 2023, doi: 10.3390/en16010098.

[6] W. B. Silva, G. D. S. Bessa, H. Alves, L. F. Oliveira, and T. V Alvarenga, “RELIABILITY AND STRUCTURAL INTEGRITY MANAGEMENT OF PETROBRAS / UN-RIO M . Sc ., Mechanical Engineer - PETROBRAS Mechanical Engineer – PETROBRAS M . Sc ., Metalurgicall Civil Engineer – DNV Ph . D ., Nuclear Engineer – DNV M . Sc ., Chemical Engineer – DNV,” pp. 1–7, 2009.

[7] Q. Ma, G. Tian, Y. Zeng, R. Li, H. Song, and Z. Wang, “Pipeline In-Line Inspection Method, Instrumentation and Data Management,” Sensors, 2021, doi: https://doi.org/10.3390/s21113862.

[8] American Petroleum Institute, API RP 1111 - Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines. p. 2021.

[9] D. Powell, “Integrity Management For Piggable And Non-Piggable Subsea Pipelines,” in Corrosion 2008, 2008. doi: NACE-08135.

[10] M. E. A. Ben Seghier, Z. Mustaffa, and T. Zayed, “Reliability assessment of subsea pipelines under the effect of spanning load and corrosion degradation,” J. Nat. Gas Sci. Eng., vol. 102, p. 104569, Jun. 2022, doi: 10.1016/j.jngse.2022.104569.

[11] X. Li, Y. Zhang, R. Abbassi, F. Khan, and G. Chen, “Probabilistic fatigue failure assessment of free spanning subsea pipeline using dynamic Bayesian network,” Ocean Eng., vol. 234, p. 109323, Aug. 2021, doi: 10.1016/j.oceaneng.2021.109323.

[12] DNV, DNV-RP-F105 Free spanning pipelines. 2021.

[13] Y. Long, J. Zhang, S. Huang, S. Member, L. Peng, and W. Wang, “A Novel Crack Quantification Method for Ultra-High-Definition Magnetic Flux Leakage Detection in Pipeline Inspection,” IEEE Sens. J., vol. 22, no. 16, pp. 16402–16413, 2022, doi: 10.1109/JSEN.2022.3190684.

[14] Petrobras, N-1487 Inspeção de Dutos Rígidos Submarinos. 2022.

[15] N. International, NACE SP0106 - Control of Internal Corrosion in Steel Pipelines and Piping Systems. 2018.

 https://doi.org/10.52202/078572-0101

[16] M. Coramik and Y. Ege, “Discontinuity inspection in pipelines: A comparison review,” Measurement, vol. 111, pp. 359–373, 2017, doi: https://doi.org/10.1016/j.measurement.2017.07.058.

[17] C. Jones and R. Smith, “Cost Effective Smart Cleaning Pigs Enabling High Frequency Pipeline Inspection,” in Offshore Technology Conference Asia, 2018. doi: https://doi.org/10.4043/28553-MS.

[18] A. Aljarah, N. Vahdati, and H. Butt, “Magnetic Internal Corrosion Detection Sensor for Exposed Oil Storage Tanks,” Sensors, vol. 21, no. 2457, 2021, doi: https://doi.org/10.3390/s21072457.

[19] Pipeline Operators Forum, Specifications and requirements for in-line inspection of pipelines, no. November. 2021.

[20] M. N. A. and R. R. † N. Roslin, M.N. Baharin, “Metal Magnetic Memory Technology: Assessment on Insulated Piping,” in 15th Asia Pacific Conference for Non-Destructive Testing, 2017, pp. 1–5.

[21] J. J. Villegas-saucillo, D. Javier, and C. A. Cer, “Measurement System of Metal Magnetic Memory Method Signals around Rectangular Defects of a Ferromagnetic Pipe,” Appl. Sci., vol. 9, no. 2695, 2019, doi: https://doi.org/10.3390/app9132695.

[22] A. Dubov, “Principal Features of Metal Magnetic Memory Method and Inspection Tools As Compared To Known Magnetic NDT Methods,” in ECNDT, 2006, pp. 1–5.

[23] K. Liao, L. Long, and H. Zhang, “Early Inspection of Weld Seams on Gas Pipelines Based on Metal,” Open Pet. Eng. J., pp. 1–9, 2016, doi: 10.2174/1874834101609010001.

[24] A. Wieczorska and A. Koson-Schab, “Using Metal Magnetic Memory to Evaluate the Effect of Welding Method and Weld Temperature on Magnetic Field Strength in Structural Steel,” Materials (Basel)., vol. 16, no. 5256, 2023, doi: https://doi.org/10.3390/ma16155256.

[25] S. Eldevik, “Measurement of non-linear acoustoelastic effect in steel using acoustic resonance,” University of Bergen, 2014.

[26] J. Verkooijen and A. Boulavinov, “Sampling phased array - A new technique for ultrasonic signal processing and imaging,” Insight Non-Destructive Test. Cond. Monit., vol. 50, no. 3, pp. 153–157, 2008, doi: 10.1784/insi.2008.50.3.153.

[27] H. Willems, H. Bjorn, T. Kristiansen, and G. Wieme, “Qualification of a Combined Ultrasonic Inspection Tool for Detection and Sizing of Circumferential Weld Cracks in Offshore Pipelines,” in International Pipeline Conference, 2014.

https://doi.org/10.52202/078572-0101